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Observed changes in heavy daily precipitation over the Nordic-Baltic region

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ABSTRACT

Study region: The Nordic-Baltic region has experienced numerous flooding episodes resulting from heavy rainfall. Such events are costly and may potentially threaten the safety of the population. In this paper we present a temporally long and spatially dense dataset of annual maximum daily precipitation and their date of occurrence measured in a large region covering Fennoscandia and the Baltics (Dyrrdal et al., 2021, doi:10.11582/2021.00015).
Study focus: We analyse the long-term (1901–2020) changes at 138 stations and short-term (1969–2020) changes at 724 stations for both annual maxima and their date of occurrence. Further, we assess the climatology of heavy precipitation including record evens, as well as changes in design values.
New hydrological insight for the region: Results show a majority of positive trends in daily annual maxima and the 5-year return level, with hotspots in southeast of Norway, southern Sweden and southwest of Finland. Generally, annual maximum precipitation events occur somewhat later in the year now compared to the beginning of the last century. The 5-year return level is relatively homogeneous across the Nordic-Baltic region, with values between 30 and 50 mm, except for a few lower values in Finland and high values mainly exceeding 70 mm at the west coast of Norway.

1. Introduction

Heavy and extreme precipitation, especially in liquid form, is associated with a variety of societal challenges. Different types of slides and avalanches, river floods and urban floods occur as a consequence of prolonged or intense precipitation, while certain

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ecosystems may suffer from direct or indirect effects of heavy precipitation. Such events can also result in large and costly damages to infrastructure, private property, agriculture, and some times human lives.

Here we examine heavy precipitation from a large station network in the Nordic-Baltic region. During recent years devastating heavy rainfall events have been reported in all countries included in this study. Of relatively recent events we can mention October of 2014, when a large rain flood in the western part of Norway (Langsholt et al., 2015; DSB, 2015) resulted in damages on more than 1000 properties and cost about 40 million euro in insurance claims. Damages to roads and railways came in addition. Within the last decade Copenhagen has experienced two major cloudbursts; July 2nd 2011 and August 31st 2014 when more than 125 mm fell in a few hours and maximum intensities exceeding 30 mm in 10 min (Arnbjerg-Nielsen et al., 2015; Vejen, 2014). The same rainfall system hitting Copenhagen in 2014 also reached Malmö, Sweden, flooding some 2200 buildings and resulting in damages exceeding 30 million euro (e.g. Olsson et al., 2017). Further, a flooding event in Latvia in August and September of 2017 occurred as a result of 123.1 mm falling in 24 h at Rezekne station, followed by the 3rd wettest September and 6th wettest October on record. These events altogether led to damages to the agriculture sector with an estimated cost of 81 million euro (The Ministry of Agriculture of the Republic of Latvia, 2018).

As temperatures increase, the atmosphere can hold more moisture and the potential for more frequent and intense rainfall is present. This is referred to as the Clausius-Clapeiron (CC) relationship (Trenberth et al., 2003) that predicts an approximately 7% increase in precipitation intensity per degree Celsius. Heavy precipitation has been shown to increase even more with a warming atmosphere compared to mean precipitation (e.g. Boucher, 2013), and Lenderink et al. (2017) showed that hourly precipitation extremes have a response to warming exceeding the CC relation, arising from the response of convection to increases in near-surface humidity. Further, Ali et al. (2021) found that the scaling of hourly extreme precipitation follows at least the CC rate at a regional scale, but often exceeds the CC rate locally. Zeder and Fischer (2015) concluded that there is robust evidence for a forced climate signal in annual and seasonal short- and long-duration extreme precipitation events in Central Europe, after detecting a significant scaling signal with Northern Hemisphere temperature anomalies for all annual maximum and most seasonal maximum single-day and multi-day precipitation events. As pointed out by Fischer and Knutti (2016), the response of precipitation to increased greenhouse gas concentrations and consequent warming is complex, and different rainfall intensities often respond differently to warming. Moustakis et al. (2020) uses hourly weather stations, 40 years of climate reanalysis and two convection permitting models to show that local features of atmospheric convection, larger-scale dynamics and orography affect the dependence of extreme rainfall on surface temperature. Additionally, some changes in precipitation extremes might be explained by natural variability. E.g. Willems (2013) showed that precipitation extremes have oscillatory behavior at multidecadal time scales, and in northwestern Europe larger and more precipitation extremes have occurred around the 1910s, 1950–1960s, and the 1990–2000s, both in summer and winter. Changes in large scale circulation, such as the North Atlantic Oscillation (NAO) (Hurrell, 1995), largely influence precipitation extremes in certain regions. According to Pfahl et al. (2020) the dynamic contribution modifies regional responses of extreme precipitation in the future.

Westra et al. (2013) studied trends in a global dataset of 8326 annual maximum daily precipitation time series with at least 30 years of data during 1900–2009. Statistically significant increasing trends were detected at the global scale, with close to two-thirds of stations showing increases. A global study of century long gridded observations, reanalysis and model data showed that the frequency of precipitation extremes has increased in more regions than it has decreased (Donat et al., 2016). Recently, Myhre et al. (2019), showed that the frequency of heavy precipitation events are the main reason for an increase in total precipitation, and that the increase of intensity is less significant. Benestad et al. (2019), however, indicated that the main cause of a general increase in the probability that precipitation exceeds 50 mm/day has been a boost in the intensity of the rain. They found positive trends over the period 1961–2020 at most locations with observations longer than 50 years in Europe and the USA. Villarini et al. (2011) studied annual maximum daily rainfall time series from 221 rain gauges in the Midwest United States with a record of at least 75 years, and found a slight tendency to increasing annual maxima. Changes over time were less significant for higher quantiles.

An increase in total precipitation and extreme precipitation was detected in Fennoscandia in 1951–2002 and in the western part of the former USSR in 1936–1997 (Groisman et al., 2005). Irannezhad et al. (2017) studied trends in a gridded 10 km × 10 km product based on observed precipitation and results suggested significant increases in the frequency and intensity of precipitation extremes over most parts of Finland during 1961–2011. Aalto et al. (2016) showed that near the same areas of significant increase in precipitation in Finland during 1961–2010, significant positive trends in relative humidity were also found. Sorteberg et al. (2018) showed mainly positive trends also for Norway, when studying changes in the highest measured daily precipitation for summer season during 1968–2017. In Dyrrdal et al. (2012) the intensity of daily annual maxima was shown to have increased in major parts of Norway during 1968–2010. In Sweden, Wern (2012) found increasing annual maxima from 1900 - to the 1930s, followed by a decrease until the 1970s and again an increase until 2010.

Positive trends in the recurrence of daily heavy precipitation events were determined in all three Baltic states: Estonia (Paadam and Post, 2011; Tammets and Jaagus, 2013), in Latvia (Avotniece et al., 2010, 2017) and in Lithuania (Rimkus et al., 2011), although the periods and the definition of the events vary between countries.

Annual maxima are, in addition to representing heavy precipitation, the basis for estimating design precipitation used in the planning and design of infrastructure in many countries. In the current study we examine heavy precipitation intensity from an extensive dataset of observed annual maxima over a long historical period and covering a relatively large region of Northern Europe, including Fennoscandia and the three Baltic countries. Also the date of occurrence corresponding to each annual maximum event is included in the dataset. We have published the dataset in an open repository (Dyrrdal et al., 2021), available for public download and conceivably useful for e.g. climatological studies and climate model evaluation. This dataset allows for an updated evaluation of changes in heavy precipitation intensity and occurrence in the study region, short (since 1969) and long (since 1901) term. A secondary objective is to study and document the spatial variability of extreme precipitation over the region, including record events.

