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

Trends in Nordic and Arctic extreme temperatures

REPORT NR: 13/98

Heikki Tuomenvirta, Hans Alexandersson, Achim Drebs,
Povl Frich and Per Øyvind Nordli

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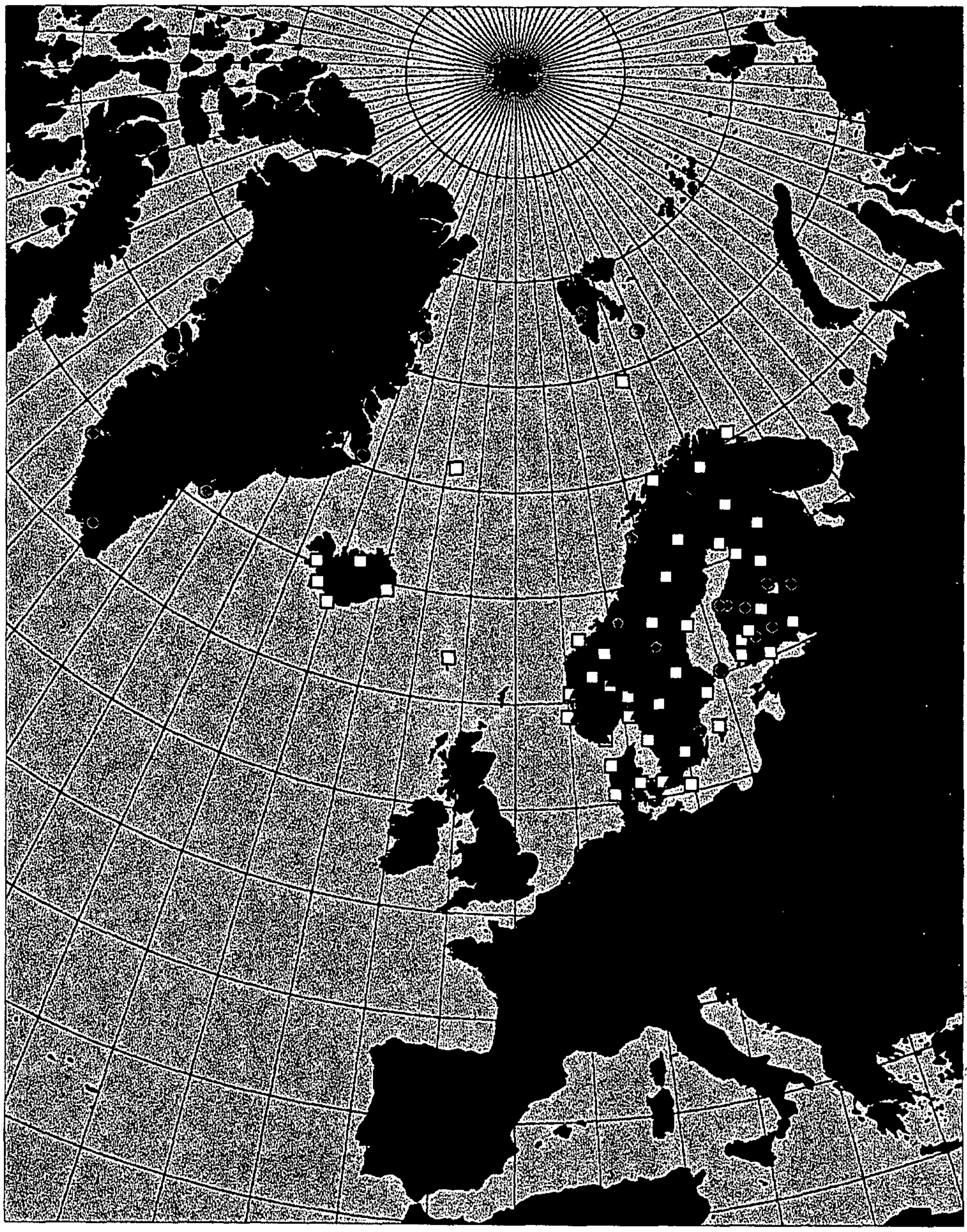

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PROJECT CONTRACTORS

Nordic Council of Ministers (contract FS/HFj/X-93001) and the national meteorological institutes in Denmark[3], Finland[1], Iceland, Norway[4] and Sweden[2].

ABSTRACT

The Nordic meteorological institutes produced a comprehensive data set of climatic extremes containing stations from Fenno-Scandia, Nordic Seas, and Greenland. Long-term time series of extreme (daily mean maximum, daily mean minimum, absolute highest and absolute lowest) temperatures and temperature ranges were analysed for trends. Indices of atmospheric circulation and cloudiness were used to explain the observed temperature changes. The work was accomplished under the REWARD (Relating Extreme Weather to Atmospheric circulation using a Regionalised Dataset) project in 1996-1997.

Mean maximum and minimum temperatures show statistically significant negative trends in West-Greenland during the period 1950-1995, while the trends are generally positive in Nordic Seas and Fenno-Scandia. The highest and lowest temperatures seem to follow the variations in the mean values. The highest and lowest temperatures have not become more extreme compared to the mean maximum and minimum. The diurnal temperature range (DTR) is decreasing significantly throughout the study area despite the fact that regional temperature trends show both warming and cooling.

The strengthening of North Atlantic Oscillation (NAO) causes the opposite temperature trends between West-Greenland and Fenno-Scandia since the 1950s. However, NAO index fails to explain the decrease of DTR in West-Greenland and explains only partly DTR narrowing in Fenno-Scandia.

In Fenno-Scandia, the long-term reliable mean maximum and minimum temperatures show cooling in winter, and warming in spring and summer during the period 1910-1995. Simultaneously, DTR has been decreasing in all seasons except winter (-0.30K/100year on annual level).

Atmospheric circulation indices defined as zonal and meridional sea level pressure differences, sea level pressure anomalies, and cloud cover were used to build multiple linear regression model for Fenno-Scandian DTR during the period 1910-1995. Seasonally, the linear models explain from 53% (winter) to 80% (summer) of the DTR variance. Cloud cover dominates as the most important predictor, but circulation give substantial support.

SIGNATURE

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CONTENTS

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 - **R**elating **E**xtreme **W**eather to **A**tmospheric circulation using a **R**egionalised **D**ataset*.

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

1. Introduction

The studies of climatic changes often focus on mean values, although the impacts of changes may be related to the changes in the frequencies or severity of climatic extremes. The Second Assessment report of the IPCC discussed on the observed (Nicholls et al. 1996) and modelled (Kattenberg et al. 1996) changes in temperature extremes and ranges. The extreme temperature events are important because natural environment and human society can be vulnerable to exceptionally high and low temperatures. The diurnal temperature range (DTR) is interesting mainly because large areas of the globe have shown decreasing trends during past the 40 years or so (Easterling et al. 1997). The decrease may be related to the anthropogenic influence (increase of greenhouse gas and aerosol concentrations) on the climate system. DTR is studied also because it affects ecosystems, e.g. agricultural productivity (Nicholls 1997).

Studies of trends in the far tails of the temperature distribution based on the highest and lowest monthly temperatures are not common. However, DTR changes have received large attention. One of the first to report on global scale DTR changes were Karl et al. (1991) and Karl et al. (1993). A comprehensive review can be found from Nicholls et al. (1996). An updated global study is performed by Easterling et al. (1997). In the Nordic and Arctic region, DTR studies have been reported by Frich (1994), Heino (1994), Kaas and Frich (1995), and Heino et al. (1998).

In the Nordic countries, the national meteorological institutes of Denmark (DMI), Finland (FMI), Iceland (VI), Norway (DNMI), and Sweden (SMHI) have worked jointly under the projects REWARD (Førland et al. 1998) and NACD (Frich et al. 1996; Dahlström et al. 1995) to collect long-term observational time series of climatological elements. In the REWARD project, one of the objectives was the preparation of data series of temperature and precipitation extremes. As a result, a climate data set including monthly maximum and minimum temperatures was created (Drebs 1998).

REWARD temperature data in Drebs (1998) is the first digital version of extreme temperature data from the Nordic and Arctic area. The longest time series start in the 1870s, but good spatial coverage is reached in the beginning of the 20th century. The data set contains many time series not published earlier in digital format and covers the Nordic countries, including the Faroe Islands, Greenland, Jan Mayen, and Svalbard. We would like to point out that the data set can be used also for practical applications like calculation of return periods.

We present temperature trends, test their significance and try to understand what causes the observed trends. The local temperature changes are influenced by atmospheric circulation pattern changes. The North Atlantic Oscillation (NAO) shows large quasi-decadal variability which affect Greenland and Northern Europe temperature trends, especially in winter (Hurrel and van Loon 1997). Besides the circulation, also changes in cloud cover are considered when discussing the mechanisms causing observed trends in maximum and minimum temperatures.

In chapter 2, we give the description of data and methods. Also, typical climatological values are given. In chapter 3, we present the methods which have been used to improve the quality of the data. An estimation of the reliability of the data is made. Trend analysis of various temperature elements are described in chapter 4. In chapter 5, temperature variations in Fenno-Scandia are described as a function of atmospheric circulation and cloudiness. The following chapter discusses the results. Finally, we list the conclusions in the last chapter.

2. Nordic and Arctic temperature data

2.1 Stations and elements

The national meteorological institutes of the Nordic countries have collected long-term extreme temperature data (Drebs 1998). Monthly mean daily maximum (Tx) and minimum (Tn), and the highest maximum temperature (Th) and the lowest minimum temperature (Tl) of each month from 67 stations have been retrieved from data archives. The geographical distribution of stations is shown in Fig. 1. The Appendix contains a list of stations used in this study. Almost all the stations have records starting before 1950 and about 65% of them started in 1910 or earlier, most of them located in Fenno-Scandia. Usually the time series of Tx and Tn start around the same time except in Norway, where the Tn series are often 50 years or more longer than the corresponding Tx series. Some of the most reliable stations were selected to describe climate changes during the past 120 years or so.

Fig. 2 shows the temperature climatology of four characteristic stations within the Arctic and Nordic region. The smallest DTR, defined as Tx-Tn, is found from Thorshavn all year round and Nordby in summer. Roughly two times larger is the widest DTR at Haparanda during summer. The large intra-monthly extreme temperature range (ETR), defined as Th-Tl, at Upernavik during winter is due to occasional Foehn situations. Haparanda is the most continental station, with the largest intra-annual ETR, as opposed to Thorshavn, which has a maritime climate of suppressed DTR and ETR throughout the year. Nordby has the largest intra-monthly ETR during summer of the four stations. Readers wishing to learn more about the climatology of extreme temperatures are referred to Tveito et al. (1998), and to the various yearbooks and climatological atlases published by the national meteorological institutes.

2.2 Handling of data

The largest distances between stations in Fig. 1 are over 3500 km. It is obvious that the data set contains stations which have experienced very different temperature evolution. For the analysis, we divided the stations into three geographical groups: Fenno-Scandia, Nordic Seas, and West-Greenland.

The Fenno-Scandia region (containing 52 stations) covers Norway, Denmark, Sweden, and Finland. Hanssen-Bauer et al. (1996) performed a principal component analysis of the NACD annual mean temperatures (Frich et al. 1996). The analysis showed that Fenno-Scandia forms a relatively uniform area, which has experienced different temperature variations than the oceanic regions to the west of Fenno-Scandia. The Nordic Seas region (11 stations) consists of stations in East-Greenland, Iceland, Jan Mayen, Faroe Islands, and Svalbard. Year-to-year temperature variations in most of the Nordic Seas stations are strongly attenuated by the ocean. The West-Greenland region (4 stations) contains stations located on the west coast of Greenland between latitudes 61°N and 73°N. On average, these stations are to the west of the Icelandic low.

Temperature anomalies are spatially conservative and, therefore, more suitable for area-averaging than the actual temperatures (Jones and Hulme 1996). In this study, the anomalies are calculated as deviations from the normal period 1961-1990 mean. Annual and seasonal anomalies are analysed. Seasons are defined as three month periods: December, January, and February (DJF); March, April, and May (MAM); June, July, and August (JJA); September, October, and November (SON).

