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ORIGINAL RESEARCH ARTICLE

Long-term precipitation events in the eastern part of the Baltic Sea region

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Abstract Precipitation anomalies have a significant impact on both natural environmental and human activity. Long lasting drought analysis has received great attention on a global and regional scale while prolonged rainy periods so far have been much less studied. However, long-term precipitation events are also important and threatening. The situation around the Baltic Sea in 2017 revealed that such periods could cause significant losses in agriculture.

The rainy periods of 30, 60, and 90 consecutive days in a given year during which the maximum precipitation amount was recorded in the eastern part of the Baltic Sea region were analysed in this study. Daily precipitation amount data from the E-OBS gridded dataset was used. The investigation covered a period from 1950 to 2019. The changes in magnitude and timing of such rainy periods were evaluated.

It was found that the annual precipitation in the eastern part of the Baltic Sea region increased significantly during the analysed period. Positive changes were observed throughout the year except during April and September. The amounts of precipitation during rainy periods of different duration also increased in most of the investigated areas but changes were mostly insignificant. Consequently, a decrease in the ratio of precipitation amount during the rainy period to annual precipitation was observed. It was also found that the rainy periods occurred earlier,

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especially in the case of the rainy periods of 60- and 90-days durations. Such tendencies pose an increasing threat to agriculture.

1. Introduction

Precipitation is an important part of the hydrological and biological environment. The climatic conditions of individual regions are changing due to global warming and one of the biggest issues is related to changes in the amount of precipitation as well as its distribution over time and space.

When the global air temperature rises, the amount of water vapour availability in the atmosphere increases, which leads to more frequent cases of intense precipitation (Kharin et al., 2007). The magnitude of the anthropogenic impact on precipitation has been found to be latitude-dependent: it is several times lower at low latitudes (<50°) than at medium (50—60°) and high (>60°) latitudes (Tabari et al., 2020).

How climate change affects different regions is not entirely clear. Some have argued that climate change causes wet regions to become wetter and dry regions to become drier (Held and Soden, 2006; Rush et al., 2021). According to other research, in only about a tenth of global landarea dry regions get dryer while wet regions become wetter, while another tenth shows the opposite trend (Greve et al., 2014).

The amount of global precipitation increases during dry seasons while remaining relatively constant during wet seasons and as a result, seasonal differences decrease; however, this effect may vary from region to region (Murray-Tortarolo et al., 2017). Results of the analysis of the amounts of daily precipitation performed by different researchers have shown that extreme precipitation was increasing and intensifying in most regions of the world (Alexander et al., 2006; Westra et al., 2013).

The duration of wet periods significantly increased in northern Europe and the central part of European Russia. It was determined that the duration of wet periods increased by 15—20%, especially in winter. Rainy periods shortened during the summer in Scandinavia and northern Russia. Furthermore, dry periods were shortened by 15—20% in both winter and summer in Scandinavia and southern Europe (Zolina et al., 2013, 2010). Apart from a few areas, mostly insignificant changes of 20-day precipitation were observed in Poland (Canales et al., 2020). In the eastern part of the Baltic Sea region the growth and frequency of intense precipitation with a duration of one to five days have also been observed in Lithuania (Rimkus et al., 2011), Latvia (Avotniece et al., 2010), and Estonia (Tammets, 2007, 2010).

The analysis of extreme precipitation on different scales (from local to global) mostly focused on the investigation of daily or even shorter (sub-hourly, sub-daily) precipitation changes as it had a significant impact on various sectors of the economy. However, it is also important to evaluate the maximum amount of precipitation that has fallen over a longer period. Prolonged periods with much more rainfall than usual can be also very dangerous and cause a lot of damage Prolonged rains can cause flooding (Kundzewicz et al., 2014; Van den Besselaar et al., 2013), reduce yields (Lobell and Burke, 2008; Tapia-Silva et al., 2011), or contribute to groundwater contamination (Andrade et al., 2018; Miotliński et al., 2012). One of the recent situations of such a rainy period occurred in 2017, when the extremely high amount of precipitation during a prolonged period of time over a significant part of the eastern Baltic Sea region resulted in reduced yields and grain quality as well as worsened winter wheat planting conditions.

Drought analysis has received great attention on both a global (Naumann et al., 2018; Schwalm et al., 2017) and a regional scale (Briede and Lizuma, 2010; Rimkus et al., 2012, 2017). Similar attention has been paid to extreme precipitation events (usually lasting one to five days) and its effects (Eekhout et al., 2018). Meanwhile, very few studies have been conducted on rainy periods lasting longer than a month, especially when talking about territories that do not have a clear seasonality of precipitation like monsoon areas.

Agriculture production is strongly affected by rainfall anomalies. The effects of droughts can be mitigated by a variety of agrotechnical measures, and droughts even make harvesting easier. Meanwhile, the damage caused by long extremely rainy periods is difficult to mitigate.