2. Data and study region

2.1. Data

We have collected series of annual maximum 1-day precipitation (hereafter; Rx1d) and date of occurrence (hereafter; dateRx1d) (Dyrrdal et al., 2021) from a dense station network covering large parts of the Nordic-Baltic region (map in Fig. 1). If the same amount was measured on several dates within the same year, the last date was selected. Additionally, we collected the highest measured event at a larger network of 5058 stations in the same region. Series of Rx1d from the following countries are collected: Finland (412), Sweden (813), Norway (605), Denmark (84), Estonia (27), Latvia (48), Lithuania (18), where the number of meteorological stations with at least 30 years of Rx1d in the period 1845–2020 is indicated in parenthesis for each country. The total number of series with at least 30 years of data is 2003, with a peak of 1760 stations in 1980. Fig. 2 shows the number of stations with digitized daily 30-year long time series for the study region through time, where red lines indicate the most recent period with a relatively high station density of digitized series; 1969–2020.

In the current study we focus on the following two subsets of the data mentioned above:

Dataset 1 724 time series containing at least 80% of data during the most recent period 1969–2020, when the station network is at its most dense. A criterion of not more than 5 consecutive missing years was used. The station selection is shown as small dots and filled circles in Fig. 1.

Dataset 2 138 time series with at least 80% data coverage during 1901–2020. The station selection is shown as open and filled circles in Fig. 1.

Dataset 3 Records (highest value) at 5058 stations, regardless of time series length. The station selection is shown in Fig. 9.

Datasets 1 and 2 are subsets of the published dataset of Dyrrdal et al. (2021).

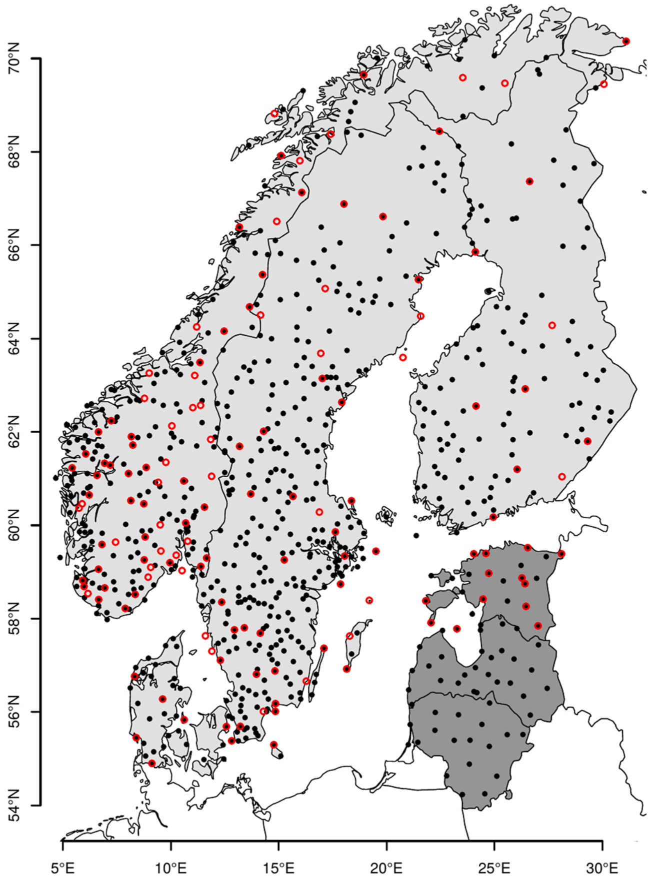

Fig. 1. Map over the study region, where Fennoscandia (Baltics) is indicated in light (dark) gray. Stations in Dataset 1 (724 time series containing at least 80% of data during 1969–2020) are indicated as small black dots; stations in Dataset 2 (138 time series with at least 80% data coverage during 1901–2020) are indicated as open red circles, while stations included in both datasets are indicated as red circles filled with black. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

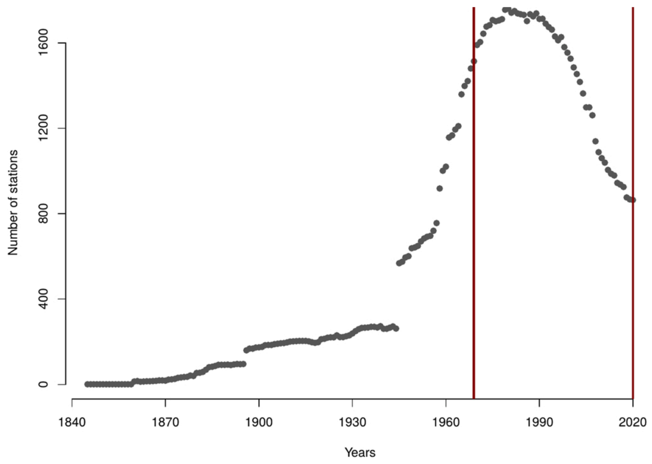

Fig. 2. Number of digitized daily precipitation series with time. Red lines indicate the period 1969–2020, covered by Dataset 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Limitations in the data

Heterogeneities in our data introduced by differences in station density and time series lengths complicates the study of temporal and spatial variability. Also, the procedure for accepting a value as a valid annual maximum varies somewhat between the countries. Some countries exclude years with more than a certain number of observations missing, for instance one month, while others exclude years with crucial months missing. One example of the latter is when the annual maximum most likely occurs during summer or autumn, an annual value is accepted if observations during May through November are available. As this season of high likelihood may vary between countries due to different climates, we assume the introduced heterogeneity to be acceptably low. Criteria for extracting annual maxima in the different countries are reported in Table 1, along with the number of stations included in the two datasets described below. Quality control is performed by the data deliverers in each country. In addition, we confirmed the validity of low values (<10 mm) in the entire dataset.

Our dataset consists of daily values from measurements every morning, not the highest running 24-hour value, meaning that an extreme precipitation event can be divided into two days. We also computed trends for 2-days annual maxima (not shown), but found them to be very similar to trends in Rx1d.

Although most heavy precipitation in the study region falls as rain, there might be events of snowfall present in our dataset. Snow is to a larger degree subject to wind-induced undercatch compared to rain, thus any positive precipitation trends may partly be explained by a larger fraction falling as rain due to higher temperatures. However, as shown by e.g. Wolff et al. (2014), the catch ratio for heavy precipitation is not influenced significantly by the wind.

2.3. Climate in the region

The Nordic-Baltic region is characterized by strong climate gradients, both in the south-north and east-west (coast-inland) direction. The coldest areas are found in the mountain regions, and in the northern continental parts. In these areas solid precipitation dominates during the winter season. The rainiest seasons are generally summer and autumn over the whole region, while spring is the driest. The encounter between cold arctic air and mild air from the south favors the development of fronts, giving rise to variable and often wet weather.

The western coast of Denmark and Norway are exposed towards the Nordic ocean and the Norwegian sea, and particularly Norway is located in the westerly wind belt where storms frequently travel towards east-northeast along the North Atlantic jet stream during

Table 1
Criteria for extracting annual maximum precipitation for a given year in each country. The three columns to the right indicate the number of stations within each dataset after quality control.

