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OCCURRENCE OF METEOROLOGICAL SUMMER DRY SPELLS AND DRY DAYS IN NORTHERN EUROPE DURING THE 20TH CENTURY

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Occurrence of meteorological summer dry spells and dry days in Northern Europe during the 20th century

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Abstract

In spite of the relatively humid climate of Northern Europe, prolonged meteorological dry spells do occasionally cause problems for the water supply in different sectors of society. During recent decades, total annual precipitation has increased in the region, especially during winter. A linear change in total precipitation does not necessarily indicate a change in the occurrence of meteorological drought across different time scales. In this study, temporal changes of meteorological summer (May-August) dry spells (MDS) and dry days (MDD) are analysed using measured precipitation observations from 12 weather stations located around Northern Europe. The statistics studied are the number of MDDs (<1.0 and <0.1 mm) per selected periods, plus the lengths of the longest MDSs during which the total accumulated precipitation remains under certain thresholds, namely 10 and 100 mm. The results suggest that, in general, the lengths of the longest MDSs and the numbers of MDDs do not differ remarkably between the stations, median value being 26/80 days (<10/<100 mm rain) and 87/70 days (<1.0/<0.1 mm/day), respectively. A distinct exception is Bergen, in Norway, where the lengths of the longest MDSs are shorter (19 and 41 days, on average) and the numbers of MDDs lower (ca. 64 and 50 days) than at the other stations. During the period of homogeneous instrumental precipitation observations, the occurrence of summer MDSs and MDD have remained the same at most of the stations. Only a few statistically significant increasing temporal trends appear in the time series of MDDs in the southern parts of the region. In the north, one statistically significant decreasing trend has been detected.

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Nimeke Kesäajan meteorologisten kuivuusjaksojen ja sateettomien päivien esiintyminen Pohjois-Euroopassa 1900-luvulla

Tiivistelmä

Pohjois-Euroopan ilmastolle tyypillisestä kosteudesta huolimatta, meteorologiset kuivuusjaksot voivat toisinaan pitkittyä ja aiheuttaa ongelmia eri toimialojen vedensaannille. Viimeisten vuosikymmenten aikana Pohjois-Euroopan kokonaissademäärä on kasvanut jonkin verran, erityisesti talvikuukausina. Sadannan muutos ei välttämättä vaikuta suoraviivaisesti meteorologisen kuivuuden esiintymiseen eri aikamittakaavoissa. Tässä tutkimuksessa tarkastellaan kesäkauden (touko-elokuu) meteorologisten kuivuusjaksojen (MDS) pituuksissa ja kuivien päivien (MDD) lukumäärissä tapahtuneita ajallisia muutoksia. Analyysit perustuvat 12 pohjoiseurooppalaisen sääaseman sademittauksiin. Tarkastellut muuttujat ovat kuivien päivien (<1.0 ja <0.1 mm) lukumäärät sekä sellaisten kuivuusjaksojen pituudet, joiden aikana kokonaissadanta ei ylitä 10 ja 100 millimetriä. Tulosten perusteella keskimääräiset pisimpien kuivuusjaksojen pituudet ja kuivien päivien lukumäärät eivät näytä eroavan suuresti eri asemien välillä. Mediaaniarvot ovat 26/80 päivää (<10/<100 mm) ja 87/70 päivää (<1.0/0.1 mm/päivä). Merkittävin poikkeus on Norjan Bergen, missä pisimmät kuivuusjaksot ovat lyhempiä (19 ja 41 päivää keskimäärin) ja kuivien päivien lukumäärät vähäisempiä (noin 64 ja 50 päivää) kuin muilla asemilla. Ajanjaksona, jolloin homogeenisia instrumentaalisia sademittauksia on tehty, kesän pisimpien kuivuusjaksojen pituudet ja kuivien päivien lukumäärät eivät näytä muuttuneen useimmilla asemilla. Kuivien päivien lukumäärä on kasvanut tilastollisesti merkitsevästi vain muutamilla Pohjois-Euroopan eteläosien sääasemilla. Alueen pohjoisosassa puolestaan havaitaan yksi tilastollisesti merkitsevä laskeva trendi.

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Sivumäärä 46

CONTENTS

1 INTRODUCTION

In the relatively humid climate of Northern Europe, water availability is generally adequate to meet the needs of modern societies and to sustain water-demanding boreal ecosystems. However, prolonged meteorological dry spells do occur. Meteorological drought, sometimes also referred to as climatological drought (Tate and Gustard, 2000), is defined as a prolonged period with little or no rainfall. Prolonged spells of limited precipitation are sometimes, but not always, followed by severe agricultural and hydrological types of drought that cause problems for agricultural water supply, hydropower production and domestic and industrial uses of water (for examples in Northern European countries, see Hansen, 1992; Silander and Järvinen, 2004). Severe drought events often affect wide geographical areas and several sectors of society and, therefore, their financial costs are typically very high. This underlines the importance of understanding the spatial and temporal variation of meteorological drought and makes it a crucial topic for water resource studies. Knowledge of drought events, including information about average values, variations and extreme events, are important since, generally, societies and ecosystems are adapted to local “climatologically appropriate” water availability (Palmer, 1965) and will eventually suffer if the conditions deviate too much, and for too long from the normal level.

The methods used to analyse meteorological drought based on precipitation time series vary widely in the research literature. There are also several studies focusing on the analysis of agricultural and hydrological types of drought; these use variables such as lowered soil moisture status (Heikinheimo et al., 1996; Narasimhan and Srinivasan, 2005) or river discharges (Hisdal et al., 2000) as drought indicators. A drought event can only seldom be considered simply either meteorological, hydrological or soil moisture related. Typically, dry periods involve impacts across all these drought types. The occurrence and spatial extent of the drought events have been examined, e.g., by Hannaford et al. (2011) and Parry et al. (2011). For example, in a study including north-western Scandinavia, Hannaford et al. (2011) noted that spatial coherence of hydrological droughts in the studied area is normally low with many short events affecting only a small proportion of the region at a time. On the other hand, using similar analysis, Parry et al. (2011) found the infrequently occurring hydrological droughts in southern Scandinavia to be spatially very coherent. The same was not true for the meteorological droughts, though. Even though drought is not as typical a characteristic of the Northern European climate as it is, for example, of the Mediterranean climate, it still occurs quite often. In the Appendix, we have listed drought events that have occurred in Northern Europe since the beginning of the twentieth century. Although the list is not complete, it appears that drought has taken place almost every year somewhere in Northern Europe.

Analyses of long precipitation statistics suggest that the total annual precipitation in Northern Europe has increased since the beginning of the 20th century (Trenberth et al., 2007). However, the changes have varied in different regions and in different seasons (Heino et al., 2008). Generally, the increase in precipitation has been largest in winter months during the last half of the century (Beck et al., 2005). Summer rainfall has decreased in parts of northern and south-western Europe and increased in southern Finland, south-eastern and northern Sweden and in the Baltic countries. Lloyd-Hughes and Saunders (2002) found significant wetting trends in Standardized Precipitation Index (SPI) computed for all 12 months and for three winter months in wide areas in the Nordic and Baltic countries in the 20th century. SPI is a commonly used drought index, calculated solely from the precipitation statistics (Hayes et al., 1999). To a lesser extent, Lloyd-Hughes and Saunders (2002) also found similar spatial trends in the Palmer Drought Severity Index (PDSI), which is based on multiple drought variables. During summer, no significant trends were detected in SPI or in PDSI. On the other hand, Bordi et al. (2009) found drying trends over Fennoscandia and Baltic countries in 1949-1997 and wetting trends in 1997-2009 when they studied SPI computed for 24 months. Parry et al. (2011) studied the Regional Standardised Precipitation Index (RSPI) for 3 months in North-West Scandinavia and suggested that the meteorological drought has decreased in this area during the twentieth century.

It is possible that over various time scales, the change in the frequency of dry spells is not equally dependent on the change in total accumulated precipitation over various time scales. It has been suggested that, over time periods lasting less than one month, precipitation extremes are mostly related to the intensity of individual precipitation events (Räisänen, 2005). These events are partly dependent on the maximum atmospheric moisture content according to the Claussius-Clapeyron relation and are, therefore, associated with short-term temperature variation (Trenberth, 1999; Allen and Ingram, 2002; Trenberth et al., 2003). Dynamical effects related to convective precipitation also affect the short-term precipitation extremes. A more detailed description of these can be found in the studies of Doswell III et al. (1996) and Lenderink and Van Meijgaard (2008). Changes in precipitation extremes on longer time scales are more likely to follow changes in mean precipitation (Räisänen, 2005). Annual total precipitation increase may be caused either by higher frequency or higher intensity of rainfall events, or both. Thus, the essential factors in the development of a meteorological dry spell are the time between the consecutive precipitation events and the timing of the low precipitation period with respect to evaporative conditions. In other words, fluctuation in the mean annual precipitation does not necessarily indicate change in short term or seasonal drought occurrence.

In this study, we will analyse the spatial and temporal variations, and potential changes, in the occurrence of meteorological drought in Northern Europe during the period of regular homogeneous instrumental precipitation measurements. Due to the limitations produced by the quality of available data, we restrict our analysis solely to summer months (May-August). We examine the total numbers of dry days and the lengths of the longest dry spells, defined as periods of consecutive days within which the precipitation accumulation total remains below a certain threshold (Venäläinen et al., 2007, 2009). The methods are rather simplistic compared to more complicated drought indices, such as SPI and PDSI, but they are easier to use and offer an insight in to the basic statistical drought characteristics of the study area.