The main task of this study was to analyse the maximum precipitation values during 30-, 60-, and 90-day periods in the Eastern Baltic Sea region. The 30-, 60-, and 90-day precipitation maxima were selected by associating them with the most commonly analyzed standardized precipitation index, SPI, which also includes 30-day (SPI1), 60- (SPI2), 90- (SPI3), or even 360-day (SPI12) analysis. The research aimed to assess the spatial and temporal distribution of extreme long-term precipitation events as well as their changes over the period from 1950 to 2019.

2. Material and methods

In this article, we analysed the eastern part of the Baltic Sea region, which covers the area 53—60°N and 20—30°E. The study area includes Estonia, Latvia, and Lithuania, as well as the northwestern part of Belarus, the outskirts of north-eastern Poland, the Kaliningrad district of Russia, and the part of Russia near the border with Estonia and Latvia (Figure 1).

Daily precipitation data from the eastern part of the Baltic Sea region from E-OBS gridded dataset (V22.0) was used in the research (Cornes et al., 2018). The database grid size was 0.25° × 0.25°. A total of 845 grid cells above land

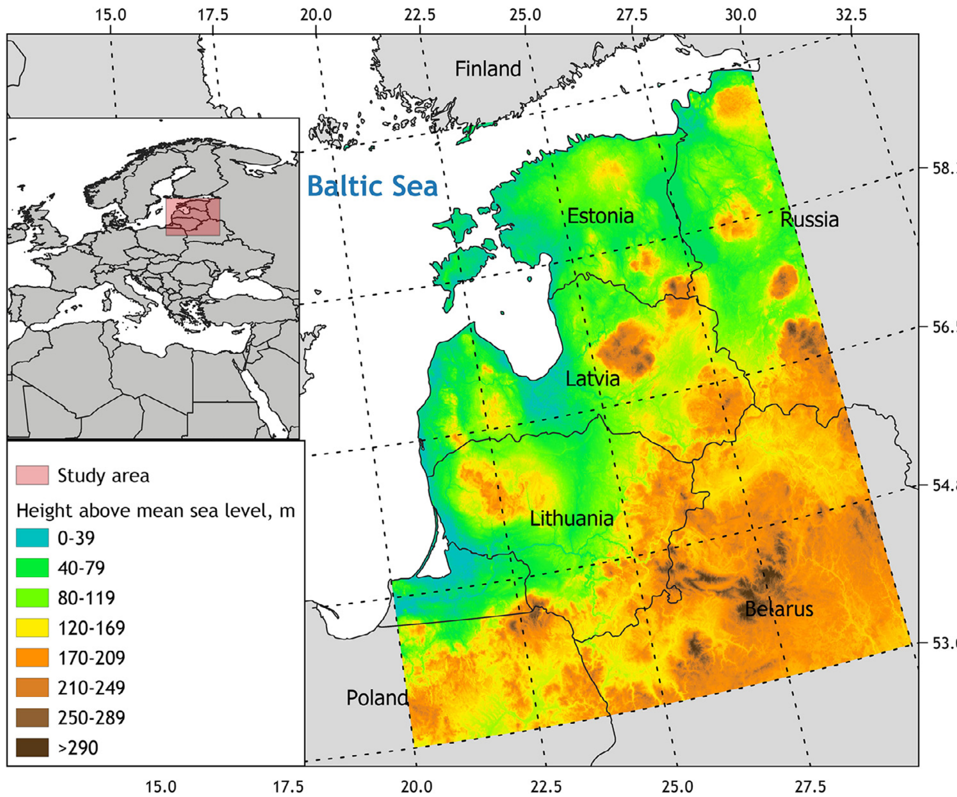

Figure 1 Location map and topography of the study area.

were analysed. Grids above large terrestrial water bodies (e.g., Lake Peipus) and the grids, parts of which were above the Baltic Sea, were not included in the analysis. The investigation covered the time period from 1950 to 2019.

In this research, we analysed the periods of 30, 60, and 90 consecutive days in a given year during which the maximum precipitation amount was measured (hereinafter — rainy period: RP_{30}, RP_{60}, and RP_{90} respectively). The shortest 30-day period with high precipitation is long enough to cause disturbances and damages, especially if it coincides with the time of agricultural activities such as seeding and harvesting, and might affect sensitive agricultural plant species. The mean intensity of precipitation decreases with the increase of rainy period length, but over a long time the effect of precipitation accumulates and it can reduce harvest, affect ecosystems or industries.

We determined the maximum 30-, 60- and 90-days rolling precipitation sum values for each year of the studied period. The date of the rainy period was taken as the middle date of the such 30-, 60-, and 90-day periods when maximum rolling sum values were recorded, i.e., on the 15th, 30th, or 45th day. In several cases when there were several maxima per year with the same amount of precipitation, the date of the first RP was taken. The precipitation maximums observed at the beginning of the calendar year may be predetermined by the conditions at the end of the previous year and the same rainy period can influence the maximum values for two consecutive years. For this reason, the RP_{30}, RP_{60}, and RP_{90} peaks were calculated only as the sum of precipitation during the calendar year. Therefore, the RP_{30} peak dates may be from 15 January to 16 December, RP_{60} from 30 January to 1 December, and RP_{90} from 14 February to 16 November.