Country	Inclusion criteria	Dataset1	Dataset2	Dataset3
Finland	Low observation counts are checked	103	8	928
Sweden	Maximum two days of missing values during June - October	309	42	2001
Norway	Maximum 30 days of missing values during one year	207	68	1889
Denmark	Low observation counts are checked	35	4	147
Estonia	Complete data during April - September. Low observation counts are checked	24	13	27
Latvia	Maximum 15 days of missing values during one year, and maximum three days of missing values during one month	28	0	48
Lithuania	No criteria used, but low values are checked	18	0	18

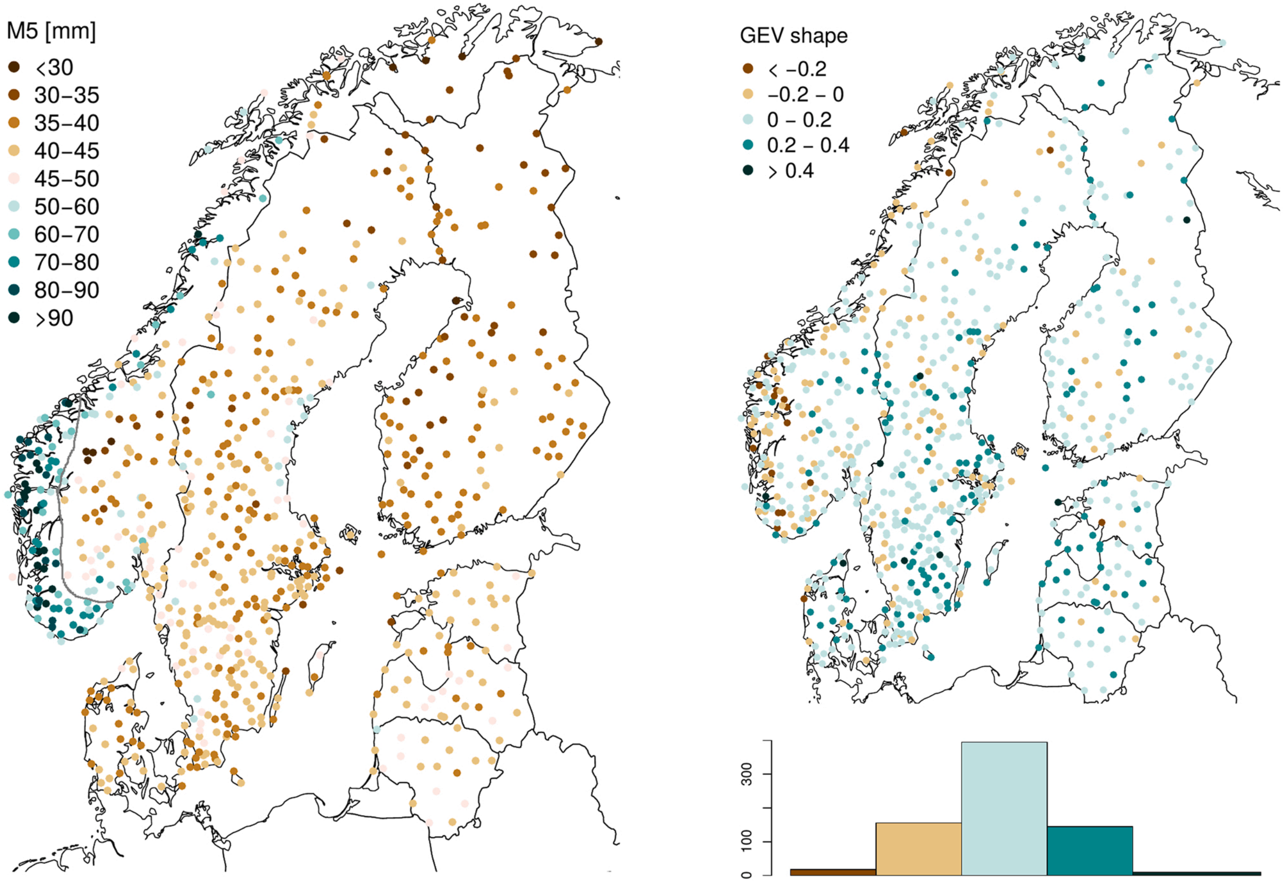

Fig. 3. Maps of the 5-year return level (a) and estimated shape parameter (b) from Dataset 1 (1969–2020), according to the stationary GEV analysis. Red/orange colors indicate smaller values while green colors indicate higher values. The gray line roughly indicates the border between the two Norwegian clusters, E-Norway and W-Norway. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fall or early winter. Annual precipitation amounts of 3000–4000 mm are common in these areas. A recent study of Michel et al. (2021) showed that during the period 1979–2018 78.5% of the daily extreme precipitation events in Southwestern Norway are linked to atmospheric rivers. The driest areas of the study region are found in northern Finland, with annual mean precipitation of about 400 mm, while the south coast and eastern parts have up to 750 mm (Pirinen et al., 2012). Annual precipitation sums in Sweden generally lie between 500 and 800 mm, with higher values in the southwest (1000–1200 mm) and up to 2000 mm locally in mountain regions near the border to Norway (SMHI, 2021). In the Baltic region annual precipitation varies between approximately 500 and 800 mm, with the wettest areas found along the Latvian and Lithuanian coast (Tammets and Jaagus, 2013; Jaagus et al., 2010).

3. Methods

We study short-term and long-term changes given in Dataset 1 and Dataset 2, respectively, while focusing on the recent period 1969–2020 (Dataset 1) to assess climatology of heavy rainfall in the region.

3.1. Design values

One way to study extreme precipitation is through so-called design precipitation. Design precipitation in terms of return levels are often used when planning and building certain types of hydrological infrastructure. Return level refers to the precipitation amount which on average occurs every T years (the return period), where T is chosen based on considerations on the cost of additional infrastructure versus cost of overloading the infrastructure, leading to e.g. dam breaks. When the statistical properties of precipitation change in time, design values become very sensitive to the time period of observations going into the computation. Thus, we investigate how any changes in Rx1d affect the 5-year return level (M5), by computing these for different 30-year periods from Dataset 1 and 2. We also address the spatial distribution of M5 and the change in M5 as given by a non-stationary estimation approach. To compute M5 we fit the well known Generalized Extreme Value (GEV) distribution (e.g. Coles, 2001) to annual maxima and apply the Maximum Likelihood (ML) approach (Prescott and Walden, 1980) to estimate the parameters. The relatively short return period is selected to avoid sensitivity to the choice of extreme value distribution and parameter estimation method. We compute return levels through a standard approach assuming stationarity. But as we suspect a non-stationary precipitation climate, we also compute return levels through fitting a non-stationary GEV distribution, allowing the location parameter to vary with time. For return level estimation, we apply the R-package “extRemes" (Gilleland and Katz, 2016).

3.2. Trends and records

To examine trends in Rx1d for the recent period 1969–2020 (Dataset 1) and for the long period 1901–2020 (Dataset 2), we use the non-parametric Mann-Kendall trend test (Mann, 1945; Kendall, 1975). Mann-Kendall tests the hypothesis of a monotonic increasing or decreasing trend in data assuming that data are independent and identically distributed (Yue and Pilon, 2004), and it is known to be well suitable for the study of hydro-meteorological time series as these are usually non-normally distributed. Trends are tested for statistical significance at the 0.05 level.

As given by our experiment design, the probability of the null hypothesis (no trend) being falsely rejected at an individual location is equal to 5%. Thus, we want to evaluate the joint statistical significance of the estimated local trends. We adopt the False Discovery Rate (FDR) procedure (Benjamini and Hochberg, 1995), where local p-values, sorted in increasing order, are evaluated against a critical level given by

$$p_{FDR} = \max_{j=1,\dots,k}\left[p_{(j)} : p_{(j)} \leq \alpha_{global}\left(\frac{j}{k}\right)\right]$$

where α_{global} is the global test level, set to 0.05. We test for field significance for each country separately. As both positive and negative trends might be present within a region, these trend types are considered separately.

To assess whether the heaviest rainfall events in the different regions occur at another time of year in today’s climate compared to the climate of the early 1900s, we analyse changes in the date of annual maxima.