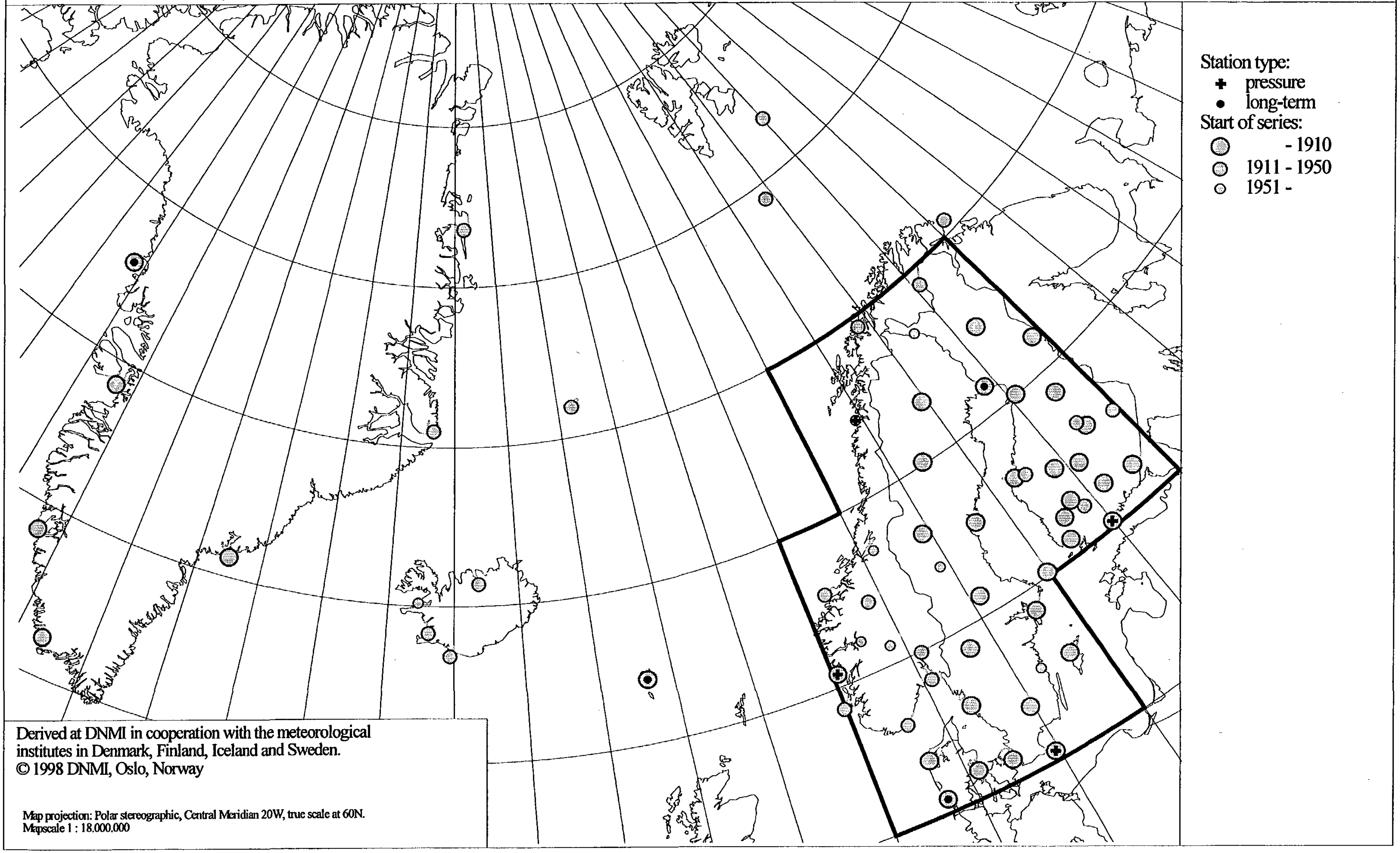

Fig. 1. Map of stations. Start year of the shortest series (Tx, Tn, Th, or Tl): >1950 or not all elements, >1910, or <=1910. The air pressure and selected long-term stations are marked. The grid used in the calculations of Fenno-Scandian area-averages is marked.

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

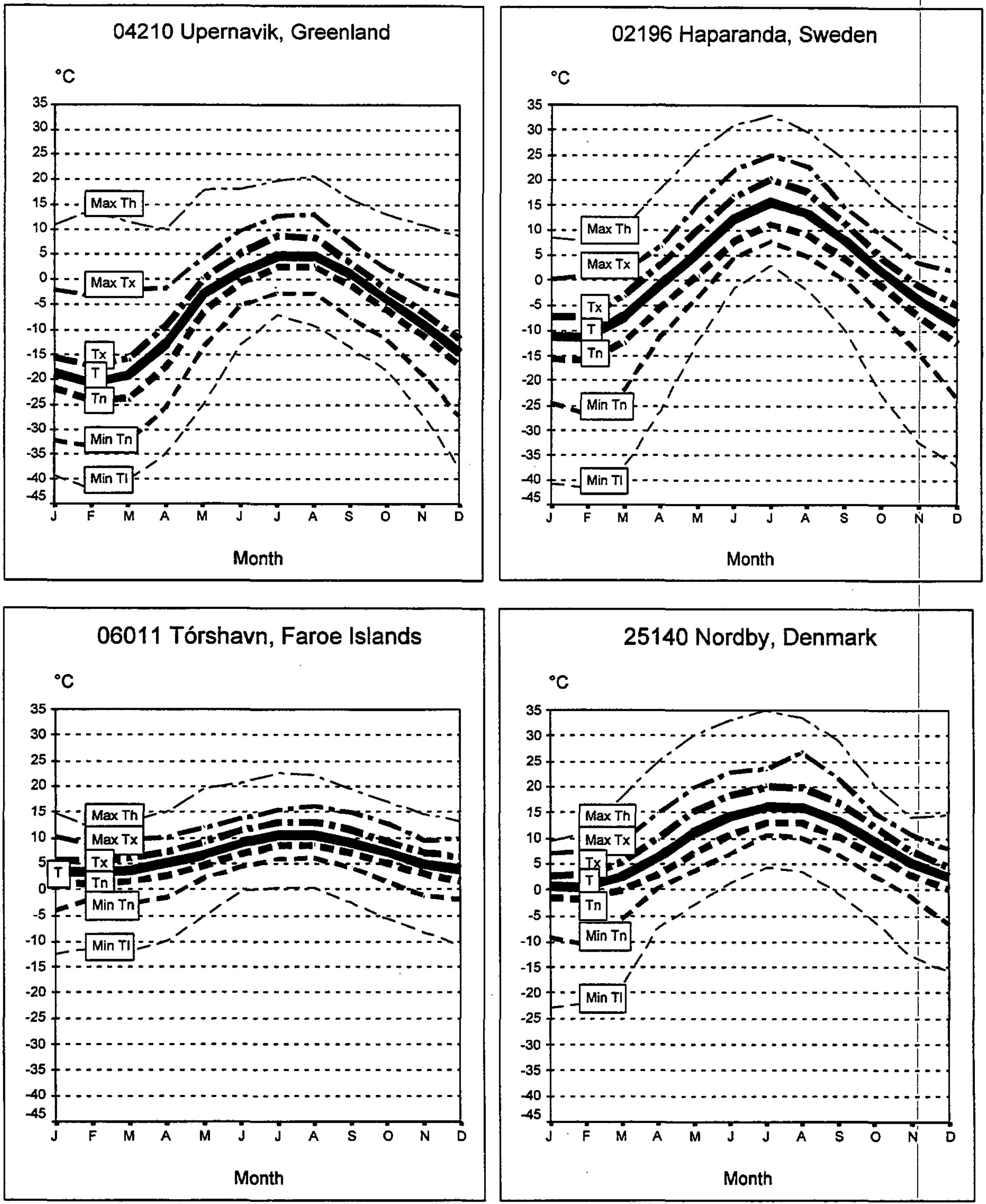

Fig. 2. Temperature climatology of four selected stations in the Arctic and Nordic regions for the period 1890-1990. See text for explanations and map for location of stations (Fig. 1).

In Fenno-Scandia, the anomaly series of gridded temperature extremes as well as temperature ranges, were established for 5° by 5° latitude-longitude grid boxes (Fig. 1). The grid box value is an arithmetic average of temperature anomalies for all stations in the grid box. Two Norwegian stations (Utsira and Vardø) located just outside the grid were included to the nearest grid boxes. Fenno-Scandia value is an area-weighted average of the grid box values. Nordic Seas and West-Greenland values are simply averages of temperature anomalies for all stations in the regions.

Two types of low pass filters including Gaussian weighting coefficients have been used to smooth out inter-annual variability and to display long-term trends. The standard deviation of the Gaussian distribution used in the filters are 3 and 9 years, referred to hereafter as GF3 and GF9, which approximately correspond to 10- and 30-year moving averages. The shape of the curves at the beginning and the end of series can change when new values are added.

The non-parametric Mann-Kendall test is chosen for testing the significance of trends, as it can be used without knowing the exact distribution of the time series. Its test statistic, t, is defined by the equation

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

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). Providing that $n > 10$, the test statistic is very nearly normally distributed under the hypothesis of randomness (the null hypothesis). Moreover, its expectation, E(t), and variance, var t, are given by the equations

$$E(t) = \frac{n(n-1)}{4} \qquad \operatorname{var} t = \frac{n(n-1)(2n+5)}{72}$$

The standard distribution, u(t), of the test statistic is then

$$u(t) = \frac{t - E(t)}{\sqrt{\operatorname{var} t}}$$

A percent table of the normal distribution function may be used to decide whether the null hypothesis should be rejected or not.

3. Reliability of data

3.1 Quality control and homogeneity testing

The standard quality control routines have been applied to the data in each national meteorological institute. Because the focus is on the extreme values, especially the highest and lowest values were checked.

In climate change studies, it is important that the time series are as homogeneous as possible, i.e. the variations in time series result solely from the variations of climate. Otherwise, the trend estimates are unreliable. In reality, the long-term time series are seldom homogeneous, but contain besides natural climate variations also artificial jumps or gradual shifts due to changes in station location, instrumentation, or environment (Heino 1994). The growth of towns to cities usually affects temperature trends. It certainly has an effected on a few of the Nordic cities, but we will show that urbanisation is not biasing the area-averages. Therefore, it is critical that the homogeneity questions are addressed before moving into any analysis of trends.

The homogeneity testing and adjusting of inhomogeneous data followed the principles adopted during the NACD project (Frich et al. 1996). The Standard Normal Homogeneity Test (SNHT) developed by Alexandersson (1986), and refined by Alexandersson and Moberg (1997) were used. Hanssen-Bauer and Førland (1994) give a good example of the use of the test. SNHT is a parametric test using reference series to identify non-homogeneities in time series. Usually the reference series are composed of time series of neighbouring station(s). Another method to build reference series is to use other climatic elements from the station being tested, e.g. test mean maximum/minimum temperatures against clock-mean temperatures.

At DMI, all the extreme temperature elements (Tx, Tn, Th, and Tl) of the Danish and Faroe station data were tested with SNHT. Programs and methods described in Steffensen et al. (1993) and Steffensen (1996) were applied. The testing and adjusting of Th and Tl was the first attempt to adjust these very noisy elements. Adjustments of Tx and Th were very similar, as were the adjustments of Tn and Tl. Greenlandic temperatures were not tested.

In total, about 100 Finnish stations with time series of Tx and Tn were tested with SNHT. Also, station history information were used in identification of the homogeneity breaks. Method of testing and adjusting followed the principles used for the Finnish mean temperatures (Tuomenvirta and Heino 1996; Tuomenvirta and Drebs 1994). It appears that the maximum and minimum temperatures are more sensitive to site, screen, and environment changes than the mean temperatures. Finally, besides the 10 Finnish stations included into NACD, also 8 additional good quality stations were included into the analysis. Th and Tl series were not tested. However, the test results of Tx and Tn suggest that many of the Finnish Th and Tl series are not homogeneous.

Tx and Tn are influenced by the definition of the temperature day interval. At DNMI an old practice was to set the thermometer only at the morning observation, but from 1 January 1938 it was also set in the evening. Since then the temperature day interval has been defined as the last 24 hours preceding the evening observation. The change led to negative bias in the minimum temperature before 1938 compared to the current practice. The bias (-1.7 - 0.0 °C) varies with season, climate and latitude. Thus, before 1938 individual adjustment terms are required to ensure homogeneity (cf. Nordli 1997). These were applied to the series of the present data set before the series were tested for other inhomogeneities by the SNHT. Due to the lack of digitised reference stations near by the test station, mean temperature of the test station was used as reference. Only if the inhomogeneities revealed by SNHT were confirmed by station history, the series were adjusted.

The Icelandic and Swedish temperature data have not been tested. The Icelandic time series (starting 1949 or later) are of good quality. The long Swedish series very likely contain some homogeneity breaks due to station relocations and screen changes.

3.2 Comparison with NACD mean temperatures

The reliability of Tx and Tn series was estimated by performing a comparison with the updated and partly readjusted NACD mean temperatures, hereafter referred T. A commonly used formula (e.g. in USA, UK, Australia) for calculating daily mean temperature is ½(Tx+Tn). However, none of the Nordic institutes has ever used it in the official yearbooks. Instead, different variations of formulas based mainly on observations at fixed hours have been used (Nordli et al. 1996).

Fig. 3 shows the GF3 smoothed differences between the two estimates of the annual mean temperature anomalies, T - ½(Tx+Tn), during the period 1890-1995. In Fenno-Scandia, the agreement is good. The largest annual difference is 0.23°C (not shown). There are no large, systematic biases despite some inhomogeneous stations. This indicates that the Fenno-Scandian average series of Tx and Tn are reliable. Nordic Seas and West-Greenland regions have systematic, negative differences in the early parts of the series. The largest annual differences are -0.6°C in Nordic Seas and -0.8°C in West-Greenland. Most of the untested Tx and Tn series are too warm compared to homogenised T. The station relocations and screen type changes have caused the biases. However, the period 1950-1995 seems to be reliable in all regions.