As the distribution of precipitation sum during the rainy period over most of the territory was characterised by a strong positive asymmetry, the median was chosen as the measure of the position of the data. The magnitude of changes during the investigation period was estimated using the non-parametric Sen's slope estimator. Another non-parametric Mann-Kendal test was employed for the evaluation of the statistical significance of the observed trends. The trends were considered statistically significant when $p < 0.05$.

3. Description of the study area

According to the Köppen climate classification, almost the entire study area belongs to the Dfb type (warm-summer humid continental climate) while a narrow stretch near the Baltic Sea coast belongs to Cfb type (Chen and Chen, 2013). Based on E-OBS temperature data 1951—2019 years the average temperature of the coldest month (January) is −5.2°C and the warmest (July) is 17.6°C. The average annual temperature in the research area is 6.1°C and ranges from 4.4°C (northeast) to 7.8°C (southwest).

A permanent snow cover forms over most of the territory during the winter. In the northeast of the area, snow cover lasts from early December to mid-March (on average >130 days with a snow cover), while in the southwest of the area (near the Baltic Sea) winters can be characterized by frequent thaws and snow cover instability (Rimkus et al., 2018).

Territorial differences in average annual precipitation amount were relatively small (from 513 to 729 mm)

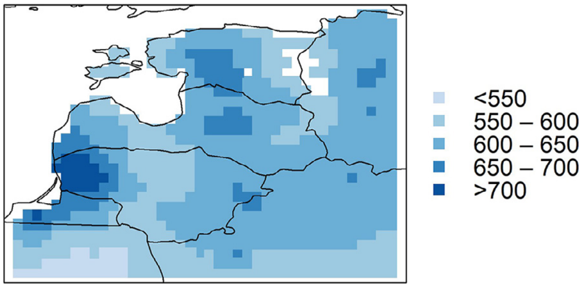

Figure 2 Mean annual precipitation (mm) in 1950–2019.

(Figure 2). The highest amount of precipitation was measured in western Lithuania and in the Kaliningrad district of Russia; the lowest was recorded in Poland, in the most southwestern part of the studied area. Here are the most prominent annual precipitation gradients and precipitation decreases rapidly moving south. Highlands near the sea have a significant impact on the territorial distribution of precipitation. The highest precipitation values were recorded on the windward slopes of the Žemaičiai Upland in Lithuania.

The highest precipitation values in the analysed area were recorded in the summer and autumn, while in the winter and spring the values were lower (Figure 3). July and August were characterised not only by the highest amounts of precipitation, but also by frequent positive precipitation anomalies. The highest monthly precipitation values exceeding 300 and 250 mm were recorded in August and October, respectively. During the winter, snowfall still prevailed, although due to climate change, the share of rain in total precipitation was increasing.

4. Results

4.1. Amount of precipitation during a rainy period

Analysis showed that slightly more than 100 mm of precipitation usually fell during RP_{30} (Figure 4). In rare cases, this amount could be less than 50 mm or more than 250 mm. During RP_{60}, 150–200 mm of precipitation was usually reached, although in some cases it was less than 100 mm or exceeded 400 mm. During RP_{90}, the precipitation sum was often higher than 150 mm, while several cases above 450 mm were recorded. On average, slightly more than 200 mm of precipitation usually fell during RP_{90}.

In all cases, the distribution of precipitation during RPs of different durations was close to the spatial distribution of annual precipitation (Figure 5). The maximum amount of precipitation amount during the rainy periods fell in the western part of Lithuania. During the wettest 30-day period, more than 150 mm of rain usually fell in this area, while during the 90-day period this amount reached 300 mm. The lowest amount of precipitation was observed in the lowlands which stretch from the southwest to the northeast. The territorial differences in median precipitation values during rainy periods of different duration were approximately 30%.

The share of annual precipitation which fell during RP_{30} varied from 17.9 to 21.9%; during RP_{60} this number increased up to 29.1–33.5%, and during RP_{90} this amount reached 38.4–43.8% (Figure 6). The largest share of RP was recorded in the southern part of the study area and in the north near the Gulf of Finland. Vidzeme upland in the central part of Latvia stood out with the lowest values.

The RP dates in the area varied quite strongly. The RP_{30} date was the earliest in the south of the area (mid-July), while on the Baltic coast this date shifted to September or even October (Figure 7). During the autumn, the sea is still very warm, while the land cools quickly. This contrast in the coastal zone leads to a shift of the maximum precipitation towards autumn. The same features of territorial distribution remained in the cases of RP_{60} and RP_{90} with small shifts of RP dates toward the autumn. This is due to the more frequent precipitation in the autumn than in early summer.