As trends are particularly sensitive to the start and end point of the time series, we need to consider the last decades’ trends in a larger picture. We examine decadal variability in annual maxima from Dataset 2 by computing the median, the 90th and 99th percentile (p90 and p99) and the maximum for each decade and country, unfortunately excluding Latvia and Lithuania as no long series are available here (see Table 1). Norway is divided in two clusters due to the large difference between values along the Norwegian west coast and the rest of the study region. The two clusters were determined according to M5 being lower than 60 mm (referred to as E-Norway; E stands for East) or higher than 60 mm (referred to as W-Norway; W stands for West), and they are indicated in Fig. 3a. The value of 60 mm is chosen as it aligns well with the mountain ridge stretching across southern Norway which to a large degree affects the precipitation climate here. Inspired by Westra et al. (2013), we performed a temporal bootstrap, conserving spatial correlation, to test the null hypothesis of no trend. The uncertainty in the decadal median was assessed through the 90% confidence interval.

Finally, we report on the highest measured 1-day precipitation values in each country and at all stations in Dataset 3 (5058 values), and discuss the spatial variability and the different record-giving events in the light of climatic differences.

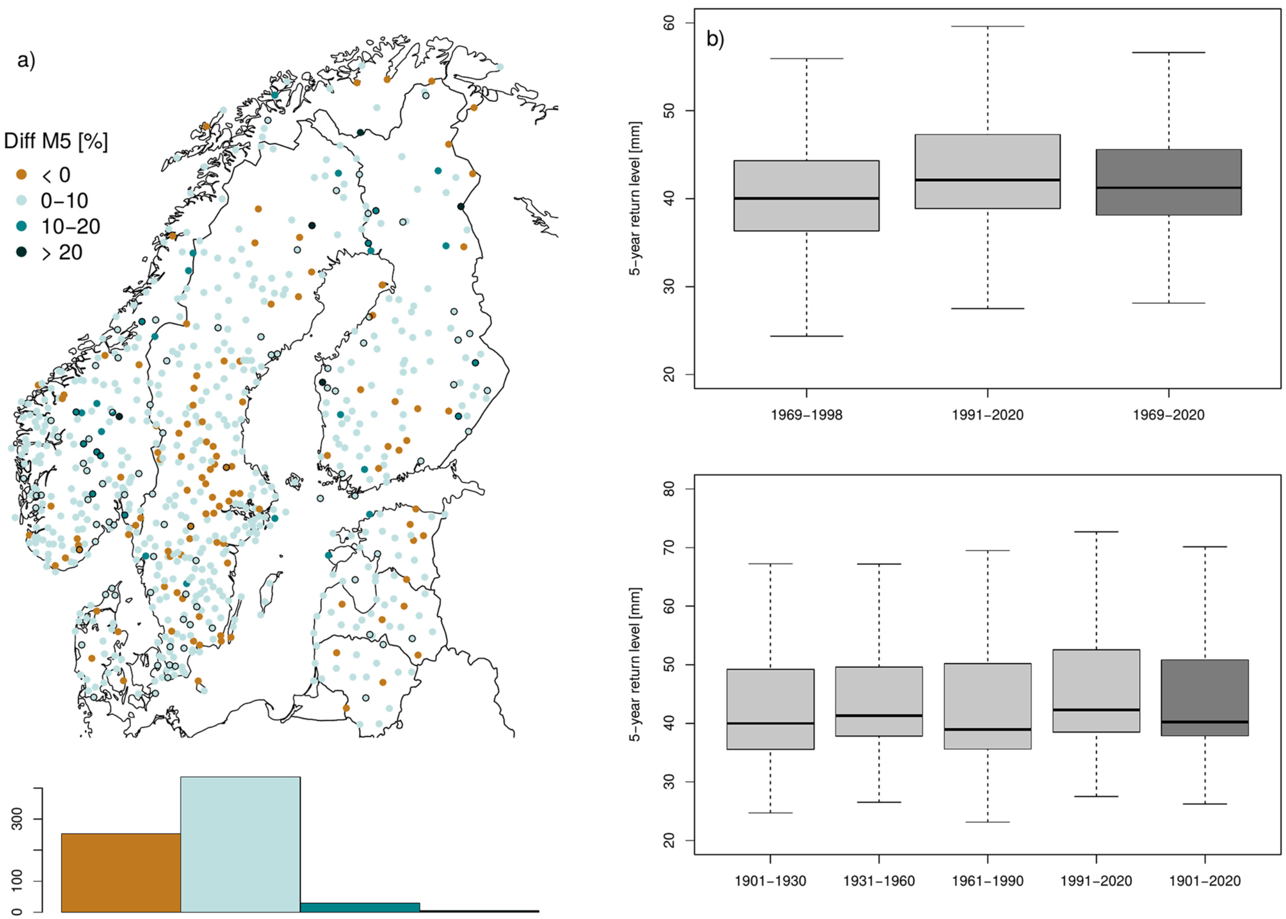

Fig. 4. a) Change in M5 from 1969 to 2020 (Dataset1), according to the non-stationary GEV analysis with time-varying location parameter. Black outer circle indicates stations with statistically significant trends according to the Mann-Kendall test. b) Boxplots of 5-year return levels, according to the stationary GEV analysis, for a) three time slots during 1969–2020, computed from Dataset 1 and b) five time slots during 1901–2020, computed from Dataset 2. Boxes represent the upper (0.75) and lower (0.25) quantiles, while the bold line represents the median (0.5 quantile). Outliers are cut off as we are interested in the bulk of the distribution.

4. Results

4.1. Return levels

The 5-year return level (M5) computed from Dataset 1 using the stationary GEV approach is presented in Fig. 3a. M5 is relatively homogeneous, with mainly values of 30–50 mm in the entire Baltic region plus Denmark and Sweden. Finland has a few values below 30 mm, while values along the west coast of Norway mainly exceed 70 mm.

The GEV shape parameter (Fig. 3b), representing the tail behavior of the distribution, shows mainly values between − 0.2 and 0.4, with a large portion between 0 and 0.2. This corresponds well with findings by e.g. Papalexiou and Koutsoyiannis (2013), who also show how the shape parameter is largely dependent on record length and in reality varies within a quite small range, which was supported by Dyrrdal et al. (2014). Negative shape values are seen along the west coast of Norway in Fig. 3b, again supported by Dyrrdal et al. (2014) indicating a dependence on the degree of orographic enhancement, which was confirmed by Ragulina and Reitan (2017). Positive values > 0.2 are mainly found in southeastern Sweden, parts of Denmark (supported by Madsen et al. (2017)), Latvia and central Finland. Observed summer precipitation from Helsinki, Finland during 1951–2000 suggested a heavy-tailed distribution (positive shape parameter) also here (Kilpeläinen, 2008).

Fig. 4 a shows how M5 has changed between 1969 and 2020 according to the non-stationary GEV analysis (difference in first and last years' estimate), while Fig. 4b provides boxplots comparing M5 computed from 30-year slots and for the entire period. At the majority of stations M5 has increased by up to 10%. The largest increases (> 20%) are seen in central parts of South-Norway and at some scattered stations in Finland, while week decreases are seen in central Sweden and at scattered stations around the entire region.

For Dataset 1 (Fig. 4b; upper panel) there are relatively small variations between the three periods, however, there is a clear tendency to higher M5-values in the most recent 30-year period. For Dataset 2 (Fig. 4b; lower panel) a cycle becomes evident, with lower values in the first (1901–1930) and third (1961–1990) period, and higher values in the second (1931–1960) and particularly the forth (1991–2020) period.

