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KLIMATA PĀRMAIŅU IETEKMES LATVIJĀ - AKTUĀLI PĒTĪJUMI

CLIMATE CHANGE IMPACTS IN LATVIA

Compilation of studies

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CHANGES OF EXTREME CLIMATE EVENTS IN LATVIA

Abstract - **Extreme climate events are increasingly recognized as a threat to human health, agriculture, forestry and other sectors. To assess the occurrence and impacts of extreme climate events, we have investigated the changes of indexes characterizing positive and negative temperature extremes and extreme precipitation as well as the spatial heterogeneity of extreme climate events in Latvia. Trend analysis of long–term changes in the frequency of extreme climate events demonstrated a significant increase in the number of days with extremely high air temperatures and extreme precipitation, and a decrease in the number extremely cold days.** *Key words* - **climate change, trends, temperature extremes, precipitation extremes, Latvia**

I. INTRODUCTION

Climate change has been recognized as a major challenge to human beings and natural ecosystems [14]. Climate change affects all elements of the climate system: air and water temperature, precipitation, river runoff, ice and snow cover and others. A significant worldwide increase in the mean temperature near the surface of the Earth has been reported, indicating that climate is changing: the global mean temperature increase over the period 1861–2000 was 0.61°C, with a 90% confidence interval 0.45–0.77°C, while between 1901 and 2000 the observed warming was 0.57°C, with a 90% confidence interval 0.40–0.74°C [1]. However, climate change is not only characterized by changes in the mean values, but also by changes in the variability of climate indicators and extremes for example, extreme heat events and heat waves, extreme precipitation, floods [16], [3]. In respect to the damage to the society and natural ecosystems, extreme climate events may pose much more significant threats than climate change itself.

Today there is a growing interest in extreme climate events [9], [2], [4] , [10], [5] and trends of their changes. Changes in extremes may be due to the mean effect, the variance effect or the structural change in shape of distribution [13]. Determining changes in the behaviour of extreme weather events has been the topic of several international projects ECA&D [30], [20], EMULATE [22], STARDEX [12]. Often extreme climate events have been identified using internationally agreed, predefined indices that is a day count exceeding a fixed threshold, percentile threshold, extreme event duration, etc [9].

In several studies in Europe a significant increasing trend of many extreme indices has been found over the later part of the 20th century [26], [20]. A study based on the analysis of temperature extremes [20] has reported an increment of the warm extremes and a decrease of the cold extremes in Europe. In summer, the increase concerns both daily maximum and daily minimum air temperatures while in winter – mostly daily minimum air temperatures [22]. The countries around the Baltic Sea have also experienced an increase in the number of warm nights and a decrease in the number of cold nights and days in the latter part of the 20th century as well as a slightly increased number of summer days with daily maximum temperatures of above +25°C [21]. According to studies brought out in Europe, there are significant spatial differences in the trends of changes for extreme precipitation events [19], [5], though the most significant increasing tendency has been observed in the Baltic Sea region [6], [18]. According to the Fourth Assessment Report (2007) it is very likely that in the northern part of Europe the extremely high temperature events and heat waves as well as extreme precipitation events will continue to become more frequent [15].

So far studies of the climate change in Latvia and other Baltic countries have been mostly carried out based on trends of changes of mean values. Climate extreme variability and changes has been studied in several meteorological stations in Latvia and Lithuania [3], [17]. The aim of this study is to determine the long-term variability and trends in the time series of extreme climate events in Latvia.

II. MATERIALS AND METHODS

Daily climate data were provided by 14 major meteorological observation stations in Latvia (Fig. 1). Variable data obtained from the Latvian Environment, Geology and Meteorology Centre included maximum, minimum and average daily temperatures and daily precipitation amount recorded by the weather stations over the period 1950-2010. Data from the Rīga University observation station over the period 1852-2010 were used for the analysis of the historical changes in the extreme events, but for the case-study of the extremely hot summer of the year 2010 daily observation data of all 23 observation stations in Latvia were used.

Figure 1. Major meteorological observation stations in Latvia

Ensemble climate change indices derived from daily temperature data describing changes in the mean indices or extremes of climate were computed and analysed. The indices follow the definitions recommended by the *CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices* [29] with a primary focus on extreme events (Table 1).

TABLE 1

LIST OF CLIMATE INDICES USED IN THIS STUDY

Index name	**Explanation**	**Value**
TX	Annual or monthly mean of daily maximum temperature	°C
TN	Annual or monthly mean of daily minimum temperature	°C
TNn	Annual or monthly minimum value of daily minimum temperature	°C
TNx	Annual or monthly maximum value of daily minimum temperature	°C
TXn	Annual or monthly minimum value of daily maximum temperature	°C

TXx	Annual or monthly maximum value of daily maximum temperature	°C
FD	Frost days (annual count when daily minimum temperature <0ºC)	Days
ID	Ice days (annual count when daily maximum temperature<0ºC)	Days
SU	Summer days (annual count when daily maximum temperature >25ºC)	Days
TR	Tropical nights (annual count when daily minimum temperature >20ºC)	Days
CSDI	Cold spell duration indicator (Annual count of days with at least 6 consecutive days when minimum temperature <10th percentile)	Days
WSDI	Warm spell duration indicator (Annual count of days with at least 6 consecutive days when maximum temperature >90th percentile)	Days
Ptot	Annual total precipitation amount in wet days (precipitation amount ≥ 1mm)	mm
SDII	Simple daily intensity index (annual total precipitation divided by the number of wet days (precipitation amount ≥ 1.0mm) in the year)	mm/day
CDD	Consecutive dry days (annual maximum number of consecutive days with precipitation amount <1mm)	Days
CWD	Consecutive wet days (annual maximum number of consecutive days with precipitation amount ≥1mm)	Days
R10	Annual number of heavy precipitation days (precipitation amount ≥10 mm)	Days
R20	Annual number of very heavy precipitation days (precipitation amount ≥20 mm)	Days
R95p	Very wet days (annual total precipitation when precipitation amount>95th percentile)	mm
R99p	Extremely wet days (annual total precipitation when precipitation amount>99th percentile)	mm
Rx1day	Max 1-day precipitation amount (annual or monthly maximum 1-day precipitation)	mm
Rx5day	Max 5-day precipitation amount (annual or monthly maximum consecutive 5-day precipitation)	mm

The climate indices were computed by using The RClimDex 1.0 developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of Meteorological Service of Canada. RClimDex 1.0 was designed to provide a user friendly interface to compute indices of climate extremes. RClimDex 1.0 runs in the R platform and besides the computation of indices it also includes a simple quality control of the data [27].

Trends in the meteorological event time series were analysed by the MAKESENS test, which was developed for detecting and estimating trends in the time series of annual data. The procedure is based on the nonparametric Mann-Kendall test for the trend and the nonparametric Sen's method for the magnitude of the trend. The Mann-Kendall test is applicable to the detection of a monotonic trend of a time series with no seasonal or other cycle [24]. Within this study the Mann-Kendall test was applied separately to each variable at each site. The trend was considered as substantial at a significance level of $p \leq 0.1$ if the test statistic was greater than 1.6 or less than -1.6, as statistically significant at a significance level of $p \leq 0.01$ if the test statistic was greater than 2.6 or less than -2.6 and as very significant at a significance level of $p \leq 0.001$ if the test statistic was greater than 3.3 or less than -3.3.

III. RESULTS AND DISCUSSION

Climate in Latvia is influenced by its location in the northwest of the Eurasian continent (continental climate impacts) and by its proximity to the Atlantic Ocean (maritime climate impacts).

A. Trends in the changes of extreme air temperature in Latvia

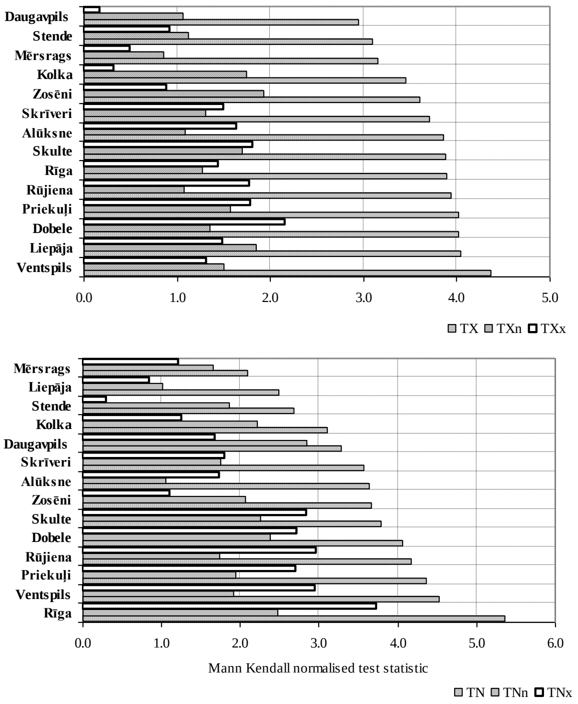

Figure 2. Long-term trends of mean annual minimum and maximum air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics).TX - Annual or monthly mean of daily maximum temperature; TN- Annual mean of daily minimum temperature; TXn - Annual minimum value of daily maximum temperature; TXx - Annual maximum value of daily maximum temperature. TNn - Annual minimum value of daily minimum temperature; TNx - Annual maximum value of daily minimum temperature.

A highly variable weather pattern is determined by the strong cyclonic activity over Latvia. These variable conditions over the territory contribute to differences in the regimes of air temperature and precipitation, and also to the spatial inhomogeneity in the occurrence and long-term trends of extreme climate events.

The overall results of trend estimates of mean annual minimum and maximum air temperatures for 14 meteorological observation stations in Latvia (the spatial location of the meteorological observation stations can be found in Fig. 1) are summarized in Figure 2. The mean of daily maximum air temperature (TX) and mean of daily minimum air temperature (TN) showed a statistically significant increasing trend at all 14 meteorological observation stations covered by the study, as well as the annual minimum value of daily minimum air temperature (TNn) with statistically significant increasing trend at 12 meteorological observation stations (with exception of Liepāja and Alūksne). Trends of changes of annual maximum value of daily minimum air temperature (TNx) and annual minimum value of daily maximum air temperature (TXn) as well as the annual maximum value of daily maximum air temperature (TXx) for all stations has a positive character, but the statistical significance is lower, especially for the stations located in the eastern part of Latvia, revealing spatial heterogeneity of temperature extreme changes and impact of local factors affecting climate at regional/local level. An example of trends of changes of daily maximum, mean and minimum temperatures in capital of Latvia – Rīga, demonstrates the impact of city microclimate and visually seen increase of the studied temperature extremes (Fig. 3).

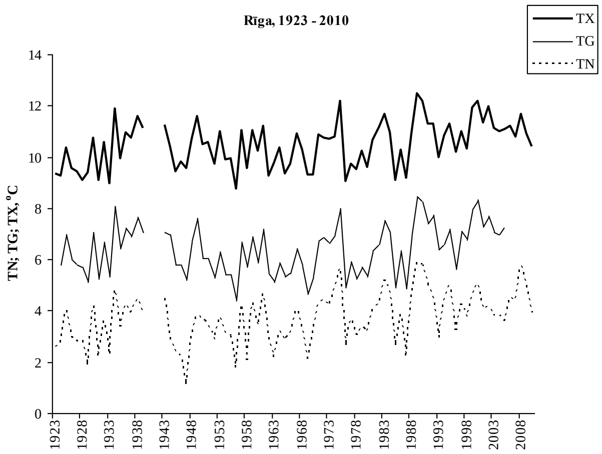

Figure 3. Trends of annual daily maximum (TX), mean (TG) and minimum (TN) temperature in Rīga for the period from 1923 to 2010

A detailed study of the character of monthly mean of daily maximum temperature changes within a year (Table 2) reveal a strongly seasonal character of maximum air temperature increase. On one hand, the daily maximum air temperature increase is not even throughout the year, but occurs in some seasons, but on the other hand is relatively even for all meteorological stations over Latvia. The increase of daily maximum air temperature is statistically significant for January till May and again for July and August, but there is a common decreasing trend for June. Within September till December daily maximum temperature increase is evident unless these changes are statistically insignificant.

TABLE 2

LONG-TERM TRENDS OF MONTHLY MEAN OF DAILY MAXIMUM AIR TEMPERATURE (TX) IN LATVIA OVER THE PERIOD 1950-2010

(MANN-KENDALL TEST STATISTICS)

	J	F	M	A	M	J	J	A	S	O	N	D
Alūksne	**2.40**	**1.72**	**2.76**	**2.92**	**1.99**	-0.67	**2.08**	**1.69**	1.05	0.50	1.17	0.45
Daugavpils	**2.10**	1.39	**2.86**	**2.66**	0.82	-1.53	1.08	1.10	0.50	0.48	0.87	0.14
Dobele	**2.23**	**1.79**	**2.71**	**2.92**	**2.55**	0.01	**2.55**	**2.65**	1.23	0.62	**1.81**	0.79
Kolka	**1.86**	**1.93**	**2.19**	**2.50**	**2.81**	-0.35	**1.88**	**2.65**	0.75	-0.45	0.84	0.65
Liepāja	**1.89**	**1.84**	**2.83**	**2.84**	**2.95**	0.88	**2.19**	**2.67**	1.36	0.20	0.88	0.64
Mērsrags	1.40	**1.67**	**2.01**	**2.42**	**2.37**	-0.55	**1.77**	**2.22**	0.11	0.13	0.47	0.19
Priekuļi	**2.21**	**1.81**	**2.79**	**2.73**	**2.23**	-0.32	**2.41**	**1.79**	1.23	0.81	1.08	0.80
Rīga	**1.91**	**1.66**	**2.61**	**1.95**	**2.51**	0.06	**2.58**	**2.15**	0.91	0.06	1.13	0.43
Rūjiena	**2.19**	1.33	**2.66**	**2.56**	**2.10**	-0.53	**2.46**	**1.68**	1.06	0.80	1.47	0.87
Skrīveri	**2.42**	**1.65**	**2.98**	**2.78**	**2.00**	-0.59	**2.35**	**1.80**	1.10	0.73	1.27	0.49
Skulte	**2.29**	**1.72**	**2.94**	**1.85**	**1.66**	-0.26	**2.20**	**1.85**	1.07	0.58	1.27	0.67
Stende	1.64	1.41	**2.26**	**1.89**	**2.05**	-0.76	1.45	1.54	0.12	-0.42	0.87	1.29
Ventspils	**2.10**	**2.00**	**2.74**	**2.30**	**2.44**	0.42	**2.70**	**3.18**	1.46	0.77	**1.69**	1.08
Zosēni	**2.11**	1.31	**3.08**	**2.08**	**2.35**	0.12	**1.93**	**1.74**	0.60	0.32	0.65	0.10

TABLE 3

Long-term trend of monthly mean of daily minimum air temperature (TN) in Latvia over the period 1950-2010

(Mann-Kendall test statistics)

	J	F	M	A	M	J	J	A	S	O	N	D
Alūksne	**2.63**	1.38	**2.53**	**2.21**	1.54	0.21	**2.36**	**2.08**	0.98	0.06	1.34	0.66
Daugavpils	**2.53**	1.46	**2.66**	**2.01**	1.10	0.12	0.86	1.21	0.29	-0.25	1.05	0.60
Dobele	**2.45**	**1.83**	**2.73**	**2.55**	**2.22**	1.53	**3.15**	**3.38**	**1.80**	-0.06	**1.71**	0.96
Kolka	**2.09**	**1.76**	**2.34**	**1.73**	**2.39**	0.38	**1.69**	**2.10**	0.82	-0.42	1.13	0.28
Liepāja	**1.87**	1.41	**2.02**	1.52	**2.28**	0.63	**1.86**	**2.24**	-0.24	-1.21	0.58	0.48
Mērsrags	**1.84**	1.15	**2.16**	0.92	0.64	0.02	0.42	0.51	-0.16	-0.59	0.19	0.01
Priekuļi	**2.56**	1.52	**2.79**	**2.58**	**2.41**	1.26	**3.58**	**3.38**	1.46	0.27	1.42	0.95

Rīga	**2.74**	**2.07**	**3.29**	**3.39**	**4.41**	**3.53**	**4.99**	**5.66**	**2.99**	1.24	**1.82**	1.13
Rūjiena	**2.63**	1.28	**2.47**	**2.40**	**2.03**	1.29	**3.32**	**3.14**	**1.70**	0.19	1.07	0.98
Skrīveri	**2.58**	1.49	**2.54**	**1.72**	1.17	0.20	**2.40**	**2.08**	0.94	-0.31	1.31	0.68
Skulte	**2.45**	1.60	**2.84**	**2.08**	**2.05**	1.26	**2.71**	**3.47**	1.10	0.09	1.41	0.50
Stende	**1.76**	1.50	**2.09**	1.00	1.03	0.44	0.78	1.42	0.29	-0.66	0.76	0.91
Ventspils	**2.39**	**2.01**	**2.66**	**3.15**	**4.24**	**2.26**	**3.64**	**5.03**	**1.84**	0.55	**2.01**	1.16
Zosēni	**2.19**	1.07	**2.73**	1.27	1.25	1.36	**2.32**	0.76	0.25	-0.65	0.99	0.12

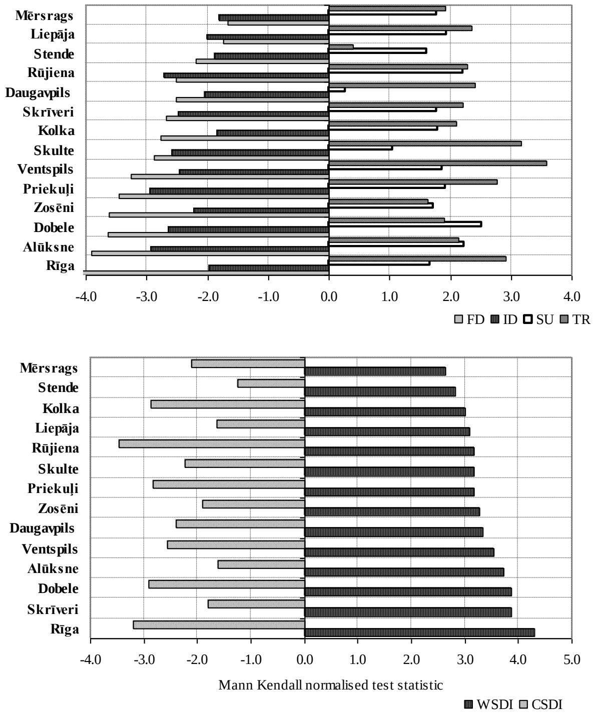

Figure 4. Long-term trends of extreme temperature events and events of prolonged periods of extremely low and high air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics). FD - Frost days; ID - Ice days; SU - Summer days; TR - Tropical nights; CSDI- Cold spell duration indicator; WSDI - Warm spell duration indicator.

The same trends as for monthly mean of daily maximum air temperature (TX) are common also for monthly mean of daily minimum air temperature (TN) (Table 3). However trends for monthly mean of daily minimum air temperature differ, for example, in February in most of studied meteorological stations. As remarkable can be considered the trends of changes of in Rīga, where statistically significant increasing trends are common for nearly full year (except October and December), stressing the role of the city microclimate [11] as one of the factors affecting climate in general also regionally.