The RP_{30} dates were usually recorded from mid-June to early August, RP_{60} from late June to mid-July, and finally RP_{90} in July with a clear peak in the middle of July (Figure 8). The rainy periods could often be recorded during the second half of the year (especially in September–October), while in February–April, such cases were extremely rare.

4.2. Long term changes

The annual amount of precipitation increased throughout the study area (Figure 9). The largest changes (in some places exceeding 200 mm) during the analysed 70-year period were recorded in the northeastern part of the territory. Here, the changes were statistically significant in almost all grid cells. Moving to the southwest, the magnitude of

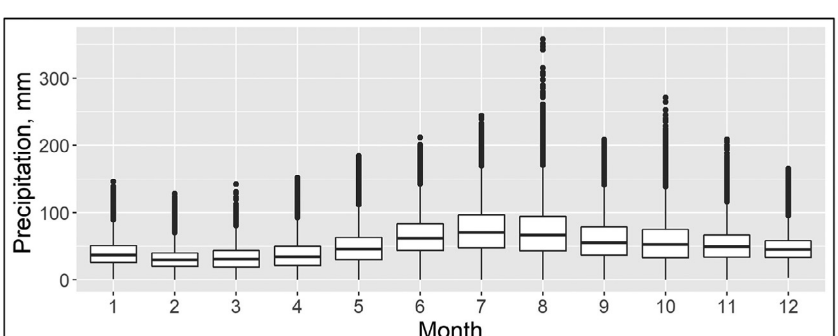

Figure 3 Box-whisker plot of monthly precipitation (mm) in individual grid cells of the analysed area in 1950–2019.

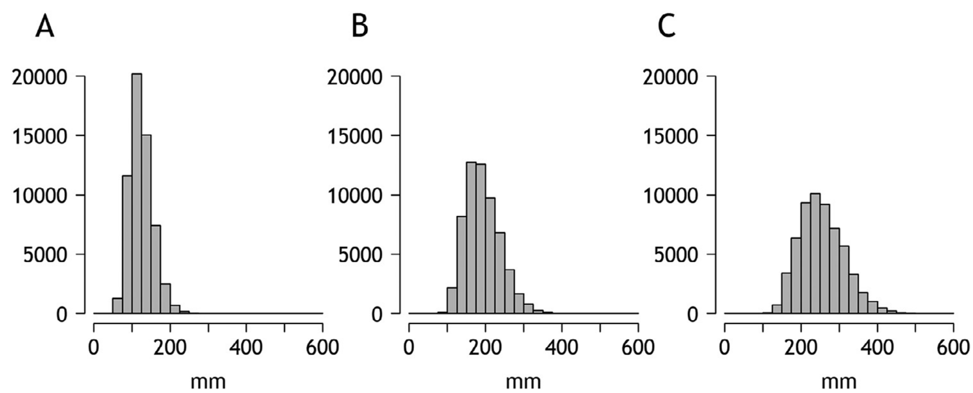

Figure 4 Recurrence of precipitation (number of cases) during RP30 (A), RP60 (B) and RP90 (C) in 1950—2019.

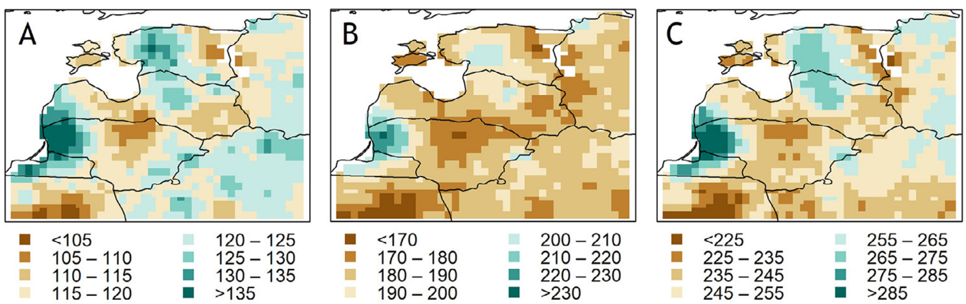

Figure 5 Median precipitation amount (mm) during RP30 (A), RP60 (B) and RP90 (C) in 1950—2019.

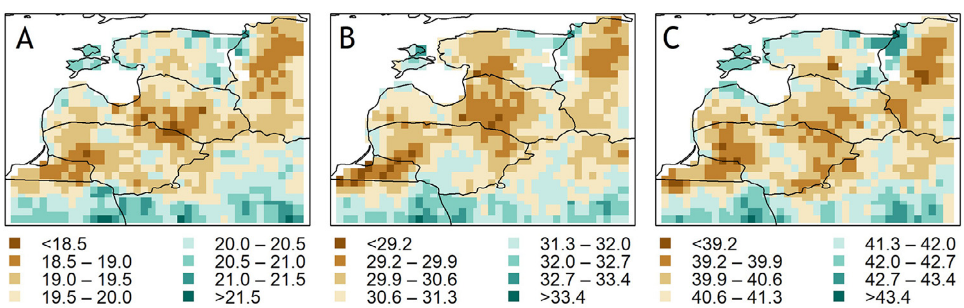

Figure 6 Median ratio (%) of precipitation during the RP30 (A), RP60 (B) and RP90 (C) to annual precipitation in 1950—2019.