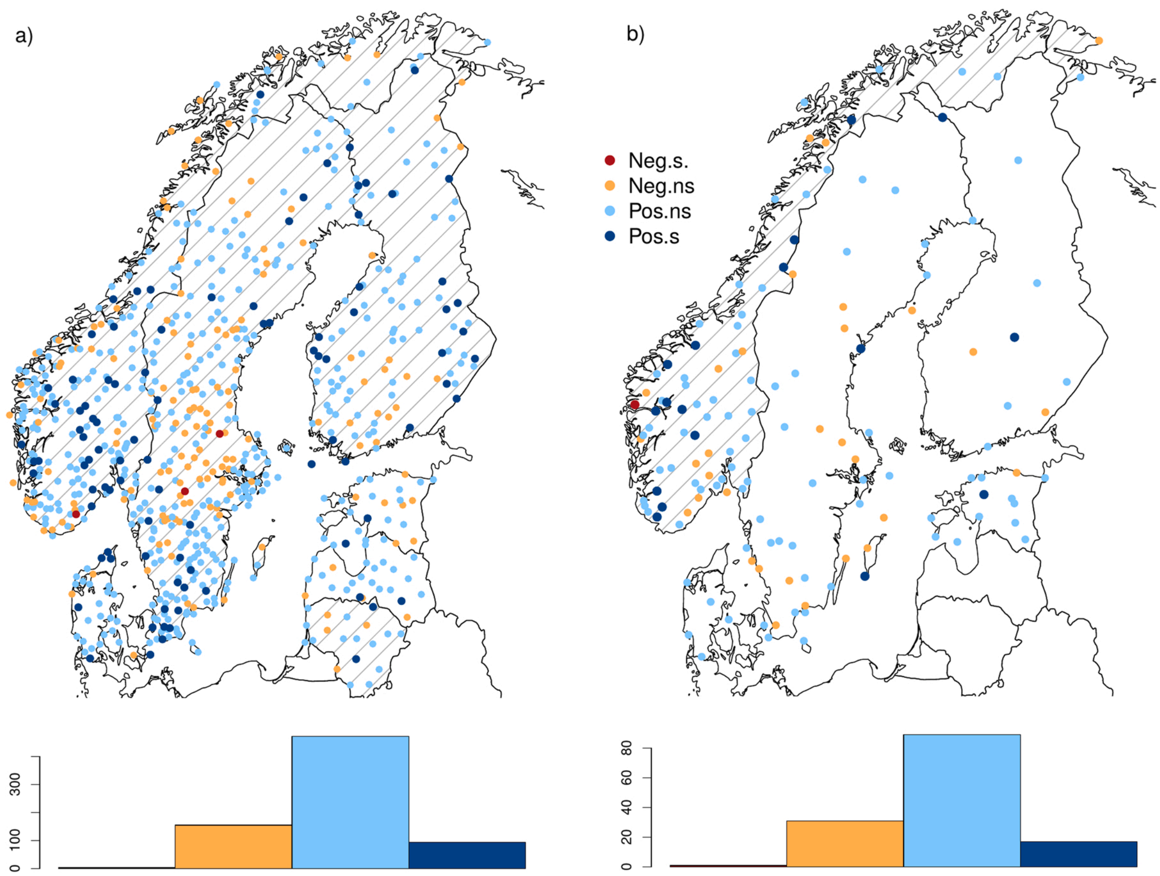

Fig. 5. Trends in Rx1d for the periods a) 1969–2020 (Dataset 1) and b) 1901–2020 (Dataset 2). Blue (red) colors indicate positive (negative) trends, and larger/darker bullets indicate statistical significance at the 5% alpha level. Field significance is found in hatched countries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

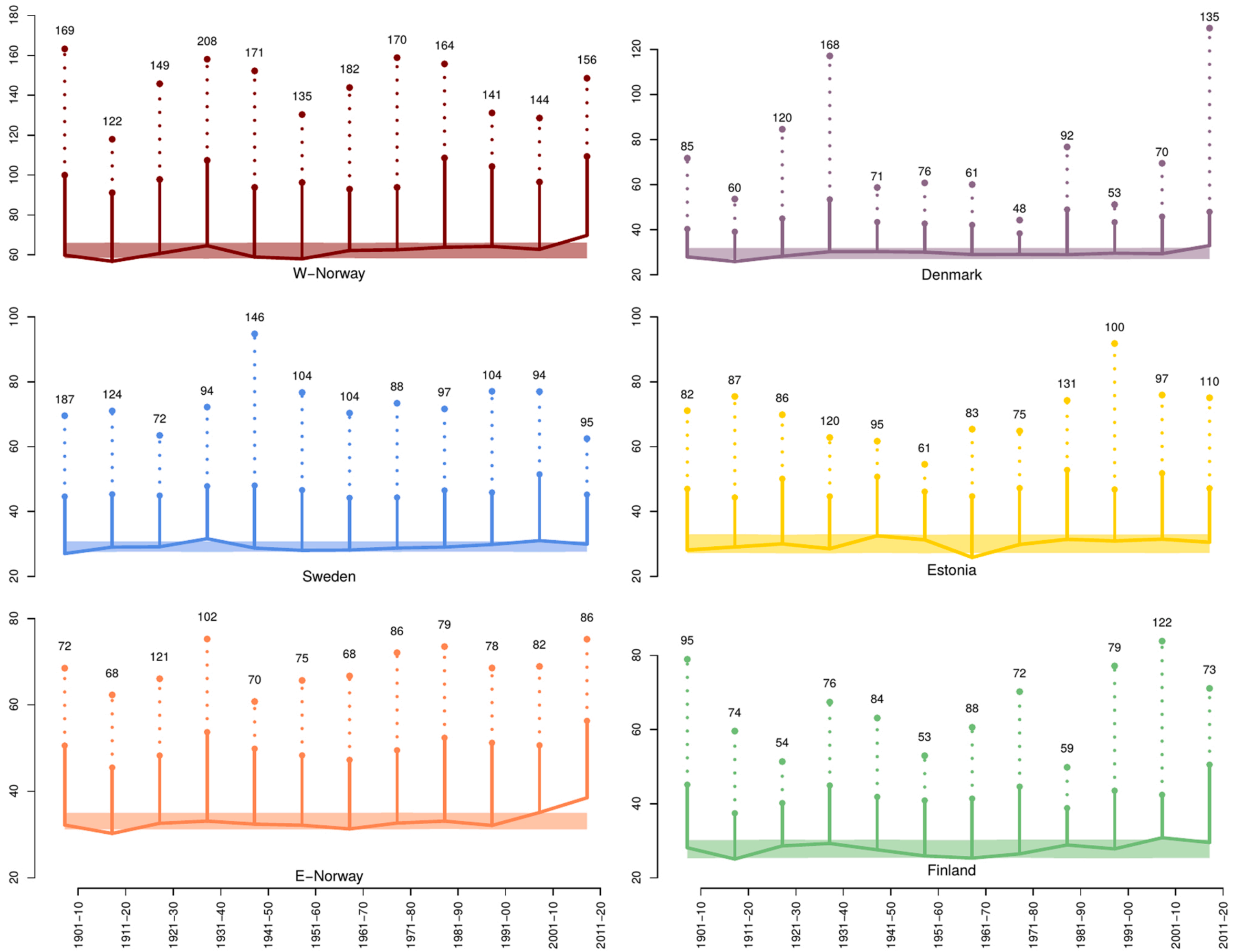

Fig. 6. Median (bottom line) including the 90% confidence interval, 90th percentile (middle points) and 99th percentile (upper points) for annual maxima within each decade during 1901–2020, computed from Dataset 2. Numbers on top indicate the highest decadal 1-day precipitation amount in the region (y-axis is not relevant for these). Note that the y-axis differs between countries, and especially W-Norway has much higher values.

4.2. Trends in daily annual maxima

Trends in Rx1d during 1969–2020 (Fig. 5a) are predominantly positive. We count 94 (472) statistically (non-)significant positive trends, as opposed to only three (155) (non-)significant negative trends. Regions of high concentration of significant positive trends include southeastern Norway, southern part of Sweden and large parts of Finland. Also the Baltics has some significant positive trends in Latvia and Lithuania. Negative trends, although only two statistically significant, dominate a rather large region of central Sweden. Negative trends are also seen in parts of Western Norway, in southern parts of Finland and in Estonia.