From different climate extreme indicators special attention deserves indices describing number of days with extremely high or low air temperatures, as far as such events pose major threat to human health, productivity in working places, agriculture and other kind of human activities. As there is a significant increase in the mean values of air temperature in all of the meteorological observation stations also the extreme values of air temperature have been increasing along with the increase in the means. Thus also an increase in the number of days with extremely high air temperatures is common for all the studied stations. A statistically significant increase in the number of summer days (TX > + 25°C) has been observed in 10 out of 14 meteorological stations, as well a statistically significant increase of tropical nights (TN > + 20°C) in 13 out of 14 meteorological stations (Fig. 4). However according to the long-term data from the station Rīga -University, the number of summer days was much higher in the 1850-60ties (Fig. 5). The increasing tendency observed from the beginning of the 20th century is caused by warm summers, especially the summer of the year 2002 (with 60 days of maximum air temperatures above +25°C in Rīga - the highest for the whole period of instrumental observations) and the summer of 2010. At the same time, other studies confirm that, similarly to the trends found in the summer day time series in the station Rīga-University, in the period from 1946 to 1999 in Europe, the number of summer days has increased by 4.3 days [19] and that the overall warming tendency is more evident in the central part of Europe, in the mountainous regions and in the north-eastern part of Europe [23].

Warm spell duration indicator (WSDI - annual count of days with at least 6 consecutive days when maximum temperature >90th percentile) characterizing the length of prolonged heat events has an statistically significant increasing trend all over Latvia, and this can be considered as the most alarming result of this study, because an increase in the frequency and length of the periods of prolonged heat can have a significant negative effect on human morbidity and mortality [8], [4], [25]. Overall the most expressed increasing trend of high temperature extremes is common for regions at the coastline of Baltic Sea, more continental stations (Alūksne, Daugavpils and the capital city of Latvia – Rīga (Fig. 4).

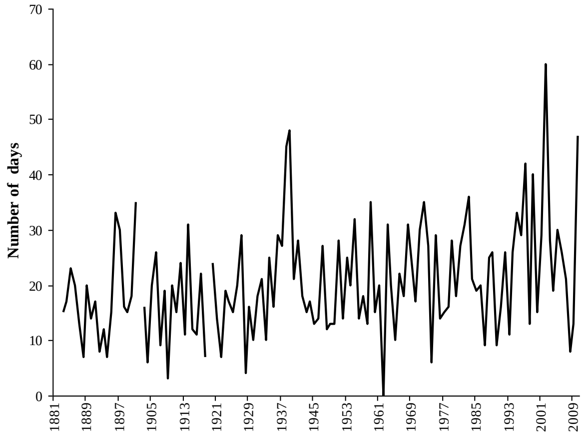

Figure 5. The annual number of summer days in Rīga-University observation station over the period 1881-2010

On the other hand extremes associated with negative air temperatures (despite relatively cold winters in 2009/2010, 2010/2011) have statistically significant negative trend of changes all over Latvia (Fig. 4). Indices of climate extremes associated with negative air temperatures are cold spell duration indicator (CSDI - annual count of days with at least 6 consecutive days when minimum air temperature <10th percentile), frost days (FD - annual count when daily minimum air temperature <0ºC), ice days (ID - annual count when daily maximum air temperature <0ºC). According to the analysis of the World Meteorological Organization [31], the year 2010. along with the years 2005 and 1998 globally has been the hottest year since the beginning of the instrumental meteorological observations in 1850. In Latvia, due to the extremely low wintertime temperatures, the average air temperature of the year 2010 was close to the reference (+5.6°C), ranking the year as the coldest of the 21st century, however during the summer the air temperatures were extremely high (Fig. 6), the excessive heat lasted for a long period of time, and in most of the meteorological observation stations of Latvia the maximum temperature records were broken. Such extremely hot conditions were observed due to a south-easterly air flow that was established over the area for a prolonged period of time [28].

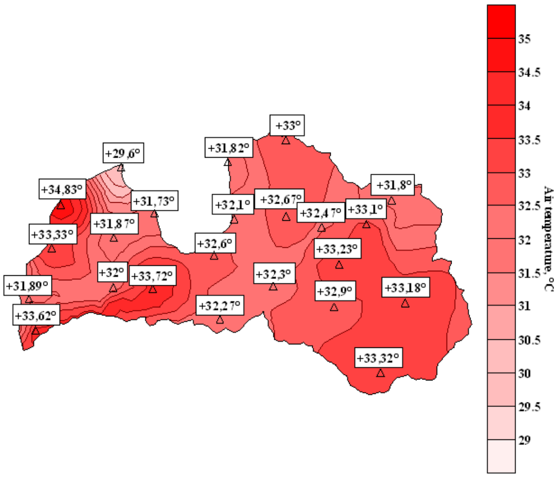

Figure 6. The maximum values of air temperature in Latvia during the summer 2010

Figure 6 shows the maximum air temperatures of the summer 2010 recorded in 23 meteorological observation stations in Latvia. One can see that in all meteorological stations except Kolka the maximum air temperature exceeded +30°C. The pattern of the maximum air temperature distribution was not directly related to geographical factors such as the distance from the Baltic Sea or the Gulf of Riga – due to prevailing south-east winds the highest air temperature of +34.83°C has been observed in Ventspils.

B. Trends in the changes of extreme precipitation in Latvia

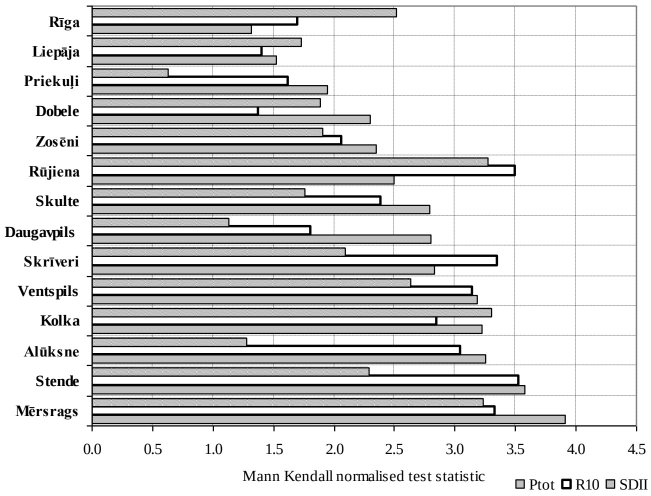

Figure 7. Long-term trends of changes in precipitation amount and heavy precipitation events in Latvia over the period 1950-2010 (Mann-Kendall test statistics). Ptot - Annual total precipitation amount in wet days; R10 - Annual number of heavy precipitation days; SDII - Simple daily intensity index.

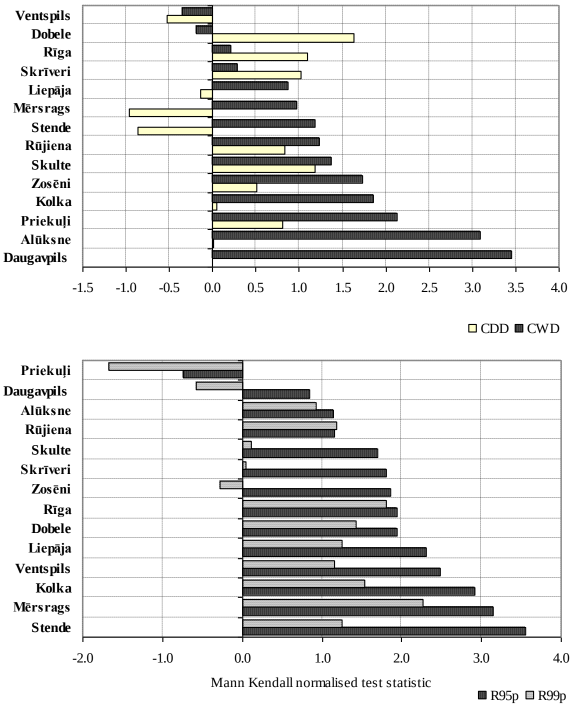

Figure 8. Long-term trends of prolonged dry and wet periods and extremely heavy precipitation in Latvia over the period 1950-2010 (Mann-Kendall test statistics).CDD - Consecutive dry days; CWD - Consecutive wet days; R95p - Very wet days; R99p - Extremely wet days.

Another group of meteorological events may be related to precipitation regime. Precipitation regime is a group of processes controlling hydrological processes in lakes and rivers, water supply for agricultural and human needs, recreational purposes. At the same time extremes in precipitation amount can be related to floods (including flash floods), but also droughts. Trend analysis of changes in precipitation amount and intensity in Latvia (Fig. 7, 8) at first reveal changes in the precipitation amount distribution on a yearly basis. For example, our study demonstrated a statistically significant increase (in most of the meteorological stations) in annual total precipitation amount (Ptot) in wet days (precipitation amount ≥ 1mm) and major changes in a simple daily intensity index (SDII - annual total precipitation divided by the number of wet days (precipitation amount ≥ 1.0mm) in the year) stressing a significant changes in the precipitation intensity character and consecutively in the damaging potential of the heavy precipitation events. At the same time number of consecutive dry days (CDD - annual maximum number of consecutive days with precipitation amount <1mm) does not have well expressed trends of changes at all, but number of consecutive wet days (CWD - annual maximum number of consecutive days with precipitation amount ≥1mm) has a statistically significant increasing trend only in 5 stations (out of 14) ((Fig. 8).

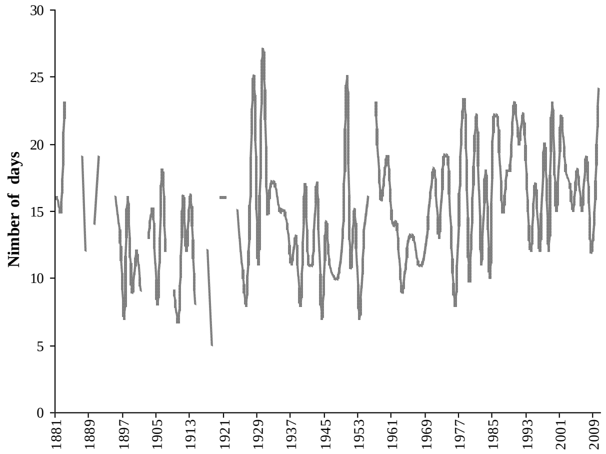

Figure 9. Long-term trends in the number of days with heavy precipitation (daily precipitation amount ≥ 10 mm) in Rīga-University observation station over the period 1881-2010

In all of the meteorological observation stations studied there has been an increase in the number of days with heavy precipitation (R10 - daily precipitation total ≥ 10 mm), and very heavy precipitation (R20 - precipitation amount ≥20 mm) and also in the number of very wet days (R95p - annual total precipitation when precipitation amount>95th percentile) and extremely wet days (R99p - annual total precipitation when precipitation amount>99th percentile). For most of the observation stations in the territory of Latvia the trends of precipitation intensity changes are increasing and statistically significant (Fig. 8), however, it becomes evident that impacts of regional factors are affecting the precipitation regime, so, for example the number of extremely wet days in Priekuļi is significantly decreasing (Fig. 10), reflecting the importance of the local relief as a factor affecting precipitation regime. Also the well-expressed increase in the number of days with heavy precipitation in Rīga (Fig. 9) especially evident throughout the past ~80 years could be associated with the influence of the Gulf of Rīga and the urban climate specifics [7].

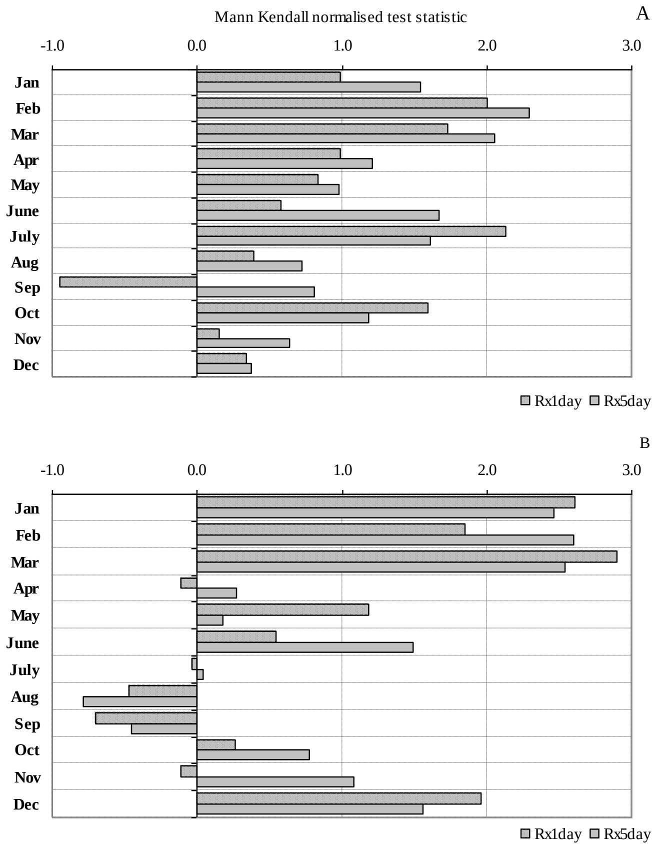

Figure 10. Long-term trends of monthly maximum 1-day and 5-day precipitation amount in Mērsrags and Priekuļi observation stations over the period 1950-2010 (Mann-Kendall test statistics).Rx1day - Max 1-day precipitation amount (monthly maximum 1-day precipitation); Rx5day - Max 5-day precipitation amount (monthly maximum consecutive 5-day precipitation). A – Mērsrags (3.2 m a. s. l.); B – Priekuļi (117 m a. s. l.)

Also maximum 1-day precipitation amount (Rx1day - annual or monthly maximum 1-day precipitation) and maximum 5-day precipitation amount (Rx5day - annual or monthly maximum consecutive 5-day precipitation) demonstrate the overall redistribution of the precipitation intensity, but changes from station to a station (Fig. 10).

IV. CONCLUSIONS

The analysis of the long-term trends in the occurrence of extreme temperature and precipitation events demonstrates significant changes in climate variables throughout the territory of Latvia. There has been a significant increasing tendency in the number of days with high temperature extremes and a decrease in the number of days with extremely low air temperatures in most of the observation stations included in this study. The overall warming tendency evident in both the mean values and extremes of air temperature as well as the increased occurrence of heat waves that is even more significant in the major cities of Latvia should raise the awareness of the necessity for adaptation actions, as extreme heat can have a significant negative effect on human mortality and morbidity. The increase in extreme precipitation has a local character, however such events can also have a strong negative influence to both human health and infrastructures. It is expected that the future climate change will result in a further increase in both extreme precipitation and heat events in Latvia.

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FLOOD PATTERN CHANGES IN THE RIVERS OF THE BALTIC COUNTRIES

Abstract. Flooding is the most pervasive natural hazard. Estimation of both the frequency and variation of spring floods is a key issue for the assessment and management of flood risks. Changes in river floods in the Baltic countries (Estonia, Latvia and Lithuania) have been investigated in few national studies. However, there are no studies of the changes of flood patterns by using a common methodology for the rivers of the Baltic region. In this study flood pattern changes in the rivers of the Baltic countries were estimated applying trend and frequency analysis. The territory of the Baltic States is divided into nine hydrological regions (3 regions in each country - marine, continental and transitional zones). 19 long-term hydrological data series of spring flood maximum discharges were analysed in four periods (1922–2010, 1922-1960, 1961–2010 and 1991–2010). The Mann-Kendall test was used to detect trends in time series for selected periods. A comparative study of five widely used probability distributions was performed in order to estimate which distribution at best represents statistical characteristics of flood data in the studied rivers. The results showed that maximum discharges of spring floods decreased over the study period. Only some insignificant positive trends of maximum discharges were found in the last time period (1991-2010) in continental and transitional rivers. Generalized extreme value distribution provided the best approximation to the maximum discharge data series of the rivers of Baltic countries for the whole observation period.

Keywords: rivers, Baltic countries, spring floods, trends, probability distributions

1. Introduction

Flooding is the most pervasive natural hazard and the third most damaging (after storms and earthquakes) (World Bank/United Nations 2010). According to EU Directive 2007/60/EC on the assessment and management of flood risks, floods have the potential to cause fatalities, displacement of people and damage to the environment, to severely compromise economic development and to undermine the economic activities of the Community. It is feasible and desirable to reduce the risk of adverse consequences, especially for human health and life, the environment, cultural heritage, economic activity and infrastructure associated with floods.

Recently significant attention is paid to analysis of this very special hydrological regime phase. Since the 1990s extensive and repeated floods across Europe have been bringing a lot of damage and loss (Handmer 2001; Barredo 2009). That shows failure of contemporary flood prevention approaches to control natural processes, despite the significant funding that is spent for flood prevention measures.

When evaluated the risk of flooding it is important to predict the time of its occurrence and magnitude of floods heights as early as possible and also it is necessary to ensure the reliability of various hydro technical structures. This analysis should neither underestimate nor overestimate magnitude of such an event. At the same time climate change is expected to increase flood frequency and its magnitude through increased precipitation (IPCC 2008). Several studies showed that seasonality of changes varies with location: increases are strongest in the warm season in the USA; while in Europe changes are most notable in the cool season (Groisman *et al*. 2004; Haylock, Goodess 2004). Research in the Baltic countries showed that maximum discharge of spring floods tends to decrease in the most regions (Meilutyte-Barauskiene, Kovalenkoviene 2007; Reihan *et al.* 2012; Klavins, Rodinov 2008; Apsite *et al.* 2009), however, there some questions may arise in the context of climate change: if trends observed in flood series continue in the future or if the historical data are quite good to represent the future flood events? Many studies showed not clear increase of magnitude of flood events but what is promised that flood events can be more frequent (IPCC 2008). In the Northern Europe, Dankers and Feyen (2008) reported a considerable reduction of 10–40% in 100-year discharges in Finland, much of northern Sweden and north-western Russia by the end of the century due to decrease in snow accumulation; however Lehner *et al*. (2006) evaluated that the 100-year floods in the same areas will occur more frequently by the 2070s.

To protect inundated areas and provide floods risk assessment the flood frequency analysis (FFA) is used as the most well-known procedure to ensure the reliable estimation of expected floods and their frequency. Main spring flood parameters, such as maximum discharge, flow duration, are usually used in FFA analysis. These parameters have already been investigated in the Baltic States (Gailiusis *et al.* 2001; Simaityte 2007; Dumbrauskas *et al.* 2008; Meilutyte-Barauskiene *et al.* 2010; Klavins *et al.* 2009; etc.). The annual peak series with more than 50 observations for 40 streams in Estonia, Latvia and Lithuania were studied previously, however, there is no common procedure for the FFA in all these three countries and therefore the results of the same analysis can differ from one another. In Lithuania and in Latvia usually normal and Gumbel distribution laws were used to calculate the parameters, but Estonian hydrologists preferred log-Pearson type III distribution. Therefore, choice of the distribution most suitable to the recorded sample series is important from these aspects.

Gailiusis *et al.* (2001) and Ascila *et al.* (2002) calculated parameters of probability curve for the most of Lithuanian rivers. Recently Sarauskiene and Kriauciuniene (2011) examined different probability distributions for spring flood frequency analysis in Lithuania for different periods with a focus on probability distribution fitting to the actual data in spring flood time. Their studies showed that the log-Pearson type III and generalized extreme value distributions are the most suitable for the Lithuanian rivers. However, such an analysis is not done yet in Estonia and Latvia.