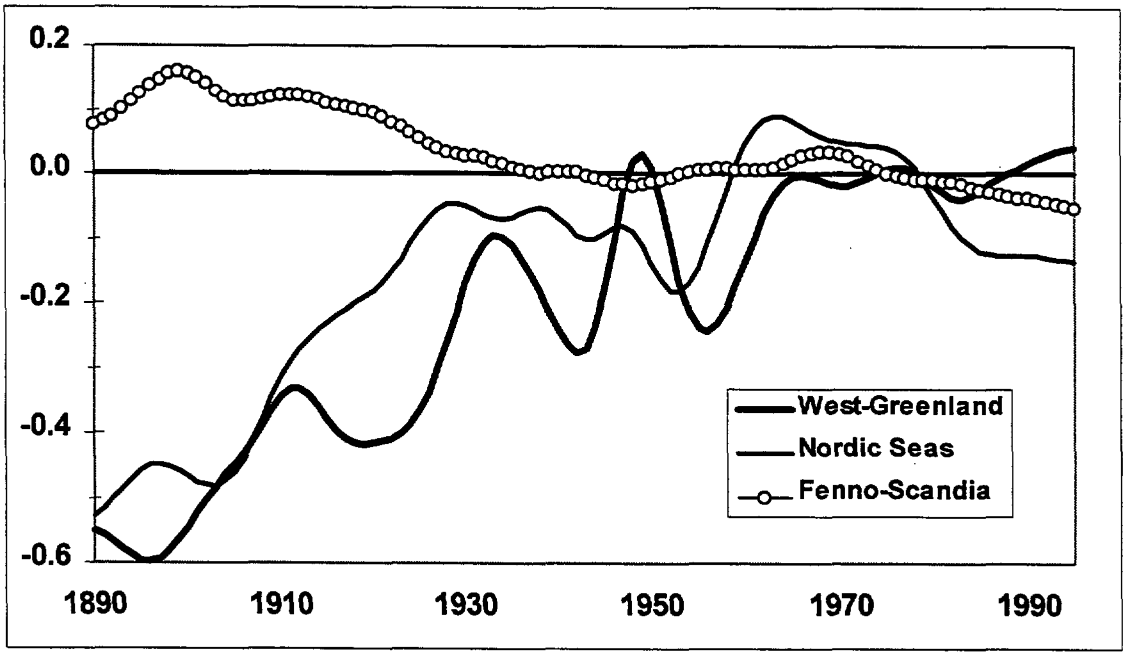

Fig. 3. GF3 smoothed differences between two estimates of annual mean temperature anomalies (reference period 1961-1990): T from NACD (updated and readjusted) - ½(Tx+Tn) from REWARD.

In the Nordic countries several types of screening of the thermometers have been in use, i.e. open shelters, wall screens, free-standing screens of old and new types (Nordli et al. 1997). In Denmark, Iceland and Norway most of the old stations still running have once in history undergone changes from wall screens to free-standing screens. These changes may especially impede Th and Tl and may for individual months and stations amount to a few degrees in the worst cases (unpublished Danish measurements). The sign of the adjustments also varies from station to station, however, it seemed to be a tendency of higher Th and lower Tl in the wall screens compared to the free-standing screens. This might be a result of less mass, and as a consequence, less time lag for temperature changes in the wall screen than in the free-standing screen. Another systematic change in the national networks is the replacement of single by doubled louvered screens leading to artificial reduction of Th and Tx in summer (about 0.2°C or less for Tx and probably more for Th). Most of the screen changes took place before 1950. Thus, inhomogeneities caused by screen changes will not hamper the analyses of the period 1950-1995, cf. next chapter.

Especially Th and Tl but also Tx and Tn are sensitive to station relocations and screen type changes, even more sensitive than the mean temperature calculated from fixed hourly observations. It is unrealistic to think that all inhomogeneities are removed from the data sets. However, by area and seasonal averaging, non-systematic inhomogeneities might be regarded as noise without causing false trends. The main problem is the systematic inhomogeneities of the long untested series that can give severely biased regional averages like Tx and Tn in West-Greenland and Nordic Seas, as shown in Fig. 3. These area-averages cannot be used for long term trend analysis. The test results of the Fenno-Scandian data indicate, however, that the long Tx and Tn time series can be adjusted to give homogeneous regional averages.

I should be emphasised, that the formula ½(Tx+Tn) of calculating mean temperature could lead to a bias in the hemispheric and global mean temperature of about 0.2 - 0.3 degrees, if similar screen changes as in Greenland and the Nordic Seas have taken place over wider part of the Globe during the early decades of this century, and if they have not been properly adjusted. This however needs to be documented and will require access to the station metadata.

4. Trends of extreme temperatures and temperature ranges

4.1 Period 1950-1995

Easterling et al. (1997) have calculated annual and seasonal trends from 1950 to 1993 for Tx, Tn, and DTR for the Northern Hemisphere (NH). Their data set covered 54% of the total global land area. REWARD data set contains many stations which were not yet available for Easterling et al. (1997) or Karl et al. (1993) and expands to regions not covered earlier. It gives much better coverage over Fenno-Scandia, Nordic Seas and Greenland covering roughly 2% of the global land area. However, one can claim that the "representative coverage" is larger because it contains several stations located in data sparse ocean areas, e.g. in Iceland, Jan Mayen, Svalbard, and Faroe Islands.

In Fig. 4, the seasonal and annual trends of Tx, Tn, and DTR anomalies in Fenno-Scandia, Nordic Seas, and West-Greenland are compared with those of the Northern Hemisphere (NH), see Table 1 for the exact values. The annual time series are displayed in Fig 5.

Fenno-Scandian and NH trends of Tx and Tn generally have the same sign, except JJA Tx and SON Tn (neither of them statistically significant). NH has experienced significant warming on annual level and in all seasons, except autumn. In Fenno-Scandia, the only statistically significant trend in is the spring warming of Tn. The NH summer warming is not visible in Fenno-Scandia.

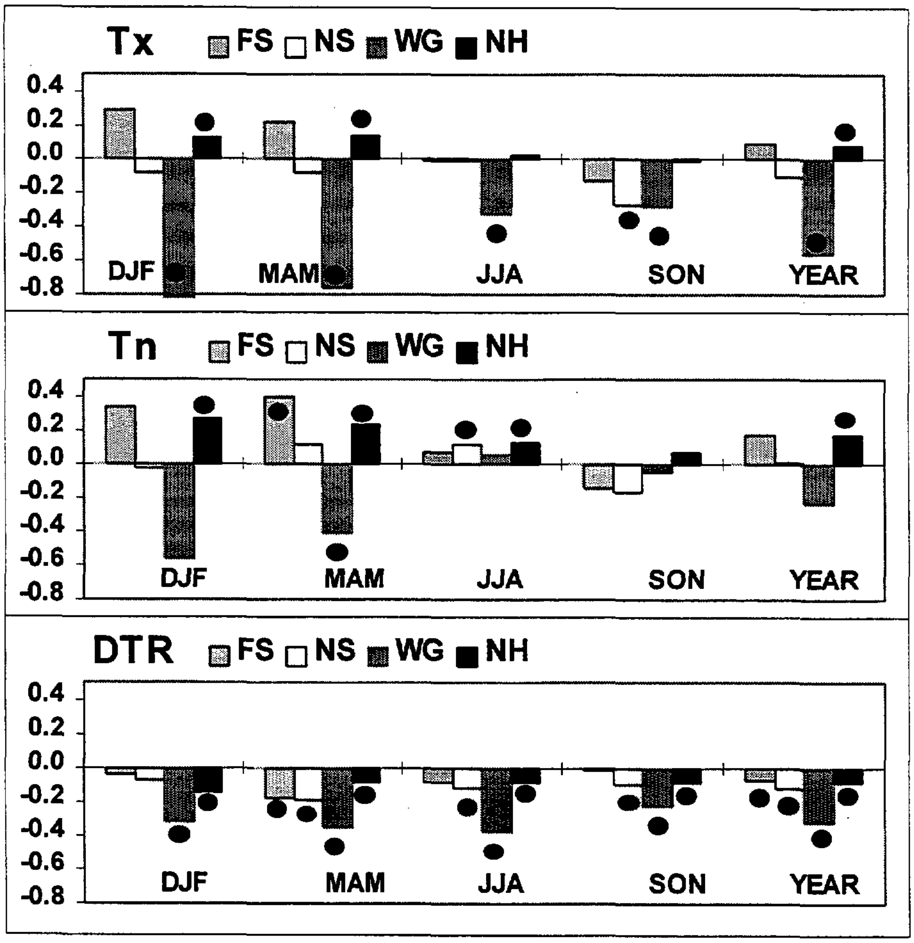

Fig. 4. Linear trends of Tx, Tn, and DTR (°C/10 years) of Fenno-Scandia (FS), Nordic Seas (NS), West-Greenland (WG), and Northern Hemisphere nonurban stations (NH) from Easterling et al. (1997), in 1950-1995 except 1950-1993 for NH. The statistically significant trends, Mann-Kendall at the 0.05 level, are marked with black dots (t-test at the 0.05 level for NH data).

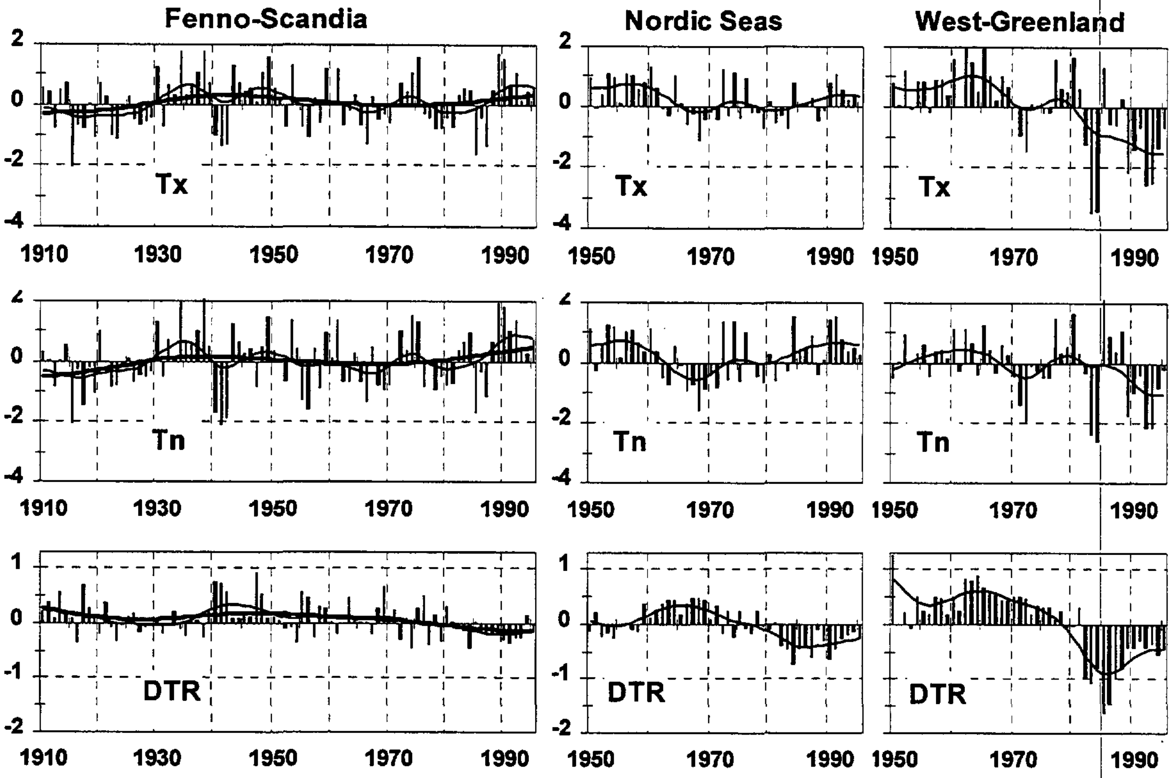

Fig. 5. Annual anomalies (°C) of Fenno-Scandian, Nordic Seas and West-Greenland area-averaged Tx, Tn, and DTR, smoothed with GF3 (thin line) and GF9 (thick line), (reference period 1961-1990). N.B. Different scales for Tx/Tn and DTR.

In West-Greenland, the Tx trends are negative and statistically significant and the area also shows significant negative Tn trends in MAM. The West Greenland trends have mostly opposite sign compared to the NH trends. The Nordic Seas represent a transition region from the mostly positive Tx and Tn trends in Fenno-Scandia to negative trends in West-Greenland. In general the Nordic Seas trends are small due to strong oceanic influence. However, a negative SON Tx trend and a positive JJA Tn trend are significant.

The winter temperature seesaw between Greenland and northern Europe, i.e. the tendency for temperatures to be low over northern Europe when they are high over Greenland, and conversely, is well-known (van Loon and Rogers 1978). It is linked to the North Atlantic Oscillation (NAO), which is strongest in winter, but is evident also in other seasons. The NAO index is defined as sea level pressure difference between Ponta Delgada, Azores and Stykkisholmur, Iceland, distance almost 3000 km (data provided by T. Jónsson, Icelandic Meteorological Office). It describes the strength of the westerlies over the extratropical North-Atlantic.

In recent years, the winter NAO index has been high producing warm winters in Fenno-Scandia (e.g. Tuomenvirta and Heino 1996, Alexandersson 1994). This is not, however, the only circulation pattern producing warm winters as described by Rogers (1997). Correlation coefficients between NAO and Tx/Tn in Fenno-Scandia and West-Greenland are high during the period 1950-1995 while the NAO correlations within the Nordic Seas area are lower.

The highest correlation coefficients are found with NAO and the temperature difference between Fenno-Scandia and West-Greenland. They range from 0.85 in winter to 0.55 in spring. The linear regression of NAO with temperature difference (Fenno-Scandia minus West-Greenland) explains about 60% of the variance on annual level during the period 1950-1995. The opposite temperature trends in Fenno-Scandia and West-Greenland are in accordance with the strengthening of NAO which has occurred in the winter half year (Nov-Mar) since the 1960s. In fact GF3 values of NAO have been positive since the early 1970s. This prolonged positive phase of the NAO is unprecedented since the beginning of the series in 1823-1824 (Jones et al. 1997).

Table 1. Linear trends of Tx, Tn, DTR, Th, Tl, and ETR (°C/10 years) of Fenno-Scandia (FS) area-average, Nordic Seas (NS), West-Greenland (WG), and Northern Hemisphere non-urban stations (NH) from Easterling et al. (1997), in 1950-1995 (NH period 1950-1993). The statistically significant trends, Mann-Kendall at the 0.05 level, are in bold numbers (t-test at the 0.05 level for NH data).