Long-term trends in Rx1d (Fig. 5b) are also mostly positive, with 17 (89) statistically (non-)significant positive trends and only one (31) (non-)significant negative. Statistically significant trends are mainly found in Norway, except for positive trends at three stations in Sweden, one in Finland and one in Lithuania. One significant negative long-term trend is found on the mid-west coast of Norway. Denmark and Estonia only have positive trends, but none are statistically significant.

The FDR test reveals field significance for positive short-term trends in all countries except Denmark, Estonia and Latvia, while for short-term trends fields significance is only true for Norway (hatched lines in Fig. 5).

To investigate trends in the context of decadal variability we show the development of median, p90 and p99 for annual maxima in each decade during 1901–2020, based on Dataset 2 (Fig. 6). The highest value per decade is indicated as numbers. A 90% confidence interval computed through temporal bootstrapping illustrates the uncertainty of the sample median if no trend is present.

Despite the large deviance in values between the two Norwegian clusters, the decadal variability in time is similar, starting out with relatively high values in the first decade followed by low values in the 1920s. The same is seen in Denmark and Finland. A local maximum is seen in the 1930s in all countries, except Estonia, where the maximum is seen in the 1940s. The following decades have

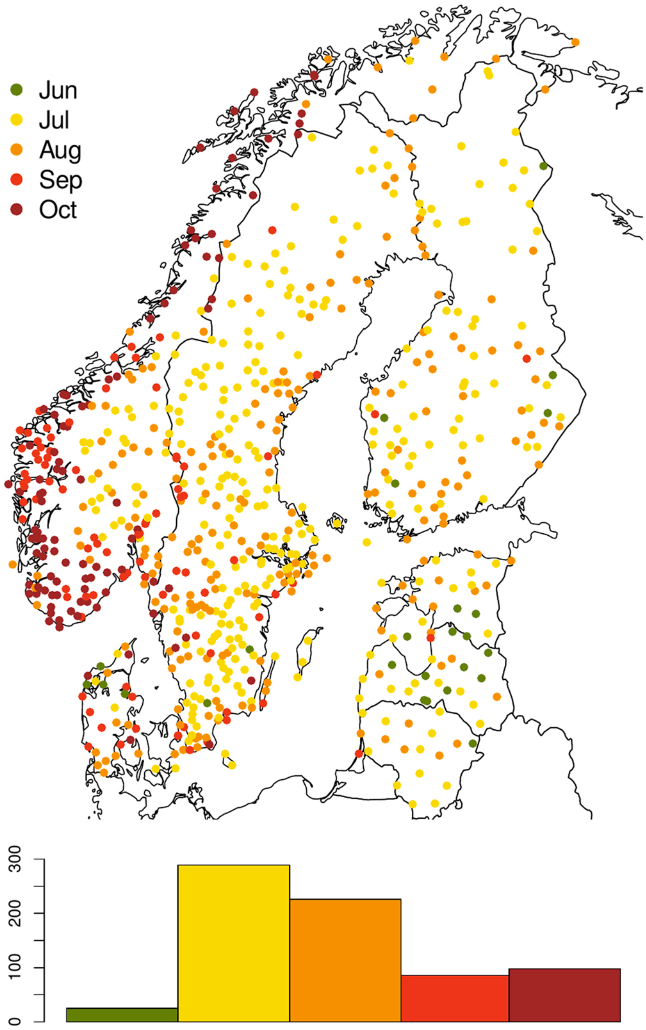

Fig. 7. Map showing the month of most frequent occurrence of annual maximum precipitation in Dataset 1. Different colors indicate months from June (green) to October (brown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

slightly lower values, until they increase again in the last three-four decades. A local maximum in the 1930s and increasing values after the mid 1970s were also found in an earlier Nordic study (Forland et al., 1998). A minimum in median values in the 1960s is obvious for Estonia and Finland.

In the Nordic countries except Sweden, there is an obvious positive trend in the median during the most recent decades. The strongest trends are seen in the two Norwegian regions. Also p90 and p99 increases in E-Norway, while in the other regions the large variability might cover any trend. Still many of the largest values are seen in the most recent decades. Sweden deviates somehow compared to other countries, with a relatively flat evolution over the whole period. At least in some regions the decadal median falls outside the uncertainty band, indicating variability beyond sampling uncertainty. In Norway and Denmark, a trend in the latest decade can be advocated as the most recent median lies above the uncertainty band.

W-Norway obviously has the largest median and percentiles. E-Norway also have relatively large median values, but p99 lies around 70 mm similar to other countries. While Denmark shows relatively small median values with low variability, and small deviance between the median and p90, two peaks in p99 in the decades 1941–50 and 2011–2020 reveal values close to 120 and 130 mm, respectively. Sweden and Estonia show similar values, although p99 in Sweden are somewhat higher. Largest variability in p99 is seen in Finland, with peaks in the first end second-last decade.

4.3. Date of annual maxima

In Fig 7a we show the spatial distribution of the month of most frequent Rx1d occurrence, while Table 2 report on the percentage of dateRx1d occurrence in each month and each region, both according to Dataset 1. Annual maxima in the study region occur within a relatively narrow time window, generally between July and October, with July (Finland, Sweden and the Baltics) and August (E-Norway and Denmark) being the most frequent months. The highest percentage of 28.2% in July is found in Finland. For the whole region, there is 21.2% occurrence in July, followed by 19.5% in August. The least frequent months are April and March. In areas corresponding to large M5 values at the southern coast of Norway (Fig. 3), annual maxima usually occur in the fall when frontal activity is high. 17.2% of events in W-Norway occur in October, closely followed by November and September. The dominance of summer months in the rest of the region suggests that convective activity is responsible for the largest rainfall events also on the daily duration.

The map in Fig. 8a indicates that almost a third of stations experience an earlier occurrence of Rx1d (green dots; 44 stations), while more than two thirds experience a later occurrence (94 stations). The shift towards a later date is much larger, with up to 52 days compared to maximum 24 days of earlier occurrence. There is no obvious regional pattern, but most stations experiencing a large shift towards later occurrence (orange and red colors) are located the southwest of Norway, along the Norwegian west coast and the Swedish east coast. Fig. 8b presents how dateRx1d in the whole region has changes between the first and the last 60-year period of 1901–2020, revealing a small shift from summer to autumn. Although annual maxima occur slightly later in the year in today's climate, the majority of events still occur between mid-July to mid-August.

4.4. Record events

In Fig. 9 we map the highest measured 1-day precipitation at all stations available at the MET service databases, regardless of measurement period, while Table 3 report on the three absolute highest values measured in each country and what year they occurred. As expected, the highest values are measured along the Norwegian southwest-coast. If excluding this wet belt, records are relatively homogeneous across the region, ranging mainly between 50 and 100 mm. Despite the large differences between the west coast of Norway and the rest of the study region, there are single occurrences of very large values in all larger regions.

The Norwegian record event of 229.6 mm is the highest in the region, and occurred in south-western Norway 25–27 November 1940. It was a result of a typical extreme orographic precipitation event. The 2-day precipitation amount reached 380 mm, while the 1-day value was probably higher than 230 mm as the observer reported that the gauge was completely filled up.

The record daily rainfall in Finland, 198.4 mm, was observed in Espoo, southern Finland on 21 July 1944. According to the

Table 2
Percentage of date of Rx1d occurrence in each month and each region, based on Dataset1.