The aim of this study is to analyse the patterns of spring flood data in the selected rivers from different hydrological regions in the Baltic countries applying trend analysis, calculating anomalies and estimating the best fit of probability distribution for the selected data series and trying to find out the climate change impact on flood data distribution as well.

2. Data

The Baltic countries are north-eastern region of Europe containing the countries of Estonia, Latvia, and Lithuania, on the eastern shores of the Baltic Sea. These countries cover relatively small area, although hydro-meteorological differences across the States are significant. The territory of the Baltic States is divided into nine hydrological regions (3 regions in each country) (Fig. 1) (according to Reihan *et al.* 2012). The regions of western Lithuania (W-LT), Latvia (W-LV) and Estonia (W-ES), the territory which is close to the Baltic Sea, belong to the marine climate zone and the main source of river feeding is precipitation. South-eastern Latvia (SE-LV) and Lithuania (SE-LT) together with eastern Estonia (E-ES) are the continental part of the Baltic States. The rivers of this territory have prevailing snowmelt and subsurface feeding and the annual discharge of these rivers is distributed rather equally. The patterns of the other hydrological regions (N-ES, C-LV and

C-LT) of the Baltic States are of a more individual character (Fig. 1a), the authors called these rivers as transitional.

Annual maximum discharge data for the present study were obtained from Estonian Meteorological and Hydrological Institute, Latvian Environmental, geology and hydrometeorological centre and Lithuanian Hydrometeorological Service. Annual maximum sequences at 19 water gauging stations across the Baltic States were used (Fig. 1b, Table 1). The rivers were selected according to availability and quality of data, i.e. there were used long data series and the rivers that are unaffected by significant upstream regulation. Average duration of observations was 83 years. The catchments of selected rivers at water gauging stations (WGS) have a different size (Table 2). The rivers were chosen so as to characterize the regime of the hydrological regions to which they belong.

a)

b)

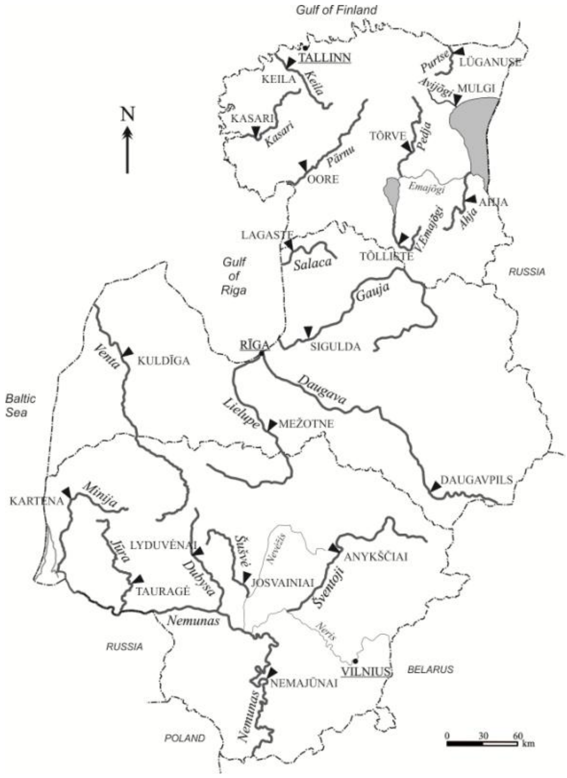


Fig. 1. Hydrological regions (a) and 19 water gauging stations across the Baltic States (b)

Table 1. Summary of the used data

Country	Sites	Station-years of data
Estonia	8	632
Latvia	5	478
Lithuania	6	470
The Baltic States	19	1580

Table 2. Description of the river data

River	WGS	Region	Catchment area, km^2	Record period (years)	Mean discharge (m^3/s)	Annual maximum discharge (m^3/s)
	Continental type rivers					

Ahja	Ahja	ES-E	909	1960-2010	29.49	111
Avijogi	Mulgi	ES-E	366	1955-2010	25.41	55.7
V. Emajõgi	Tõlliste	ES-E	1050	1922-2010	63.62	198
Pedja	Tõrve	ES-E	776	1925-2010	52.04	200
Daugava	Daugavpils	LV-SE	64500	1922-2010	2552	6930
Šventoji	Anykščiai	LT-SE	3600	1928-2010	143.42	423
Nemunas	Nemajūnai	LT-SE	42800	1922-2010	919.15	3460
	Marine type rivers					
Venta	Kuldīga	LV-W	8320	1922-2010	589.44	1300
Minija	Kartena	LT-W	1230	1925-2010	118.73	287
Jūra	Tauragė	LT-W	1690	1926-2010	206.78	510
Kasari	Kasari	ES-W	2640	1925-2010	206.06	703
Pärnu	Oore	ES-W	5150	1922-2010	319.74	810
	Transitional type rivers					
Keila	Keila	ES-N	635	1923-2010	39.18	144
Purtse	Lüganuse	ES-N	784	1923-2010	53.77	156
Lielupe	Mežotne	LV-C	9390	1922-2010	647.23	2430
Gauja	Sigulda	LV-C	8510	1940-2010	335.30	870
Salaca	Lagaste	LV-C	3220	1926-2010	173.26	457
Dubysa	Lyduvėnai	LT-C	1070	1933-2010	66.35	184
Šušvė	Josvainiai	LT-C	1100	1940-2010	80.86	312

In order to evaluate flood frequency changes over time and to investigate climate change impact on spring flood events analysis was made for different periods: 1922–2010, 1922-1960, 1961–2010 and 1991–2010.

3. Methods

The calculation of trend statistics of spring flood data series was based on the nonparametric Mann-Kendall test (Gilbert 1987). This procedure (Mann-Kendall test) is used since missing values are allowed and the data are not need to conform any particular distribution. In this study the significance of trend was tested by using three different α levels of significance: α=0.05, α=0.01 and α=0.001.

There are many probability distributions that are selected for flood projections in different countries all over the world. However, there is no theoretical basis for justifying the use of one specific distribution for modelling flood data and long term flood records show no justification for the adoption of a single type of distribution (Benson 1968). In addition, some later conclusions from the various analyses of outputs for both real and modelled data showed that by employing several alternative distributions to the time series for a catchment one can hardly get the same distribution for samples for another duration (Mitosek *et al.* 2006; Kidson, Richards 2005).

In this study five widely used probability distributions were suggested and compared. Gumbel (EV1), generalized extreme value (GEV), log-Pearson type III (LP3), three-parameter lognormal (LN3) and generalized logistic (GLO) (Table 3) were selected for the analysis of statistical characteristics of observed flood data of the rivers in the Baltic States.

Table 3. Probability density functions of the used distributions

Distribution	Probability density function	Parameters
EV1	$f(x) = \frac{1}{\sigma}\exp(-z - exp(-z))$	σ – continuous scale parameter (σ>0); μ – continuous location parameter; $z \equiv \frac{x-\mu}{\sigma}$
GEV	$f(x) = \begin{cases} \frac{1}{\sigma}\exp(-(1+kz)^{-\frac{1}{k}}(1+kz)^{-1-\frac{1}{k}} & k \neq 0 \\ \frac{1}{\sigma}\exp(-z - exp(z)) & k = 0 \end{cases}$	k – continuous shape parameter; σ – continuous scale parameter (σ>0); μ – continuous location parameter; $z \equiv \frac{x-\mu}{\sigma}$
LP3	$f(x) = \frac{1}{x\lvert\beta\rvert\Gamma(\alpha)}\left(\frac{\ln(x)-y}{\beta}\right)^{\alpha-1} exp\left(-\frac{\ln(x)-y}{\beta}\right)$	α – continuous parameter (α >0); β – continuous parameter (β≠0); γ – continuous parameter
LN3	$f(x) = \frac{exp\left(-\frac{1}{2}\left(\frac{\ln(x-y)-\mu}{\sigma}\right)^2\right)}{(x-\gamma)\sigma\sqrt{2\pi}}$	σ – continuous parameter (σ>0); μ – continuous parameter; γ – continuous location parameter

Distribution	Probability density function	Parameters
GLO	$f(x) = \begin{cases} \dfrac{(1+kz)^{-1-1/k}}{\sigma(1+(1+kz)^{-1/k})^2} & k \neq 0 \\ \dfrac{\exp(-z)}{\sigma(1+\exp(-z))^2} & k = 0 \end{cases}$	k – continuous shape parameter; σ – continuous scale parameter (σ>0); μ – continuous location parameter

Generalized extreme value and Gumbel distributions are extreme value distributions widely used for modelling of extreme or rare events such as extreme floods and snowfalls, high wind speeds, extreme temperatures. The Gumbel (EV1) distribution, also known as the extreme value type I distribution, is unbounded (defined on the entire real axis). The generalized extreme value (GEV) distribution is a flexible three-parameter model that combines the Gumbel, Fréchet and Weibull maximum extreme value distributions.

The log-Pearson type III (LP3) is mostly used for annual maximum floods. In the USA, it is a standard distribution for flood frequency analysis.

The generalized logistic (GLO) distribution is also found to perform pretty well for modelling floods in some countries.

The three-parameter lognormal (LN3) distribution is popular in the studies of the frequency analysis of floods as well.

Parameter estimation for the different probability distributions was performed using methods of L-moments (for EV1, GEV, GLO), of moments (LP3) and of maximum likelihood (LN3). Selection of the corresponding distribution was achieved through goodness-of-fit comparison based on the Anderson-Darling test (Romeu 2003). Product of MathWave Technologies – EasyFit 5.4 with the built-in distribution viewer StatAssist was used for probabilistic modelling of flood data of the selected rivers.

4. Results

4.1. Spring flood discharge anomalies

The main sources of spring floods in the Baltic rivers include accumulation of snow during wintertime, hard winters (indicated by sum of negative temperatures during winter), and intensive rainfalls that usually associated with increase of air temperature during the spring season. As far as the Baltic countries are situated in lowlands with extensive river network, the floods are one of the major sources of natural hazards. The flood impacts are aggravated due to location of major cities of the region either in the lowest reaches of biggest rivers or at rivers. Historically several major floods with high damages caused were recorded (Bukantis 1998, Eberhards 2012, RPV SSSR 1972). Flood threat since 18th century initiated building of hydrotechnical structures to reduce flood risks and, especially, in the last century number of events of major floods has reduced (Table 4); however as factors affecting flood recurrence also climate change and increase of urban areas can be mentioned. Previous studies (Jaagus 2006, Kriauciuniene *et al*. 2012) indicate positive air temperature anomalies throughout the year and higher precipitation amounts in the winter season in the recent decades in the territory of the Baltic countries. Significant changes in land use are also happening: urban areas are growing up, the strong urbanisation trend of the 1960s and 70s, which still continues, is one of the world's largest movements of people from rural to urban areas (Baltic Sea… 2003).

Table 4. Number of high spring floods (probability of ≤10%) in the different type rivers

a) continental type

Periods	Ahja	Avijogi	V.Emajogi	Pedja	Daugava	Sventoji	Nemunas
1922-2010			10	9	8	8	11
1922-1960			10	9	7	8	9
1961-1999	3	2	0	0	1	0	2
1991-2010	1	1	0	0	0	0	0

b) marine type

Periods	Kasari	Parnu	Venta	Minija	Jura
1922-2010	8	8	9	9	8
1922-1960	7	8	8	4	3
1961-1999	1	0	1	5	5
1991-2010	0	0	0	1	1

c) transitional type

Periods	Keila	Purtse	Lielupe	Gauja	Salaca	Dubysa	Susve
1922-2010	8	9	9	5	9	9	6
1922-1960	8	8	9	4	7	5	4
1961-1999	0	1	0	0	1	4	2
1991-2010	0	0	0	1	1	0	0

Table 4 shows the numbers of spring floods of probability equal or less than 10% in the studied rivers. The number of spring floods of the selected probability in the whole studied period comprised from 5 to 9. The comparison of two periods of the same length, 1922-1960 and 1961-1999, showed significant decrease of the spring floods (of the selected probability); in 7 rivers no cases of such floods were recorded. The exception is two Lithuanian rivers of the marine type, the Minija and the Jura, where the number of the spring floods increased (to 5 cases in 1961-1999). In the last two decades a single spring flood or no floods of ≤10% probability occurred. The reason of flood decreasing could be warmer winters, smaller thickness and duration of snow cover in the last year period.

Decrease of spring flood discharges can be observed using other methods of analysis, like estimation of anomalies. Anomalies of annual maximum discharge data were calculated as a difference, expressed by %, between the flood discharges of a particular year and the mean maximum spring discharge of the long-term period (Fig. 2-4).

Flood discharge anomalies in the continental rivers (Fig. 2) showed that annual maximum discharges were decreasing beginning from 1961: in the period of 1922-1960 there were many high positive anomalies (the greatest flood discharges in the studied period: in 1926 - 284% in the Pedja, in 1931 - 211% in the V.Emajogi, 172% in the Daugava and 195% in the Sventoji, in 1958 - 276% in the Nemunas and in 1960 - 276% in the Ahja). These great anomalies are caused by exceptionally high floods in the period. From 1961 the amount of positive and negative anomalies was almost the same. In the last two decades the most spring flood maximum discharges were less than the mean value of the long term period.

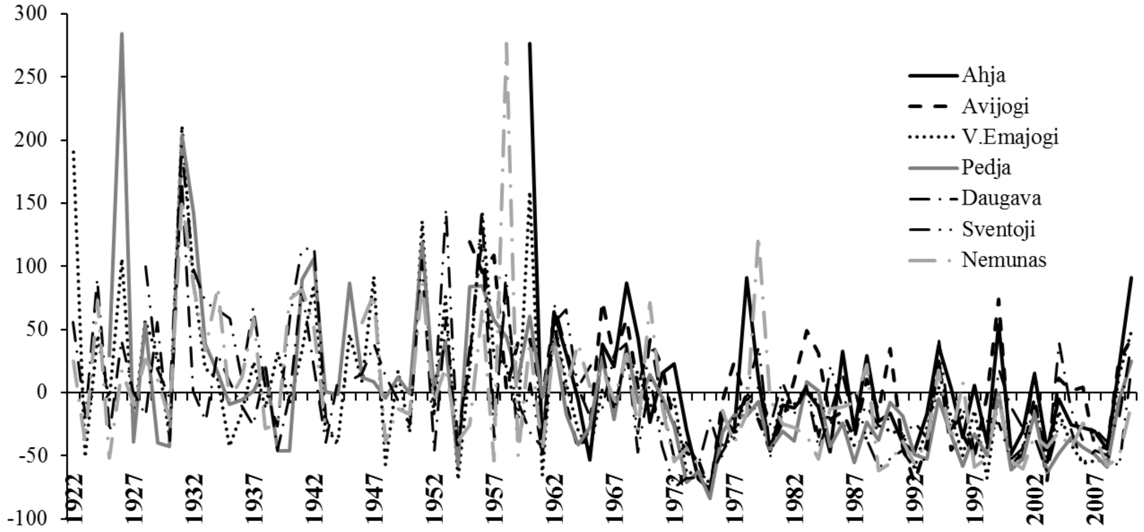


Fig. 2. Annual maximum spring flood anomalies (%) from the long-term average in the continental rivers

Flood discharge anomalies in the marine rivers (Fig. 3) indicate more even distribution of big maximum flood discharges than in continental rivers. A significant decrease of spring maximum discharges can be noticed from 1971 to 1975 that can be caused by anomalies of precipitation decreased from the seventh decade (Reihan *et al*. 2012). Only in the Minija the biggest flood is observed in 1994 (anomaly of 142%), whereas in other rivers the greatest positive anomalies calculated till 1970: in 1931 - 241% in the Kasari and 153% in the Parnu, in 1951 - 121% in the Venta, in 1968 - 147% in the Jura.

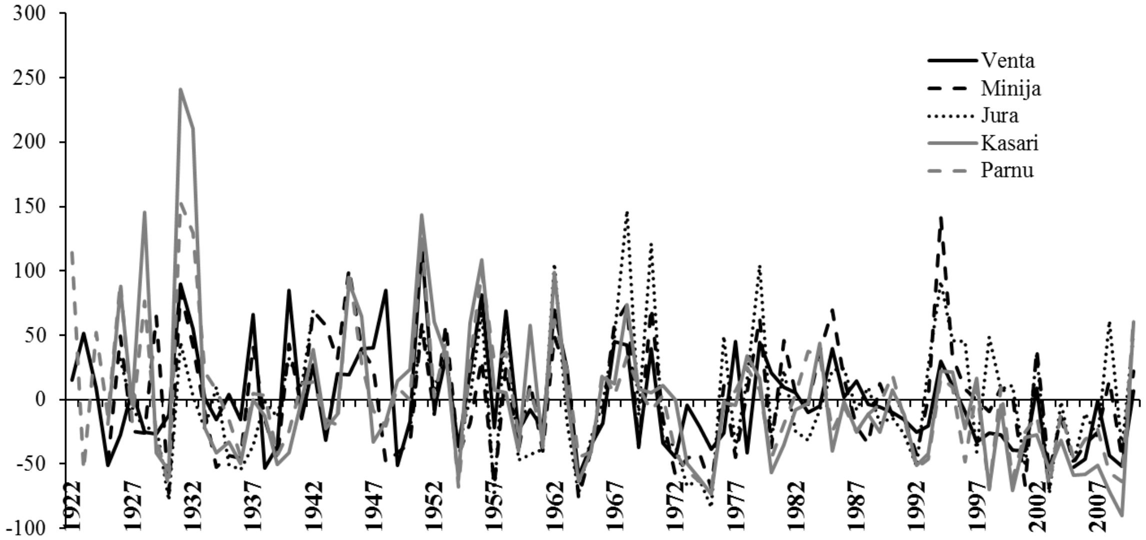


Fig. 3. Annual maximum spring flood anomalies (%) from the long-term average in the marine rivers

In transitional rivers (Fig. 4), like in continental and marine type rivers, much bigger than the average spring discharges were observed till 1970; the highest floods also occurred in this period, whereas very low values of spring floods were recorded in 1971-1977 and since then negative flood anomalies dominated.