2 METHODS

2.1 Precipitation data

In this study, the daily historical precipitation statistics from 12 stations in the Nordic countries (Denmark, Finland, Norway, Sweden) and the Baltic countries (Latvia, Lithuania) were used (Fig. 1). The data were retrieved from the database of the European Climate Assessment and Dataset (ECA&D) project (Klein Tank, 2007), except for the Finnish data that were retrieved directly from the Finnish Meteorological Institute. The stations shown in Fig. 1 were chosen because of their relatively long and continuous time series and to achieve an even and representative spatial distribution.

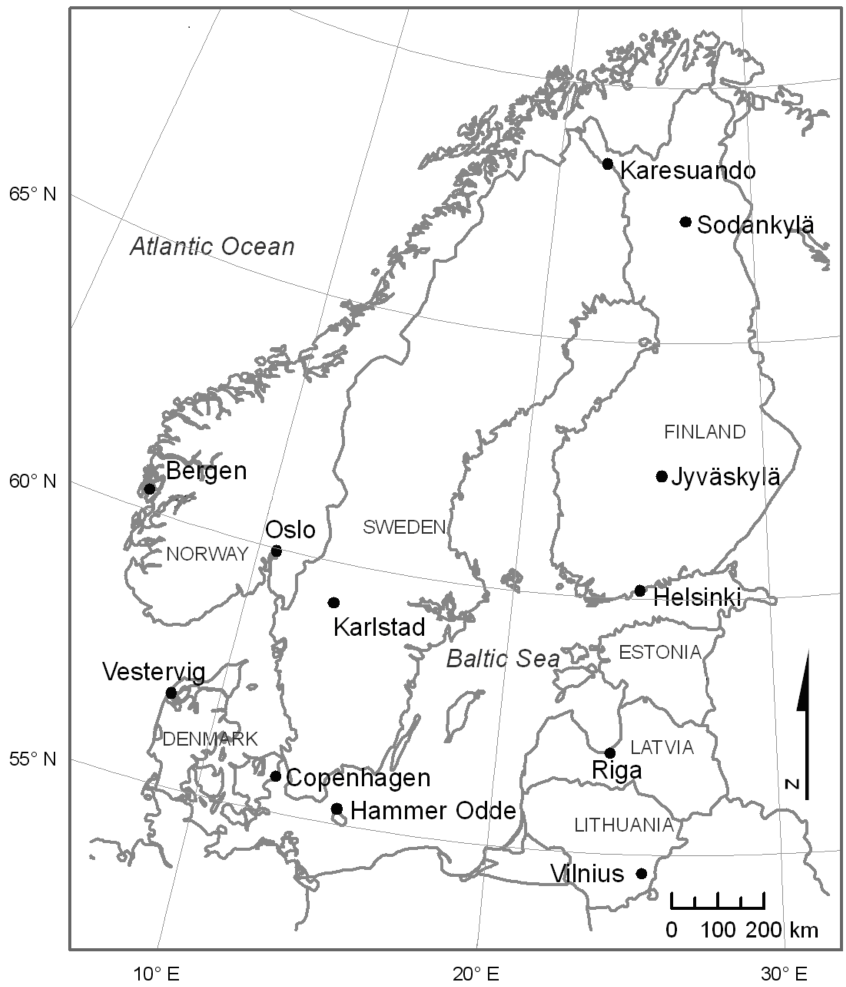

Fig. 1. Weather stations used in the study (Background map source: MapInfo 2008)

The length of the regular instrumental precipitation dataset varies from station to station with the longest time series extending back to the 19th century. However, shorter records were used for the analyses (Table 1) due to inhomogeneities in the precipitation observations (van Engelen et al., 2008; ECA&D, 2010). Measurement of liquid precipitation is generally more reliable than that of snowfall (Heino, 1994). Therefore, to minimize any uncertainties arising from inaccuracies in snowfall measurements, only dry periods that commenced during the summer months (May-August) were included.

2.2 Meteorological drought parameters

Two approaches for investigating meteorological drought were used in this study (Fig. 2). First, we analysed the longest meteorological dry spell (MDS) of each summer, defined here as the longest period of consecutive days during which the total cumulative rainfall remains below a certain threshold. To select the thresholds, the average summer (May-August) precipitation total was first investigated. According to the precipitation records used in this study, it varied between 171 mm (Hammer Odde) and 292 mm (Vilnius) for most of the stations during 1961-1990 (Fig. 3). In the marine climate of the west coast of Norway (Peel et al., 2007; Jylhä et al., 2010) at Bergen, however, the total summer precipitation was a lot higher, at 553 mm on average. Based on these findings, precipitation accumulation thresholds of 10 and 100 mm were chosen to represent drought occurrence on different time scales. A 10 mm accumulation threshold can be taken to illustrate drought occurrence over time scales of days to weeks, and a 100 mm accumulation threshold over time scales of weeks to months. For simplicity, the duration of the precipitation accumulation period was allowed to continue after August. The MDS definition used in this study also assumes that at least one MDS occurs every summer.

In the second approach, the meteorological drought occurrence was analysed by calculating the total number of meteorological dry days (MDD) with precipitation values <1.0 mm or <0.1 mm during May-August. The majority of precipitation measurements were recorded to one decimal place, 0.1 mm, as per WMO recommendations (WMO 2008), but some time series contained values with a precision

Table 1. List of weather stations used in the study, missing data and the years removed from the analysed time series

Station	**Period**	**Summers containing missing values (existing values/ year)**	**Years containing erroneous rainfall measurements**	**Precision of measurements (mm: years)**	**Years removed from the analyses**		
					Longest dry spells		**Dry days**
					10 mm	**100 mm**	
Bergen-Samnanger (NOR)	1950–1999			0.1: 1950-1999			
Copenhagen (DNK)	1901–2005			0.1: 1901-2005			
Hammer Odde (DNK)	1901–2007	1951 (92)		0.1: 1901–2005 1: 2006–2007			1951 2006-2007
Helsinki (FIN)	1901–2007	2005 (122)		0.1: 1901-2007			
Jyväskylä (FIN)	1901–2007	1954 (62) 2005 (122) 2006 (121)		0.1: 1901-2007	1954	1954	1954
Karesuando (FIN/SWE)	1961–2007	1965 (92) 2007 (121)		1: 1961–1999, 2006–2007 0.1: 2000–2005 (rounded to the nearest integer)			1965
Karlstad (SWE)	1950–2003		1998	0.1: 1950–1960 (rounded to the nearest integer) 1: 1961–2003			1998
Oslo (NOR)	1950–2004						
Riga (LVA)	1950–2007	1950 (118) 2006 (116)	1992 1993	0.1: 1950–1991, 1995 1: 1993–1994, 1996–1998, 2005–2007	1992	1992	1950 1992–1994 1996–1998 2005–2007

Table 1. Cont.

Station	**Period**	**Summers containing missing values (existing values/ year)**	**Years containing erroneous rainfall measurements**	**Precision of measurements (mm: years)**	**Years removed from the analyses**		
					Longest dry spells		**Dry days**
					10 mm	**100 mm**	
Sodankylä (FIN)	1908–2007	1927 (122) 1944 (122) 1945 (62) 1953 (122)		0.1: 1908-2007	1945	1945	1945
Vestervig (DNK)	1901–2007	2006 (0)		0.1: 1901–2005 1: 2006–2007	2006	2006	2006–2007
Vilnius (LTU)	1950–2007	1964 (122) 1976 (122)	1992	0.1: 1900–2005 1: 2006–2007	1992	1992	1992 2006–2007