°C/10years	**DJF**	**MAM**	**JJA**	**SON**	**Year**
Tx (FS)	0.29	0.22	-0.01	-0.13	0.09
Tx (NS)	-0.09	-0.08	-0.01	**-0.27**	-0.11
Tx (WG)	**-0.89**	**-0.76**	**-0.33**	**-0.29**	**-0.57**
Tx (NH)	**0.13**	**0.14**	0.02	-0.01	**0.08**
Tn (FS)	0.34	**0.40**	0.07	-0.14	0.17
Tn (NS)	-0.03	0.11	**0.11**	-0.17	0.01
Tn (WG)	-0.57	**-0.41**	0.05	-0.05	-0.24
Tn (NH)	**0.27**	**0.23**	**0.12**	0.07	**0.17**
DTR (FS)	-0.04	**-0.18**	-0.08	-0.01	**-0.07**
DTR (NS)	-0.07	**-0.19**	**-0.12**	**-0.10**	**-0.12**
DTR (WG)	**-0.32**	**-0.35**	**-0.38**	**-0.23**	**-0.32**
DTR (NH)	**-0.14**	**-0.09**	**-0.08**	**-0.08**	**-0.09**
Th (FS)	0.17	**0.38**	0.08	0.03	**0.16**
Th (NS)	-0.11	-0.13	0.04	**-0.21**	**-0.10**
Th (WG)	-0.67	**-0.48**	**-0.26**	-0.11	**-0.39**
Tl (FS)	0.45	**0.42**	0.04	-0.29	0.15
Tl (NS)	-0.01	0.22	**0.13**	-0.06	0.07
Tl (WG)	-0.76	**-0.50**	0.06	-0.19	**-0.34**
ETR (FS)	-0.29	-0.04	0.03	0.31	0.00
ETR (NS)	0.03	-0.24	-0.09	-0.16	-0.11
ETR (WG)	0.09	0.02	**-0.32**	0.08	-0.04

DTR trends reveal the differences in the evolution of Tx and Tn. The trends of DTR anomalies are negative in all regions despite the fact that the regional temperature trends are opposite (Fig. 4). For example, in Fenno-Scandia, the spring temperatures have been rising, and in West-Greenland they have been decreasing, yet both regions show statistically significant narrowing of DTR. Furthermore, the narrowing of DTR seems to be statistically significant over the entire area. The size of seasonal and annual negative DTR trends in Fenno-Scandia and Nordic seas are comparable to the NH ones. In Greenland the decrease has been roughly three times steeper than the NH average.

Easterling et al. (1997) found significant correlation, -0.37, between a westerly index (Wallace et al. 1997) and DTR over the region 60°W to 90°E, 30°N to 80°N using yearly values. This is in general agreement with our findings. A closer look shows that the NAO index correlates with DTR much less than with Tx and Tn in all three regions, Fenno-Scandia showing highest correlation. The correlation coefficients are not statistically significant in West-Greenland in any season. In Fenno-Scandia and Nordic Seas, significant correlation cannot be found in summer. The transition seasons are close to 95% significance level, from -0.12 to -0.26. The strongest correlation, -0.48, is found during winter in Fenno-Scandia. The recent increase of NAO explains a fraction of the DTR decrease in Fenno-Scandia (22% of the variance explained by linear regression between NAO and DTR on annual level), but not in the other regions. This topic will be discussed more in chapter 5.4.

Table 1 contains also the trends of Th and Tl (no figures). They tell more about the lower and upper tails of temperature distributions than Tx and Tn, e.g. a station's MAM value of Th/Tl is a mean of 3 readings compared to Tx/Tn which is a mean of 92 readings. However, it turns out that Th and Tl behave very much like Tx and Tn, e.g. linear trends have the same sign. The qualitative similarity of Tx and Th, and, Tn and Tl, variations is an indication that the tails of the temperature distributions, in a broad sense, seem to follow the variations of the mean value. This was confirmed by testing the linear trends of Th-Tx and Tl-Tn. Only in West-Greenland, MAM highest and SON lowest temperatures have became more extreme compared to Tx and Tn. No significant trends were found in Fenno-Scandia or in Nordic Seas.

We calculated also seasonal and annual extreme temperature range (ETR) trends based on intra-monthly ETR, Th-Tl. Although the sizes of linear trends of ETR are roughly comparable to DTR, ETR trends are generally not statistically significant due to larger variance.

4.2 Period 1910-1995 in Fenno-Scandia

The number of available stations for analysis decreases as the time period of study is extended, especially in the Nordic Seas and West-Greenland, where there are also problems with the homogeneity. In Fenno-Scandia, the records before 1900 are mainly from Denmark and Sweden. However, there are more than 30 (40) stations with Tx (Tn) series covering the period 1910-95 in Fenno-Scandia. During this 86 year period, the Fenno-Scandian average anomalies of Tx and Tn can be considered reliable. The use of a large number of stations effectively smooth out any possible remaining inhomogeneities in the time series of area-averages, provided that the inhomogeneities are random.

The smoothed seasonal time series of Fenno-Scandian Tx, Tn, and DTR anomalies are presented for the period 1910-1995 in Fig. 6 (annual series in Fig. 5). Linear trends do not characterise too well the Fenno-Scandian temperature variations in the period 1910-1995. Therefore, the long-term change is calculated as the difference between mean values of the periods 1966-1995 and 1910-1939 (Table 2). This particular length of the periods (30 years) are chosen in agreement with the practice of the IPCC-report (Nicholls et al. 1996). Mann-Kendall test was used to evaluate the statistical significance of the trends.

In winter, there has been large temperature variations. The recent warm winters (1988-1995) seem to surpass even the warm 1930s. The spring displays a warming through out this century. However, only the Tn warming has been statistically significant (Table 2). The summer temperatures show fluctuations but no clear trend. The autumns have been the most steady of all seasons.

The wintertime standard deviation of Tx and Tn anomalies are about two times larger than in the other seasons. During winter, the standard deviation of Tn is larger than the standard deviation of Tx, conversely in summer. In winter, the radiative cooling limits the highest temperatures and reduces Tx variability. On the contrary, the positive radiation balance during summer limits the lowest temperatures and reduces Tn variability. Otherwise, the smoothed behaviour of Tn is fairly similar to Tx. The same cold and warm periods peak out. However, the magnitudes are different, especially in summer.

The studies of long-term DTR trends reveal less coherent picture than the last 50 years seen in the previous section. Selected series from central and northern Europe show both decreasing and increasing trends (Brazdil et al. 1996, Heino et al. 1998). In USA, the DTR stayed relatively constant during the first decades of the century and the decrease has mostly appeared after the 1950s (Karl et al. 1993).

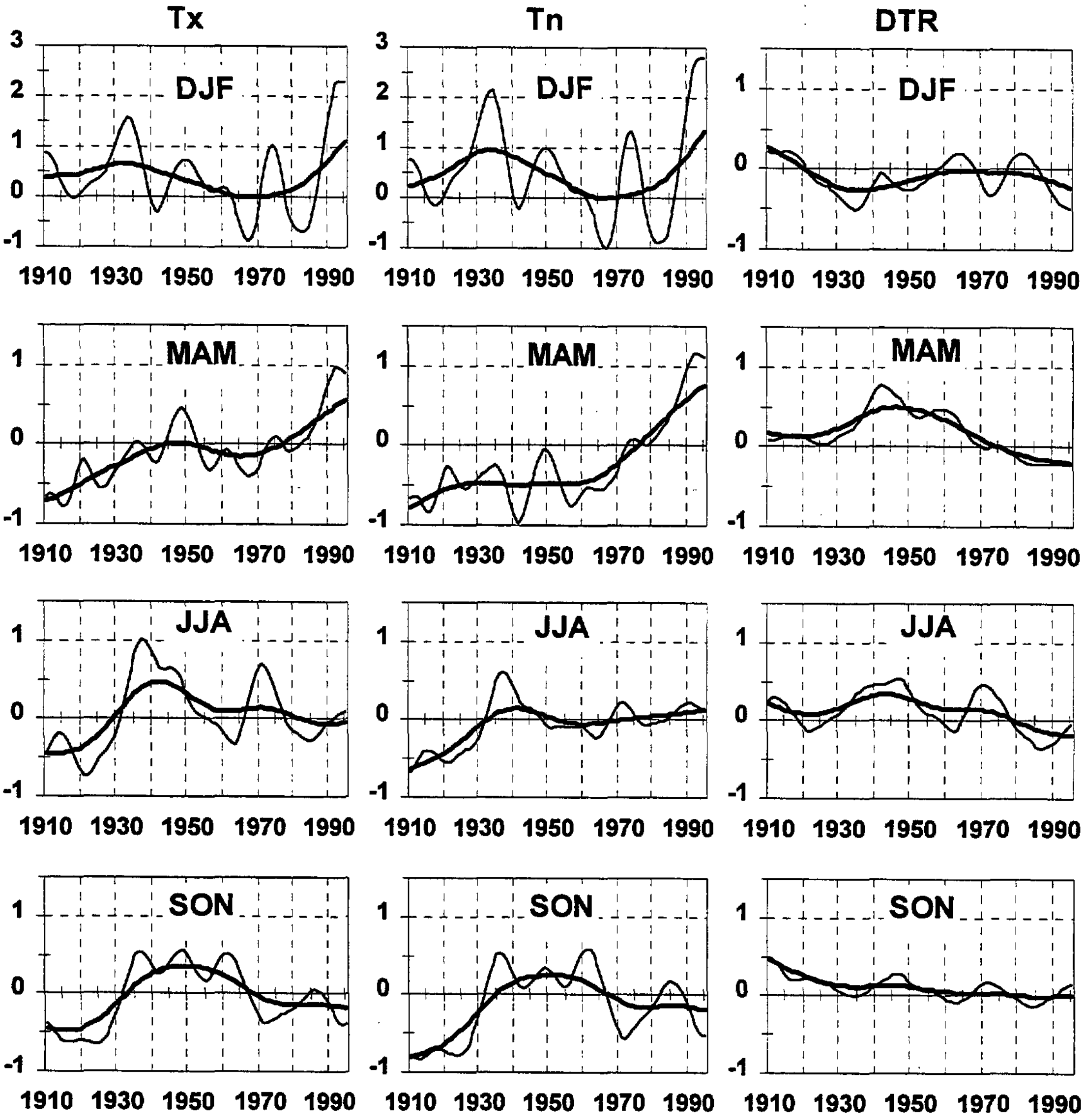

Fig. 6. Seasonal anomalies (°C) of Fenno-Scandian Tx, Tn, and DTR smoothed with GF3 (thin line) and GF9 (thick line), in 1910-1995 (reference period 1961-1990). N.B. Scale of DJF Tx and Tn.

Table 2. Seasonal and annual differences of Tx, Tn, and DTR between the periods 1910-1939 and 1966-1995 (°C) in Fenno-Scandia. The statistically significant trends (Mann-Kendall at the 0.05 level) are in bold numbers.

°C	DJF	MAM	JJA	SON	Year
Tx	-0.51	0.41	0.19	0.05	0.04
Tn	-0.64	**0.62**	0.26	0.14	0.09
DTR	0.07	-0.25	-0.11	-0.15	**-0.10**

The Fenno-Scandian annual DTR (Table 2, Fig. 5) has been decreasing during this century but not steadily. For example, the 1940s was generally a decade with large positive anomalies. There has been a decrease in spring, summer and autumn, but not in winter.

The Th and Tl data have not been tested or adjusted, except the Danish and Faroe Islands data. Usually it is assumed that the inhomogeneities are random, and the homogeneity breaks mostly cancel when averaged over large areas. However, this is not true for Th and Tl. In Fenno-Scandia, there has been a change from wall screens (small cages fastened to a wall of a building) to free-standing wooden screens during first half of this century (Nordli et al. 1997). We believe that radiation screens and other changes, e.g. relocations, have biased many of the long Th and Tl time series. Therefore, we will not present any long-term changes of area-averaged Th and Tl based on unadjusted data.

4.3 Long-term trends at selected stations

Some of the Nordic and Arctic stations have extreme temperature time series longer than 120 years. However, the geographical distribution of those stations is such that area-averages cannot be reliably calculated. Therefore, we have selected 4 long-term stations to describe the Tx, Tn and DTR changes in the past 105-120 years. The stations are (see Fig. 1): Upernavik, West-Greenland; Thorshavn, Faroe Islands; Nordby, Denmark; Haparanda, Sweden.

The Upernavik station started in 1873 and has most likely been located on the same spot until 1960, when it was replaced by a synoptic station. Apparently, the same family has taken care of the observations from 1893 to 1960, a period of 64 years (Brødsgaad 1992). From 1960 to 1980 and again from 1995, the station has been a manual synoptic station. The period in between is one of the darkest chapters of the station history, as it was then an automatic weather station of very poor quality. The station has been relocated several times over the period 1960 to 1995.

Thorshavn started in 1873 and has always been the primary station at the Faroe Islands. The station has been relocated 5 times, but two of these were well documented by overlapping series. The change from wall screen to Stevenson screen took place in April 1925 (Brandt 1994b). As the station has always been located in a small town, and as the climate is cloudy and windy, the temperature series are considered reliable.

Nordby started in 1874 and has always been a primary station in the Danish network. The station has been relocated 8 times within the same small village. The change from wall screen to Stevenson screen took place in August 1928 (Brandt 1994a). As the station has always been located within the same small village and as the climate is cloudy and windy, the temperature series are considered reliable.

Haparanda started in 1859. It is situated on a flat terrain close to the coast near the border to Finland. During the period 1859-1942, the station operated at the telegraph office. A window screen at 4 m above ground was used. After 1942, Stevenson screens have been used with thermometer height of about 1.7 m.

The smoothed annual time series Tx, Tn, and DTR of Thorshavn, Nordby and Haparanda show remarkable similarities (Fig. 7). The end of the 19th century was cooler than this century at these stations. Moberg and Alexandersson (1997) have similar results for Sweden. Especially the minimum temperatures have been rising since the end of the last century. Upernavik is located far from the other 3 stations and shows markedly different behaviour. Also, Tx and Tn anomalies differ from each other quite much at Upernavik. The temperature change from the first 30 years to the last 30 years is significant at most stations (Table 3).