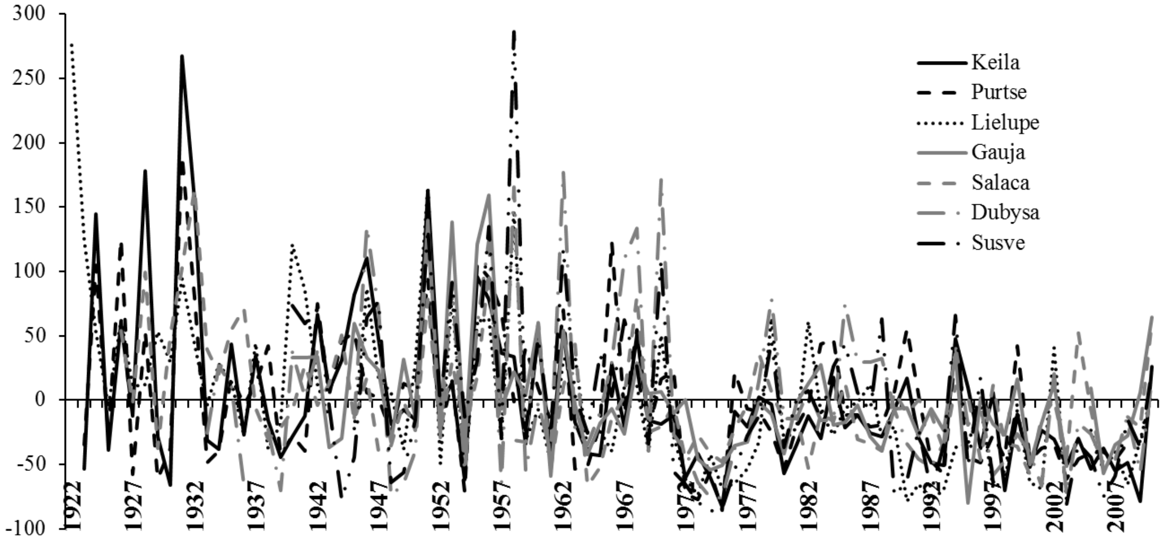


Fig. 4. Annual maximum spring flood anomalies (%) from the long-term average in the transitional rivers

4.2. Trend analysis

Trend analysis was performed for the whole spring flood data sets (1922–2010), periods before and after 1960, i.e. the beginning of the remarkable climate change, as it stated by IPCC: 1922-1960 and 1961–2010, as well as for the two past decades (1991-2010) (IPCC 2008).

In the longest analysed period (1922-2010) the studied flood discharge time series had negative trends, except in the Jura and the Minija, both marine type rivers and both with the smallest catchment area in this group. The trend can differ from other results since in small watersheds influence of local factors on the value of spring flood is more significant than other factors such as climate change for example. The Dubysa (transitional type river), where only poor insignificant trend was detected, was also the exception from the general decreasing tendencies (Fig. 5). Four (out of five rivers that have measurements for this period) continental rivers showed trend at α=0.001 level, i.e. the detected trends were very significant. Trends of the same significance found in two transitional rivers: the Keila and the Lielupe as well. The reason of such character of floods may be the fact that in all continental rivers the highest (or the second highest) floods occurred in 1931, i.e. in the beginning of the studied period, and later in most cases maximum flood discharges were getting less and less. In spring of 1931 Estonia suffered damaging floods, 2% of its land was under water (RPV USSR 1972). Table 4b and Figure 3 can explain why the data of two marine rivers in Lithuania, the Minija and the Jura, do not have clear trend: they both had high spring floods (of probability ≤10%) before and after 1961, moreover, the most spring flood discharge peaks were measured in the last four decades of 20th century.

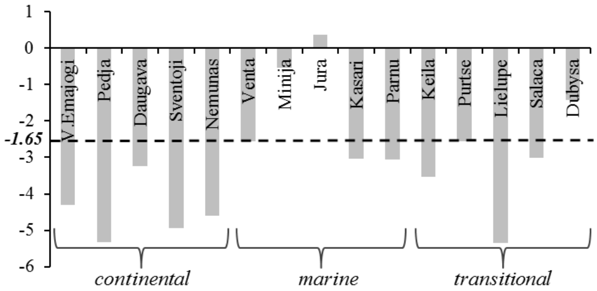


Fig. 5. Trends of annual maximum discharges of spring floods in 1922-2010 (the trend was considered as significant at 5% level when the test statistics was greater than 1.65 or less than -1.65 (Hirsch, Slack 1984)

The analysed above long-term period was split into two separate time slices: 1922-1960 and 1961-2010. Analysis showed (Fig. 6) no significant trend (neither negative nor positive) in maximum flood discharges in 1922-1960, except for two transitional rivers: the Lielupe and the Salaca in Latvia, where Mann-Kendall test displayed significant negative trends at α=0.05 level. And since is no trend in other rivers it can be concluded that in the studied river basins flood regime was relatively stable in this time period.

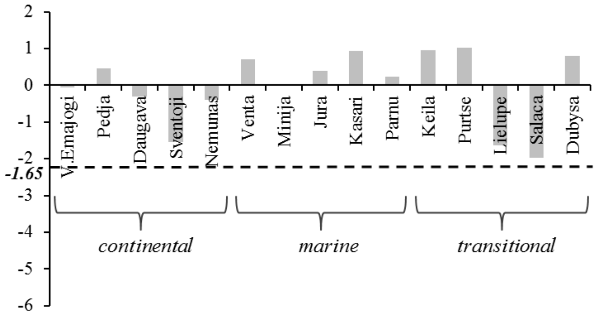


Fig. 6. Trends of annual maximum discharges of spring floods in 1922-1960

Starting from 1961 (Fig. 7) the decreasing tendencies of flood discharges in the most of rivers were detected, however only in the continental type rivers: the Pedja, the Daugava and the Nemunas, and marine rivers: the Kasari, the Parnu and the Venta, changes were more pronounced and can be defined as significant.

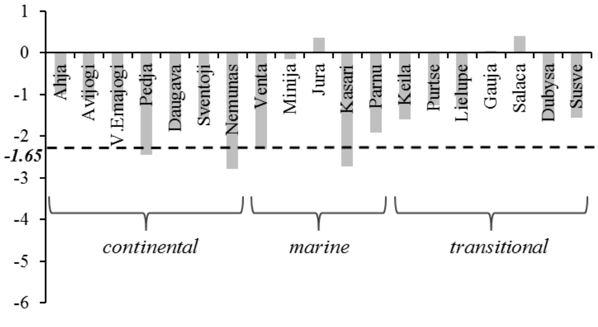


Fig. 7. Trends of annual maximum discharges of spring floods in 1961-2010

In the last 20-year period only two marine type rivers: the Kasari and the Venta had significant negative trends at α=0.05 level in the flood data sets (Fig. 8). Also it should be mentioned that some opposite (positive) insignificant trends were observed in the selected rivers of continental type, whereas for the studied group of transitional rivers no tendencies could be noticed. The recent study of temperature and precipitation changes in the Baltic States (Kriauciuniene *et al.* 2012) showed that in the last two decades in the eastern regions, i.e. continental part, amount of precipitation in winter increased the most. This precipitation increase together with higher temperatures in the whole region in this period could give such consequences – higher floods in the rivers of continental type, since more rainfall or snowmelt water reached the rivers.

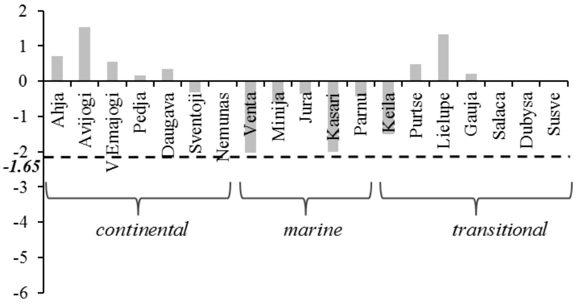


Fig. 8. Trends of annual maximum discharges of spring floods in 1991-2010

4.3. Flood frequency analysis

In order to assess the spring flood risk, the probability of this event has to be identified.

Annual maximum discharge (spring flood) data of the selected rivers have been fitted to 5 probability distribution (PD) models. The aim of the goodness of fit test is to measure the "distance" between the data and the tested distribution, and compare that distance to some threshold value. If the distance (the test statistic) is less than the threshold value (the critical value), the fit is considered good. The critical values depend on the sample size and the significance level chosen (α=0.05). The distribution with the lowest statistic value is considered as the best fitting model.

The PDs were ranked according to the results of Anderson-Darling (AD) test in order to find out the dominant PD for all studied rivers. The best fitting PD (i.e. the distribution with the lowest statistic value) received rank 1, whereas the worst got rank 6.

The PD fitting was accomplished for the same observation periods as the trend analysis (1922-2010, 1922-2060, 1961-2010 and 1991-2010).

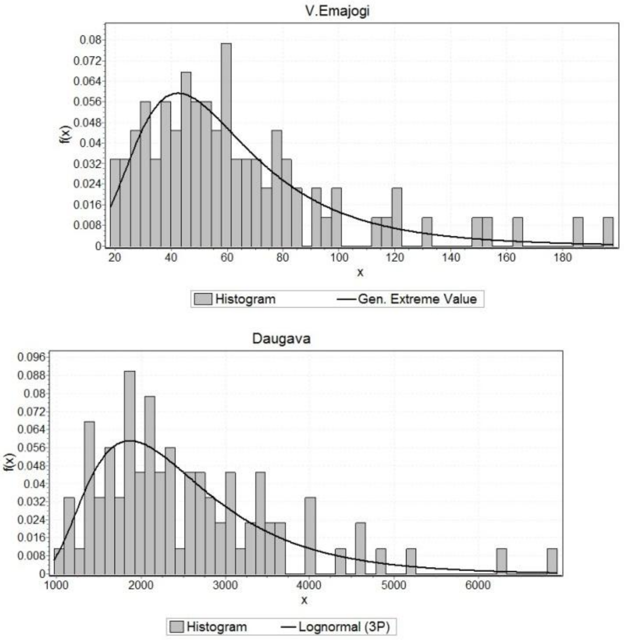
The fitting of annual maxima series of different hydrological regions showed that flood distribution approximations differed slightly (Table 5).

Table 5. Summed fitting ranks according to different distribution functions

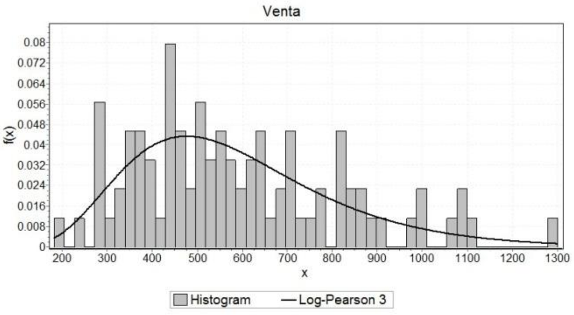
PD	GLO	GEV	LP3	LN3	EV1
River type (number of used data series)	**1922-2010**				
Continental (7)	22	**14**	15	19	35
Marine (5)	17	**9**	14	14	21

In the longest studied period (1922-2010) GEV distribution provided the best approximation to spring flood data in marine rivers, whereas in other studied rivers maximum discharges were mostly GEV or LP3 distributed. In Figure 10 visualisation of the probability distribution fitting to the actual spring flood data of the whole observation period is presented; it shows the probability density functions of the distributions which best fit to the spring flood data (the cases, where Arlington-Darling test statistics value was the lowest, i.e. less than 0.2).

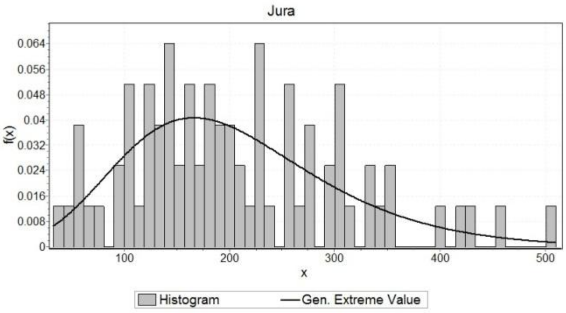
a)



b)



Transitional (7)	25	15	**14**	19	32
			1922-1960		
Continental (4)	15	8	**7**	13	17
Marine (5)	19	**10**	**10**	13	23
Transitional (6)	26	11	**8**	21	24
			1961-2010		
Continental (7)	29	**10**	17	18	31
Marine (5)	21	**8**	9	13	24
Transitional (7)	22	**11**	22	21	29
			1991-2010		
Continental (7)	26	**13**	17	16	33
Marine (5)	19	**6**	13	17	20
Transitional (7)	21	**14**	18	20	32



c)

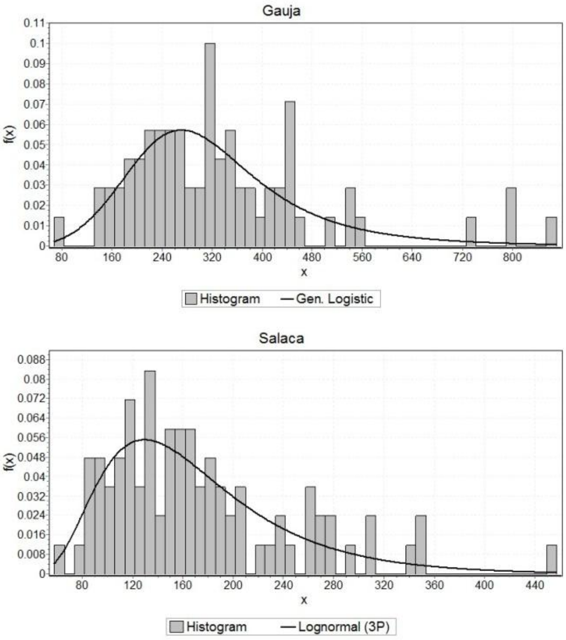


Fig. 10. Results of theoretical probability density function (PDF; displayed as a continuous curve) fitting to the empirical PDF (displayed as a histogram) for: a) continental rivers, b) marine rivers and c) transitional rivers.

In the period of 1922-1960 GEV and LP3 models showed the best (almost the same) correspondence to the flood data time series. The data sets after 1960 seemed to be the most similar to GEV distribution patterns; the used goodness of fit test gave very high ranks for this PD when fitting continental and transitional rivers data.

Maximum discharges were definitely GEV distributed in marine, continental and transitional zone of the studied territory in the last two decades as well.

Performed analysis showed that GEV distribution provides the best approximation to spring flood data in all the Baltic countries for all observation periods; LP3 and LN3 were the next best fitted PD; other models, GLO and EV1, were shown to perform poorly (Table 6). Therefore GEV distribution can be employed to estimate the occurrence probability of a given flood event in the studied rivers. This may help a lot in accurate and safe design of bridges, embankments, dams and other hydro technical structures.

Table 6. Final results of goodness of fit test

	GEV	LP3	LN3	GLO	EV1

Overall summing	129	165	204	262	321
Final rank	I	II	III	IV	V

5. Discussion and conclusions

For the analysis of flood pattern changes a group of rivers was selected from each the Baltic State. Each river group consisted of rivers representing three hydrological regions: marine, continental and transitional. The aim was to find out if there were any significant differences concerning spring flood patterns among the rivers of the separate groups in different time periods.

During the whole studied time period in the most of investigated rivers decrease of annual maximum spring flood discharges was observed. The greatest spring discharges were more frequent in the period of 1922-1960. The comparison of the periods of 1922-1960 and 1961-1999 showed significant decrease of big spring floods; only in two Lithuanian rivers of the marine type, the Minija and the Jura, number of the spring floods increased. In the last two decades a single spring flood or no floods of ≤10% probability occurred.

Calculated flood discharge anomalies revealed a clear decrease of floods exceeding mean values since 1961 as well. Beginning from 1961 the amount of positive and negative anomalies was almost the same. As Kriauciuniene *et al*. (2010) stated, the period of 1963-1977 was the driest period of the rivers runoff for all regions of the Baltic countries; that might be the reason why a significant decrease of spring maximum discharges can be noticed from 1971 to 1975-1977, since then negative flood anomalies dominated in the most of the studied rivers. The analysis of trend magnitude performed by Reihan *et al.* (2007) showed that the greatest amount of change of meteorological parameters occurred during the period of 1961-2003. During this period the average winter temperature raised by 3^{o}C and precipitation increase was 43 mm. These climate changes influenced a river discharge for the winter season. In such a way redistribution of spring runoff occurred, i.e. spring floods tended to start earlier because of the warmer winters and earlier snowmelt, and they were smaller.

In the last two decades the most spring flood maximum discharges were less than the mean value of the long term period.

Detected negative trends in spring flood data for the period of 1961-2010 confirmed the described tendencies. Decrease of the maximal discharge level and reduction of extreme yearly discharges recently in the Baltic rivers was estimated by other studies (Klavins *et al.* 2008, Apsite *et al.* 2009, Reihan *et al.* 2012) as well.

Already mentioned marine rivers the Minija and the Jura deviated from the other studied rivers the most. Big floods in these rivers were recorded in both periods before and after 1961; that may explain the absence of trends in the studied periods as well as in the whole period of 1922-2010. Catchments of these rivers are situated in Western Lithuania, this region is characterised by the highest amount of annual precipitation (735-810 mm) and exactly precipitation comprises the greatest part of a river feeding (53%) there. Moreover the catchments of the Minija and the Jura are small: the smaller a catchment, the shorter its response to changes of meteorological conditions is (Bagdziunaite-Litvinaite *et al*. 2011).

Long spring flood data series enable to use it for flood frequency analysis and make projection of floods of a certain probability. The analysis demonstrated that floods in the selected rivers may be most often represented by either GEV or LP3 distributions. These probability distribution models may be used for estimation of the design floods in the rivers of the studied area, and these models are among the most commonly applied in many countries (Abida, Ellouze 2008).

The observed variability of spring flood discharges in time is definitely climate driven, although the changing scale of urbanization plays significant role as well. Growing urban areas change infiltration capacities of water into the soil, consequently changing the runoff patterns within river catchments. It is difficult to get accurate and reliable data on land use in the studied territory, but other studies (like Theobald *et al*. 2009) show a significant impact of the land use changes on a maximum discharge formation. Other potential drivers of flood changes such as increased water use and deforestation should not be forgotten as well. Combination of all these factors together makes estimation and prediction of flood events very complicated.

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TEMPORAL AND SPATIAL VARIATION OF FOG IN LATVIA

Abstract - **Fog is a hazardous weather phenomenon, which can impact traffic (especially air traffic) and air quality. The aim of this study is to analyse fog climatology, the trends of long-term changes of fog events and factors affecting them in general, in Latvia, but especially in Riga airport. For a 50-year period of observations, the analysis of the fog frequencies, long-term changes and atmospheric conditions favourable for the occurrence of fog events in Latvia has been studied. During the analysis two inter-annual maxima of fog frequency were found in spring and autumn, and the seasonal differences in the formation of fog were also approved by the satellite data on low cloud cover.**

Key word - **fog, aviation, long-term trends, occurrence**

I. INTRODUCTION

Fog is a hydrometeor consisting of a visible aggregate of minute water droplets or ice crystals, suspended in the atmosphere near the Earth's surface and reducing horizontal visibility below one kilometre [1]. Fog is a hazardous weather phenomenon worldwide, which can cause accidents and affect urban air quality especially in combination with impacts of air pollutants [2, 3]. Traffic obstacles such as flight delays, automobile and marine accidents due to poor visibility can be considered as the most common negative effects of fog [4, 5]. At the same time, fog can be associated with critical conditions of air pollution (especially with particulate matter), because air pollutants can be trapped in the fog droplets and can reach high concentrations, causing the formation of smog or in some cases acid fog [6, 7]. On the other hand, fog as a source of humidity is also very important to the health of ecosystems and humans [8], and as fogs have an important influence on the radiation balance, the long-term changes in their frequency can play an important role in the accuracy of the climate model predictions [6].