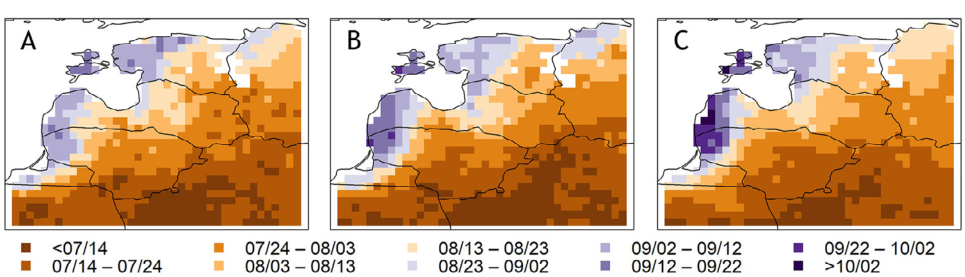

Figure 7 RP30 (A), RP60 (B) and RP90 (C) median dates in 1950—2019.

changes decreased and in the southern part of the analysed area did not exceed 100 mm; in some places, the values were close to 0 mm.

The cold period of the year (from October to March) was characterised by an increase in the amount of precipitation. The largest positive changes were observed in January (Figure 10). The changes in precipitation were statistically significant in almost the whole study area and, in most cases, exceeded 20 mm. However, only in January and March were the changes positive throughout the entire territory.

Meanwhile, the decreasing trends of precipitation prevailed in April and September. The negative trends of precipitation in April could be attributed to changes in atmo-

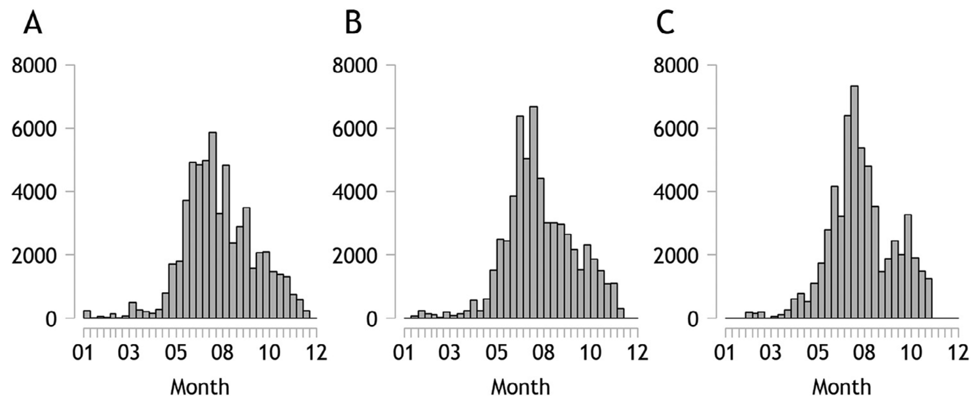

Figure 8 Recurrence of RP30 (A), RP60 (B) and RP90 (C) dates (number of cases) in 1950—2019.

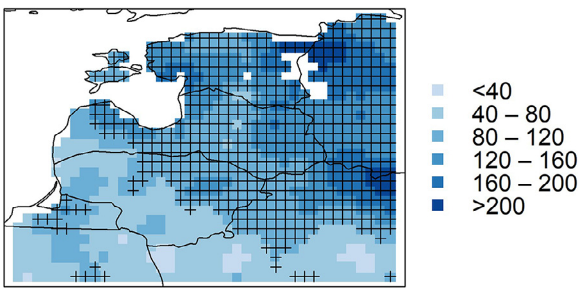

Figure 9 Changes in annual precipitation (mm per 70 years) in 1950—2019. Grid cells with statistically significant changes are marked with a plus sign.

spheric circulation in Central Europe (Ionita et al., 2020). Due to changes in atmospheric circulation, April became warmer and drier, which in turn led to a shortage of precipitation in the spring. Even more pronounced negative changes were observed in September when the decrease in precipitation east in the Gulf of Riga was statistically significant and exceeded 20 mm.

In the summer months, during which the RP was usually recorded, the changes were quite different. The amounts of precipitation decreased in the south of the area in June and especially in August, while statistically significant positive changes were recorded in the northeast. In July, by contrast, precipitation increased in the south (changes were statistically significant in some grid cells) and slightly decreased in the north.