DTR shows generally a decreasing tendency at all stations (Fig. 7). However, there are also decadal fluctuations, especially at Upernavik. The long-term changes of DTR were significant at all stations (Table 3). The large magnitude of DTR decrease at Upernavik is somewhat suspicious.

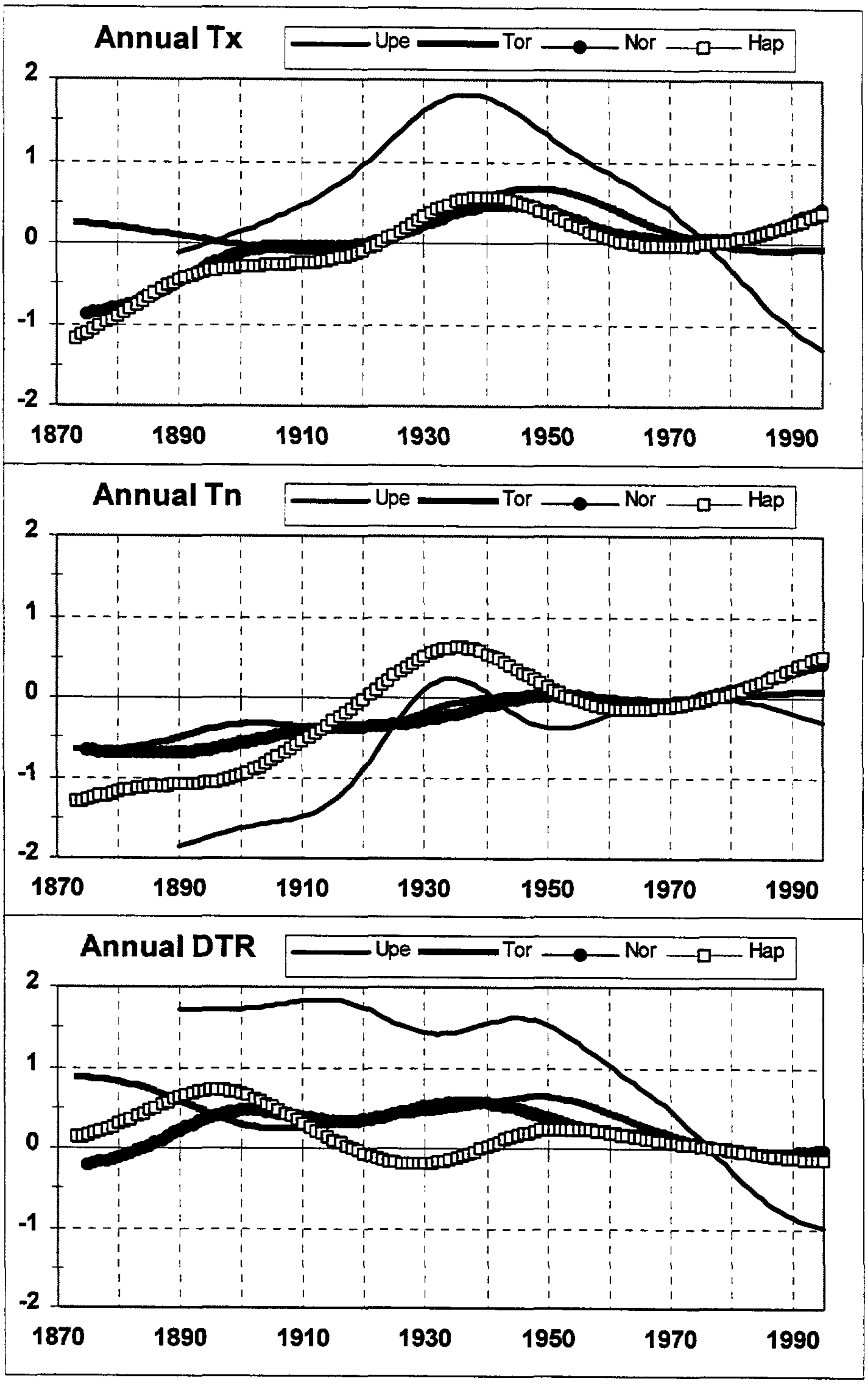

Fig. 7. GF9 smoothed annual anomalies (°C) of Tx, Tn and DTR at Upernavik, Thorshavn, Nordby, and Haparanda (reference period 1961-1990).

It must be kept in mind that all these stations have experienced site and screen changes during their over 100 year history. Not even the selection of only 'good quality' stations and homogeneity testing can guarantee that the observed temperature changes are purely due to climate. The observed changes in Table 3 may have error margins of 0.4 degrees or even more according to our subjective estimate.

Table 3. Annual differences of Tx, Tn, and DTR (°C) between the last and first 30 year periods at Upernavik, Thorshavn, Nordby, and Haparanda. The statistically significant differences (two-tailed t-test at the 0.05 level) are in bold numbers. N.B. The firsttime period in Upernavik.

°C	**Upernavik** 1966-1995 *1890-1919*	**Thorshavn** 1966-1995 1875-1904	**Nordby** 1966-1995 1875-1904	**Haparanda** 1966-1995 1875-1904
Tx	**-0.70**	-0.14	**0.70**	0.76
Tn	**1.61**	**0.47**	**0.86**	**1.40**
DTR	**-2.21**	**-0.61**	**-0.16**	**-0.64**

5. Relationships of extreme temperatures to climatic indices in Fenno-Scandia

5.1 Atmospheric circulation indices

The atmospheric circulation pattern changes are often responsible for the local temperature variations. For Fenno-Scandia, we try to find out how much of the observed temperature variations can be explained by circulation and cloudiness changes.

The atmospheric circulation is described simply with atmospheric pressure gradients in west-east and south-north directions and atmospheric pressure anomalies over Fenno-Scandia. A similar approach have been used in northern Europe e.g. by Rogers (1985), Alexandersson (1994), Tveito (1996), and Alexandersson et al. (1998). We prefer to use the high quality station data of sea level pressure from Frich et al. (1996) and Schmith et al. (1996) instead of grid data sets, which are affected by changes in station coverage.

The strength of the zonal geostrophic circulation is determined from the differences of monthly mean sea level pressure between Hammerodde, Denmark and Bodø, Norway (distance 1330 km), referred ZI hereafter. Similarly, the strength of the meridional geostrophic circulation is described with the difference of monthly mean sea level pressure between Helsinki, Finland and Bergen, Norway (distance 1080 km), referred MI hereafter. See Fig. 1 for the location of stations.

Zonal flow is dominantly westerly in all seasons (Fig. 8). However, there is year-to-year and decadal scale variations. ZI is strongest in winter and weakest in summer. During the recent winters, the westerly flow has been exceptionally strong. Only about 4% of the seasonal averages are negative. Easterly flow is most common in spring, when about 8% of ZI were negative in the period 1890-1995.

In wintertime, the Icelandic low and Siberian high are usually positioned so that they produce a southerly flow (Fig. 9). Northerly flows were rare before the 1930s, but since then, they have occurred roughly every fifth winter. In summer, there is a weak, mean northerly flow. During the transition seasons, MI is usually positive. The strong wintertime flow dominates the annual mean. The strength of the annual mean MI is about half of the annual mean ZI.

A third index used to describe the state of the atmosphere over Fenno-Scandia is the mean sea level pressure anomalies calculated as the average of four stations (Bergen and Bodø, Norway; Hammarodde, Denmark; Helsinki, Finland), hereafter called PA. The time series of PA show large inter-seasonal and annual variability (Fig. 10). The large positive anomalies are caused by persistent blocking situations. There are no clear trends, but the latter half of this century has experienced more positive anomalies in spring and summer than the first half.

5.2 Cloud cover

The records of mean monthly sky cover (in percent) were collected in the NACD project (Frich et al. 1996) and updated to 1995 for this analysis. Also, some long-term Finnish stations were added. The cloud cover was available at 36 stations in Fenno-Scandia. Cloud cover is mainly calculated from daytime observations. The several cloud cover units (octas, tenths,...) have been converted to percent.

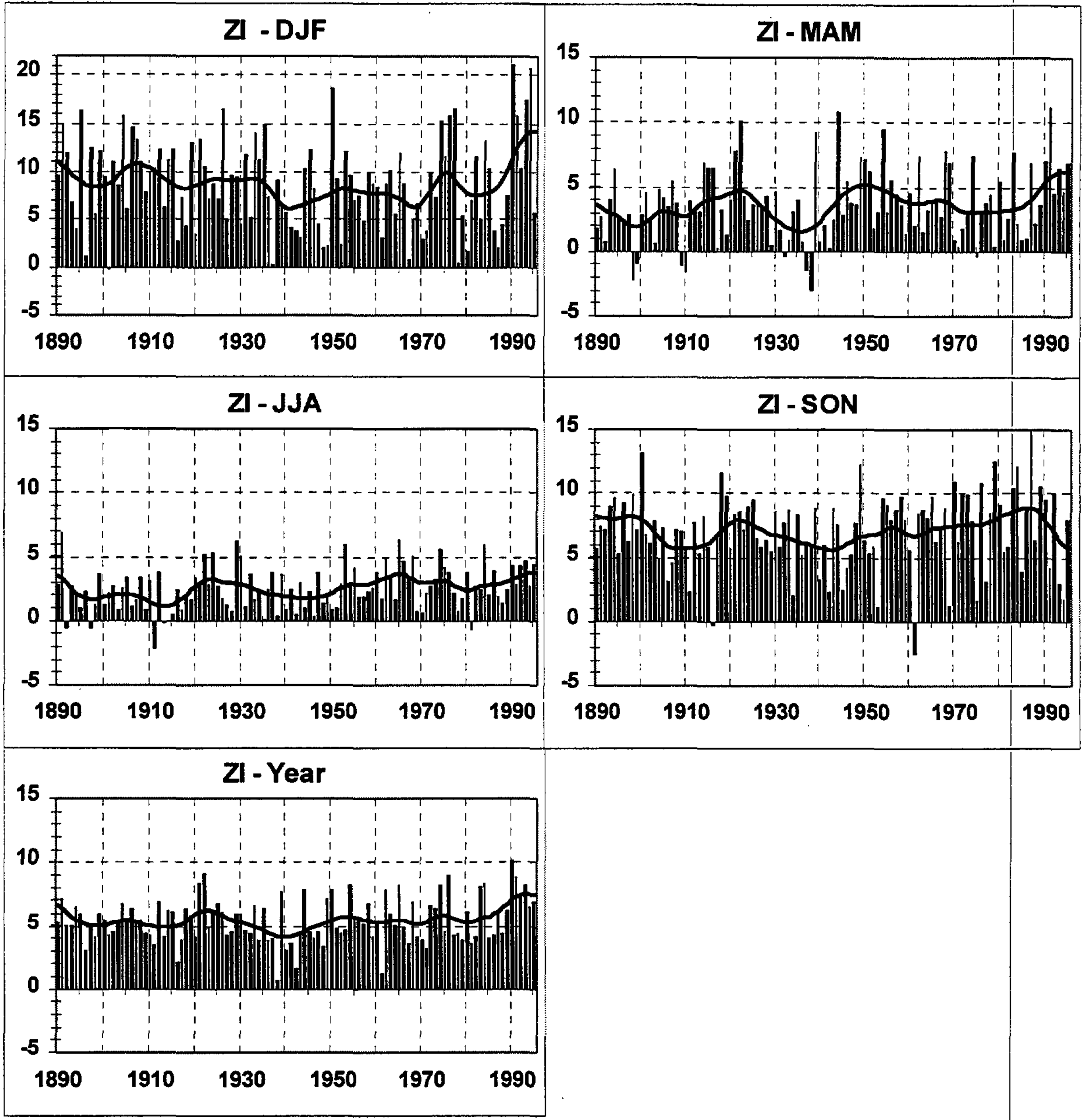

Fig. 8. Zonal index (ZI) defined as sea level pressure difference between Hammerodde (Denmark) and Bodø (Norway), smoothed with GF3, in hPa, 1890-1995. N.B. Different scale in ZI-DJF.

The Fenno-Scandian area-average cloud cover was calculated following the method described in the chapter 2.2. No attempts to test or adjust the data were made. We assume that the inhomogeneities are random. There have been new instructions of cloud cover observations (Heino 1994), but the main principles have remained unchanged. However, we cannot exclude the possibility of systematic errors without extensive comparisons with, e.g. long-term sunshine duration measurements, which are rare and, unfortunately, also suffer from homogeneity problems.

Fenno-Scandian cloud cover was at lower levels before the 1920s because of negative anomalies in spring, summer and autumn (Fig. 11). These seasons display a long-term increasing trend. Wintertime cloudiness has a period of positive anomalies in the 1920s and 1930s and has been decreasing since.