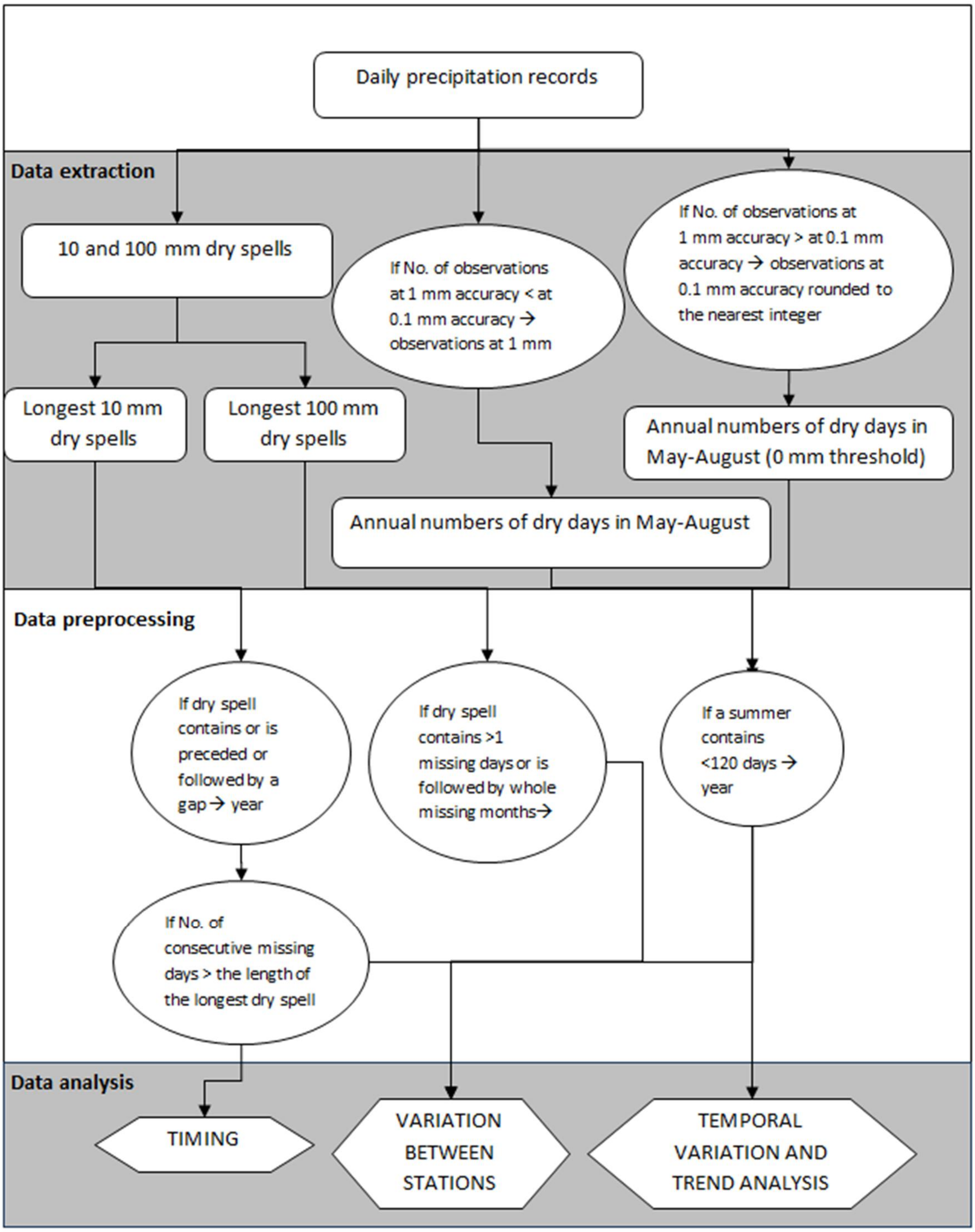

Fig. 2. Flowchart representing the phases of extraction, preprocessing and analysis of dry spell lengths and numbers of dry days

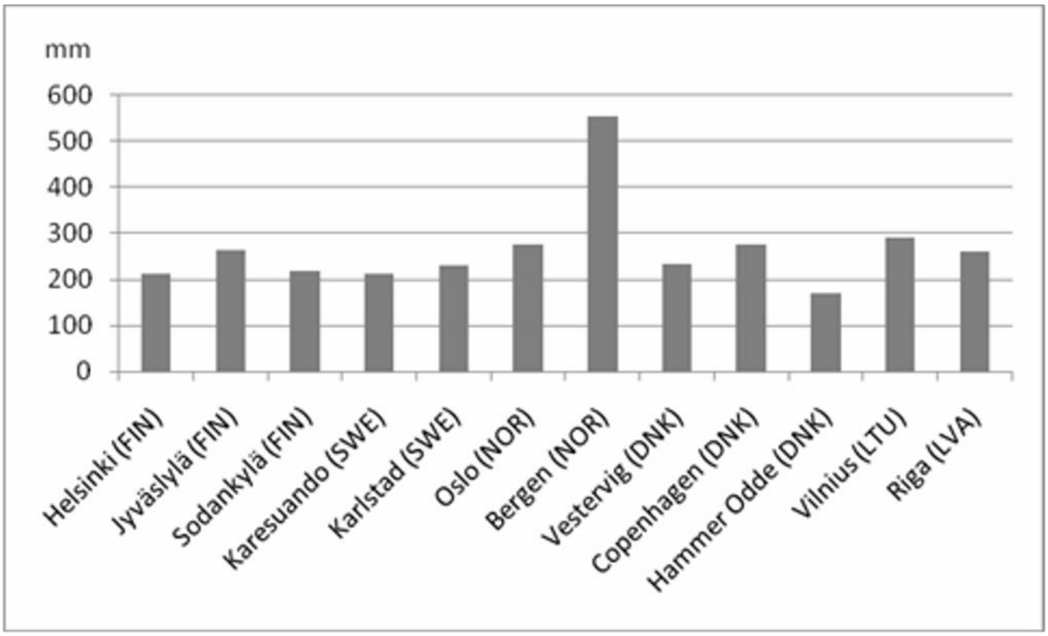

Fig. 3. Average summer (May-August) precipitation (1961-1990) at weather stations used in the study. (FIN=Finland, SWE=Sweden, NOR=Norway, DNK=Denmark, LTU=Lithuania, LVA=Latvia)

of only 1 mm (Table 1). To make each individual time series consistent in this respect, two manipulation methods were undertaken (Fig. 2). First, in cases where the number of observations recorded with a precision of 1 mm was smaller than the number of values recorded to one decimal place, the years containing any values recorded at 1 mm precision were removed from the time series, leaving only observations with 0.1 mm precision (Table 1). Second, in the opposite case where the number of observations recorded to one decimal place was smaller than the number of values represented with a precision of 1 mm, the observations recorded to one decimal place were rounded to the nearest integer (see Karesuando and Karlstad in Table 1). For these two stations, only the number of days with no precipitation (0 mm) was examined. In the next stage of the analysis, the stations containing values recorded at different accuracies were treated separately, because for time series with a precision of only 1 mm, the number of 0 mm precipitation days includes days with precipitation of 0.0-0.4 mm according to the rounding principle. This differs from the numbers of <1.0 and <0.1 mm precipitation days in the time series, whose measurements were recorded to one decimal place, because these also include days with 0.0-0.9 and 0.0 mm precipitation, respectively.

2.3 Time series preprocessing

The resulting time series of the longest MDSs and the number of MDDs still contained occasional erroneous values caused by gaps in the original precipitation statistics. Before further analysis, those years with the longest MDS being abnormally long, or with too large number of MDSs considering the climatic zone, were removed from the time series by using the criteria described below (Fig. 2).

For the longest 10 mm dry spells, we first excluded summers when the longest MDS was preceded by, or followed by, a gap, or which contained days with missing data in the original precipitation statistics. Next, years which, in the original precipitation statistics, contained more consecutive missing days than the duration of the longest continuous MDS of the whole time series were removed. Without this procedure, it is possible, in theory, for the longest MDS of a single summer to be longer than the spell that was determined as the longest of the whole time series, because a gap due to missing days would have been interpreted as a MDS. With 100 mm precipitation thresholds it was not possible to use the duration of the longest MDS of the time series as a maximum limit for the number of missing days. In this case, the longest MDSs were so long that many of the summers with incomplete data would have contained equal to or greater number of days making the criterion useless. Instead, if the longest dry spell contained a gap longer than one day, or if it ended, for example, because of a whole missing month, the summer was removed from the analysis.

Those summers in the original precipitation statistics that contained less than 120 days (real number 123 days), were removed from the time series of the MDDs. These limits were defined arbitrarily, but in such a way that the number of missing days did not significantly affect the real number of MDDs. Table 1 shows the years that were removed from the time series for each station. The removal procedure had the largest effect for Riga and Vilnius, where 17.5% and 5.3% of the years were removed, respectively. However, the accuracy of the measurements was the main reason for discarding years from these records. In other time series, the percentage of years discarded was 0.0-2.8%.

2.4 Spatio-temporal variation of drought parameters: a statistical analysis

The regional differences in the variation of the length of the longest MDSs and in the number of MDDs were analysed by comparing the ranges of the values at different weather stations. Furthermore, the different scales of drought parameters were taken into account by comparing the coefficients of variation of the parameters. The coefficient of variation is defined as the ratio of standard deviation to the mean (Spiegel and Stephens, 1999). In addition, the correlation between the medians of the drought parameter value and the average May-August rainfall (Fig. 3) were determined. The Spearman correlation coefficient was used to test the statistical significance of the correlation because the parameters were not normally distributed. The p-value 0.05 was used as the limit of statistical significance.

Temporal changes in the length of the longest MDSs and in the number of MDDs were analysed separately for each threshold (Fig. 2). The statistical significance of the linear trends was tested with a parametric t-test (Önöz and Bayazit, 2003) and with the non-parametric Mann-Kendall test (Helsel and Hirsch, 2002). The use of two statistical tests was considered necessary because both normal and non-normal distributions were found when the drought parameters were tested using the Shapiro-Wilk test (Shapiro and Wilk, 1965). It is known that the Mann-Kendall test is more likely to reject the false null hypothesis (H_0 = no trend) when the distribution of the values is clearly skewed (Önöz and Bayazit, 2003). On the contrary, the t-test is more likely to reject the false null hypothesis when the values are normally distributed. A significance level of 0.05 was used for the rejection of the null hypothesis and a trend with a significance level of 0.01 was considered "highly significant".

The monthly distribution of the longest 10 mm MDSs was determined by analysing the relative frequency of the onset month of the MDSs in the time series. The 10 mm threshold was chosen for this analysis because the timing of these MDSs during the summer is very important for agriculture, for example. Since the accumulation period of a precipitation total of 100 mm can last in some cases over four months, the timing analysis was considered redundant for the longest 100 mm MDSs.