Fog is a very local phenomenon, which can form in a result of advection, radiative cooling or a weather front moving over an area, and its frequency and spatial distribution are closely related to orography and proximity to the sea [7, 9-11]. The occurrence of fog is related to the atmospheric circulation and local geographical features of a site and thus fog climatology studies are of especial importance for airports, where local meteorological conditions (lowland and flatland territories) may support increased occurrence of fogs, but the impacts might have serious consequences. To assess the intensity of fog the measure of horizontal visibility or the persistence of fog can be used [9, 12]. The most intense fogs in both persistence and density were observed in many sites of the industrialized world in the 1940ies and 1950ies, when some famous low visibility episodes in combination with heavy air pollution such as the Great Smog of London in 1952 occurred [13]. During that event visibility below 10 m lasted for nearly 48 hours in Heathrow - such intense and persistent low visibility is almost unheard of today [7, 13]. Since then due to the introduction of clean air legislation and a decrease in total suspended particulates, fog climatology has changed considerably and many sites have experienced a decrease in the fog frequency [6, 7, 14], also in Riga, however the presence of particulates in the air still remains high where presence of particulates in air remains high [15]. High quality observation data of various parameters describing fog are not available in many countries because of the sparse observation networks, and consequently it is practically not possible to carry out a reliable and spatially coherent analysis of fog distribution based only on the surface observation data [6]. However, satellite data can provide important information on the spatial distribution, dynamics and properties of fog [4]. Despite the importance of fog both from applied research point of view, and in respect to a better understanding of extreme climate events, there have been no studies of fog meteorology carried out in the Baltic region. The aim of this study is to analyse fog climatology, the trends of long-term changes of fog events and factors affecting them in general, in Latvia, but especially in Riga airport, as well as to evaluate possibilities to use satellite data for the detection of fog.

II. DATA SOURCES AND METHODS

Daily observation data on fog events and precipitation amount were provided by 15 major meteorological observation stations in Latvia (Figure 1). Data obtained from the Latvian Environment, Geology and Meteorology Centre covered a 52-year period from 1960 to 2012. The methods of fog observations vary depending on the meteorological stations – in automatic observation stations, such as Riga airport, horizontal visibility is observed automatically by the use of sensors, while in other observation stations in Latvia observations of horizontal visibility and fog are performed visually by the meteorologist. Visual observations of horizontal visibility are performed by evaluating the distance between the observer and predefined existing objects such as trees, buildings, towers etc. or objects established specially for this purpose [16].

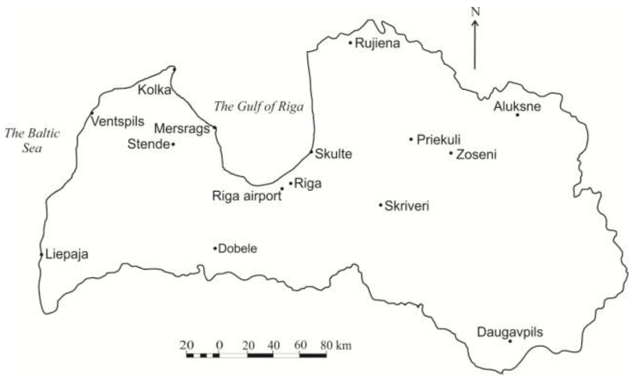

Figure 1. Major meteorological observation stations in Latvia.

In addition to the surface observations, satellite data were also used for the analysis. For the climatological characterisation of the occurrence of fog, satellite observations of low clouds for the period 2005-2011 provided by The Satellite Application Facility on Climate Monitoring (CM SAF) were used as an indicator of the most favourable sites for the formation of fog [17]. Monthly and seasonal mean amounts of low clouds were calculated from the satellite data with statistical programmes CDO (*Climate Data Operators*) and R, and compared with the surface observation data.

The visualization of the location of meteorological observation stations used in this study (Fig. 1) was performed by using Corel Draw, but the spatial distribution of fog in Latvia (Fig. 2) was visualised by using the FiSynop software with linear interpolation on a triangular grid.

Trends in the annual number of days with fog were analysed by using the non–parametric Mann–Kendall test [18, 19]. The Mann–Kendall test was applied separately to each variable at each site at a significance level of $p \leq 0.01$. The trend was considered as statistically significant if the test statistic was greater than 2 or less than -2.

III. Results and Discussion

A. Fog climatology in Latvia

Climate in Latvia is influenced by strong cyclonic activity over Latvia and location in the northwest of the Eurasian continent (continental climate impacts) and by its proximity to the Atlantic Ocean (maritime climate impacts). These variable conditions over the territory contribute to differences in the regimes of air temperature and humidity [20-22], and also to the spatial inhomogeneity in the occurrence of fog.

Fog can be classified by its formation in the processes of advection, radiative cooling or a mix of both processes [23], and each of these processes can trigger the formation of fog in Latvia throughout the year. Fog is a rather frequent weather phenomenon in Latvia, and it can be observed 19-59 days a year on average (Figure 2). The formation of fog is closely related to the local geographical features of a site, such as orography and slope exposure, proximity to the Baltic Sea and the Gulf of Riga, and the different meteorological processes favourable for the occurrence of fog; therefore, there are significant differences in the annual mean number of days with fog in Latvia. As a result, fog most commonly can be observed in the western parts of the highland areas of Latvia, while the lowest number of days with fog is observed in the eastern parts of highlands and in the coastal areas of the Gulf of Riga. Overall fog frequency is larger in the western part of the country.

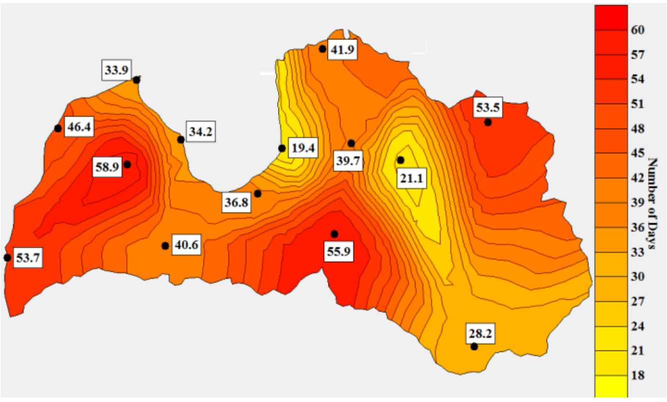

Figure 2. Annual mean number of days with fog in Latvia over the period 1960-2012.

Figure 3 illustrates the long-term variability of fog in Latvia. The bold line represents the median of the annual number of days with fog, the upper and lower sides of the boxes are the upper and lower quartiles, the whiskers represent the greatest and lowest annual number of days with fog, but the dots represent outliers, which are more than 1.5 times greater or smaller than the quartiles. The range of the annual number of days with fog in Latvia varies from 0 days in Zoseni to 110 days in Aluksne, and also the annual variations within each station are considerable. For most of the stations, the data distribution is positively skewed, which means that there are more years with the annual number of fogs exceeding the long-term average than years with a smaller number of days with fog. Under the influence of the highly variable weather pattern in three observation stations of the western part of the country – Liepaja, Mersrags and Dobele - outliers of both minimum and maximum annual number of days with fog can be found. In general, the graph shows significant differences in the spatial and temporal distribution of the annual number of days with fog in Latvia.

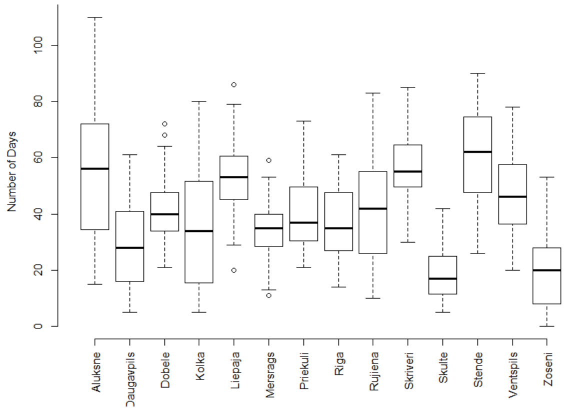

Figure 3. Variations in the annual number of days with fog in Latvia over the period 1960-2012.

The inter-annual variability of fog (Table 1) shows significant differences in the months of the maximum occurrence of fog in coastal and inland observation stations. The coloured cells indicate 3 months with the greatest frequency of fogs in each observation station. In the inland stations the maximum of fog occurrence is characteristic for the second half of the year - beginning from August to December. During the autumn months the radiation fogs form more frequently, but during winter and spring advection fogs gradually become more frequent. Therefore in the coastal observation stations the maximum frequency of fog occurs in spring – during March, April and May, when warm advection from the west triggers the formation of adjective fogs.

TABLE 1

MONTHLY MEAN NUMBER OF DAYS WITH FOG OVER THE PERIOD 1960-2012

	January	February	March	April	May	June	July	August	September	October	November	December
Aluksne	4.9	4.6	4.7	4.2	2.4	1.2	2.5	4.0	5.5	7.3	9.2	7.0
Daugavpils	1.5	2.0	2.4	1.8	2.0	1.3	1.9	3.3	4.3	4.5	3.1	2.6
Dobele	4.2	3.4	4.1	2.9	1.7	1.1	1.6	2.8	4.5	5.3	4.3	4.8
Kolka	2.7	3.3	5.4	5.9	4.6	2.1	1.7	1.9	1.9	2.3	2.6	2.0
Liepaja	3.9	4.6	6.5	7.3	7.1	5.2	3.7	3.7	2.8	4.1	3.7	4.4
Mersrags	2.3	2.4	3.6	4.5	3.4	1.8	2.8	3.6	3.2	3.2	3.2	2.3
Priekuli	3.9	3.9	3.8	3.2	2.7	1.3	2.2	3.8	4.2	4.5	4.8	4.8
Riga	3.3	3.3	3.8	3.0	2.3	1.4	2.3	3.0	3.5	4.2	5.0	4.4
Rujiena	3.6	3.7	3.7	3.1	2.2	1.7	3.0	4.8	5.0	5.2	4.8	4.5
Skriveri	5.2	4.5	4.5	3.1	2.4	2.2	3.5	6.2	4.8	7.3	7.1	6.8
Skulte	1.7	2.3	3.0	2.7	2.5	0.9	0.7	1.3	1.3	1.8	2.0	1.6
Stende	5.5	5.1	5.9	4.9	3.8	3.5	5.3	6.3	4.7	5.5	6.6	6.5
Ventspi	3.7	3.6	5.8	6.8	6.2	4.6	3.4	2.9	2.3	3.0	3.3	3.3

ls											
Zoseni	1.3	1.5	1.6	1.6	1.0	0.8	1.4	2.2	2.9	3.1	3.4	2.0

The annual number of days with fog in Latvia has decreased significantly during the past 50 years (Figure 4). The most significant decrease in the frequency of fog is evident for the 20 year period between the years 1980 and 2000 and could be associated with the rapid decrease in the industrial activities in the country, but in the past decade the frequency of fog has again increased slightly.

In spite of the observed decrease in the frequency of fog in Latvia, it is still considered as one of the most dangerous meteorological phenomena affecting transportation, especially air traffic, negatively and causing flight delays and cancellations which lead to great financial loss.

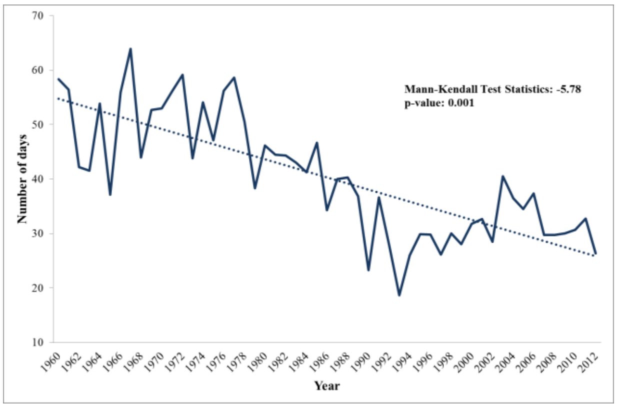

Figure 4. Time series in the annual number of days with fog in Latvia overall over the period 1960-2012.

In-depth analysis of fog climatology in Riga airport indicates several major factors affecting fog occurrence (Figure 5 – 7), such as atmospheric pressure, air humidity and wind speed, as well as presence of atmospheric precipitations during fog events.

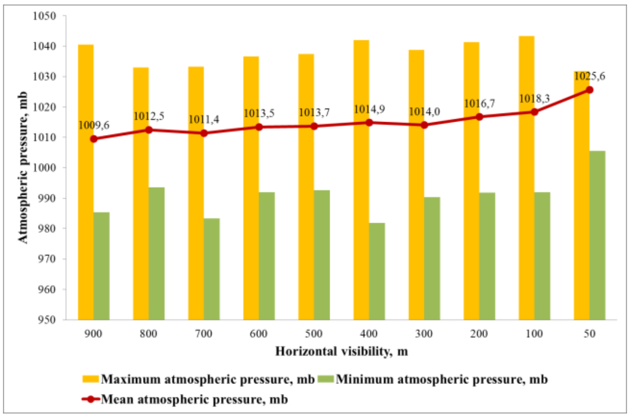

Figure 5. Atmospheric pressure during fog events at Riga airport over the period 2010-2012.

Especially low visibility (intensive fog) events have been observed under the conditions of increased atmospheric pressure (Figure 5), which indicates the great importance of radiation fogs in the area. Radiation fogs are common in the lowland area near the Riga airport, because the wetlands and swamps located to the south of the airport provide extra moisture essential for the development and persistence of dense radiation fogs.

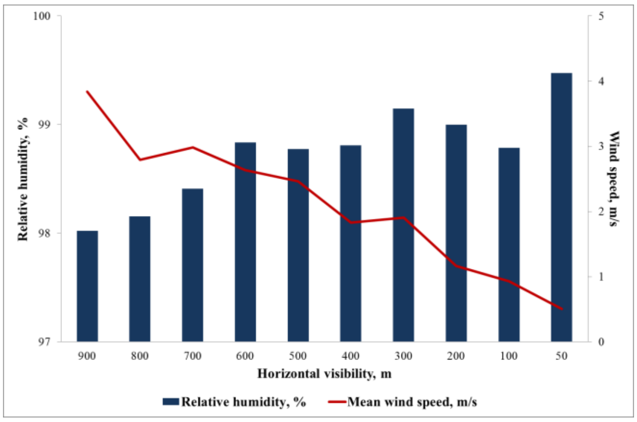

Figure 6. Relative humidity and mean wind speed during fog events at Riga airport over the period 2010-2012.

The relations between humidity and wind speed on visibility during fog events have an opposite character – increase of wind speed supports the dissipation of fog, and the most intensive fog events happen at low wind speeds as such conditions deteriorate vertical mixing of air near the surface (Figure 6). Relative humidity is a well-known indicator used for the forecasting of fog, since fog most frequently forms in the conditions of relative humidity exceeding 90% [23], which is also approved by data from the Riga airport, since the increase of air humidity supports the increase of fog thickness.

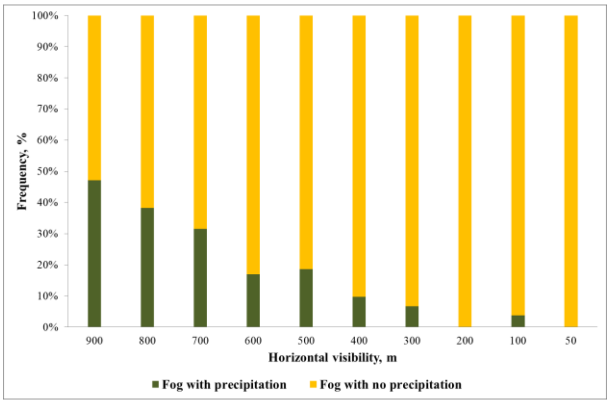

Figure 7. The frequency of dry days and days with precipitation during fog events at Riga airport over the period 2010-2012.

The analysis of fog occurrence during days with precipitation can also be an indicator of the formation process. As radiation fog commonly occurs in the conditions of clear skies, usually there is no precipitation during days with radiation fog. However in cases of very dense radiation fog, very small amount of precipitation (up to 0.1-0.2 mm) can be caused by the fog itself. Advection fogs are usually associated with frontal systems, so such fogs are frequently accompanied with precipitation. Figure 7 illustrates the relation between patterns of formation of fogs during days with precipitation. In Riga airport most of the most intensive observed fogs have formed during days with no precipitation, which could be associated with the specific local factors of the observation station favourable for the development of radiation fogs. Nevertheless, advection fogs are also observed commonly in the airport, especially in the winter and spring seasons, since the inflow of warm and moist air over the snow-covered ground is favourable for the formation of fog. In some cases in winter and spring fog can be advected to the airport also from the ice-free areas of Gulf of Riga. It is characteristic for the radiation fogs to form in the second part of the night or early morning and dissipate soon after the sunrise, however advection fogs can form any time of the day and may remain for a prolonged period of time, therefore advection fogs can be considered as a greater danger for the air traffic.

B. Use of satellite data for identification of fog

Nowadays satellites are considered as a powerful tool for the observations of fog, as satellite observations provide both wide spatial and temporal coverage which is essential for the detection and characteristics of such a variable phenomenon. In the essence, fog is very similar to low stratus clouds, and it differs from low cloudiness only by its base being located near the ground [1]; therefore, for the climatic characterisation of fog occurrence, it is possible to compare the surface observations of fog to the low cloud observations from satellites provided by the CM SAF. If compared the surface observations of fog and the satellite observations of low clouds in the autumn season (Figure 8) over a six-year period, one can see similar features: the greatest amount of low clouds (up to 47%) can be observed in the south and west regions of Latvia, while in the coastal areas the amount of low clouds is the smallest (38-44%). In the winter season, the low cloudiness in Latvia is smaller in general, and it does not exceed 44% (Figure 9). In winter, a more expressed formation of fog is evident over the valley of the river Daugava and especially over the west regions of Latvia, where it could be triggered by the influence of periodic thaws.

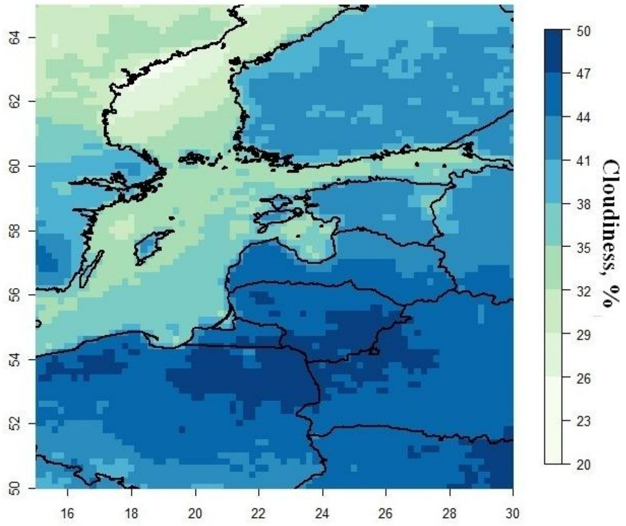

Figure 8. Mean amount of low clouds (%) in autumn (SON) over the period 2005-2011.

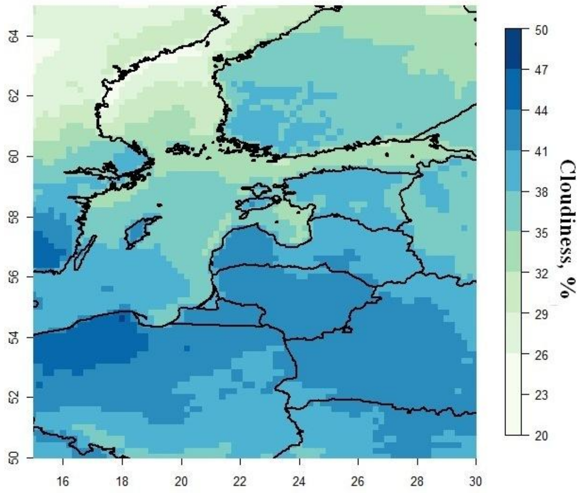

Figure 9. Mean amount of low clouds (%) in winter (DJF) over the period 2005-2011.