The magnitude and even a sign of changes in precipitation during the RP varied in the study area. Positive but mostly statistically insignificant changes were recorded in most of the investigated area (Figure 11). The highest growth during RP_{30} was recorded around the Gulf of Riga and in the southeast of the area. Here, the changes in some places exceeded 30 mm.

Statistically significant positive changes in the cases of RP_{60} and RP_{90} were recorded in the east and northeast of the analysed territory — in the territory of Russia and Belarus (Figure 11). Thus, moving away from the Baltic Sea, the positive changes were intensifying. Insignificant negative changes were observed in the western part of Lithuania and some parts of central Latvia.

It was found that the annual amount of precipitation increased throughout the entire territory, while the prevailing positive changes in precipitation during the rainy periods were mostly insignificant. Therefore, the ratio of the RP to the annual amount of precipitation during rainy periods of various durations was decreasing (Figure 12). These changes were particularly evident in the case of the RP_{90} and RP_{60} as changes were negative in almost the entire area and were statistically significant in approximately a quarter of the area. The largest changes were found in western Lithuania, western Estonia, as well as in central and northeastern Latvia. On the other hand, insignificant positive changes during the RP_{30} were determined in the southeast of the territory.

It was determined that in most of the territory the rainy period was occurring earlier in the year (Figure 13). In some cases, the changes exceeded 30 or even 50 days. The largest changes were found in the area which stretches from the Kaliningrad district to eastern Latvia. In some parts of the territory the opposite, but statistically insignificant tendencies prevailed, i.e., RPs dates were recorded later.

Significant positive changes in temperature during the spring months (Jaagus et al., 2014) led to an increase in precipitation in late spring and early summer, and thus rainy periods shifted to the beginning of the warm period. On the other hand, the majority of grids cells showed statistically insignificant trends.

The research shows that the spatial differences of precipitation during the rainy period increased in the case of all RPs. For the RP_{30}, the changes were statistically significant. This can be related to the shift of the dates to the middle of summer when convection rather than frontal precipitation was prevailing.

5. Discussion

The annual amount of precipitation was increasing in most of the analysed region. Our results are similar to those of Jaagus et al. (2018), who analysed the changes in precipitation in the meteorological stations of Baltic states in 1966—2015. The largest positive changes were recorded in the northeast of the region, while moving to the south, the changes became smaller and statistically insignificant. This is in line with trends in Europe, where precipitation is

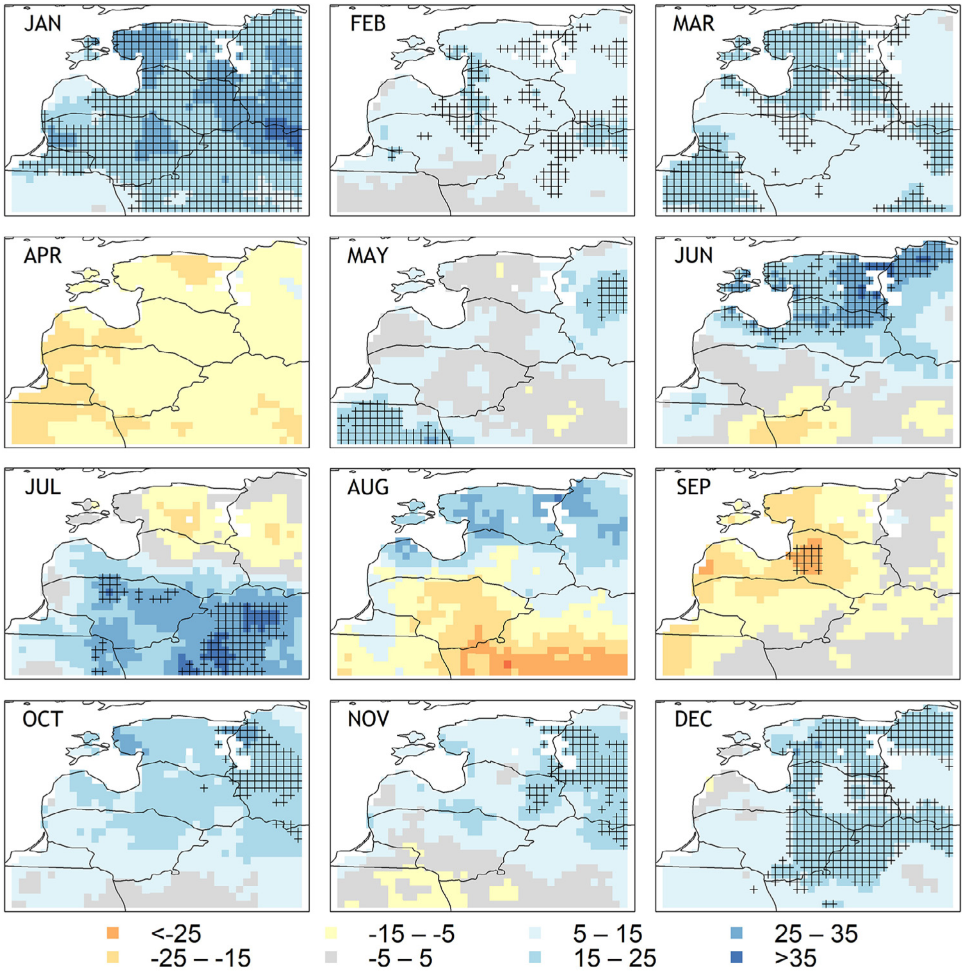

Figure 10 Monthly precipitation changes (mm per 70 years) in 1950—2019. Grid cells with statistically significant changes are marked with a plus sign.