3 RESULTS

3.1 Spatial and temporal variation of drought occurrence

The longest 10 mm MDSs are generally found at the stations of Hammer Odde, Copenhagen and Helsinki (highest medians in Fig. 4a). The longest 100 mm MDSs are in Hammer Odde, Karesuando and Copenhagen (highest medians in Fig. 4b). Hammer Odde also tend to have slightly more MDDs than the other stations (Fig. 4c-d). However, these stations do not differ as much from the other stations as Bergen, where the MDSs are noticeably shorter and the number of MDDs fewer than at other stations. Located on the west coast of Norway, Bergen is highly exposed to moist westerly winds and orographic rain due the vicinity of the Scandinavian mountains. All other stations are located on the leeward side of this mountain range or outside its influence thus receiving less rainfall.

The lengths of the longest 10 and 100 mm MDSs show more inter-annual variation around their time-averaged mean values than the numbers of MDDs (Fig. 5). The coefficients for the 10 mm MDSs are the largest and also the distribution for many stations is positively skewed (Fig. 4a). The largest coefficients of variation are found in Bergen for all parameters and the lowest coefficients in Vilnius for 10 mm MDSs, Copenhagen for 100 mm MDSs, Hammer Odde for 1.0 mm MDDs and Karesuando for 0.1 mm MDDs.

The correlation between the average rainfall and the drought parameter medians was generally negative, but only the correlations for the longest 100 mm MDS (Fig. 6b) and for 1.0 mm MDD (Fig 6c) were statistically significant.

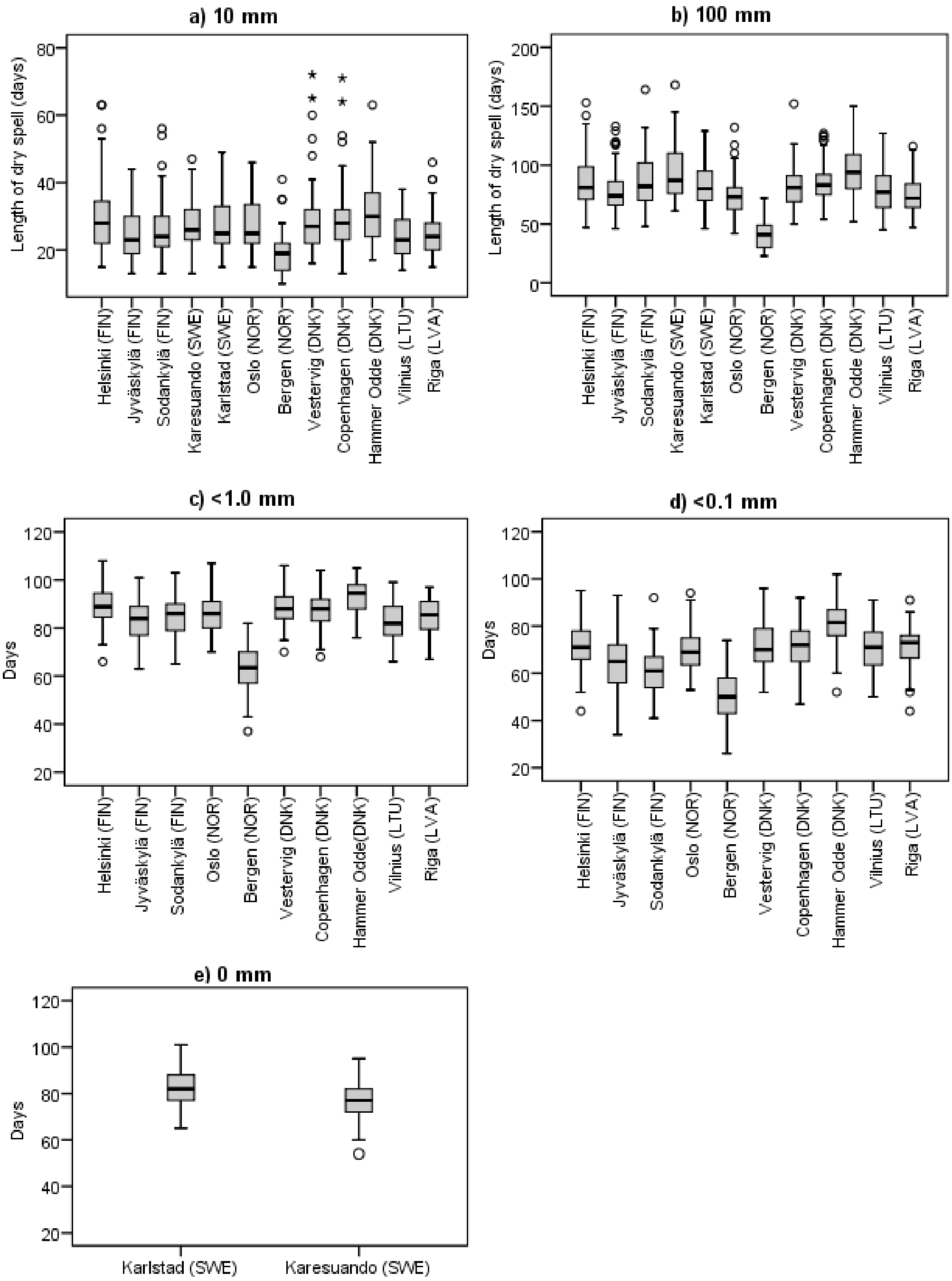

Fig. 4. Variation of the lengths of the longest dry spells (a, b) and numbers of dry days (c, d, e) in the data records used in the study. Note the different vertical axis scales for the different thresholds. The horizontal line within the box corresponds to the median, the ends of the box to the interquartile range. The whiskers denote the inner fence (±1.5 times the interquartile range). Values outside the inner fence but within the outer fence (±3 times the interquartile range) are marked with open circles. Values outside the outer fence are marked with stars.

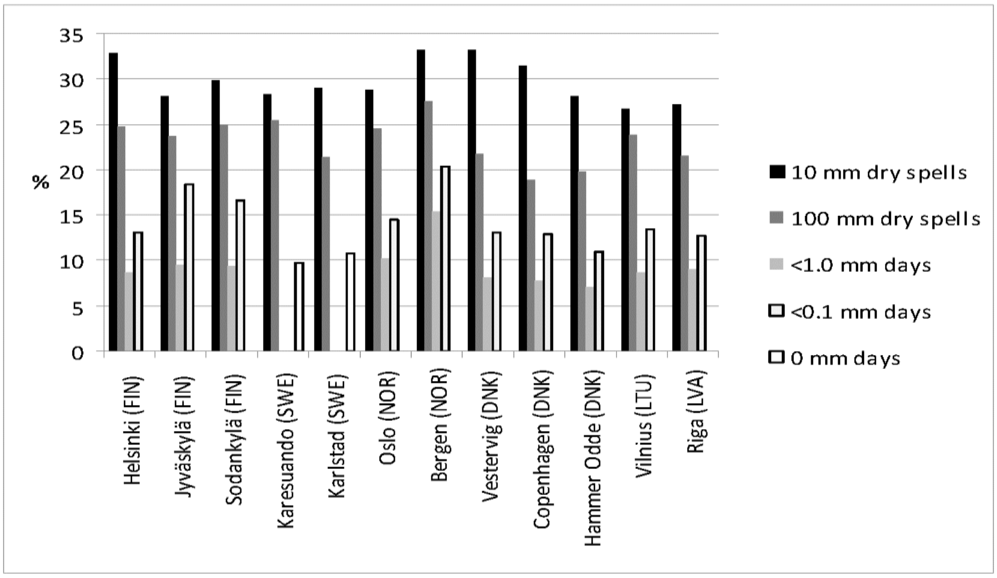

Fig. 5. Coefficients of variation of drought parameters

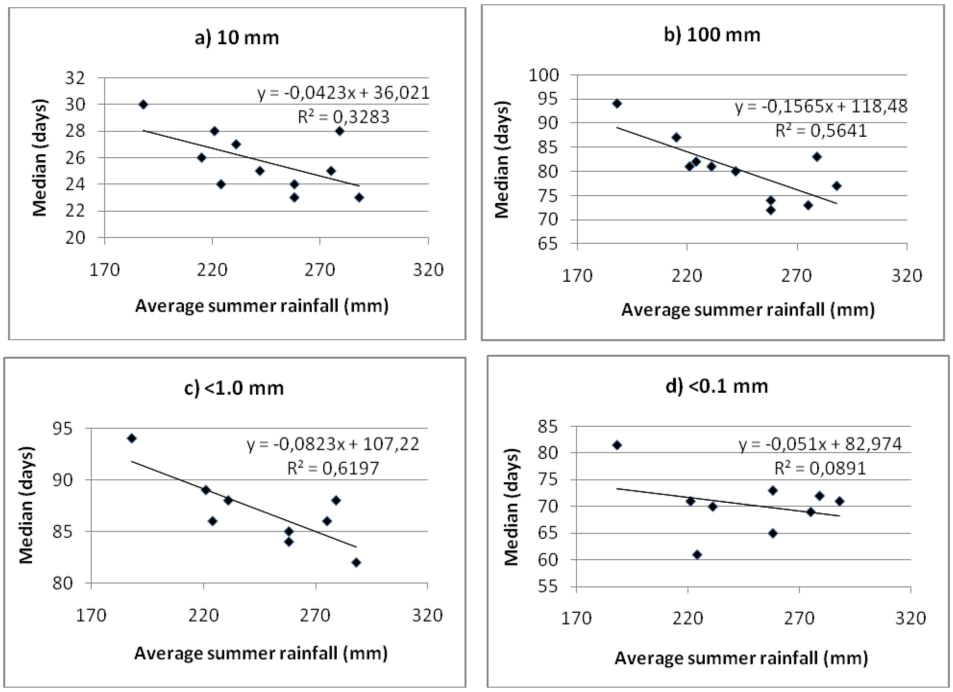

Fig. 6. Correlation between the average summer (May-August, 1961-1990) rainfall and the median of the longest dry spells, and the numbers of dry days based on data at 11 stations. Bergen was excluded from the analysis due to its substantial deviation from the other stations. Spearman correlation coefficients r_s and p-values: 10 mm MDS: r_s= -0.524, p=0.098; 100 mm MDS: r_s=-0.630, p=0.038; <1.0 mm MDD: r_s=-0.684, p=0.042*; <0.1 mm MDD: r_s -0.076, p=0.847, (*) denotes a statistically significant correlation (p<0.05).*