In spring, some differences in the low cloud and fog formation processes appear (Figure 10). In the western regions, where, under the influence of warm advection from the west, advection fogs form more frequently, the mean amount of low cloudiness is higher than in other parts of the country and reaches 40-42.5%. But at the same time in the highland areas of Latvia a gradual increase in the occurrence of radiation fogs begins. Also in summer (Figure 11) the low cloudiness is the greatest over the highland areas, where it reaches up to 40% of the total cloudiness due to the dominance of radiation fogs.

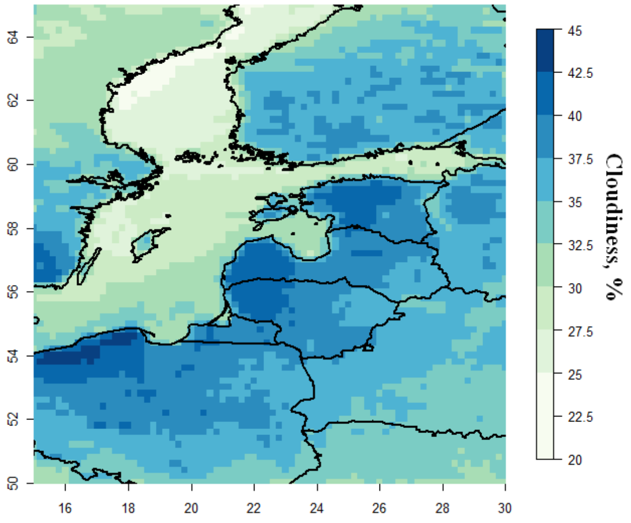

Figure 10. Mean amount of low clouds (%) in spring (MAM) over the period 2005-2011.

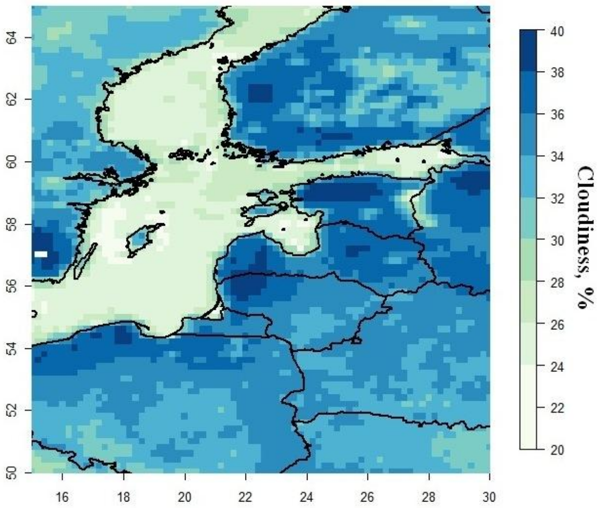

Figure 11. Mean amount of low clouds (%) in summer (JJA) over the period 2005-2011.

Satellite information can be also efficiently used to evaluate development of fog conditions locally, for example at Riga airport of the 25th October of the 2011 when a wide area of dense fog approached Latvia from the south, and moved over the central regions of the country to the Gulf of Riga (Figure 12). The south-east regions of Latvia were covered with clouds, but in the central regions at night the skies were clearing and a dense radiation fog formed. In the conditions of a strong low-level inversion the fog remained throughout the whole day, slowly moved to the north and in the evening covered the Gulf of Riga. During the fog in the morning in Riga the visibility was reduced to 100 m, but in the middle of the day in Dobele to 70 m, besides in Dobele visibility below 500 m remained for 28 hours. In this case satellite data were an essential source of information on the spatial coverage, movement and characteristics of fog, providing much wider view on the process than the surface observation network.

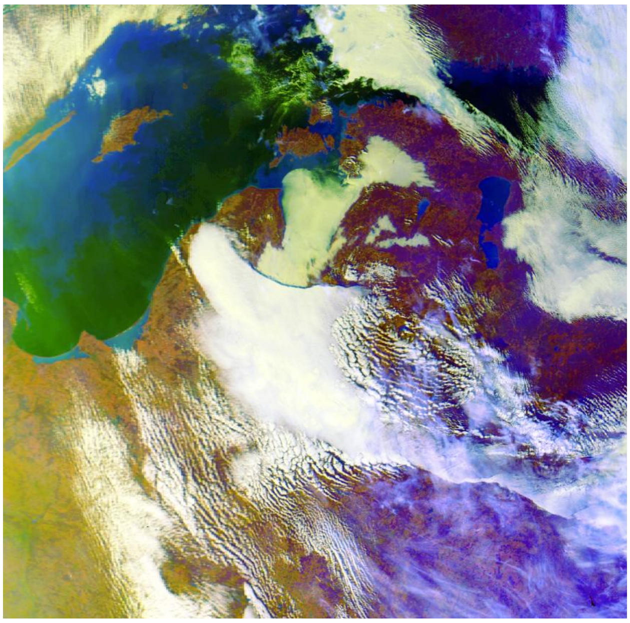

Figure 12. NOAA satellite image (channel combination 2-1-4, fog and low stratus appears as light yellowish area) at 11:10 UTC 25.10.2011.

In spite of the observed decrease in the frequency of fog in Latvia, it is still considered as one of the most dangerous meteorological phenomena affecting transportation, especially air traffic, negatively and causing flight delays and cancellations which lead to great financial loss. Therefore, in the conditions of ever increasing demand for air transport, it is essential to be aware of the general climatic characteristics of fog occurrence and synoptic patterns favourable for their development.

IV. CONCLUSIONS

Fog is a frequent weather phenomenon in Latvia, which is characterised by a significant spatial and temporal inhomogeneity in its occurrence. Since the middle of the past century the annual mean number of days with fog has decreased significantly, but in spite of the observed decrease, fog is still one of the most dangerous and harmful meteorological phenomena affecting aviation in Latvia. The analysis of fog formation in the area of the Riga airport revealed that the majority of fog events observed can be classified as radiation fogs, which due to their short persistence are not of as great danger to the aviation traffic as advection fogs. Since advection fogs play and important role in the air traffic organization, timely information provided by satellites is an essential tool for the forecasting of movement and persistence of the fog and low-cloud areas.

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Ice Regime Dynamics of Inland and Coastal Waters in Latvia and Factors Controlling it

Abstract

The sea ice regime is considered a sensitive indicator of climate change and within this study long term changes of ice regimes in the Riga Gulf, at coasts of Latvia in comparison with ice regime on inland water have been studied. The ice cover duration both on sea and inland waters has decreased during the recent decades. In addition to this, long term observational records of ice break of the studied region exhibit a pattern of periodic changes in the intensity of ice regime. The ice regime is shown to be strongly influenced by large–scale atmospheric circulation processes over North Atlantic that manifests through close correlation with North Atlantic Oscillation index.

Keywords: ice regime, long term changes, coastal waters

Introduction

Records of the dates of ice freeze-up and break-up are good indicators to assess inter-annual and seasonal climate variability, especially in relation to long-term climate change (Granskog et al., 2006; Johannessen et al., 2004). Three major reasons for studying sea ice regimes are as follows: a) the calendar dates of freezing and thawing of ice cover have been recorded for a long period; b) ice conditions are sensitive and reliable indicators of climate; c) sea and coastal ice regime affects the ship transport, fishery and other aspects of economy.

The temperature change patterns and ice regimes have been observed to be related with the North Atlantic Oscillation (NAO) pattern (Hurrell and van Loon H 1997) of large-scale anomalies in the North Atlantic atmospheric circulation. The Southern Oscillation, too, has been argued to exert influence over the ice regime in the Northern Hemisphere (Robertson et al., 2000). The so-called positive phases of NAO (associated with strong westerly winds and increased flow of warm and moist air to Western Europe) cause warmer winters later their start and early springs (Paeth et al., 1999). The changes of air temperature and the occurrence of rainfalls, influenced by airflow from the North Atlantic (indicated by NAO), significantly affect the ice regime (Loewe and Koslowski, 1998). On the other hand, a major factor possibly influencing the ice regime is the process of global warming (Morse and Hicks, 2005). The records of the last two centuries of ice break-up dates on the rivers in the Northern Hemisphere provide consistent evidence of later freezing and earlier break-up (Magnuson et al., 2000). Several studies have analyzed ice regime trends for inland waters, since easily identifiable parameters describing ice break-up have been recorded for a long period of time (Hodgkins et al., 2002). These studies have clearly shown long-term changes in climate, and have also argued that natural processes and the ice regime in the Northern Europe are related to the changes in NAO (Yoo and D'Odorico, 2002). The sea ice conditions of the Baltic Sea have been previously studied using a historical time series of ice break-up at the port of Riga (Jevrejeva, 2001) and along coastline of Estonia (Sooaar and Jaagus, 2007).

The aim of this article is to study character of long-term changes of the sea ice regime at the coastline of Latvia and factors affecting it in relation to long-term climate change (temperature) and large scale atmospheric circulation processes (North Atlantic Oscillation (NAO).

Data sources and methods

The data of ice regime (starting data of establishment of permanent ice cover, data of ice break-up and calculated length of ice-cover) were extracted from the Bulletins of hydrological observations (1925–2013) at the Latvian Centre of Environment, Geology and Meteorology. The time series of the River Daugava ice break-up dates were first published by P.Stakle (1931). The air temperature records for the period 1795 to 2013 were obtained at the Meteorological Station Riga–University. During the studied period the sampling and observation methods followed standard approaches and historical observations were re-evaluated to adjust them to the existing principles of time measurement (Stakle, 1931). This study used only observation data and no data were substituted.

Table 1. Basic characteristics and ice regime of the study sites in Latvia and its coastline

River-sampling station	Length of observations, years	Mean date of freeze over	Mean date of break-up	Average number of days with ice cover	Decrease, day/10year *p*=0,17 (95%)
Baltic Sea – Liepāja	1949-2013	24 Dec	03 Mar	71	2.8
Baltic Sea - Ventspils	1949-2013	26 Dec	27 Mar	76	3.0
Baltic Sea – Kolka	1950-2013	03 Jan	22 Feb	58	2.5
Gulf of Rīga - Mērsrags	2000-2013	24 Dec	03 Mar	53	0.7
Gulf of Rīga - Jūrmala	2000-2013	02 Jan	05 Mar	52	0.2
Gulf of Rīga - Salacgrīva	1949-2013	12 Dec	12 Mar	64	2.7
Venta - Kuldīga	1926-2013	02 Dec	22 Mar	65	3.2
Gauja - Sigulda	1939-2013	01 Dec	30 Mar	78	4.1

The non-parametric Mann-Kendall test for monotone trends in time series of data grouped by sites, plots and seasons was chosen for determination of trends, as it is a relatively robust method concerning missing data and it lacks strict requirements regarding data heteroscedasticity. The Mann-Kendall test was applied separately to each variable at each site, at a significance level of $p<0.05$. A trend was considered as statistically significant at the 5 % level if the test statistic was greater than 2 or less than -2. The code COND/MULTIMK (Libiseller and Grimvall, 2002) was used for trend analysis.

Results and discussion

Ice development begins in the bay of Pärnu, where the first new ice formations occur in the middle of December. Thereafter the ice-covered area extends along the north-eastern coast of the Gulf of Riga, and in the middle of January it’s width is 5 to 6 nautical miles on average. At the same time some new ice formation near the southern and western coast of the Gulf occurs.

The most intensive ice development occurs in February when under favourable conditions the Gulf of Riga becomes completely ice-covered. In the middle of the month the pack ice brought by currents freezes and covers the Irbe Strait with rigid and ridged ice. At the same time along the rest coastline of the Gulf the width and thickness of the fast ice increases, and various ice forms intensively develop also in the Central part of the Gulf. In moderate winters by the end of the month the Gulf and the Irbe Strait becomes completely ice-covered. However during severely cold winters a solid and rigid ice-cover over the Gulf of Riga can occur already in the middle of January, but in mild winters the Gulf can remain mostly ice-free throughout all the winter season.

The development of the pack ice usually begins in the coastal waters and extends in parallel to isobaths, however it's development is uneven, reflecting alterations of the cold and warm spells. The maximum of the pack ice occurs in late February – early March, and during moderate and severe winters the pack ice completely covers both the Gulf of Riga and the Irbe Strait.

During winters the surface water is cooled so much that ice may form also in the coastline of the Baltic Sea. However, the extent of the ice varies widely from year to year depending on whether the weather is mild or cold. Mostly the territory is ice free, and only during the most severe winters the water territories are covered with ice. However, ice is mostly thin and fragile, and if the wind direction is favorable, the ice rapidly floats from the shore to the open sea. In the coastal waters of the Baltic Sea the ice development begins at the end of December, sometimes in the middle of November.

With the prevailing westerly winds the ice break-up begins in the western part of the Gulf and gradually progresses to the east. The first area of the Gulf to become ice-free is the Irbe Strait followed by western and southern part of the Gulf, but in the north, north-east areas the melting and rotten pack ice remains the longest.

During late and cold springs there can be some differences in the disappearance of ice: at first the ice disappears in the comparatively shallow north-eastern part of the Gulf as the water temperature begins to rise due to the river inflow. In this case the pack ice longer remains in the central part of the Gulf.

The average length of the ice season is the longest in the Bay of Pärnu and in the north part of the Gulf of Riga – 145 days or almost 5 months. The shortest ice season of 2 months is characteristic for the south-western part of the Gulf, the Irbe Strait and near the Latvian coast of the Baltic Sea, but in the south part of the Gulf as well as in the region near Kolka the average ice season is 2.5 to 3 months long. The maximum observed length of the ice season in the Gulf of Riga is 168 days, but in the coastal waters of the Baltic Sea – 127 days. The most severe winter during the observation period has been the winter season of 1941/1942. During this winter the maximum ice cover in the coastline of the Baltic Sea was observed at the end of March - beginning of April, with the ice thickness of about 60 cm. The measurements of ice thickness show that 6.4 km from the coast near Liepaja the ice was 55.7 cm thick and at 14.5 km from Ventspils it was 48.6 cm thick.

The ice conditions are observed in 6 marine observation stations of Latvia (Figure 1). The stations of Ventspils and Liepāja which are situated in the east of the Central part of the Baltic Sea represent the ice conditions characteristic for the open part of the Sea, where usually the concentration of ice is the smallest and the length of the ice season is the shortest. The station of Kolka represents the ice conditions in the shallow Irbe Strait, but the station of Mērsrags represents the conditions of the western part of the Gulf. Both of these stations are subjected to comparatively rapid changes in the concentration of ice as with the prevailing westerly winds the ice tends to break up and drift to the east, forming an ice-free areas. The observation station of Jūrmala represents the shallow southern coast of the Gulf. The station Salacgrīva represents the north-east part of the Gulf where the ice extent usually is the greatest and the ice season is the longest.

Table 2. Long term trends of ice cover duration according to Mann-Kendall normalised test statistic

River - Sampling Station	Period of observation	Normalised test statistic	*p*-value (one-sided test)
Baltic Sea – Liepāja	1949-2013	-2.61	0.009
Baltic Sea - Ventspils	1949-2013	-3.34	0.009
Baltic Sea – Kolka	1950-2013	-2.85	0.014
Gulf of Rīga - Salacgrīva	1949-2013	-4.42	0.001
Venta - Kuldīga	1926-2013	-1.21	0.113
Gauja - Sigulda	1939-2013	-2.87	0.002

During the past ~150 years there has been a significant increasing trend in the values of the air temperature, which is even most obvious during the winter season (Klavins et al. 2002). The changes in the air temperature have also lead to significant changes in the ice conditions both in the Latvian coastline of the Baltic Sea and in the Gulf of Riga (Jevrejeva, 2001)). A significant decreasing tendency of the length of the ice season for the period 1949-2013 has been observed in the coastline of the Baltic Sea (Figure 2) and even more significant decreasing trend has been observed in the Gulf of Riga (Figure 3).

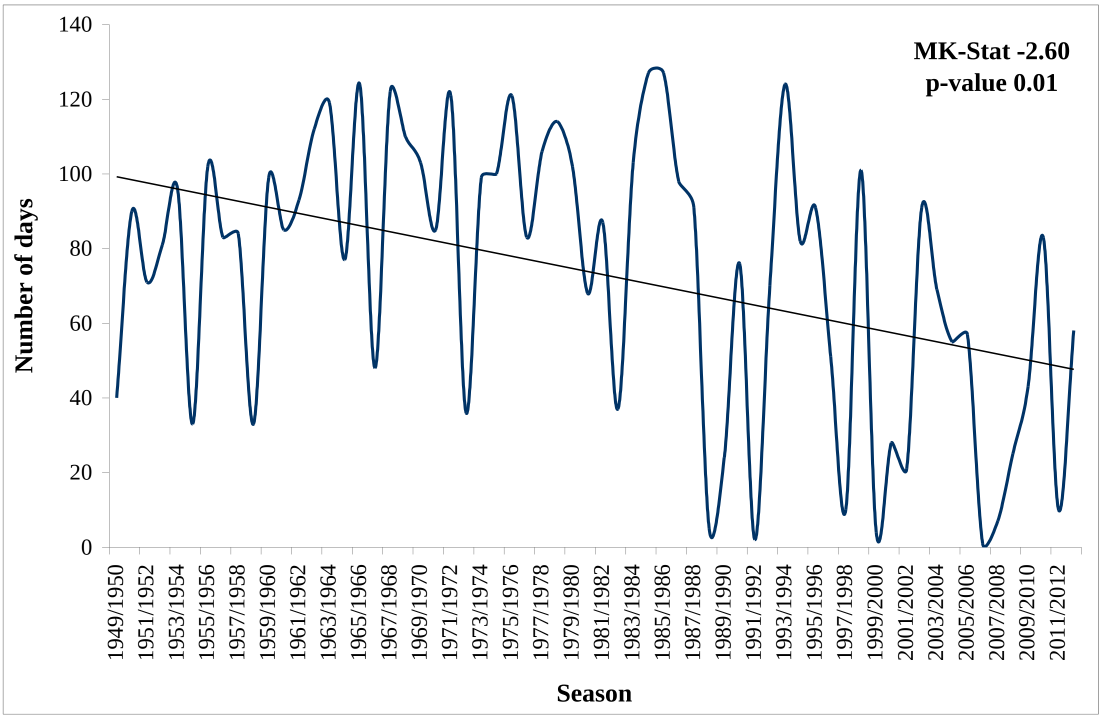

Figure 2. **Trend in the length of the ice season in the coastal areas of the Baltic Sea (Liepāja) for the period 1949-2013**

Conclusions

The duration of sea ice cover on the Baltic Sea and in Riga Gulf during last 60 years is decreasing and is related to decreasing start of the ice cover and earlier ice melt. Exist significant differences in respect to ice cover in Riga Gulf and coastline at the Baltic Sea. The time of ice break-up depends on global climate change and can be related to increasing air and sea water temperatures, however the trends of sea ice regime not consistent between periods and changes of mild and severe winters are clearly seen.