	All	Fin	Swe	W-Nor	E-Nor	Den	Est	Lat	Lit
Jan	2.6	0.6	1.5	7.8	4.2	2.9	0.4	3.4	1.1
Feb	2.2	0.6	1.3	6.8	3.0	2.0	0.6	3.4	0.0
Mar	2.1	0.4	1.1	7.2	3.1	1.4	0.2	3.3	0.4
Apr	1.9	1.3	2.0	2.2	1.5	2.1	1.5	3.8	2.8
May	4.3	4.8	4.5	1.1	3.4	6.7	6.8	8.2	7.1
Jun	11.9	15.8	12.8	2.3	9.4	14.0	18.6	17.0	15.8
Jul	**21.2**	**28.2**	**25.3**	3.9	17.0	16.4	**24.9**	**19.1**	**27.6**
Aug	19.5	25.1	21.9	7.3	**17.4**	**18.0**	24.0	14.9	22.0
Sep	14.0	12.5	14.6	14.6	14.0	17.2	12.6	10.0	11.4
Oct	9.5	6.7	7.7	**17.2**	12.4	10.5	6.0	6.7	7.6
Nov	6.4	2.8	4.6	15.8	9.0	5.7	3.5	4.7	3.6
Dec	4.3	1.3	2.7	13.7	5.6	3.1	1.0	5.5	0.6

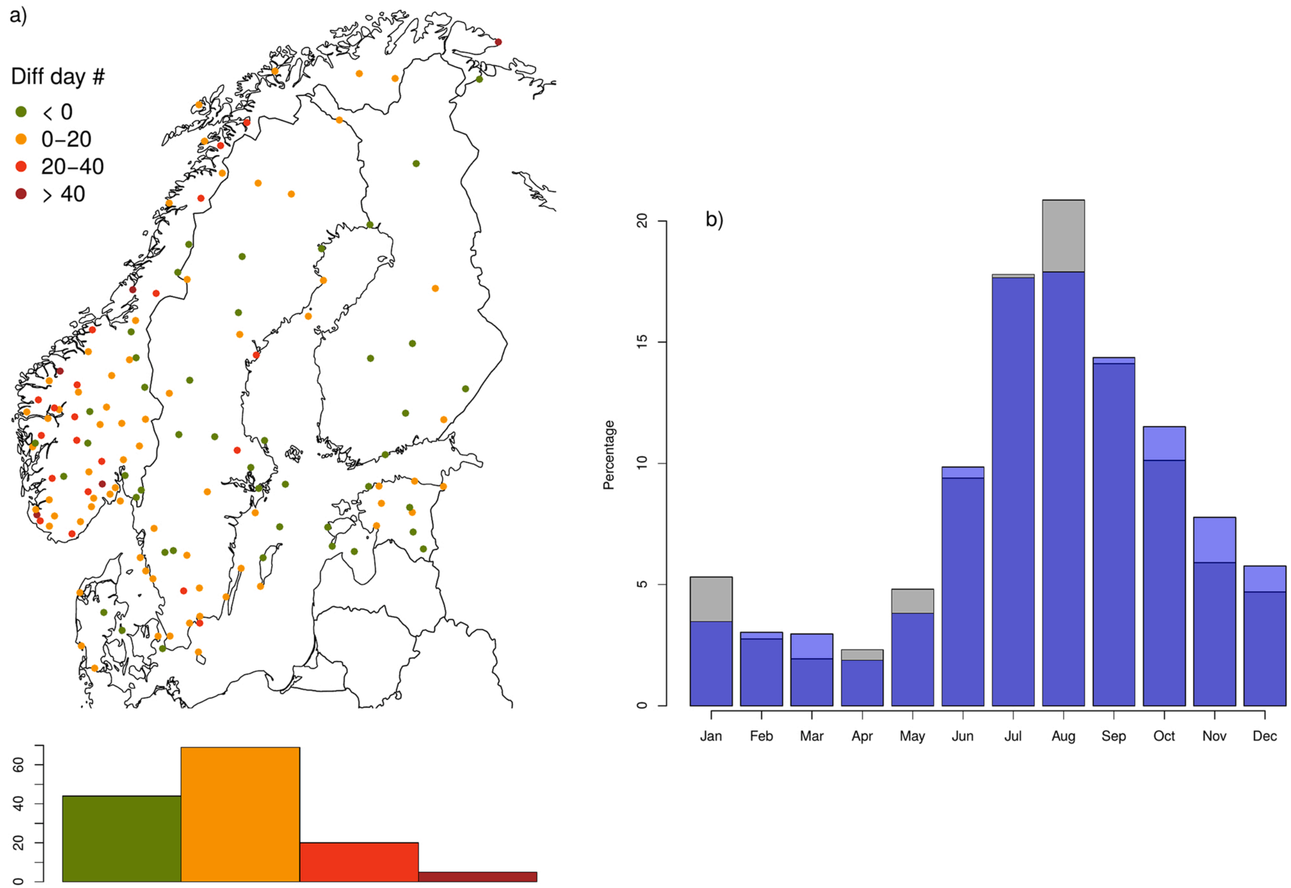

Fig. 8. a) Map showing the change in date of occurrence of annual maximum precipitation between the first and the last 60-year period of Dataset 2, and b) percentage of dates of Rx1d occurrence in each month for the first 60-year period (1901–1960; gray) and the last 60-year period (1961–2020; blue) of Dataset 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

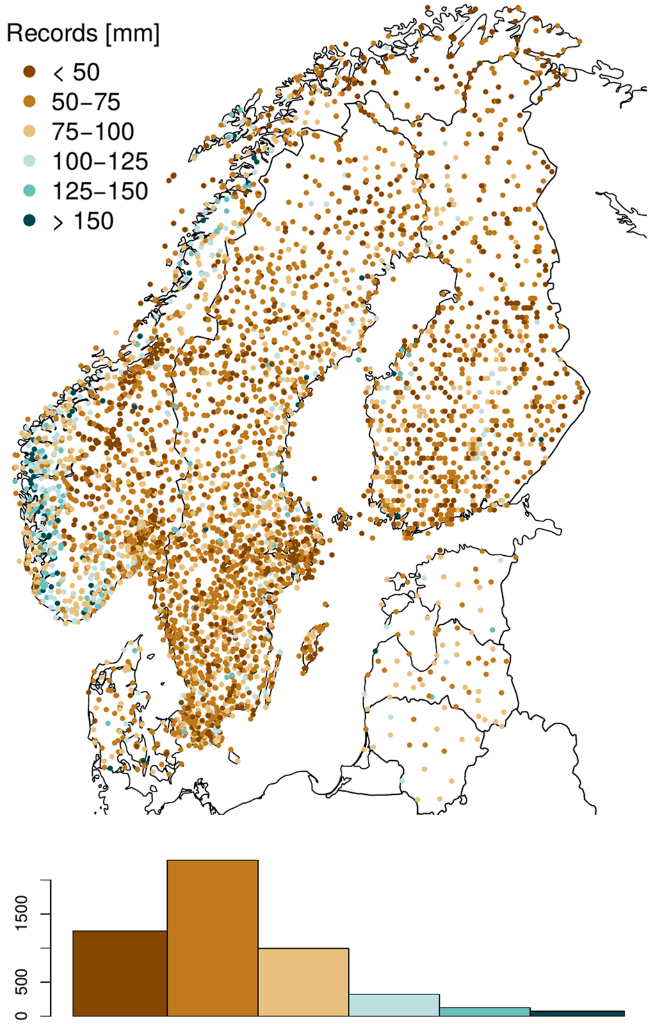

Fig. 9. Highest measured 1-day precipitation value at all stations and throughout each stations' observation period (Dataset 3). Red/orange colors indicate smaller values while green colors indicate higher values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
The three largest 1-day precipitation events (in mm) in each country, and the years they were recorded.

	Fin	Swe	Nor	Den	Est	Lat	Lit
Record	198.4	198.0	229.6	167.5	148.0	160.2	138.6
Year	1944	1997	1940	1931	1972	1973	1958
2nd	182.0	188.6	223.0	135.4	137.0	135.6	103.8
Year	1927	2004	2005	2011	1985	1982	1978
3rd	159.4	187.3	218.4	132.0	136.0	122.8	100.5
Year	1988	1908	1955	2010	1998	2014	1953

observer notes and newspaper reports, an "exceptionally intense" thunderstorm moved over the southern coast during the night accompanied with extreme precipitation causing, for example, four bridges to collapse.