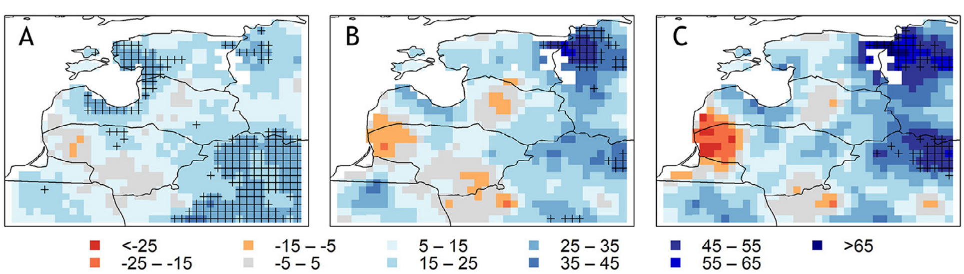

Figure 11 RP30 (A), RP60 (B) and RP90 (C) value changes (mm per 70 years) in 1950—2019. Grid cells with statistically significant changes are marked with a plus sign.

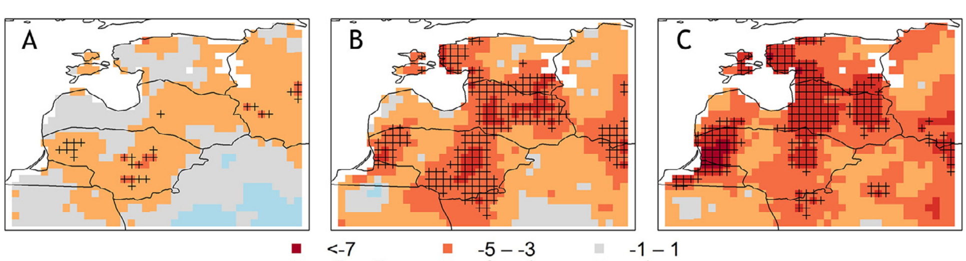

Figure 12 Changes in the ratios of the RP30 (A), RP60 (B) and RP90 (C) to the annual precipitation (% per 70 years) in 1950—2019. Grid cells with statistically significant changes are marked with a plus sign.

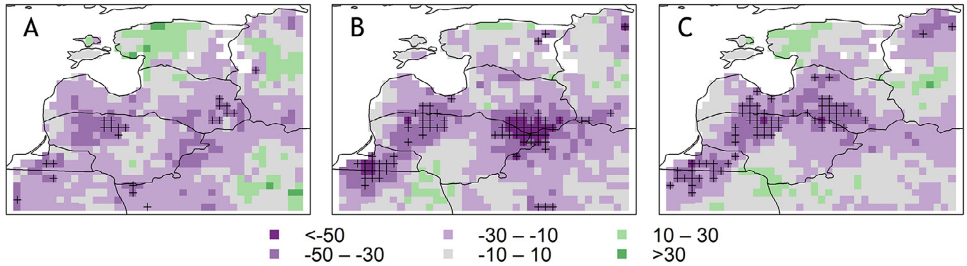

Figure 13 RP30 (A), RP60 (B) and RP90 (C) date changes (in days per 70 years) in 1950–2019. Grid cells with statistically significant changes are marked with a plus sign.

statistically significantly increasing in the north and declining in the south (Kovats et al., 2014). Similar changes are expected in the future (Christensen et al., 2015; Spinoni et al., 2018). The most important feature of changes in intra-annual precipitation regimes throughout the analysed area was that the differences in precipitation between winter and summer decreased. As winter temperatures rose, so did the amount of precipitation, while the changes in the summer months were not so significant. The sign of the change was also different during the summer months.

Researchers have generally paid more attention to periods of long negative precipitation anomalies — droughts — rather than the analysis of periods of excessive rainfall. Indeed, many studies have assessed the damage caused by droughts (Leng, 2021; Toreti et al., 2019). However long-term positive precipitation anomalies may lead to a higher loss in excess moisture area. Particularly large losses are recorded if such a period occurs in the second half of the summer during harvesting. Anaerobic conditions in flooded agricultural fields are one of the reasons for the poor condition of plant roots (Steduto et al., 2012). Indirect effects include delayed farming operations (Falloon and Betts, 2010). The losses caused by excessive rainfall in the U.S. have been found to be comparable to the losses caused by droughts (Li et al., 2019).