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UNUSUAL WEATHER CONDITIONS IN LATVIA (900-1860)

Abstract

The historical sources that describe weather conditions in the Baltics and Latvia over a period of more than 900 years – which are to a certain extent summed up in this work – provide an insight into unusual winters, springs, summers and autumns; catastrophic floods in the Daugava River and other rivers; high heat and unimaginable drought, when rivers and wells dry up, forests and swamps burn out; steady rain going on for months; winter snow and blizzards continuing for 1-2 months; situations when all sowings wither in spring or early summer around the solstice, or are flooded up by the summer and autumn rains, resulting in long-term hunger without bread throughout the Baltics; when the Baltic Sea (not to mention the Gulf of Riga) freezes up in particularly severe winters several times in a century, and people from Denmark, Germany and Poland travel back and forth to Sweden and Finland, and also to the Baltics on foot or by sleigh, because it is easier to move over ice than through snowbound fields and forests.

Key words: *climatic extremes**, history**, climate change,*

Introduction

What we are witnessing today and in recent decades is neither unusual, nor unprecedented. In the second half of the 20th century and early 21st century, there have been no such extraordinary years, when rye could be reaped already in June or cherries could be picked already in May. Nor there have been years in which, in late spring frosts or even around the Midsummer Day in June, when the last night frosts occasionally occur in Latvia, all crops and vegetable gardens had perished (with cold), resulting in food shortage. Unusual, extreme weather conditions are yet to come. To have an idea of what has been and, perhaps, of what we can expect in the near or distant future, let us take a look at the events of the remote past, their descriptions found in various historical sources, such as chronicles, annals, newspapers and monographic materials.

Unusual winters

Information about the earliest known harsh winter in 991 is found in the newspaper *Latviešu avīzes* (Latvian Newspapers) (28, No. 22). According to the ancient archive data, the winter in the Baltics was very severe: everything was destroyed by frost, including crops, and there was a famine.

In 1172, in contrast, as written in the *Latviešu avīzes* (28, No.47) on the basis of archival data, the winter in the Daugava River basin was so warm that trees sprouted buds and birds started to build nests. The Chronicles of Livonia, in turn, report that in 1214 and 1216, winters again were so severe that the Gulf of Riga was covered with ice so thick that a large army of Rigans could freely move over it, marching out in a campaign against the Livs of Vidzeme and Latgallians. Also in 1219, when traffic between Riga and Estonia took place over the ice of the Gulf of Riga, it was so cold that masses of wayfarers had face, feet, joint and nose frostbites and were forced to turn back. Their old, frost-bitten skin peeled off and new skin appeared, as the Chronicle of Livonia describes (6).

It is also written in the Chronicle of Livonia (6) that Bishop Albert with his army went in a campaign from Riga to Saaremaa across the Gulf of Riga in 1225 and 1227, when the winters were harsh and the gulf was frozen. The noise caused by the moving army was like thunder: weapons clanging, sleds colliding, people shouting, people and horses falling and getting up on the slippery ice. Similar campaigns and travels over the frozen Gulf of Riga from Livonia to Estonia took place also in 1228, 1260-1261 and 1269-1270.

The *Latviešu avīzes* provided information according to the chronicle data that there was no winter at all in 1289. In Christmastime, young women adorned themselves with violets coming into flower in the fields (28, No. 4).

Then comes the beginning of the 14th century – the years 1315 and 1316/1317 – when winters were extremely cold in the Baltics and Russia. All crops were destroyed by frost and famine followed (13, 16, 26, 28, 30). Bread and other foodstuffs in Livonia were as expensive as never before. Hundreds of people died of hunger. The famine lasted for three years, as rye and barley sowings were frost-bitten each year (13).

The winters were harsh again in 5 years (1322 and 1323). The Baltic Sea was frozen for 7 weeks. Wayfarers from Germany and Sweden made their way to Riga by ice. So wrote the *Latviešu avīzes* in 1868 (28, No. 9). However, referring to the archive data, the same newspaper (28, 1873, No. 4) wrote that the winter was particularly warm in 1341: cherries blossomed in March and were ripe already in May!

A harsh winter again in 1345, and the Baltic Sea froze over. The weather conditions were similar also in the early 15th century (the years 1408, 1418 and 1426). Extremely cold and snowy winters also in 1432, 1433 and 1434: “The winters were very severe; once it was snowing steadily for 40 days and nights in a row,” so says the *Latviešu avīzes* in 1876 (28, No. 22).

Relying on archival materials, the *Latviešu avīzes* wrote in 1873 (28, No. 4) that the winter was very warm in 1538: gardens were in blossom already in December and January.

Several sources (13, 15 and 17) reported unusually harsh weather conditions in the autumn and first half of winter in 1576. Storms like no one had seen before raged all autumn until the New Year. People died in the thick snow. The strong wind bent down the rooster on the steeple of St. Peter’s Church in Riga on the 2nd of October. Terrible winds razed over the sea. In Revel (Tallinn), no one could remember before this occurrence a storm toppling down a bell-tower and the waves and wind in the port of Revel smashing and sinking loaded ships and boats in the course of one autumn (13).

In contrast, the winter in the Baltic States in 1617 was very warm and rainy, without snow. The wind blew from south-east and it rained all January, grass grew, flowers opened and cherries started to blossom. There was snow only in February, when it was possible to make sledge routes just for one and a half week (31).

There was a similarly warm winter again in 7 years, in 1624. In December 1623, there was frost about 2-3 weeks before Christmas. On 18 March 1624, the spring high water started in the Daugava River, and in April it was as warm as around the midsummer. On the 15th of April, cherries were in blossom. So wrote J. Brotze (17).

The winter of 1636 was severe, the Baltic Sea froze over, while the winter of 1666 was so cold that peasants froze to death while riding in sleigh, remaining in a sitting position as if alive (31).

A. Sapunovs (14) writes that the winter in 1696 was again so warm that the Daugava River did not freeze up all year round.

Many historical sources report a very severe and snowy winter in Latvia and Russia in 1709. The *Latvijas avīzes* inform that the soil froze 9 feet deep (2.42 m), the Baltic Sea froze over completely, while ice thickness in the Daugava River reached 2.5 arschines (1.73 m). Catastrophic floods followed in Riga afterwards (31).

In 1722, the winter was again warm in Latvia, and there was little snow. Trees were in leaves already in February. The winter was dry and warm in most of Europe (28, 1873, No. 4). The winter was warm in the Baltics also in 1741. January, February and March were rainy with thunder. The summer was also rainy (23). 3 years later, in 1744, as reported in many sources, the winter was extremely cold. In 1814, the newspaper *Rigasche Stadt-Blätter* noted that the ice cover thickness in the Daugava River was two times the height of a man (31). Then great floods followed in Riga.

In 1760, the winter in the Daugava basin area was long and cold, the snow cover depth reached 1-2 arschines (> 1 m). There were no thaw days throughout the winter (32). Conditions were similar also in 1789: a severe winter was followed by a beautiful spring and very hot summer with good hay crops.

The winter of 1823 was severe not only in the Baltics but also in England, Germany and even in the Crimea on the Black Sea. The air temperature fell below -30 degrees. Many people got frostbites and died of cold. On the 23rd of February, a strong thunderstorm moved from the West across the Daugava River in the direction of Vitebsk, causing great damage to the local population. A nasty thunderstorm with lightning started at 10 o'clock in the morning, followed by warm rain already in 20 minutes. The rain was particularly heavy in the vicinity of Krāslava. The temperature fell below zero again in 2 hours (28). The spring was long and cold.

The winter in 1835 was even milder than that of 1831/32. The air temperature did not fall below -8 degrees, there was only little snow, and livestock could be let out for grazing the whole winter (27).

The snow cover in Latvia was exceptionally thick in 1835, reaching 1.8-2.1 m (27). Snowfalls started from the New Year, getting especially heavy in March. In April, the sun and rain quickly melted the snow, and massive flooding began. The ice cover on rivers reached the thickness of the height of an adult man (31).

The winter of 1844 was unusually rich in snow in Courland. There were just a few days without snowing (27).

In the 50s of the 19th century, the press wrote about an unusual winter in Latvia in 1850 (28, 1850, No. 16). It started with extreme frost and lots of snow. In January, there was a snowstorm going on for 2 weeks in a row, and it was so heavy that no one could leave their houses. All roads were totally snowbound. In February, in turn, it rained for 2 weeks, melting all the snow. The waters of the rivers rose, then the temperature fell below zero again, up to -12 degrees, and everything froze over.

In contrast, the winter of 1859 was particularly mild. The newspaper *Latviešu avīzes* wrote (21) that such a warm winter has not been seen for a long time. In January and February, the average monthly temperature was between +0.5 and -0.5 degrees (the norm is between -4.9 and -4.5 degrees), and orchards started to bloom. Then, on the 13th of March (25), lots of snow fell, but the rain melted it down soon – on the 16th of March (28).

Unusual summers and autumns

Hot and dry summers

M. Bogolepov writes that the year 1170 was extremely hot and dry throughout Europe (2). The soil cracked and there were so much dust and such a haze in the air that one could hardly see the road in front of one's feet, causing many people trip and fall. Similar drought occurred in 1173. It is reported about the unusual summer of 1223 that exceptionally hot weather lasted for a long time (6). There were a lot of people and livestock in the castle, and they started losing weight from hunger and thirst (6). Plague broke out in the castle from the horrible stench, coming from the dead animals and humans.

After a turbulent winter in the Daugava basin in 1368, a dry and hot summer set in. Based on the annals, A. Gacisskiy (5) described the events as follows: the sky was sometimes blood-red, sometimes black, haze persisted for 3 months. These were hard and distressed times for people. The fish died out in the rivers.

There was extreme drought in the summer of 1431, which is described as follows (3, 4): "Dry land and swamps were on fire, haze in the same summer stood for 6 weeks, the sun was not visible, the fish in the water died and birds were not seen flying, as they had fallen on the ground" (1). Also in 1473, there was a big drought in Lithuania, West Poland and the rest of Europe. Forests, villages and cities were on fire (4, 30). Similar situation was in 1533 (1).

The year 1679. Dry and hot summer with severe night frosts in June. All cereal sowings had been destroyed by frost (23).

Dramatically changeable weather conditions along the seasons were in 1708. After a harsh winter, there were very heavy rainfalls in the summer, at the end of June. The water level in the Daugava rose so high that all the surrounding gardens were flooded for 4 weeks. After that, the summer was hot and dry, followed by heavy rains again in November and bitter cold in December (18, 23).

After a snowy and cold winter, the summer of 1745 was dry, with the dominating wind from the East. The water level in the Daugava River was so low that the cannons that had been sunk by the Saxon troops in 1701 were found and taken out of the dry river bed in the surroundings of Koknese (23).

The summers of 1748, 1749 and 1750 also were dry and hot, with extensive forest fires. Also in 1776, as shown by entries in the parish chronicles of Courland, a moderate winter was followed by a dry summer with fires everywhere for 6 weeks (27).

Quite unusual events were observed in Riga in the summer of 1795. On the 10th of June, a whirlwind with heavy hail was raging over the city, causing major damage in a 2 km-wide and 160 km long area. Hailstones were of the size of eggs. The thermometer in the Riga Dome Church wall at a height of 170 feet (51.9 m) showed a temperature between -3 and -4 degrees on the Réaumur scale; at a height of 4 feet (1.22 m) – +16 - + 18 degrees Réaumur (19).

In 1819 in Latvia, there was hot weather nationwide from May to September. The air temperature reached +25 ... +27 degrees in the shade for many consecutive weeks. Rain showers were rare. There was no drought though (27).

The year 1826 came with a very hot and dry summer. Throughout the summer, fires broke out in forests, peatlands and heaths, as they were very dry. There was a horrible drought. Watermills stopped working without water (27). The average air temperature was +18.9 in June, +22.5 in July and +20.7 in August.

The year 1827, especially the summer, was very unusual in Courland. According to the data of the Courland parish chronicles (27), the summer set in very early: rye was harvested already at the end of June (i.e., for more than a month earlier than now –around the first half of August). The autumn was also warm and dry.

The summer was very hot and dry also in 1834. There was absolutely no rain in June, July and August. The Daugava River was so shallow that it could be easily forded in some places, and barges could be pulled with great difficulty even downstream, as they rubbed against the river bottom. Forest fires were everywhere. Swamps dried out to such an extent that hunt birds perished of thirst. It was a disastrously dry year, witnessed by a number of sources (27, 28, 1834, No. 45).

There was a dry and hot summer without rain for 10 weeks (two and half months) also in 1855 (27, 28, 1855, No. 35).

Wet, rainy, chilly summers

In different historical sources, there are less data about particularly rainy and chilly than extremely hot and dry summers. It is understandable, since heatwaves and drought bring great disaster to people and natural world. There is lack of water for plants, animals, birds and humans; forest and bog fires rage; in calm weather conditions, vast areas are covered with smog.

The first recorded facts, indicating a very rainy and wet summer, are from the year 1370. Weather conditions were so unfavourable, with prolonged rains and high air humidity, that the army of the Riga Order could not embark on any campaigns (33).

In 1579, the summer in the Baltics was so rainy that there had been no three days without rain, which continued day and night. The rain was so long-lasting that soldiers' uniforms started to rot while being worn (13).

The year 1679 was also referred to as very rainy in Latvia. Incessant rain continued throughout the summer and autumn. It rained for 14 weeks (three and a half months) in a row in the autumn (23).

In 1746, there were very unstable weather conditions in the Baltic States: 106 rainy days per year; snow fell on the 15th of October (23).

The year 1838: May and June were quite dry, with low precipitation; then it started to rain and continued for 2 months, causing great flood in rivers. Even more terrible conditions followed already in 2 years. It was raining throughout the spring, summer and autumn. The weather was chilly, and there was not a single hot day. Over the period from the beginning of the winter until the 17th of October, rivers went out of their banks 4 times, causing major damage.

The *Rīgas avīzes* and other newspapers report about an even more horrible summer in 1844 (22, 27, 28). The *Rīgas avīzes*: "Rain and flooding here. Not a single dry day since the Trinity Sunday. There were only 15 days without rain within a 12-week (3-month – G.E.) period. We didn't see even two consecutive days with no rain, and there were no perfectly clear days at all. It rained even more in July. Meadows and lowland fields were more flooded than in spring. Moreover, roads and bridges were also flooded. Rain poured non-stop for more than two months; all trenches turned into rivers, rivers – into large water streams, meadows – into lakes. Bridges, dams and a number of watermills were ruined, and roads became impassable" (28, 1844, No. 35). Similar weather conditions were also in Russia.

The year 1849 was also unusually rainy.

Grouping by centuries (Table 1) the yearly data of unusual winters and summers published by E. Moskovkina (10), we see a distinctive picture. According to the data of chronicles, annals and other sources, the highest numbers of extremely severe and severe winters were recorded during the period from 1200 to 1500 and also in the 18th century, whereas the highest number of particularly warm winters – during the 13th and 18th centuries.

Table 1

Grouping of unusual winters and summers

Years	1000-1099	1100-1199	1200-1299	1300-1399	1400-1499	1500-1599	1600-1699	1700-1799	1800-1864
Severe and extremely severe winters	2	2	**17**	11	**15**	4	10	**15**	6
Particularly warm winters		3	1	**8**	4	2	4	5	**22**
Hot and extremely	3	2		2	2	4	7	**14**	5

hot summers									
Chilly, cold and rainy summers	1	1	3	1	2	4	**7**	3	**9**

The table has been composed according to E. Moskovkina's (10) estimated data by years.

Very warm, hot and extremely hot summers frequently occurred in the 17th century (14 summers mentioned). Particularly cool, also extremely rainy summers most frequently occurred in the 16th and 18th centuries.

Extreme spring high waters and floods in the Daugava and other rivers

The first scientific study on weather conditions in the Baltics and Latvia and on river runoff and flooding, based on historical evidence (chronicles, annals, church books) from a period of a thousand years is E. Moskovkina's book (10) *Pavodki na reke Daugava* (Floodings on the Daugava River). According to the descriptions by years given in the appendix to the book, the author has grouped the spring high water levels as follows: catastrophically high, high, above average, close to average, below average, low and catastrophically low. The overview table composed by centuries according to the yearly descriptions (Table 2) shows the main characteristics.

Table 2

The spring high water levels on the Daugava River in Riga

Years	1000-1099	1100-1199	1200-1299	1300-1399	1400-1499	1500-1599	1600-1699	1700-1799	1800-1870
Catastrophically high	1		3	2	3	3	3	**6**	**5**
High	1	**7**	3	6	**13**	3	**15**	**11**	**8**
Above average		3	**11**	7	**15**	8	**11**	**12**	6
Close to average			2	4	3	7	6	**19**	**21**
Below average		3	1	4	3	7	2	**10**	5
Low			2	4	6	3	4	**12**	**26**
Catastrophically low				2		1			2

Over a period from the year 1000 until the second half of the 19th century, especially catastrophic spring floods on the Daugava River occurred in 23 years, most often from 1600 to 1860, 4-6 years per century.

The rise of catastrophically high water levels from 1600 to 1700 can be explained for the most part by the fact of rapid deforestation, land cultivation and reclamation relating to the increase in population, development of agriculture, construction of buildings in cities and countryside, building of ships, also exports of timber, production of coal and extraction of tar. As we know, snow melts faster and water drains to the rivers quicker in woodless than in wooded areas.

It should be noted that the characterisation of spring high waters in the Daugava River until 1871 provided by E. Moskovkina is based on historical observations as well as on P. Stakle's estimates of spring high water levels on the Daugava River in Riga. Only starting from 1871, the yearly water levels were determined in accordance with official water level measuring points, with exact absolute height marks. Therefore, the data on the spring flood water levels in Riga until 1871, especially according to P. Stakle's estimation, should be regarded as quite approximate. Only the level of the disastrous flood that occurred in 1709 is accurate, because the correct absolute height in accordance with the Baltic height system was later determined by the mark left on the Dome Church wall.

The first reports of large, catastrophic floods in the Daugava River in Riga appeared in written historical documents around the mid-14th century. So, several sources reported on the catastrophic floods on the Daugava River in 1358. The newspaper *Rigasche Stadt-Blätter* wrote on the basis of annals that water stood above man's head in the Riga Dome aisle. To revive a memory of this event, an iron cross was mounted to the church building's wall (31). Later on, J. Brotze (17) also wrote that the Daugava River had catastrophically flooded the Riga Dome Church, although the wall-mounted iron cross was no longer there at that time. P. Stakle (24), estimating the likely water level of the Daugava River in the year 1358, concluded that it rose about 5.5-6 m above the summer water level.

Multiple sources (22, 24, 29) report that the spring flood levels in the Daugava were catastrophic also in 1578, when vast areas around Riga had been submerged, causing huge damages. On April 14, according to P. Stakle's estimation, the water level could have possibly risen by 5-6 m.

Great floods caused by spring high water occurred in Riga in the years 1589 and 1597, when the water level rose by 5.5-6 m (P. Stakle's estimation). In 1810, the *Rigasche Stadt-Blätter* (31), referring to archive data, wrote that, on 18 April 1597, the ice broke through the embankment (rampart) near Jacob's Gate in Riga, roads were washed off, buildings were ruined, and ships sunk in the Daugava River. Many people and livestock were drowned. The city incurred massive losses.