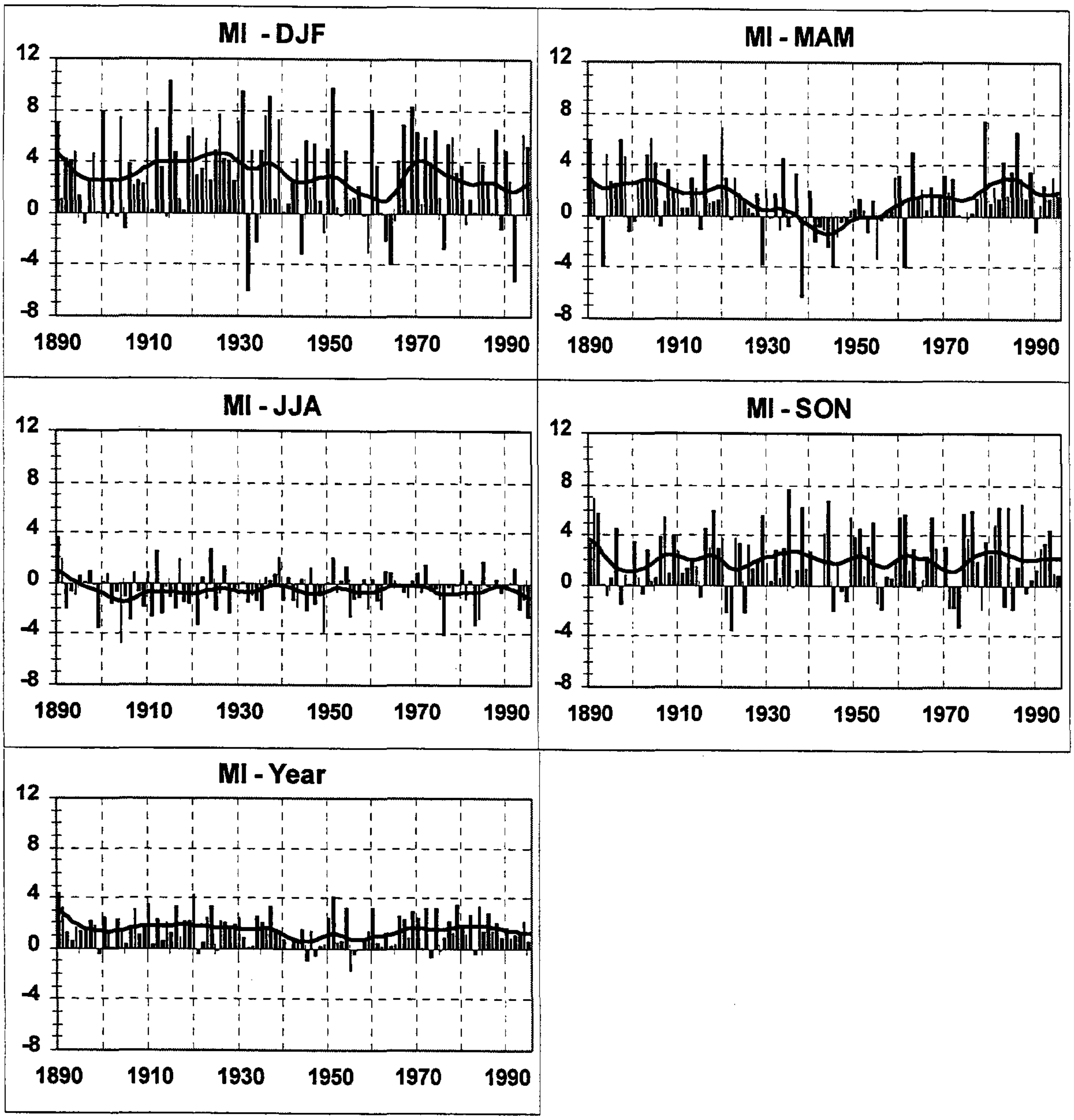

Fig. 9. Meridional index (MI) defined as sea level pressure difference between Helsinki (Finland) and Bergen (Norway), smoothed with GF3, in hPa, 1890-1995.

5.3 Correlation matrices

As a first attempt to study relationships of temperature, circulation and cloudiness in Fenno-Scandia seasonal correlation coefficients between various temperature elements and indices were calculated (Table 4). Some of the relationships are obvious and they mainly confirm that the data is reliable, e.g. very high correlation among T, Tx and Tn. The lowest correlation in temperatures is found between Th and Tl in summer, 0.35. Temperature ranges (DTR, ETR) have physically meaningful negative correlations with temperatures in winter and positive in summer.

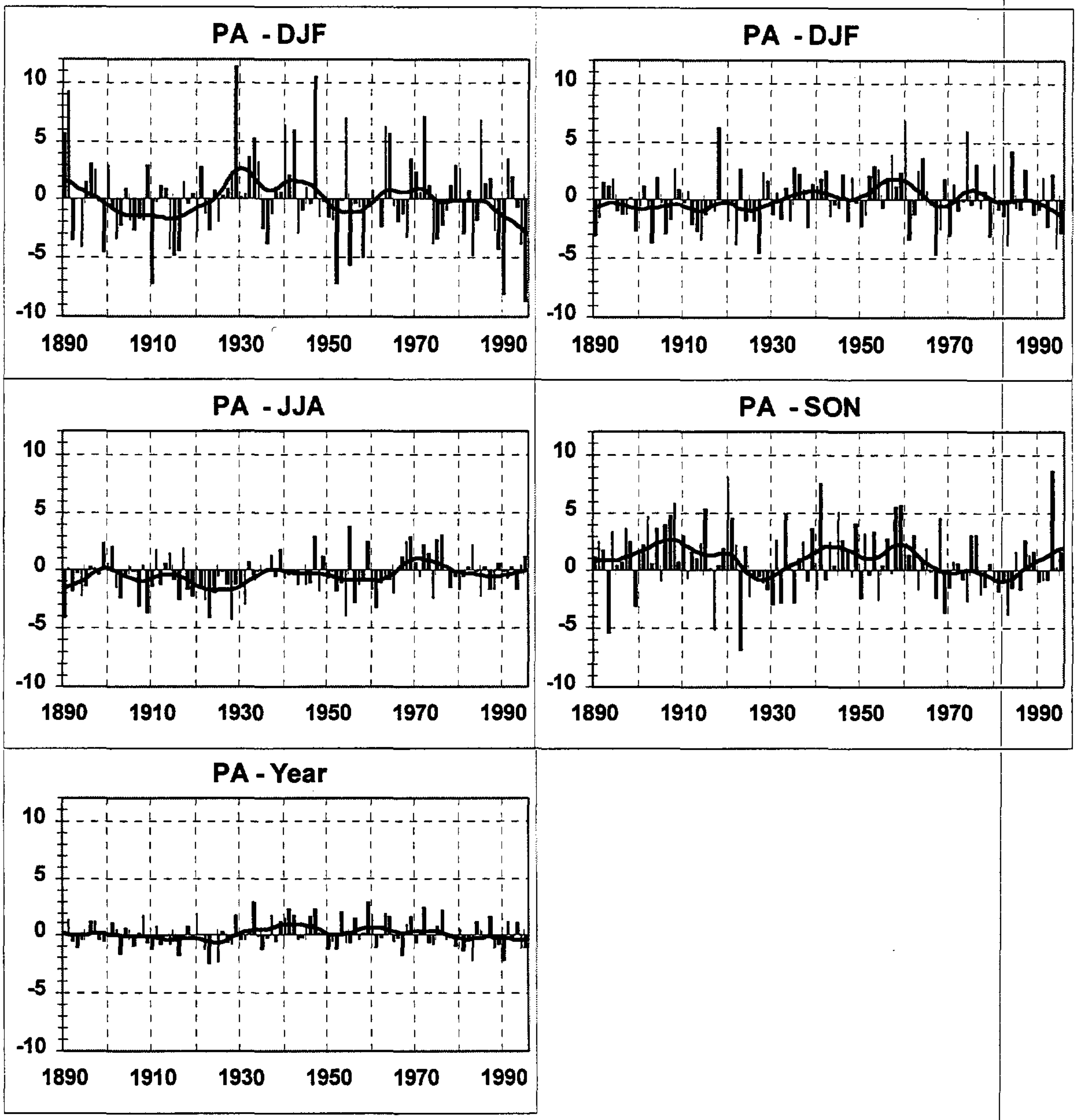

Fig. 10. Fennos-Scandian mean sea-level pressure anomalies (PA), smoothed with GF3, in hPa, 1890-1995.

It is interesting to see that significant correlations between circulation indices and temperatures and their ranges can be found. NAO and ZI are both indicators of zonal flow, but on different spatial scales. They are closely linked. But their connection is broken in summer when NAO and ZI give opposite correlation coefficients with the other climate indicators.

Pressure measurements are considered quite reliable. On the other hand, visually determined cloud cover has a subjective nature and it can be questioned whether the records are reliable. Also, cloud cover makes no difference between cloud types, e.g. a thin cirrus layer controls both long and short wave radiative fluxes differently from that of a thick stratus layer. However, it turns out that cloud cover gives high, physically reasonable correlation with more reliable elements. For example, high positive correlation with temperature in winter and negative in summer. Also the very high summer values between cloudiness and DTR is an indication that the cloud cover data is fairly reliable.

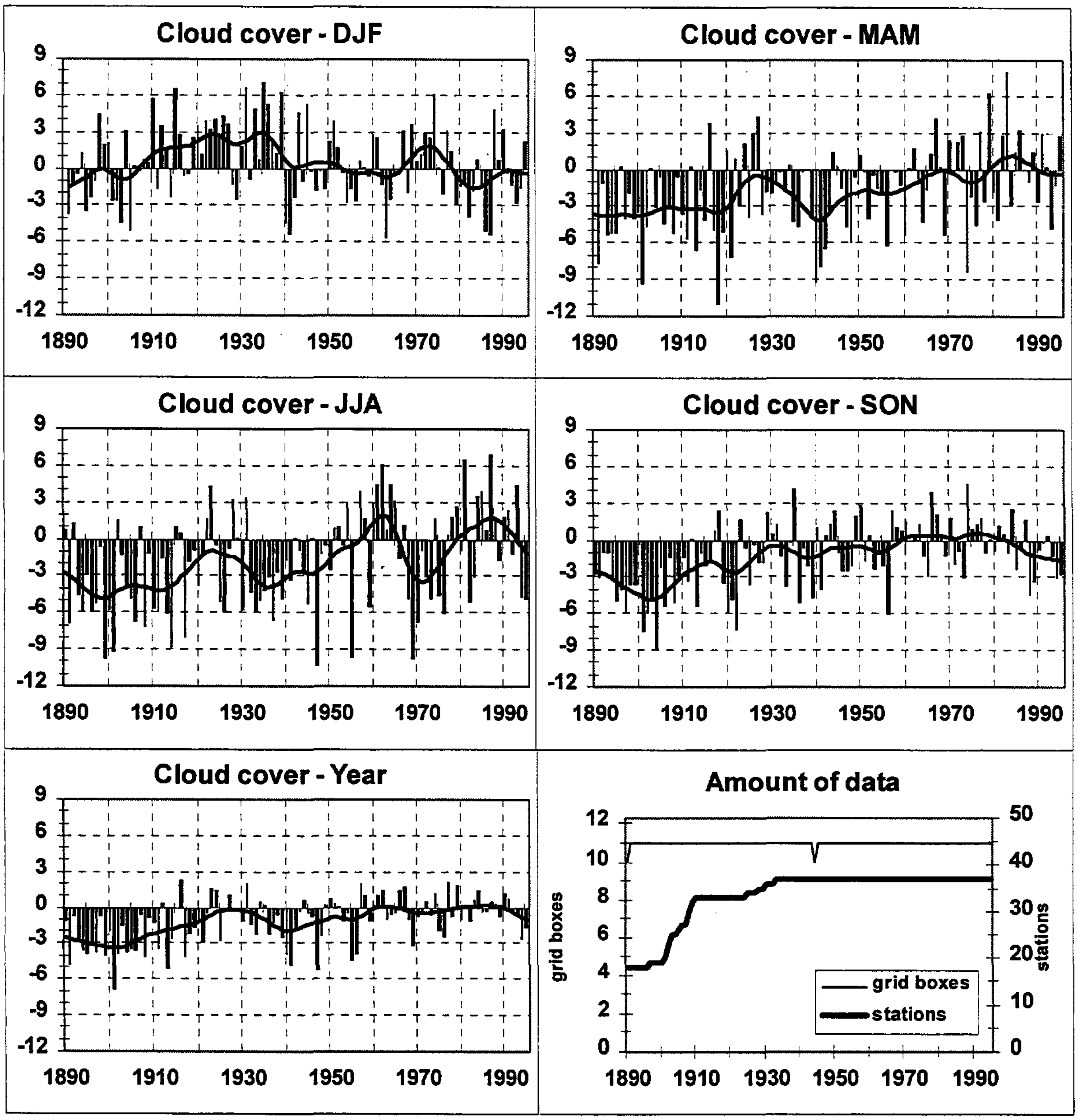

Fig. 11. Seasonal and annual anomalies (%) of Nordic area-averaged cloud cover, smoothed with GF3, 1890-1995 (reference period 1961-1990). Panel on the low-right corner shows the number of grid boxes and stations used in the calculation of annual cloud cover anomalies.

The hypothesis that early cloud observations might not be reliable was studied by comparing correlations at different time periods. The correlation coefficients are somewhat lower for the longer time period 1890-1995 than for the recent, supposedly more reliable, normal period 1961-1990 (not shown). However, there was practically no difference at all between the normal period and the sequence 1910-1995. The same applied also to the other elements.

Table 4. Seasonal correlation coefficients between T, Tx, Tn, Th, Tl, DTR, intra-monthly ETR, circulation indices and cloud cover in Fenno-Scandia calculated from the period 1910-1995. Limits of statistical significance are ±0.21 (95%), ±0.28 (99%) and ±0.35 (99.9%).