However, so far, there is a lack of research on long rainy periods. Our investigation allows this gap to be filled partially. In the eastern part of the Baltic Sea region, the long rainy periods are analyzed for the first time, thus as a first step, it was important to evaluate the spatial distribution of precipitation sums during different length rainy periods as well as the seasonal distribution of precipitation sum during these events. The RP_{30}, RP_{60}, and RP_{90} show the sum of precipitation, which has an advantage over standardized values, because it can be easier linked to the risk of long rainy periods. The seasonal distribution of precipitation in different parts of the study area is similar, consequently, it was possible to compare and interpret the RP_{30}, RP_{60}, and RP_{90} values throughout the territory. On a larger spatial scale or in regions with different seasonal climatology, the standardized values (for example SPI1, SPI2, SPI3) would perform better in the diagnosis of long periods with excess precipitation.

In the analysed region during the periods of RP_{30}, RP_{60}, and RP_{90}, a large part of the annual precipitation was recorded (approximately 20, 30, and 40%, respectively). The middle of this period usually coincided with the middle of the summer, but in a large part of the territory, RPs were recorded later. Meanwhile, the RP season gradually moved into the spring months.

With increasing annual precipitation, the changes in the RP_{30}, RP_{60}, and RP_{90} values were not so significant. The largest positive changes were determined in the eastern and northern parts of the territory. However, in a large part of the area, changes were close to zero or even negative. As a result, the share of precipitation during RPs of different duration decreased in almost the entire area. However, it should be noted that absolute values and as consequence the threat posed by such periods, were growing in most of the area.

It should also be considered that the amount of RP precipitation can be more and more often influenced by short-term one- to five-day rain events, when the amounts of precipitation exceeding a monthly climate normal may fall over a noticeably short period of time. This may be important because the effects on the environment and economic sectors caused by short-term rains and prolonged rains are different. In the future, the number of one- or few-day extreme precipitation events in Europe is expected to increase more than the number of longer-term precipitation events lasting several weeks (Huo et al., 2021). A major threat is the fact that RP in most of the analysed area is occurring earlier. This means that rains can have a strong impact on agricultural crops during the late stages of their development and during harvest, severely affecting yields.

An example of such an extreme case in a large part of our analysed region was July—September 2017. Since June 2017 the amount of precipitation has been much higher than the climate normal, but there has been no negative impact and conditions have been described as good in mid-summer. Prolonged rains in mid-September in northern Europe, as well as the Baltic countries, worsened wheat quality. Due to the delayed harvest, sugar beet yields were lower in quality as well (JRC, 2017a). In Finland, not all agricultural crops reached maturity due to unusually humid, cool weather and shorter sun duration (JRC, 2017b). Although the rains at the end of the summer did not damage all crops, harvesting in the Baltic States and Germany was disrupted (EU, 2018). Due to prolonged rain and excessive soil moisture during the autumn, the sowing of winter crops was also hampered (JRC, 2017b).

Our study shows that precipitation is increasing in the analyzed area. Precipitation also increases during the RP, although the changes are not statistically significant in most cases. As a result, the effects of RP are strengthening. Additional threats to agriculture are posed by the earlier dates of the RPs. Therefore, it is necessary to take care of the existing drainage system. It is necessary to emphasize, that successful adaptation to climate change requires an assessment of the various threats posed by rainfall anomalies. Therefore, in addition to integrated drought management plans, which may not be as relevant for northern Europe, pathways must be provided for adapting to positive precipitation anomalies of various durations.

6. Conclusions

In the eastern part of the Baltic Sea region, the significant amount of annual precipitation in 1950-2019 was recorded during long rainy periods RP_{30} (≈20%), RP_{60} (≈30%), and RP_{90} (≈40%). The spatial distribution of the precipitation amount during RP's is similar to the annual distribution of precipitation. With the increase of annual precipitation, the ratio of the RP precipitation amount to annual precipitation decreased over the analyzed 70 years, and these changes were particularly evident in the case of the RP_{90} and RP_{60}.

The median timing of RP varied from mid-July in the south of the study area to September-October near the Baltic coast. The largest gradient between PR dates was in the 30—70 km zone from the Baltic Sea Proper coast. The largest shift of RP dates towards spring was at the same zone, suggesting that in the beginning of 1950—2019 the coastal zone with frequent PR events in autumn was wider than at the end of the studied period.

The spatial distribution and timing patterns of RP_{30}, RP_{60}, and RP_{90} are similar but the magnitude of trends in precipitation amount and PR timing is different. Shorter RP's are more sensitive to extreme precipitation events, which are likely to increase due to climate change, thus the distribution and timing patterns might become more dissimilar in the future. The different length of rainy periods has different effects on economy and ecosystems, consequently it is advisable to use the different time period lengths for the analysis of rainy period climatology and risk.

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.

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