The lengths of the longest MDSs vary considerably from year to year at all weather stations throughout the period of the instrumental precipitation measurements (Fig. 4 and 5) without any clear statistically significant trends (Table 2). At most stations, no statistically significant trends in the numbers of MDDs are found either. An indication of (mainly positive) linear trends can be found only at few stations. An example of the temporal variation of the lengths of the longest MDSs and the numbers of MDDs in Copenhagen (DNK) is given in Fig. 7.

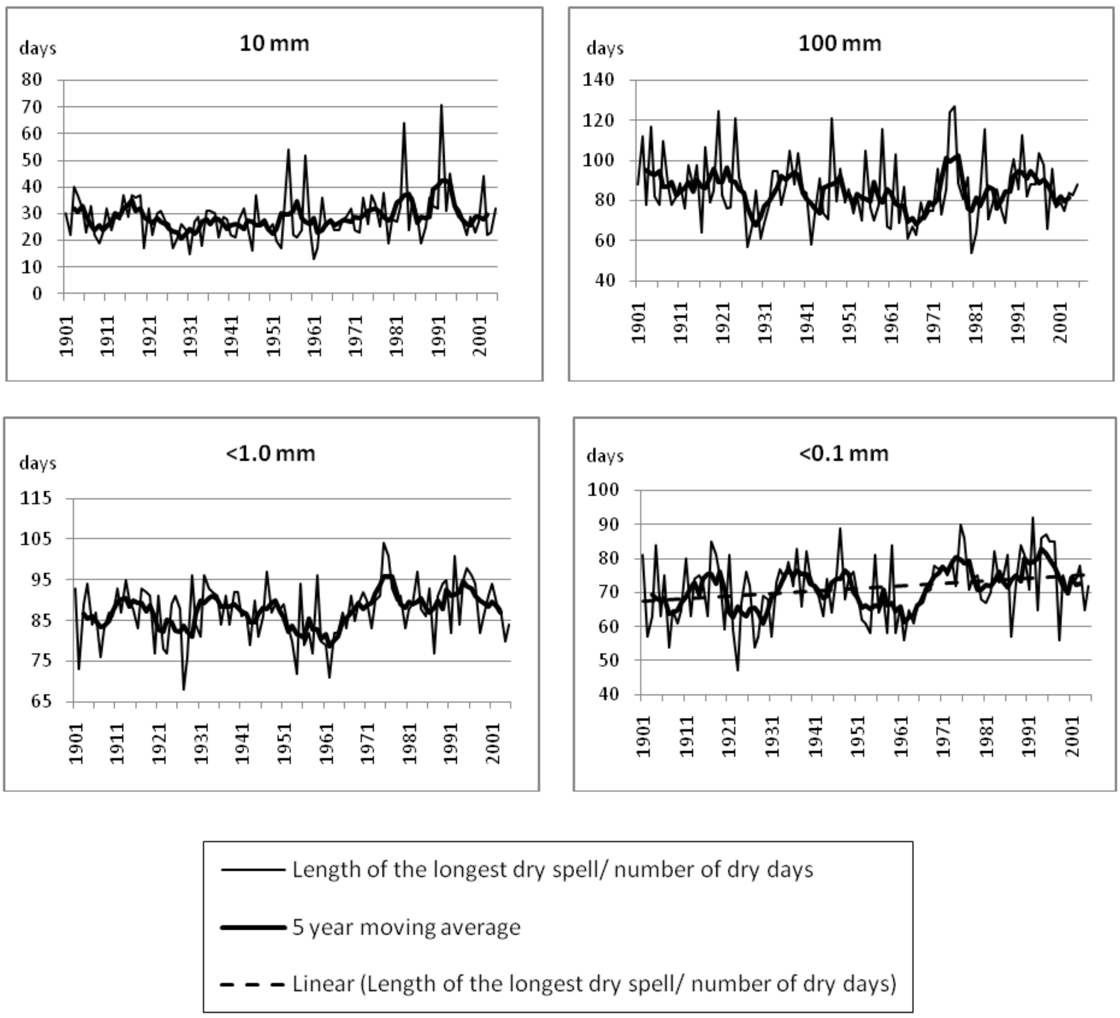

Fig. 7. Temporal variation of the length of the longest summer dry spells and number of dry days in Copenhagen (DNK). A linear trend line is displayed in the panel only if it is statistically significant (p<0.01). Note the variation in the y-axis scale between the panels.

*Table 2. Temporal trends of the lengths of the longest dry spells and the numbers of dry days. r_k/r_p = Kendall/Pearson correlation coefficient, z/t = Mann-Kendall test/t-test statistic, p = p-value, ** = p<0.01, * = p<0.05. The Kendall correlation coefficient and Mann-Kendall test were used to analyse parameters with skewed distributions, whereas the Pearson correlation coefficient and t-test were used for normally-distributed parameters. Most of the trends are statistically non-significant.*

Station	**Period**	**Trend**														
		10 mm			**100 mm**			**<1.0 mm**			**<0.1 mm**			**0 mm**		
		r_k/r_p	**z/t**	**p**	**r_k/r_p**	**z/t**	**p**	**r_k/r_p**	**z/t**	**p**	**r_k/r_p**	**z/t**	**p**	**r_k/r_p**	**z/t**	**p**
Bergen	1950–1999	0.065	0.654	0.513	0.193	1.365	0.179	0.233	1.660	0.104	0.257	1.844	0.071			
Copenhagen	1901–2005	0.054	0.804	0.421	-0.047	-0.709	0.478	0.177	1.822	0.071	0.252	2.640	**0.001****			
Hammer Odde	1901–2007	0.103	1.553	0.120	0.100	1.026	0.307	0.137	2.048	**0.041***	0.096	1.420	0.156			
Helsinki	1901–2007	0.089	1.340	0.180	0.068	1.037	0.300	0.141	1.458	0.148	0.057	0.590	0.556			
Jyväskylä	1901–2007	-0.042	-0.632	0.528	-0.006	-0.085	0.933	0.083	0.852	0.396	0.052	0.532	0.596			
Karesuando	1961–2007	-0.105	-0.710	0.481	0.065	0.643	0.520							0.167	1.122	0.268
Karlstad	1950–2003	0.025	0.262	0.794	0.029	0.206	0.838							-0.005	-0.037	0.971
Oslo	1950–2004	0.178	1.884	0.060	0.175	1.874	0.061	-0.001	-0.005	0.996	0.014	0.099	0.921			
Riga	1950–2007	-0.017	-0.186	0.852	-0.129	-1.406	0.160	-0.175	-1.209	0.233	0.310	2.214	**0.032***			
Sodankylä	1908–2007	0.100	1.437	0.151	0.052	0.759	0.448	0.057	0.564	0.574	-0.224	-2.261	**0.026***			
Vestervig	1901–2007	0.029	0.435	0.664	0.011	0.167	0.868	0.049	0.495	0.622	0.199	2.060	**0.042***			
Vilnius	1950–2007	0.209	1.587	0.118	0.024	0.179	0.859	0.027	0.201	0.841	0.205	1.528	0.132			

3.2 Timing of the longest 10 mm dry spells

For every time series, the longest 10 mm MDSs began most often in May (Fig. 8). Therefore May is the most probable timing of short-term meteorological drought occurrence. The droughts in spring and early summer can partly be associated with a more stable atmospheric boundary layer caused by a colder sea surface relative to the air mass.

In Helsinki, Sodankylä, Karesuando and Hammer Odde, July displays the lowest frequency as an onset month of MDSs. A distinct exception is Oslo, where July displays the second highest frequency. In Jyväskylä, Karlstad, Bergen, Vestervig, Copenhagen and Riga, the 10 mm MDSs start least often in August, whereas in Oslo, the lowest frequency is seen in June.