DJF	T	Tx	Tn	Th	Tl	DTR	ETR	NAO	ZI	MI	Cloud	PA
T	1.00	1.00	0.99	0.84	0.95	-0.68	-0.80	0.65	0.77	-0.07	0.40	-0.33
Tx	1.00	1.00	0.98	0.87	0.94	-0.62	-0.76	0.64	0.80	-0.14	0.33	-0.34
Tn	0.99	0.98	1.00	0.82	0.96	-0.75	-0.82	0.65	0.72	-0.00	0.44	-0.33
Th	0.84	0.87	0.82	1.00	0.74	-0.38	-0.42	0.51	0.81	-0.35	0.10	-0.27
Tl	0.95	0.94	0.96	0.74	1.00	-0.74	-0.92	0.65	0.67	0.03	0.41	-0.25
DTR	-0.68	-0.62	-0.75	-0.38	-0.74	1.00	0.78	-0.48	-0.20	-0.49	-0.67	0.20
ETR	-0.80	-0.76	-0.82	-0.42	-0.92	0.78	1.00	-0.58	-0.43	-0.25	-0.50	0.17
NAO	0.65	0.64	0.65	0.51	0.65	-0.48	-0.58	1.00	0.63	0.17	0.37	-0.43
ZI	0.77	0.80	0.72	0.81	0.67	-0.20	-0.43	0.63	1.00	-0.42	-0.00	-0.31
MI	-0.07	-0.14	-0.00	-0.35	0.03	-0.49	-0.25	0.17	-0.42	1.00	0.67	-0.11
Cloud	0.40	0.33	0.44	0.10	0.41	-0.67	-0.50	0.37	-0.00	0.67	1.00	-0.35
PA	-0.33	-0.34	-0.33	-0.27	-0.25	0.20	0.17	-0.43	-0.31	-0.11	-0.35	1.00
MAM	T	Tx	Tn	Th	Tl	DTR	ETR	NAO	ZI	MI	Cloud	PA
T	1.00	0.97	0.97	0.76	0.88	-0.30	-0.38	0.64	0.52	0.15	0.07	-0.07
Tx	0.97	1.00	0.90	0.82	0.80	-0.07	-0.24	0.60	0.47	0.09	-0.10	0.08
Tn	0.97	0.90	1.00	0.66	0.90	-0.51	-0.48	0.63	0.52	0.22	0.29	-0.19
Th	0.76	0.82	0.66	1.00	0.51	0.10	0.24	0.49	0.38	-0.01	-0.22	0.20
Tl	0.88	0.80	0.90	0.51	1.00	-0.47	-0.71	0.50	0.41	0.17	0.24	-0.16
DTR	-0.30	-0.07	-0.51	0.10	-0.47	1.00	0.61	-0.24	-0.26	-0.32	-0.85	0.59
ETR	-0.38	-0.24	-0.48	0.24	-0.71	0.61	1.00	-0.16	-0.16	-0.19	-0.44	0.35
NAO	0.64	0.60	0.63	0.49	0.50	-0.24	-0.16	1.00	0.50	0.30	0.05	-0.18
ZI	0.52	0.47	0.52	0.38	0.41	-0.26	-0.16	0.50	1.00	-0.15	0.15	-0.40
MI	0.15	0.09	0.22	-0.01	0.17	-0.32	-0.19	0.30	-0.15	1.00	0.26	-0.09
Cloud	0.07	-0.10	0.29	-0.22	0.24	-0.85	-0.44	0.05	0.15	0.26	1.00	-0.58
PA	-0.07	0.08	-0.19	0.20	-0.16	0.59	0.35	-0.18	-0.40	-0.09	-0.58	1.00
JJA	T	Tx	Tn	Th	Tl	DTR	ETR	NAO	ZI	MI	Cloud	PA
T	1.00	0.98	0.93	0.84	0.68	0.66	0.53	0.42	-0.33	0.24	-0.66	0.51
Tx	0.98	1.00	0.87	0.88	0.60	0.77	0.61	0.37	-0.34	0.21	-0.73	0.60
Tn	0.93	0.87	1.00	0.71	0.79	0.35	0.33	0.49	-0.20	0.34	-0.36	0.30
Th	0.84	0.88	0.71	1.00	0.35	0.73	0.87	0.17	-0.36	0.20	-0.68	0.60
Tl	0.68	0.60	0.79	0.35	1.00	0.12	-0.16	0.46	-0.19	0.30	-0.22	-0.01
DTR	0.66	0.77	0.35	0.73	0.12	1.00	0.70	0.08	-0.40	-0.05	-0.91	0.73
ETR	0.53	0.61	0.33	0.87	-0.16	0.70	1.00	-0.05	-0.27	0.05	-0.59	0.64
NAO	0.42	0.37	0.49	0.17	0.46	0.08	-0.05	1.00	0.30	0.09	-0.14	0.05
ZI	-0.33	-0.34	-0.20	-0.36	-0.19	-0.40	-0.27	0.30	1.00	-0.10	0.38	-0.16
MI	0.24	0.21	0.34	0.20	0.30	-0.05	0.05	0.09	-0.10	1.00	0.11	-0.18
Cloud	-0.66	-0.73	-0.36	-0.68	-0.22	-0.91	-0.59	-0.14	0.38	0.11	1.00	-0.69
PA	0.51	0.60	0.30	0.60	-0.01	0.73	0.64	0.05	-0.16	-0.18	-0.69	1.00
SON	T	Tx	Tn	Th	Tl	DTR	ETR	NAO	ZI	MI	Cloud	PA
T	1.00	0.99	0.99	0.70	0.86	-0.29	-0.47	0.62	0.38	0.44	0.31	-0.06
Tx	0.99	1.00	0.95	0.75	0.80	-0.14	-0.37	0.57	0.41	0.35	0.20	-0.02
Tn	0.99	0.95	1.00	0.64	0.88	-0.44	-0.52	0.64	0.34	0.52	0.43	-0.13
Th	0.70	0.75	0.64	1.00	0.40	0.11	0.22	0.25	0.38	0.04	0.02	0.07
Tl	0.86	0.80	0.88	0.40	1.00	-0.47	-0.81	0.70	0.23	0.57	0.37	-0.10
DTR	-0.29	-0.14	-0.44	0.11	-0.47	1.00	0.56	-0.38	0.10	-0.64	-0.79	0.37
ETR	-0.47	-0.37	-0.52	0.22	-0.81	0.56	1.00	-0.58	-0.00	-0.58	-0.38	0.15
NAO	0.62	0.57	0.64	0.25	0.70	-0.38	-0.58	1.00	0.42	0.53	0.32	-0.27
ZI	0.38	0.41	0.34	0.38	0.23	0.10	-0.00	0.42	1.00	-0.22	-0.10	-0.36
MI	0.44	0.35	0.52	0.04	0.57	-0.64	-0.58	0.53	-0.22	1.00	0.60	-0.13
Cloud	0.31	0.20	0.43	0.02	0.37	-0.79	-0.38	0.32	-0.10	0.60	1.00	-0.37
PA	-0.06	-0.02	-0.13	0.07	-0.10	0.37	0.15	-0.27	-0.36	-0.13	-0.37	1.00

5.4 Cloud cover and circulation as predictors of temperature

Multiple linear regression has been used to construct a model for Fenno-Scandian averages of DTR for the period 1910-1995. We have used four predictors: ZI, MI, mean cloud cover (C), and PA. The model used was:

$$\mathrm{DTR} = a \bullet \mathrm{ZI} + b \bullet \mathrm{MI} + c \bullet \mathrm{C} + d \bullet \mathrm{PA} + e$$

This equation was applied on seasonal and annual data and both predictors and predictands were anomalies from 1961-1990 averages except ZI and MI. This does not affect the multiple regression as all data anyhow are normalised in the calculation procedure. The large scale index NAO was not used here as it is so closely connected to the other, more local, circulation indices used. Results for the coefficients a, b, c, and d are presented along with standard deviations for each. Roughly speaking the absolute value of the coefficient must be at least twice the standard deviation to be significantly different from zero on the 95% level. We have indicated this in Table 5 with a star and then with two stars if the 99% level is reached and with three stars for the 99.9% level (assumption of normal distribution). For each of the seasons and for the year we have also given, in percent, the explained variance F and the correlation coefficient ρ.

Table 5. Results from the multiple linear models for DTR, Fenno-Scandian averages, 1910-1995 (see text for further explanations).

	DJF F=53.1%, ρ=0.73		MAM F=73.6%, ρ=0.86	
Predictor	**Coefficient**	**St.dev.**	**Coefficient**	**St.dev.**
ZI	-0.0471***	0.0114	-0.0273*	0.0132
MI	-0.0550**	0.0195	-0.0391*	0.0153
C	-0.0913***	0.0212	-0.1204***	0.0118
PA	-0.0186	0.0127	0.0422*	0.0174
	JJA F=80.1%, ρ=0.90		SON F=66.0%, ρ=0.81	
Predictor	**Coefficient**	**St.dev.**	**Coefficient**	**St.dev.**
ZI	-0.0353*	0.0176	0.0042	0.0086
MI	0.0327	0.0191	-0.0384***	0.0115
C	-0.0897***	0.0098	-0.0861***	0.0130
PA	0.1068***	0.0213	0.0179	0.0098
	Year F=71.2%, ρ=0.84			
Predictor	**Coefficient**	**St.dev.**		
ZI	-0.0386***	0.0100		
MI	-0.0503**	0.0157		
C	-0.1135***	0.0117		
PA	0.0215	0.0152		

The model is really successful with high correlation coefficients. It gives best fit in summer when it is mainly low cloudiness and high pressure that favours large DTR values. As we can see in Table 4 cloudiness and pressure are quite strongly negatively correlated so we would get good results with just one predictor for the summer season. For DTR what mostly matters is that cloud cover controls incoming short wave radiation in summer and outgoing long wave radiation in winter. Overall, cloudiness dominates as the most important predictor but the other ones give substantial input now and then.

In winter and the year as a whole, strong zonal geostrophic winds dampen DTR effectively (negative coefficients). Large ZI means advection of moist maritime air reducing long wave radiative cooling and increasing Tn. Moisture can suppress also Tx but this is not important during the high latitude winter when ZI and MI are most important. Furthermore, strong air flow does not allow inversions to build and it prevents rapid surface cooling.

In Figs. 12 and 13 we have plotted calculated versus observed DTR anomalies for winter and summer, respectively. In these plots the calculated anomalies have been inflated, i.e. they have been multiplied by the ratio between observed and model-calculated standard deviation. We can see that these models quite well simulate the observed DTR, in spite of the fairly large area with sometimes contrasting weather, and in spite of the long averaging period of three months when the weather can change considerably and several times. These smoothing factors give, however, quite small values on all anomalies.

One reason to construct these linear models is to get independent estimates of the overall linear trends. In Table 6 we have compared linear trends 1910-1995 from observed and calculated DTR, and then also for the residual series, which simply are the difference observed minus calculated values. Except for winter, there is a strong support from the model-calculated trends.

Thus we could feel quite confident in our area-average Fenno-Scandian DTR values in spite of homogeneity problems at some stations. Also worth noticing is that the DTR trends are small compared to e.g. Tx or Tn trends, but still the predictors are accurate enough to reproduce the observed trends.

Table 6. Linear trends (°C/10 year) for observed, calculated and residual Fenno-Scandian DTR, 1910-1995. The statistically significant trends (Mann-Kendall at the 0.05 level) are in bold numbers.

°C/10year	**Observed**	**Calculated**	**Residual**
DJF	-0.011	**0.055**	**-0.067**
MAM	-0.046	**-0.055**	0.009
JJA	-0.038	-0.035	-0.003
SON	-0.031	-0.021	-0.010
Year	**-0.030**	**-0.026**	-0.004

The somewhat lower capability of the regression model to explain DTR in winter may result from several reasons. The residual term contains possible errors in the predictors and the shortcomings of the model. Pressure data is reliable, so it is the cloud cover which may bring in errors. In summer, the cloud cover successfully explains DTR variations, but the cloud types and diurnal cycle of cloudiness are different in summer and winter. So, there is some possibility for errors. However, it is also likely that the model is too simple for winter situations. The governing processes are not necessary linear and/or important predictors may be missing. As an example, the wind speed can be a valuable predictor as calm weather often gives large DTR while strong winds from opposite directions often can give fairly normal DTR.

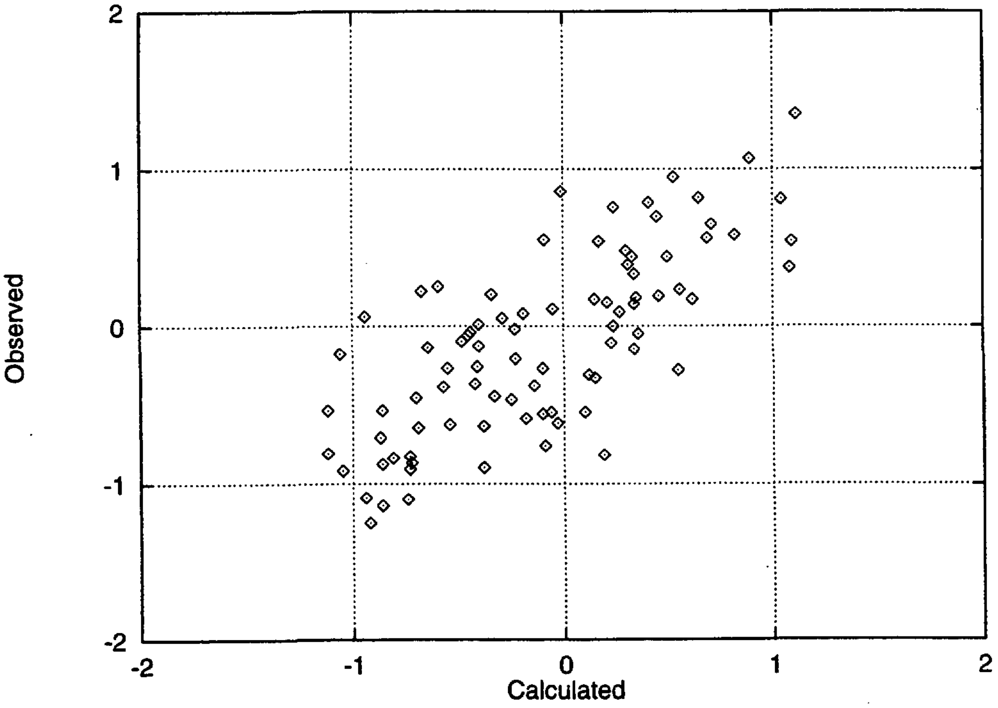

Fig. 12. Model calculated versus observed Fenno-Scandian DTR anomalies in winter (DJF), 1910-1995 (reference period 1961-1990).