The level of the Swedish record is similar to the Finish record, with 198.0 mm in 1997. Along an almost stationary front in the east-west direction over southern Norrbotten in the north of Sweden, powerful thunderstorms with heavy rain were formed on 27 and 28 July 1997. The worst exposed area was west of the city Piteå, where it rained extremely heavily from about 11 am on July 27 until the morning July 29. A total of 256 mm of rain fell during two days.

On 9 July 1931 Denmark experienced, according to a newspaper (Berlingske, 2013), what at the time was described as the closest thing to a tropical storm. More than 20% of the country experienced more than 100 mm rainfall within 24 h. The storm lasted several days and in some locations led to more than 200 mm rainfall, however, the official record of 167.4 mm was measured in Marstal, Ærø. This event is not included in our dataset, but the amount of 167.5 mm (Table 3) measured in Broderup i Sønderjylland is indeed from the same event.

The daily precipitation record in Estonia, 148 mm occurred on 4 July 1972 in Metsküla (not included in our dataset), resulting from a minor low level cyclone as classified by Matlik and Post (2008). This was a very local event registered by a rural station. The record of 160.2 mm in Latvia resulted from a thunderstorm, which occurred on 9 July 1973 in Ventspils station, located very close to the Baltic Sea. In Lithuania, the record of 138.6 mm was observed at Nemajūnai station on 17 July 1958, after a hot and sunny day. According to Galvonaite (2007) the large difference between air temperature (∼ 30˚C) and water temperature (only about 20 ˚C) caused intense turbulence and convection. Although 138.6 mm is the official record, an amount of 250 mm was measured in Sartai, Lithuania on 1 July 1980. This station did however not comply with the World Meteorological Organization standards.

5. Discussion

The precipitation climate in terms of return levels seems to be quite homogeneous over a large region in the Nordic-Baltic countries, at least when excluding the shortest time series and focusing on the same time period. This might explain our unsuccessful attempt to derive sensible geographical regions based on a clustering analysis (not shown). Usually, design values are computed using all available data, thus deviations between time series length and the period of coverage may introduce larger heterogeneity than what is seen here. At least this is true for shorter duration precipitation associated with small-scale convection. Longer duration events, however, including 1-day precipitation, are mostly associated with large-scale systems, producing similar rainfall amounts over a large region.

We have shown the sensitivity of return level calculation to the time period of available data. Using Rx1d from the entire period as basis for planning and design could result in less robust infrastructure as opposed to using design values from the most recent period. This points to a risk in using traditional methods for estimating design values that assumes stationary, when climate change alters the probability of heavy precipitation. Many studies in the recent years have therefore developed and tested non-stationary methods for extreme value analysis (e.g. Ouarda et al., 2019).

The predominance of positive short-term and long-term trends identified here are in line with former studies (see Section 1), and as expected under a warming climate. The general later occurrence of maxima might be related to the extension of the summer season in a warmer climate, and thus a longer season of favorable convective conditions.

Assuming the difference in extraction of annual maxima (see Table 1) does not significantly affect trends and that most values result from rainfall as opposed to snowfall, our results strongly suggest a change in the statistical properties of heavy precipitation over the Nordic-Baltic region in the past 50 years, namely through a lengthening of the tail of the distribution. It is likely that some of the increase can be explained by the increase in temperature over the region (e.g. Hartmann et al., 2013). However, as mentioned in Section 1, natural and multi-decadal variability might explain parts of the observed changes in heavy precipitation. Gregersen et al. (2015), for instance, found that the frequency of daily rainfall extremes in Denmark and southern Sweden has increased from 1874 to present, but with an oscillation cycle of 25–40 years, which corresponds rather well with the cycles evident in Fig. 6. Gregersen et al. (2015) also found a low period for Denmark in 1970–1979, which explained parts of the strong positive trend during the recent period. We found a low in the same decade (Fig. 6), when also the lowest decadal maximum Rx1d of 43 mm occurred. Similar lows are seen in the decades close to our start year in Dataset 1 (1969), which may partly affect the trends in the last 50 years.

Finland shows low probabilities of heavy precipitation events, according to the M5 map in Fig. 3a, while W-Norway shows the highest probability. Still, high precipitation amounts have occurred also in Finland, and the record event of 198.4 mm is the second largest in the study region, closely followed by Sweden with 198.0 mm. Record events in Denmark and the Baltic countries are lower than in the northern countries (down to 138.6 in Estonia). Although different precipitation climates govern, the larger amount of data in Finland, Sweden and Norway (see Table 1) could possibly explain parts of the deviance. Another explanation might be that the distribution of daily rainfall in the Baltics is more heavy-tailed yet short compared to the rest of the study region. Unfortunately, the investigation of this theory was hampered by some regions being poorly represented in the analysis.

The described weather conditions during the record-giving events in Table 3 cover orographic, frontal and convective rainfall. In a warmer future climate convective events may play an even greater role in the heavy precipitation statistics, further increasing the pressure on infrastructure and the need for reliable cloudburst prediction. We would also emphasize the important role of stations with long time series in monitoring climate development, and the need for careful planning when replacing, moving of removing historical stations.

6. Conclusions

We have collected and analysed a temporally long and spatially dense dataset of annual maximum 1-day precipitation (Rx1d), and the corresponding date of occurrence, over the Nordic-Baltic region (Finland, Sweden, Norway, Denmark, Estonia, Latvia and Lithuania). Our aims were to evaluate short-term and long-term changes and spatial variability of heavy precipitation. Our analysis reveals: .

- The 5-year return level is relatively homogeneous across the Nordic-Baltic region, with values between 30 and 50 mm, except for a few lower values in Finland and high values mainly exceeding 70 mm at the west coast of Norway.

- Almost all stations with a statistically significant trend, showed an increase in the intensity of annual maximum 1-day precipitation during the last 50 years
- At a majority of stations, there has been an increase in annual maximum 1-day precipitation since 1901
- In the region as a whole, annual maximum precipitation events occur somewhat later in the year now compared to the beginning the last century
- Hotspots for significant positive trends are found in southeast of Norway, southern Sweden and southwest of Finland.
- A hotspot for negative trends, although mostly non-significant, is found in central Sweden.
- Decadal annual maxima vary somewhat differently between countries. However, all countries except Estonia, exhibit a local maximum in the 1930s followed by slightly lower values, until values increase again in the last three-four decades.
- In all regions except Estonia, there is a tendency to positive trends in the median decadal annual maxima. This is particularly obvious in the two Norwegian regions.

Although the highest daily precipitation values are found along the west coast of Norway, we expect records on shorter durations to have hotspots further south, since convection is mainly driven by high temperatures and available humidity. In later papers we intend to study annual maxima for sub-daily durations, as well as expected changes in precipitation design values in a future climate.

CRediT authorship contribution statement

Anita Verpe Dyrrdal: Conceptualization, Methodology, Data curation, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing, **Jonas Olsson:** Conceptualization, Methodology, **Erika Médus:** Conceptualization, Methodology, Data curation, **Karsten Arnbjerg-Nielsen:** Conceptualization, Methodology, Data curation, **Piia Post:** Conceptualization, Methodology, Data curation, **Svetlana Aņiskeviča:** Conceptualization, Methodology, Data curation, **Søren Thorndahl:** Conceptualization, Methodology, **Eirik Førland:** Conceptualization, Methodology, **Lennart Wern:** Conceptualization, Methodology, Data curation, **Viktorija Mačiulytė:** Conceptualization, Methodology, Data curation, **Antti Mäkelä:** Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The dataset of annual maximum daily precipitation is published in NIRD research data archive and is open and publicly downloadable (Dyrrdal et al., 2021).

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