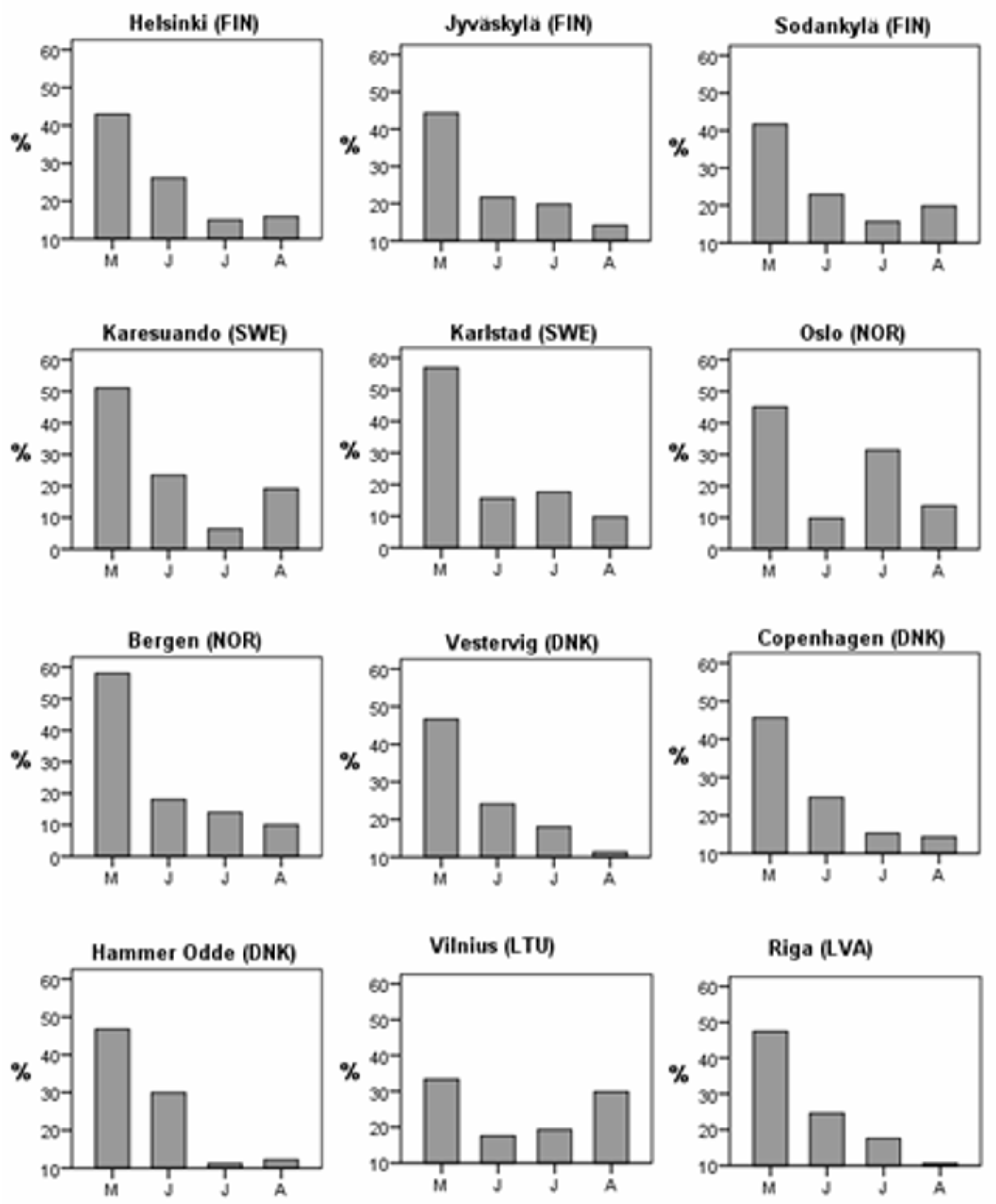

Fig. 8. Relative frequency of onset month for the longest 10 mm dry spells during May-August

4 DISCUSSION

4.1 Spatial variation and timing of meteorological summer drought occurrence in Northern Europe

When analyzing the spatial variability of the drought parameters, there are some issues to be taken into account. In general, the spatial differences in the occurrence of meteorological drought should be taken as indicative only, because the large spatial variation of precipitation makes the spatial interpolation of point data somewhat questionable over a heterogeneous area (Panu and Sharma, 2002). According to Groisman and Legates (1995), for example, the correlation distance of the monthly rainfall amount between two weather stations can vary from hundreds of kilometers over flat terrain to only tens of kilometers over mountainous regions. In summer, the correlation distance is generally shorter, due to the prevalence of rainfall of a convective nature (Osborn and Hulme, 1997). The furthest distance between two adjacent weather stations used in this study is over 300 km, between Oslo (NOR) and Bergen (NOR), and the shortest is 150 km, between Copenhagen (DNK) and Hammer Odde (DNK) (Fig. 1). Because of these distances, the lengths of the longest MDSs or the numbers of MDDs may be somewhat different during a single summer at adjacent stations. A larger number of stations or use of gridded data would be recommended to get a better estimation of the spatial differences in meteorological drought occurrence. As well, inclusion of weather radar measurements might improve the coverage of analyses.

As shown above, the coefficients of variation of the lengths of the longest MDSs and the numbers of MDDs around the mean are the largest at Bergen where the summer precipitation total is also the highest. However, no significant linear correlation between the coefficient of variation and the mean precipitation among the other stations exist. Tests of Spearman correlation give p-values above 0.41 (not shown). One distinct character worth noting is that the 10 mm MDSs have the highest coefficients of variation at all stations. This indicates that the shorter term drought is more variable than the longer term drought, which is represented by the 100 mm MDS lengths. This is also supported by the fact that the numbers of dry days during the whole summer period show the least variation. This has possibly some severe consequences to the agricultural drought, for example. Even if the whole summer was relatively moist, there is still a chance that a short term dry spell occurs during some critical stage of the crop growth.

Intuitively it would seem clear that higher average summer precipitation corresponds to shorter lengths of the dry spells and fewer dry days. Generally the findings of this study support this hypothesis (Fig. 6). The negative correlation was the highest for the 100 mm MDSs and for the <1.0 mm MDDs. The increase in the small precipitation amounts of <1.0 mm seems to contribute more to the increasing cumulative summer precipitation than the increase in the actual precipitation days.

According to the results, the short term dry spells are most likely to start in May in Northern Europe. The advantage is that the temperatures and evapotranspiration are not as high yet as they are later in summer. The melting snow may also increase the soil moisture. On the other hand, the more south we go, the more likely it is that the moisture from the melting snow does not anymore affect the upper soil layers, where it would be the most needed for the early growth stages of crops.

4.2 Interannual variation and long-term temporal trends of meteorological drought occurrence

The lengths of the longest dry spells and the numbers of dry days vary greatly from one year to another (see for example Fig. 7). However, over longer time periods, the limits of the variation in the lengths of MDSs and the numbers of MDDs become apparent, giving a clearer picture of the local meteorological drought occurrence. The lack of long-term trends in the time series (Table 2) also suggests that the distributions of the lengths of the MDSs and numbers of MDDs presented in this study are also valid in the current climate.

The time series analysis suggests that meteorological drought occurrence has not significantly changed at any of the stations in this study during the observation periods.

Only at three Danish stations, and at Riga, there are weak statistically significant increasing trends. At Sodankylä, Northern Finland, there is one statistically significant decreasing trend. These trends may be related to the possible long-term decrease in total precipitation in the southern region of Northern Europe and an increase in the northern region of Northern Europe (Beck *et al*., 2005; Trenberth *et al*., 2007). On the other hand, the lack of statistically significant trends in summer drought statistics may be explained by the fact that most of the increase in total annual precipitation has occurred during winter months (Heino et al., 2008).

It has been postulated that a rise in global temperatures potentially intensifies the global hydrological cycle, which in turn, may influence the frequency and intensity of extreme hydrological events such as droughts and floods (Trenberth, 1998; Huntington, 2006). However, the effect may vary greatly across the globe. Generally, higher temperatures increase the moisture holding capacity of the atmosphere leading to higher evapotranspiration, which increases the risk of drought occurrence. The increase in moisture holding capacity is greater at lower latitudes than at higher latitudes (Trenberth, 1998). Conversely, an increase in the moisture holding capacity may also increase the intensity of rainfall events. However, the amount of actual evapotranspiration is dependent on the available moisture, which varies spatially.

In summer (June-August), according to Lehtonen et al. (2013), the number of dry days, with precipitation less than 1 mm, is projected to slightly increase in southern Fennoscandia, including South-West Finland, but to decrease rather than increase further north. Nonetheless, these projected changes from 1971–2000 to 2081–2100 were not significant at the 95% level.

In this study, we have analysed linear trends. However, it should be noted that there is no particular reason to assume that changes in nature would occur linearly (Bordi *et al.* 2009). For example, the time series of drought parameters for Copenhagen appears to show strong fluctuations (Fig. 7). Recent results from the study of the relationship between large-scale atmospheric circulation patterns and European summer precipitation (Zveryaev and Allan, 2010) suggest that the interannual variability of summer precipitation is probably not related to the irregular fluctuation of the large-scale circulation patterns such as the North Atlantic Oscillation (NAO) or Scandinavian teleconnection, but more likely to the local temporal variation of evaporation from land and sea areas. On the other hand, it has been observed that the wintertime NAO index is connected to summer temperatures through soil moisture, especially in the Mediterranean area (Wang *et al*., 2011), which is then linked to the evaporation and summertime drought. Van der Schrier *et al*. (2006) also found relatively high positive correlations between the extended wintertime (December-March) NAO index and summer index of self-calibrating Palmer Drought Severity Index (SC-PDSI) in Northern Europe, especially in the south-western coast of Norway, in years 1901-2002. The larger values of SC-PDSI indicate increasing wetness and vice versa and, therefore, the negative phases of NAO seem to be related to lower SC-PDSI values and increasing drought. Hannaford *et al*. (2011) also found a similar wintertime correlation between NAO index and Regional Standardized Precipitation Index (RSPI), as well as between NAO index and Regional Deficiency Index (RDI), which is used as a hydrological drought indicator, in north-western and southern Scandinavia. In addition, they found negative correlation between those indices and NAO during May and autumn months and an interesting positive correlation in southern Scandinavia in July.