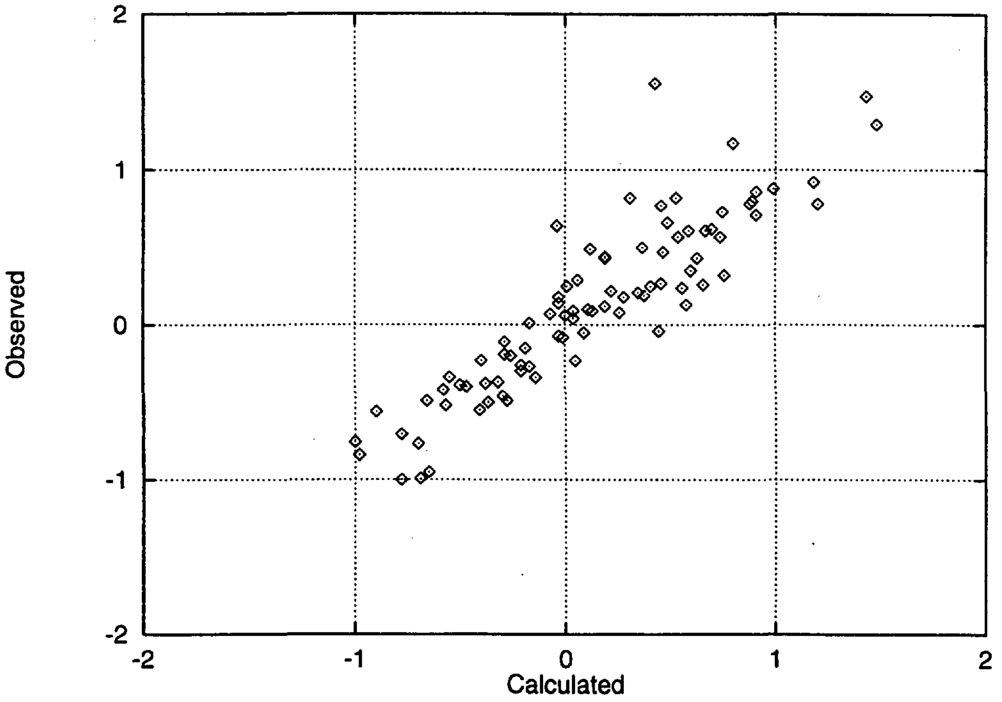

Fig. 13. Model calculated versus observed Fenno-Scandian DTR anomalies in summer (JJA), 1910-1995 (reference period 1961-1990).

6. Discussion

The NAO index was not very successful in explaining the DTR decrease in West-Greenland and Nordic Seas during the period 1950-1995. However, we cannot conclude that circulation changes are not important factors at these regions. It may well be that the large scale NAO simply is not a descriptive index for West-Greenland and the Nordic Seas.

West-Greenland and the Nordic Seas averages are based on much smaller number of stations than Fenno-Scandia averages. It is clear that these regions are represented less accurately than Fenno-Scandia. Also, the possible homogeneity breaks can have some effect on the trend values. Anyway, the presented data is the best available and the detected trends display real climatic changes.

In Fenno-Scandia, simple atmospheric circulation indices and cloud cover explain the observed, significant DTR trends in the period 1910-1995. The residuals are small and display no statistically significant trends, except in winter.

The direct, local effects of increased greenhouse gas and aerosol concentrations on DTR are restricted to the residual of our model. It seems that they are not very large compared to the variations caused by cloud cover and circulation changes. Similarly, we can conclude that the local environmental factors e.g. urbanisation and changes in land use are not causing the observed DTR decrease at regional scale, although some individual stations are affected. However, it is possible that the increased levels of greenhouse gases and aerosols may well be responsible for the changes in the circulation and increased cloud cover over Fenno-Scandia. At least, the cloud cover displays an increasing trend during this century.

In Fenno-Scandia, three estimates of linear trends based on 46, 86, and 123 year time periods can be compared. The short-term (1950-1995) linear trends are in Table 1. In Table 2 are changes and in Table 6 trends of the period 1910-1995. The long-term changes of selected stations (1875-1904, 1966-1995) are in Table 3. The Fenno-Scandian 46-year linear trends are generally steeper than the 86-year trends. The 86-year linear trends are in many cases the smallest of the three estimates because of the warm 1930s which reduces Tx and Tn warming calculated over the period 1910-1995. The 123-year linear trends based on just Nordby and Haparanda in Fenno-Scandia are 0.9°C/100y for the annual mean Tx, 1.2°C/100y for Tn, and -0.3°C/100y for DTR. They settle between the 46- and 86-year trends based on large amount of stations.

The return periods of extreme temperatures were not studied, but we would like to make a few remarks. The long time series used in this study provide, at least in theory, reliable basis for calculation of return periods. However, one should take into account that some of the temperature elements show clear trends. Also, conflicting results may arise between adjusted Tx/Tn and uncorrected Th/Tl series.

7. Conclusions

The major findings and conclusions of this study are listed below.

REWARD temperature data set:

- REWARD data set is a first attempt to build a comprehensive collection of extreme temperatures in the Nordic region including some of the key long-term stations from the Arctic region. The data set brings a relevant contribution to studies of climate changes, but can also be used for practical applications.

- The homogeneity testing and adjusting is needed before any studies of trends.

- Comparisons with other climatic elements confirm that in Fenno-Scandia the period 1910-1995 and the period 1950-1995 in Nordic Seas and West-Greenland the extreme temperatures are relatively homogeneous and can be used for trend studies. Longer temperature time series may suffer from systematic biases raising from screen and site changes, especially Th and Tl. Larger error margins should be attached to the old observations.

Temperature trends:

- During the period 1950-1995, Tx and Tn have increased in Fenno-Scandia and decreased in West-Greenland which result from strengthening of the NAO. Trends in Nordic Seas are quite small. Also the far tails of the temperature distribution, Th and Tl, have followed variations of Tx and Tn. DTR has been significantly decreasing in all three regions.

- The period 1910-1995 in Fenno-Scandia shows smaller trends than the shorter period. Temperature changes are not significant except the springtime Tn warming. The narrowing of DTR is significant and can be to large extent explained with cloud cover increase and atmospheric circulation changes in Fenno-Scandia.

- There is some discrepancy between 46, 86, and 123 year trends of yearly Tx, Tn and DTR in Fenno-Scandia. The recent, shortest trends are generally the steepest. Decadal scale natural climate variability makes differences in regional trends determined from different time periods. However, the warming of Tn and decreasing of DTR seem to be the strongest signals in Fenno-Scandia.

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APPENDIX: Station Catalogue

		Reward	WMO		first year of data			
Station name	Country	number	number	Lat./Long.	Tx	Th	Tn	Tl
FENNO-SCANDIA								
Vestervig	DK	21100		56°46'N 08°19'E	1890	1890	1890	1890
Nordby	DK	25140		55°26'N 08°24'E	1890	1890	1890	1890
Tranebjerg	DK	27080		55°51'N 10°36'E	1890	1890	1890	1890
København	DK	30380	6186	55°41'N 12°32'E	1890	1890	1890	1890
Hammerodde Fyr	DK	06193	6193	55°18'N 14°47'E	1890	1890	1890	1890
Maarianhamina	FIN	00001		60°07'N 19°54'E	1908	1908	1908	1908
Helsinki	FIN	00304	2978	60°10'N 24°57'E	1882	1882	1882	1882
Turku	FIN	01101	2972	60°31'N 22°16'E	1903	1903	1903	1903
Huittinen	FIN	01103		61°10'N 22°47'E	1901	1901	1901	1901
Tampere	FIN	01202		61°28'N 23°45'E	1902	1902	1902	1902
Hattula	FIN	01303		61°04'N 24°14'E	1925	1925	1925	1925
Heinola	FIN	01506		61°13'N 26°03'E	1909	1909	1909	1909
Lappeenranta	FIN	01701	2958	61°05'N 28°09'E	1906	1906	1906	1906
Jyväskylä	FIN	02425		62°12'N 25°43'E	1902	1902	1902	1902
Vaasa	FIN	03001		63°03'N 21°46'E	1908	1908	1908	1908
Ylistaro	FIN	03101		62°56'N 22°30'E	1928	1928	1928	1928
Ähtäri	FIN	03301	2924	62°32'N 24°13'E	1910	1910	1910	1910
Kuopio	FIN	03602		62°54'N 27°41'E	1902	1902	1902	1902
Maaninka	FIN	03603		63°09'N 27°19'E	1930	1930	1930	1930
Joensuu	FIN	03801	2929	62°40'N 29°38'E	1933	1933	1933	1933
Kajaani	FIN	04601	2897	64°17'N 27°40'E	1903	1903	1903	1903
Oulu	FIN	05404		65°02'N 25°29'E	1905	1905	1905	1905
Kuusamo	FIN	06801	2869	65°59'N 29°13'E	1908	1908	1908	1908
Sodankylä	FIN	07501	2839	67°22'N 26°39'E	1908	1908	1908	1908
Tromsø	N	01026	1026	69°39'N 18°56'E	1931	1931	1876	1890
Karasjok	N	01065	1065	69°28'N 25°31'E	1950	1950	1877	1890
Vardø	N	01098	1098	70°22'N 31°05'E	1931	1931	1876	1890
Bodø	N	01152	1152	67°16'N 14°26'E				1890
Ona	N	01212	1212	62°52'N 06°32'E	1931	1931	1876	1890
Kjøremsgrendi	N	01235	1235	62°06'N 09°03'E	1931	1931	1876	1890
Værnes/Trondheim	N	01271	1271	63°28'N 12°56'E				1890
Bergen-Fredriksberg	N	01316	1316	60°24'N 05°19'E	1904	1890	1876	1890
Lærdal	N	01355	1355	61°04'N 07°31'E	1953	1953	1876	1890
Nesbyen	N	01372	1372	60°34'N 09°07'E	1954	1954	1897	1897
Utsira Fyr	N	01403	1403	59°18'N 04°53'E	1931	1931	1876	1890
Oksøy Fyr	N	01448	1448	58°04'N 08°03'E	1931	1931	1876	1890
Ferder Fyr	N	01482	1482	59°02'N 10°32'E	1931	1931	1885	1890
Oslo-Blindern	N	01492	1492	59°57'N 10°43'E	1937	1890	1876	1890
Falun	S	10537	2433	60°37'N 15°37'E	1875	1885	1875	1885
Sveg	S	12402	2324	62°01'N 14°21'E		1885		1885
Härnösand	S	12738		62°37'N 17°56'E	1879	1885	1879	1885
Östersund	S	13411	2226	63°11'N 14°29'E	1875	1885	1875	1885
Stensele	S	15772		65°04'N 17°09'E	1885	1885	1885	1885
Haparanda	S	16395	2196	65°49'N 24°08'E	1873	1885	1873	1885
Jokkmokk	S	16988	2142	66°37'N 19°38'E	1882	1885	1882	1885
Karesuando	S	19283	2080	68°26'N 25°31'E		1885		1885
Växjö	S	06452	2640	56°52'N 14°48'E	1873	1885	1873	1885
Göteborg	S	07147	2512	57°46'N 11°53'E	1881	1885	1881	1885
Västervik	S	07647		57°43'N 16°28'E		1885		1885
Visby	S	07840	2590	57°40'N 18°20'E	1879	1885	1879	1885
Karlstad	S	09322	2418	59°21'N 13°28'E	1881	1885	1881	1885
Stockholm	S	09821	2485	59°20'N 18°03'E	1873	1885	1873	1885

		Reward	WMO		first year of data			
Station name	Country	number	number	Lat./Long.	Tx	Th	Tn	Tl
NORDIC SEAS								
Thorshavn	FR	06011	6011	62°01'N 06°46'W	1890	1890	1890	1890
Jan Mayen	N	01001	1001	70°56'N 08°40'W	1937	1937	1921	1921
Bjørnøya	N	01028	1028	74°31'N 19°01'E	1937	1937	1921	1921
Hopen	N	01062	1062	76°30'N 25°04'E	1948	1945	1945	1945
Stykkisholmur	IS	04013	4013	65°05'N 22°44'W	1952	1952	1952	1952
Reykjavik	IS	04030	4030	64°08'N 21°54'W	1949	1949	1949	1949
Vestmannaeyar	IS	04048	4048	63°24'N 20°17'W	1949	1949	1949	1949
Akureyri	IS	04063	4063	65°41'N 18°05'W	1949	1949	1949	1949
Danmarkshavn	G	04320	4320	76°46'N 18°46'W	1949	1949	1949	1949
Ittoqqortoormiit	G	04339	4339	70°29'N 22°00'W	1924	1924	1949	1949
Tasiilaq	G	04360	4360	65°36'N 37°38'W	1897	1894	1894	1894
WEST-GREENLAND								
Upernavik	G	04210	4210	72°47'N 56°10'W	1890	1890	1890	1890
Ilulissat Airport	G	04221	4221	69°15'N 51°04'W	1894	1894	1890	1890
Nuuk	G	04250	4250	64°10'N 51°45'W	1890	1890	1890	1890
Narsarsuaq	G	04270	4270	61°11'N 45°25'W	1890	1890	1890	1890