The positive and negative phases of the NAO index last for several years and have varied irregularly in the past (Jones *et al*., 1997, UCAR, 2008), which may explain the wavelike pattern in the drought occurrence. However, the existence of a link between the wintertime NAO index and summer droughts in Northern Europe, and to which extent the droughts in Northern Europe may be connected to Central or even Southern European droughts, requires further research, which is beyond the scope of this study. Also other less prominent large-scale atmospheric patterns, such as the East Atlantic pattern, Eurasian type-1 and Eurasian type-2, have been shown to correlate, at least to some extent, with the drought occurrence in Northern Europe (van der Schrier *et al*. 2006; Hannaford *et al*. 2011).

4.3 Applicability of the described methods in drought analysis

The high values of the length of the longest MDSs, and the number of MDDs, illustrate the association between meteorological drought and precipitation in Northern Europe. In comparisons between the stations, it should be noted that the precipitation climate of Bergen is different from the rest of the stations (Fig. 3) due to its maritime location. Actually, it is rather obvious that the longest MDSs of similar length in Bergen and in other stations do not actually have similar effects on the development of other drought types, such as agricultural drought. For example, it is quite common for the longest accumulation period of 10 mm rainfall to take around 30 days in Helsinki, but in Bergen this rarely occurs, and can therefore be considered a sign of an extreme event. This underlines the relative nature of the drought phenomenon and adaptation of organisms and functions to the dominant moisture conditions. Use of different kind of thresholds when comparing different climatic regions is therefore recommended in further studies.

The temporal variation of drought parameter values can also be used to estimate the effect of climate change on drought occurrence at a general level. Although changes in the amount of precipitation are the main driving force in the occurrence of drought, there are additional climatic factors to consider (Sheffield and Wood, 2008). For example, Briffa *et al*. (2009) showed that changes in temperature and evapotranspiration have potentially had a large impact on drought occurrence in Europe. The drought definition should also somehow link meteorological drought conditions to their consequences, such as a lower soil moisture or stream discharge. Without this, it is difficult, if not impossible, to estimate, for example, how many dry days would be required to make a summer actually “dry”. The closest approximations of the normal levels of summer drought parameters within the climatic zone represented in this study are the median values shown in Fig. 4. However, around these median values, additional factors, such as the rate of potential evaporation and preceding soil moisture, determine the emergence of drought conditions.

An example of the number of “drought” days defined according to soil moisture content, also known as the Finnish Forest Fire index (FFI), is given in Fig. 9 for the exceptionally dry summer at 2006 in Finland. According to the soil moisture index statistics of the Finnish Meteorological Institute, in summer 2006 the number of "drought" days was above the long term average at all four Finnish weather stations used in this study. In Helsinki, for example, the number of drought days in May-August 2006 was 78, whereas in the years 1966-1995, the average number was approximately 50 days. However, care must be taken in comparing these figures because different data sources were used before 1997. The lengths of the longest MDSs in Helsinki in 2006, were 63 and 153 days for 10 and 100 mm thresholds, respectively. The numbers of the MDDs were 108 and 92 days for <1.0 and <0.1 thresholds respectively. These were among the highest on record. Compared to the number of "drought" days, it seems that the dry spell length measured with 10 mm precipitation threshold underestimates the drought occurrence, whereas the other parameters tend to overestimate it. The soil moisture parameter includes more variables and therefore, presents a broader approximation of drought development. However, none of these measures seems to offer a completely objective or universal definition for drought.

5 CONCLUSIONS

For most of the Northern European stations analysed in this study, the summer time MDS length ranged between 9-73 days (10 mm) and 42-168 days (100 mm), and the numbers of MDDs ranged between 34-101 days (0.1 mm), 63-108 (1.0 mm), with no significant variation between the stations. The notable exception is the station of Bergen, which receives a plenty of orographic precipitation due to its location on the west coast of Norway between the North Atlantic and the Scandinavian mountain range. Therefore, it is recommended to use different kind of precipitation thresholds to analyse MDS lengths and numbers of MDDs in stations in different kind of precipitation climate in future studies.

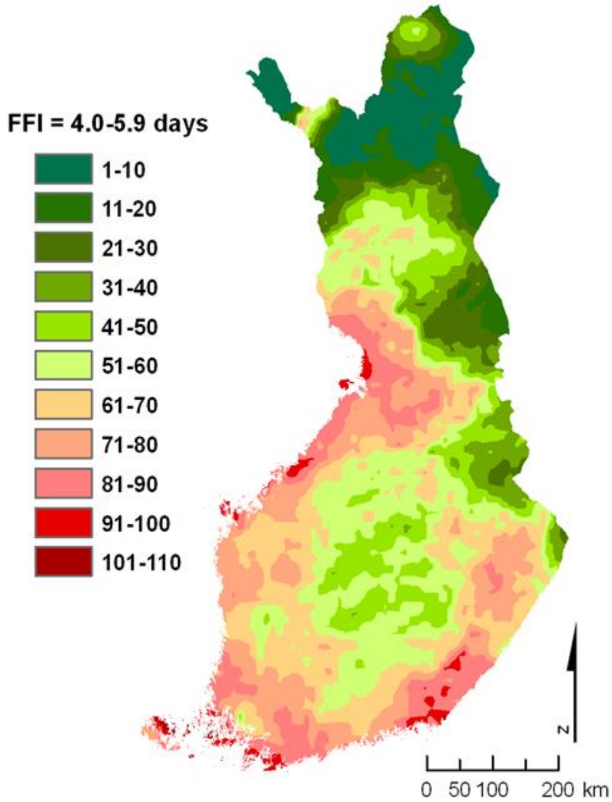

Fig. 9. Number of "drought days" in Finland in summer 2006 (May-August) according to the soil moisture index (also known as the Finnish Forest Fire index, FFI) (Heikinheimo et al. 1996; Venäläinen and Heikinheimo 2003). When the index value is 4.0-5.9 the day is regarded as "moderately dry" or "dry" and the forest fire warning is given. In 2006, the number of these "drought" days was well above long-term average in all the Finnish stations used in this study.

The longer term drought parameters (100 mm MDDs) show less variation around their mean values than the 10 mm MDSs. This suggests that it is possible for a short term dry spell to occur during some critical crop growth stage even if the summer as a whole was relatively moist. Most short term dry spells start in May. The melting of snow can help to counteract drought by increasing the soil moisture and stream discharges in some areas. However, the longer the MDS, the more severe are the consequences in other stages of the hydrological cycle.

The positively skewed distributions and high coefficients of variation of the length of the 10 mm MDSs suggest that even though relatively short 10 mm MDSs are more common, longer 10 mm MDSs also occur from time to time. It is hence highly possible that rainy summers with short MDSs are sooner or later followed by dry summers with very long MDSs. This should be taken into account when water-dependent activities, such as agricultural production, and drought management strategies are planned, including preparation for a large variation in climatic circumstances.

The analysis of the temporal variation in the length of the longest MDSs and the number of MDDs suggests that meteorological summer drought occurrence has remained relatively unchanged in Northern Europe during the period of homogeneous instrumental precipitation observations. Statistically significant increasing trends were found to be rare and were detected mainly in the time series of MDDs of the Danish stations located in the south-western part of the study region. For example, in Hammer Odde, the number of days with <1.0 mm precipitation has increased from 68 to 75 during the 20th century. One decreasing trend was found at Sodankylä in Northern Finland. It is possible that these trends are related to long-term changes in summer precipitation totals as a consequence of climate change. However, it should be kept in mind that most of the trends are not statistically significant. Besides, most of the long-term changes in mean precipitation have occurred in winter. In any case, the strong interannual variation of the length of the longest MDSs and the number of MDDs makes differentiation of any linear trends difficult.

The methods employed in this study proved applicable in the evaluation of meteorological drought occurrence at a general level and with respect to variation of precipitation amounts. Including potential evapotranspiration in the analysis would give more insight into the effect of changing temperatures on meteorological drought occurrence. To improve the analysis of spatial variance of drought parameters a larger number of stations should be included.

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APPENDIX: REPORTED DROUGHT EVENTS IN NORTHERN EUROPE

Table A1 lists some of the drought events that have occurred in Northern Europe since the beginning of the twentieth century. The list is not complete. It should also be noted that in this paper, Northern Europe is limited to cover only the Baltic and Nordic Countries, excluding Iceland and Estonia (Fig. 1) and many of the droughts included were selected from studies covering wider regions. The way the drought was studied in the reference research is mentioned in the list by naming the drought type, which indicators were analysed. However, this does not mean that a drought event could simply be considered meteorological, hydrological or soil moisture related, but in reality, many of these dry periods may involve impacts across all those drought types. All the referred studies in Table A1 do not cover the whole of Northern Europe and therefore it is not valid to draw conclusions on the spatial extent of the drought events.

Table A1. Drought events in Northern Europe since the beginning of the twentieth century. Drought type is marked as meteorological (M) if the respective study is based merely on the analysis of precipitation anomalies, or if no other particular effects have been mentioned in the reference. The drought types of the analyses based on river flow data and soil moisture status are named as hydrological (H) and soil moisture (S) drought, respectively. References: 1 = Bradford (2000), 2 = Hannaford et al. (2011), 3 = Hisdal and Tallaksen (2003), 4 = Mauget (2006), 5 = Parry et al. (2005), 6 = Stahl (2001), 7 = van der Schrier et al. (2006), 8 = Wilhite and Glantz (1985), 9 = Zaidman et al. (2001).
Region 1 = Northern Europe including the British Isles and western parts of Russia;
Region 2 = North-west Scandinavia including northern and western parts of Norway and north-west Sweden, >50% of the area affected by drought;
Region 3= Southern Scandinavia including Denmark and southern parts of Norway and Sweden, >50% of the area affected by drought

Time period	Affected region	Type	Reference
1901–1911	Region 1	M	4
1901 July, September	Region 2	M	5

Time period	Affected region	Type	Reference
1901 September, November	Region 3	M	5
1902 May- July	Region 2	M	5
1902-1903 November-January	Region 3	M	5
1904 January, July-September	Region 3	M	5
1904 February-April	Region 2	M	5
1905-1906 December-January	Region 3	M	5
1906 September	Region 3	M	5
1907 December	Region 2	M	5
1908 May-June, October	Region 2	M	5
1908 October-December	Region 3	M	5
1909 February	Region 3	M	5
1910 July-September	Region 2	M	5
1911 July-September	Region 3	M	5
1911 July, December	Region 2	M	5
1912 January-February, July-August	Region 2	M	5
1913 June, October	Region 3	M	5
1914 July	Region 2	M	5
1914 July-November	Region 3	M	5
1914-1915 December-February	Region 2	M	5
1915 October-December	Region 2	M	5
1915 June, October-November	Region 3	M	5
1916 April	Region 2	M	5
1917 January	Region 2	M	5
1917 March, July	Region 3	M	5
1918 May	Region 3	M	5
1919 January-February, July	Region 2	M	5
1919-1920 December-January	Region 2	M	5
1920 October-December	Region 2	M	5
1920 November-December	Region 3	M	5
1921 summer	Denmark, Southern Sweden	M	7
1921 summer	Baltic countries	M	7
1921 June-July, November	Region 3	M	5
1922 November-December	Region 3	M	5
1923 April-May	Region 2	M	5

Time period	Affected region	Type	Reference
1926 February	Region 2	M	5
1928 January, May	Region 2	M	5
1928 January, May-June	Region 3	M	5
1929 February	Region 2	M	5
1929 February-April	Region 3	M	5
1930 September-October	Region 2	M	5
1931 February-April	Region 2	M	5
1931 November-December	Region 3	M	5
1932 February-March	Region 3	M	5
1932 May-June	Region 2	M	5
1932–1947	Region 1	M	4
1933 January, May	Region 3	M	5
1933 June-July, November	Region 2	M	5
1933-1934 December-February	Region 3	M	5
1935 December	Region 2	M	5
1936 January-February, June	Region 2	M	5
1937 March-May	Region 2	M	5
1937 December	Region 3	M	5
1938 April	Region 3	M	5
1938-1939 December-January	Region 2	M	5
1939 May, October-November	Region 3	M	5
1939 October-November	Region 2	M	5
1940 February, June	Region 3	M	5
1940 May-June	Region 2	M	5
1941 February-March, May-July, November	Region 3	M	5
1941 April-June	Region 2	M	5
1942 January-April	Region 3	M	5
1942 March	Region 2	M	5
1944 April	Region 3	M	5
1944 November	Region 2	M	5
1945 September	Region 2	M	5
1945 November	Region 3	M	5
1946 May	Region 3	M	5
1947 February, June-October	Region 3	M	5
1947 January-March	Region 2	M	5

Time period	Affected region	Type	Reference
1948 January	Region 2	M	5
1950 October	Region 2	M	5
1951 January-March	Region 2	M	5
1952 November-December	Region 2	M	5
1953 March, December	Region 3	M	5
1954 April, November	Region 2	M	5
1955 March-April, July-September	Region 3	M	5
1955 April-September	Region 2	M	5
1956 April-May, November-December	Region 3	M	5
1957-1958 December-January	Region 3	M	5
1959 July-October	Region 3	M	5
1959-1960 December-March	Region 2	M	5
1960 May	Region 3	M	5
1960 -1961 October-January	Region 2	M	5
1962-1963 December-March	Region 3	M, H	5
1962-1963 October - May (8 months)	Denmark	M	3
1963 January-February (2 months)	Denmark	H	3
1963 June-July	Region 2	H	5
1963-1964 December-March (4 months)	West coast of Norway	H	6
1963-1964 December – May (6 months)	Denmark	M	3
1964 February-May	Region 3	M, H	5
1964 May-October	Denmark	H	3
1964 June	Region 2	M	5
1965 March, November	Region 3	H	5
1965-1966 Winter	North-western Scandinavia	M, H	2
1965-1966 January-February	Region 2	H	5
1966 January-February, December	Region 2	M	5
1966 April, July, December	Region 2	H	5
1967 September	Region 2	H	5
1968 July-November	Region 2	M, H	5
1968-1970	North-western Scandinavia	M, H	2
1969 January-March, June, August	Region 2	M, H	5
1969 summer	Sweden and Denmark		1

Time period	Affected region	Type	Reference
1969 August	Region 3	M	5
1969-1970 December-March	Region 3	H	5
1969–1976	Region 1	M	4
1970 January-April, June	Region 2	M, H	5
1970 February	Region 3	M	5
1972 March	Region 2	M	5
1972 October-November	Region 3	M, H	5
1972 September-October (2 months)	Southern Scandinavia	H	6
1973 September	Region 3	H	5
1973 October	Region 3	M	5
1974 spring	Norway, Sweden and Denmark	M	1
1974 March-April (2 months)	Parts of Europe south of 60°N	H	6
1974 April-June	Region 3	M, H	5
1974 May, November	Region 2	M, H	5
1975 May-October (6 months)	Denmark	M	3
1975 June – November (6 months)	Denmark	H	3
1975 June-August, October-December	Region 3	M, H	5
1975 summer	Sweden	M	1
1975 August	Region 2	M	5
1975 October	Denmark	M	3
1976 February-April (3 months)	Denmark	M	3
1976 March-September (7 months)	Norway, Sweden and Denmark	M	1
1976 Spring-Summer	Denmark	M, H	9
1976 April – November (8 months)	Denmark	H	3
1976 summer	Denmark, Southern Sweden	M	7
1976 June-September (4 months)	Denmark	M	3
1976 late summer	Northern Europe	H	6
1976 March-April, June-December	Region 3	M, H	5
1976 October, December	Region 2	M, H	5
1977 February	Region 2	M, H	5
1977 April	Region 2	H	5
1978 June, December	Region 3	M	5
1978 August	Region 2	H	5
1979 February	Region 3	M, H	5

Time period	Affected region	Type	Reference
1979 February	Region 2	M	5
1980 March-May	Region 3	M	5
1980 March, July	Region 2	M, H	5
1981 April	Region 2	H	5
1981 October-November	Region 2	M	5
1982 January-December (12 m.)	Area extending from Latvia to Lithuania and south-western Russia		8
1982 October	Region 2	H	5
1983 January-August (8 months)	Area extending from Central Europe to central parts of Norway and Sweden		8
1983 July-December (6 months)	Area extending from Sweden to Central Europe	H	6
1983 August	Region 3	M	8
1984 April	Region 3	M	8
1985 January	Region 2	M	5
1985 May	Region 2	H	5
1986 March	Region 2	M	5
1986 April, July, August	Region 2	H	5
1987 March	Region 3	H	5
1987 March	Region 2	H	5
1988 March	Region 2	M	5
1988 June	Region 3	M	8
1989 July, October, November-December	Region 3	H	5
1989 January	Region 3	M	8
1989-1990	Denmark	M, H	9
1991 September	Region 3	H	5
1989 May-July (3 months)	Denmark	H	6
1990 August-September (2 months)	Northern Europe	H	6
1991 September	Region 3	M	5
1992 June-August	Region 3	H	5
1992 July	Region 3	M	5
1992 October	Region 2	H	5
1993 April-June	Region 3	M, H	5
1993 November	Region 2	M, H	5
1994 January	Region 2	H	5
1994 April	Region 2	M	5
1994 July	Region 3	M	5

Time period	Affected region	Type	Reference
1995 summer and autumn	Norway and Sweden	M, H, S	1
1995 September	Region 2	H	5
1995-1996 December-April	Region 3	M, H	5
1996 February-March, September	Region 2	H	5
1996 March, September	Region 2	M	5
1996 May, July-October	Region 3	H	5
1996-1997 (7 months)	Region 3	H	5
1997 June-July	Region 2	M	5
1997 November	Region 2	H	5
1998 October	Region 2	H	5
2000 November	Region 2	M	5
2001 April	Region 2	H	5
2002 winter	North-Western Scandinavia	M, H	2
2002 December	Region 2	M	5
2002 August, October-December	Region 2	H	5
2003 February, October	Region 3	M	5
2003 April	Region 3	H	5
2003 April, July	North-Western Scandinavia	M	2
2003 July-August (2 months)	North-Western Scandinavia	H	2
2003 March, September-October (3 m.)	Southern Scandinavia	M	2
2003 (3 months)	Southern Scandinavia	H	2
2004 June, August	Region 2	H	5

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