Catastrophic floods caused by the spring high water occurred in Riga again in 1615. A huge ice jam (dam) formed by the former Bisenieki Isle, causing a rapid rise in water level upstream of it. The water washed down and flooded the embankments in the area of Mārstaļu Street, running through the rampart towards the Riga Castle. Ch. Kelch (26) wrote about this disaster that such an unprecedented rise in the water level began on the Daugava River by Riga that the water not only flooded the city surroundings but also broke into the city behind the gates, so that many buildings stood in water. According to P. Stakle's estimation, the maximum water level reached 5.5-6 m on the 7th of April.

Multiple sources (17, 26, 31, 1812) write about a fierce storm and flooding in Riga in 30 May 1626. Large masses of sea water were driven into the Daugava River (presumably with northwest winds – G.E.) from the Gulf of Riga, which, together with the spring flood waters of the Daugava, made the water level rise unusually high. The entire city and pastures were submerged, many buildings were ruined, the wind downed lots of trees, a lot of people and livestock perished. This natural disaster was caused by simultaneous action of two elements: water and storm. Although there are no data on the maximum water level, it is possible that it reached 4-5 m.

Disastrous spring floods with large piles of ice on the Daugava River occurred again in 1649 (138, 149, 150). According to P. Stakle's estimation (24), the water level reached 5.8-6 m on the 11th of April. The city ramparts by the gates of Jacob's and Smilšu Streets were washed off by the forceful flow, just as the Hincene dam by Latgale Street and about a half of Kube Hill (dune – G.E.) (17), many buildings were destroyed and people killed. The strong northwest wind brought water in the Daugava River also in autumn, and the high water level caused wide flooding with significant damages for the second time in the same year (22, 24).

There were heavy storms in the sea in November and December 1704. The northwest and north winds drove the sea water and ice into the Daugava River up to Katlakalns and the Lucavsala Island. The areas by the Grēcinieku Street gate in Riga as well as the Klīversala Isle were flooded. Many houses were carried out into the sea (18). Also in late June 1708, there were big rainfalls in Latvia and flooding in the Daugava River. The water level in Riga rose by 4.5 m (P. Stakle's estimation). Gardens were submerged in the vicinity of Riga for 4 weeks. All plantations and sowings perished.

The year 1709. After a particularly harsh winter, when the Baltic Sea froze over and ice thickness in the Daugava reached 1.7 m, ice started drifting on the 6th of April. Since the Gulf of Riga was still covered with thick ice, the ice pieces carried by the river flood waters were piled on the isles and shores of the Daugava River. The water level rose catastrophically, reaching the absolute height mark of 4.68 m on the 16th of April. To leave a proof of this disastrous flood, a cross was carved in the Riga Dome Church wall. According to J. Brotze's records (20), the water in the city reached the depth of human height. All isles and the valley of the other side of the Daugava were flooded, whereas the water on the right side of the river reached Kube Hill and the Citadel. Since the ice blocked free water outlet from the Daugava into the sea, part of the water diverted to the Lielupe River (the current Buļļupe River – G.E.) and another part – to the sea across the Mangaļsala peninsula in the area of Vecāķi.

Compiling the historical data, P. Ludvigs (9) wrote that the most terrible flood ever seen in Riga occurred in 1709. The author describes the overall situation as follows: "They (the flooding and the subsequent disaster-causing events – G.E.) began in the autumn of the previous year. In November, an exceptionally strong storm raged, tearing down the roofs not only of many buildings but also partly of the Riga Dome Church. The storm-blown water flooded the Daugava River banks and isles, washing away houses, livestock and people. Several ships were smashed and cast ashore. The storm was followed by severe frosts, which persisted almost continuously throughout the winter. The ice cover on the Daugava River reached the thickness of 1.5 m, so that in some places the river was frozen to the bed. 22 ships were stranded in the ice. In that winter, almost all fruit trees were frostbitten. When the spring thaw began, the stream brought the ice from the Daugava upriver downwards, while the ice at the downriver did not break, remaining where it was. Consequently, a huge ice dam was formed. The water then broke two new outlets to the sea, flooding Pārdaugava and isles of the Daugava. The ice-bound ships could not be salvaged anymore, and they were crushed, destroyed and carried into the sea, along with large quantities of timber and several houses with their inhabitants. The Zaķusala Island alone lost 52 houses. Situation in Riga was even worse. The masses of ice and flood waters broke through the Riga city gates, flooding the streets, buildings and cellars. Water in the Dome Church rose up to the altar. Pews, coffins and corpses floated in a jumble inside the church" (pp. 230-231).

Like in the year 1709, also in 1744, when the ice thickness in the Daugava River was twice the height of a man after a harsh winter (31, 1814), ice started drifting at the beginning of April. The drifting started in the morning, and at four in the afternoon the water has already reached the Dome Church. A few days later the ice forced the Šabļi Street gate, and the old town was submerged subsequently. Pews floated around the Dome Church aisles. Johan's dam was also destroyed, and the outskirts were flooded, with the exception of Lielā Smilšu Street and Kube Hill. The maximum water level was reached on the 10th of April, though it was lower than in the year 1709. Water in the city washed away many houses and bridges.

Catastrophic flooding caused by the spring high waters in the Daugava River occurred in Riga also in 1770, with the maximum water level on 11 April.

After the snowy winter in the Daugava basin, ice drifting and catastrophic flooding started in Riga at the end of April 1771, reaching the peak level on the 26th of April (around 5.5-6 m according to P. Stakle's estimation). At that time, the Daugava River mouth and the Gulf of Riga were still covered with ice. The waters of the Daugava broke through Catherine's dam, and a large part of the city, wide surroundings and the isles flooded. Countless houses with people floated together with ice from the direction of the upriver toward the sea. Townspeople could do nothing except helplessly watch from higher places the doomed people drifting by on their houses and ice floes. P. Sapunov has so described the tragic scenes (14).

During the disastrous spring floods, when large ice jams built up by the upper end of the Dole Island and on the small islands in the Main Daugava, in the years 1615, 1771 and 1867, the waters of the Daugava River, bypassing ice jams (piles) in the Main and the Dry Daugava, ran over the old river-bed (the Brekšupe River), past the Church of Salaspils (located on an elevation formed by the old isle – G.E.) to Ulbroka, finding its way to Lake Jugla through the valley of the Pičurga Creek.

There were great flood damages in Riga also in the spring of 1783, when dams were washed out and broken in 11 places (11). There was a catastrophic flooding with ice drifts in Riga also after the harsh winter in 1795. J. Brotze (19) wrote that the lower houses, that the residents left, were in water up to roofs, whereas the newspaper *Rigasche Stadt-Blätter* wrote in 1825 that the flood level caused by spring high water exceeded the level of 1744 in Riga on April 13. There were high flood levels also in the spring of 1807, when the waters of the Daugava River broke the dams and flooded the city's canals and the Citadel and carried away bridges.

The catastrophic flooding on 12 April 1814 was conduced by the thick cover of sludge and ice. A big flood occurred again in 2 years (in 1816), when large ice jams formed opposite to Catherine's dam in Riga. The waters of the Daugava River ruptured the dam and flowed through the present Sarkandaugava distributary. All the bigger islands of the river's lower reaches of that time, such as Ķīpsala, Bieķēnsala and Mazā Kliversala were submerged, along with parts of Iļģuciems and the Moscow Vorstadt, as well as Pārdaugava (from the present Torņakalns railway station downwards, including Uzvaras Square and the Agenskalns bight).

After 13 years, in 1829, after a harsh winter without thaws, ice drifts started on the 9th of April in the Daugava River in Riga. As usual, ice piles formed on the many low isles and banks. The river bed was obstructed, and the water level rose rapidly upstream of the jam. The low flood-land of the Daugava valley in Pārdaugava up to Māra's Pond Mills, Catherine's dam, Sarkandaugava and St. Petersburg's suburbs were submerged. The old town was saved with great efforts (28, 1829).

in 1837, catastrophic spring floods with ice drifts took place in rivers throughout Latvia. Damages in Riga were not as big as in previous years, unlike in Dinaburg (Daugavpils) and especially in Slobod on the Courland coast side, where the water rose so quickly (due to a large ice jam) that poor people were able to save little, trying to save themselves on the rooftops. The Daugava River flooded the entire wide valley, and the city looked like a big lake (28, 1837, No. 20). 190 families suffered losses during the spring flood of the Daugava River. There were very high levels of flood water also in the Lielupe, the Abava and other river valleys (28, 1837).

In 1844, there was a late spring after a snowy winter. Ice drifting started in the Daugava by Riga in mid-April. On the 18th of April, a huge ice jam formed in the river downstream in Mīlgrāvis, by the White Church on the right bank of the Daugava River. The water level rose by about 4 m. The Moscow Vorstadt was submerged because the water broke through the protecting dam. Other low flood-land areas were also submerged.

Also the next year, 1845, a big pile of ice formed again on the left bank of the Daugava River by Riga, opposite to Tsar's Garden (now Viestur's Garden). The water level rose rapidly on the 16th and 18th of April. Then a large part of the ice with flood waters found a new outlet across the grasslands of Spilve to the sea (31, 1845). Opposite to Rīnūži, the forceful flow of the river washed off a 500 metres long bank section with three peasant houses, forming a new 4-6 m deep riverbed (7).

Even greater flooding and devastation took place in Riga after 10 years. On 11 April 1855, after a snowy winter without thaws, ice breaking and drifting towards the sea started in the Daugava River. The ice stalled in the river by the White Church in Vecmīlgrāvis, since the ice cover was still firm on the river mouth. Huge piles of ice formed by Podrags. On the 12th of April, the water rapidly rose and flowed over the protective dam, submerging the entire lower flood-land on the left bank, the area of Ganību dam on the right bank, a large part of the Moscow Vorstadt and the isles of the Daugava River. Houses on the isles were in water up to roofs (8). Bypassing the ice jam, the ice and waters of the Daugava made a new way across the grasslands of Spilve, carrying away 2 houses and other structures. On the 14th of April, the water level began to subside.

According to A. Sapunov's estimation (14), the maximum spring high water level in Riga was 8.24 m higher than the water level during the summer low flow, whereas P. Stakle estimated the level at 5.5-6 m.

The end of the year 1856 also came with major floods on the Daugava River and other rivers of Latvia and water devastation in Riga. Bitter frost started already in September and continued through November, followed by a deep thaw and major floods at the end of November. During the disastrous flooding of the Daugava River, the outskirts of Jelgava (on the left bank of the river – G.E.), the Moscow Vorstadt, the isles and many streets were flooded, since several dams had been destroyed. Bridges had been carried away. In St. Petersburg's suburb, the first floors of buildings were in water. The maximum water level in the Daugava was only for 1.22 m lower than in 1855 (31, 1862).

Ice drifting and congestions also occurred on the Lielupe and Venta Rivers, whereas the Gauja River overflowed its banks. In the Bārta River, there was the largest flood in 50 years (31, 1862).

Big floods ravaged Riga also in 1865, when a large ice jam formed on the Daugava River and the water level rose by 4.56 m. The city canal and aqueduct, Parade Square, Kārļa Street and Vērmaņdārzs Park overflowed. The water flow washed out a large hollow on Suvorov's Street, while the Tsar's Garden was in 1 m deep water. All houses on the Zaķusala Island were in water up to the roofs, while in Pārdaugava the water flooded the entire vast lowland territory (including today's Victory Park – G.E.) up to Torņakalns (28, 1865; 31, 1865). After such spring floods, warm and dry weather continued until August (28, 1865).

Unusual, unprecedented floods struck the city of Riga at the beginning of March 1871. The strong wind from the sea forced large amounts of ice from the Gulf of Riga into the Daugava River mouth, making ice piles as high as never seen before. Their height reached 70 feet (21.35 m!) and width – around 20-30 m. The length of ice ranges reached 2-3 versts (2.12-3.18 km!). The ice piles reached the river bottom, which was said to have been more than 5 m deep. However, the ice piles did not stay for long in the Daugava River, since intense ice drifting started on the 17th of April. The piles were carried into the sea. Therefore, there was no major flooding, except in the low Pārdaugava (24).

At the beginning of the last century, the largest flooding in Riga related to ice jams occurred in 1917. The ice that was carried downstream by the Daugava River current jammed between the Zaķusala Island and the Zvirgzdi Isle. Large piles of ice were driven onto the river banks by the Moscow Vorstadt up to the tramway rails, toppling on their way several cast iron poles. The water stream running from the Lucavsala Island and Zaķusala Island washed off large plots of land. Several small ships were cast ashore. In the river basin upstream of the jam, the water level rose by 5.18 m (!).

Serious flooding occurred also in the years 1924 and 1929.

To sum up, over the period of almost 600 years, from the 14th century until the early 20th century, Riga and its inhabitants endured devastation of more than 20 cases of catastrophic flooding caused by ice jams: in the years 1358, 1363, 1587, 1589, 1597, 1615, 1618, 1643, 1709, 1727, 1744, 1770, 1771, 1783, 1795, 1807, 1814, 1829, 1837, 1912, 1917, 1924 and 1929.

Daugavpils also sustained damages caused by spring high waters a number of times. The worst floods in Daugavpils occurred in the 18th century (1702, 1709, 1723, 1729, 1735 and 1739), the most devastating – in the year 1709, when Riga also was catastrophically flooded.

In 1729, the spring flood waters also rose so high that Daugavpils resembled Venice (9, p. 232). In order to protect the city from similar floods, a 6 km long protective dam was built along the right bank of the Daugava River. The protecting structure was completed in 1841. The Riga-Daugavpils-Krāslava motorway runs over this dam. However, during the great flood in 1922, when the maximum water level in the Daugava reached 9 m, the dam breached, flooding the lower part of the city.

Today, just as before, the flood risk area encompasses the Daugava valley from Daugavpils to Līvāni (including) and Jēkabpils, where the flood risk is particularly high after the Pļaviņas HPP reservoir has been created.

Jaunjelgava also incurred significant damages in the floods of 1740, 1743, 1773, 1924 and 1929. In the year 1773, this small town on the Daugava bank was almost completely erased from the face of the Earth. Around 100 houses were ruined. Also in 1924, during the spring flood, the Daugava waters carried away 4 and damaged several other buildings (9). After the construction of Ķegums HPP had been complete, the flooding risk for Jaunjelgava increased, as the reservoir's backwater level reached quite far upstream of the town. The situation was similar to that of Jēkabpils and Pļaviņas now, after the formation of Pļaviņas HPP reservoir.

A protective dam was built along the Daugava River bank for the purpose of protecting Jaunjelgava. After putting Pļaviņas HPP into operation, regular spring floods is no longer a threat for Jaunjelgava, as Ķegums HPP regulates the water level, and the large masses of ice remain in the reservoir of Pļaviņas or, in smaller quantities, go into Ķegums Lake through the hydropower plant's floodgates.

In some years, major floodings occurred also in the Venta River downstream, by Nabes Lake, Zlēkas and Piltene.c P. Ludvigs (9) wrote about an unusually high, catastrophic flood on the Venta River by Kuldīga in 1615: "Then the spring flood waters (presumably due to an ice jam, G.E.) rose so high that the town of Kuldīga was submerged. They (the waters) also entered into the castle yard. The chain bridge mounted on the stone piers at the times of the German order – linking the two banks of the Venta River opposite to the Castle gate – was then destroyed and carried away. A new bridge across the Venta by Kuldīga (downstream of the Kuldīga Falls) was built only in 1874 and is still there" (p. 126).

The main cause for the disastrous floodings on the Daugava River in Riga over a period of more than 750 years since the founding of the city until the Ķegums HPP was built was the wide and shallow bed of the Daugava River with many larger and smaller isles and sandbars, often changing their location and size. The river washed away some isles during flood, some isles formed anew elsewhere. The sandy, gritty and pebbly material carried from the river sections with rapids from Pļaviņas to the downstream end of the Dole Island accumulated in the river within the city limits of Riga and was partly washed into the sea. During the spring high water, the ice-drifts, from the upper reaches of the river piled on sandbars and isles, completely damming up the river with huge ice jams. Upstream of the congestions, water levels were rising fast, flooding vast areas of the Daugava valley and the city of Riga, which some 500-600 years ago – especially the territory that presently is the city centre with multi-storey dwellings – was about 2-3 m lower. During the last centuries, especially beginning with the demolition of the city ramparts, the territory was banked and elevated up to 5-5.5 m above the sea level to avoid flooding. The 5-8 m thick cultural layer is the evidence for this fact.

The present-day topographic maps of Riga that show the parts of the city that were often submerged during last centuries effectively demonstrate the extent of floods (Figure). If, in some distant future, wind-caused water run-up in the Gulf of Riga and the coastal area rose for 4-5 m, then the scene would be similar to that 400-500 years ago.

In some years, when the Gulf of Riga and the Daugava were under ice cover, the strong north-western storms drove large masses of ice from the gulf into the river mouth, forming large ice piles, which caused flooding in the city. Beginning with the 80s of the 19th century, when the Daugava riverbed deepening and straightening works, building of dams – which direct the river's flow into its main watercourse – as well as removal of certain isles and sandbars commenced, the risks of ice jams and devastating floods in the city decreased. The situation was also improved by building ramparts along the city, stop gates at the ends of streets leading to the river and water-gates on both ends of the city canal, as well as by elevating the ground surface in lower built-up areas, using debris as a material for banking. In the 19-20th centuries, iceboats were started to be used for breaking ice in the Daugava River before the spring high water season. Construction of the Ķegums HPP prevented the ice jam formation in the city.

Nevertheless, in our day, in autumns and winters, when violent storms rage in the Baltic Sea, and SW, W winds drive large masses of water from the open sea into the Gulf of Riga, and then the wind turns from NW, the threat of flooding increases in the low built-up areas of the city, situated on the Daugava valley. In such circumstances, the water level in the Daugava, the Lielupe and the Gauja downstream rises for about 1.5-1.8 m. In the devastating storms of 1969 and 2005, the water level in Riga reached an absolute height mark of 2.1-2.15 m, and large vacant and built-up city territories were flooded. As the climate becomes warmer and storms increase in power, the water level rise caused by wind-driven water run-ups in the peak of the Gulf of Riga and in Riga might in the near future reach a 2.5-3 m mark.

We can only guess what was the actual height of the ground surface above the summer low flow level of the Daugava in the 12-13th centuries, when Riga was founded. Nowadays, the data of excavations made during the Town Hall restoration, as well as the data of many geological and engineering-geological exploration drillings in the central part of the city show that, as a result of making banks for centuries (cultural layer), the city area has been elevated for about 3-6 m. In many places, the former high floodplains of the Daugava valley – from Ķengarags to the Academy of Sciences multi-storey building, including the areas of Central Market, Railway Terminal, Vērmaņdārzs Park and the Freedom Monument – have been banked and built up. Initially these areas could have been only 2-3 m above the summer level of the Daugava River.

In the excavation made during the restoration of the Riga Town Hall, a massive oak tree trunk with roots was uncovered by the building foundations. Apparently, it was brought there together with ice during the spring high water when the city was flooded. The natural (unbanked) ground surface height mark on the building foundation, in accordance with the geological exploration drilling data, corresponds to "0" in the Baltic height system. Of course, neither the Dome Church, nor the Town Hall, could be built in places, the altitudes of which were close to the summer water level of the Daugava River, but, in all probability, at least 2.5-3 m higher. This factor allows for a possibility that the average water level in the Gulf of Riga and the Baltic Sea (and also in the Daugava River downstream) have risen by at least 2-3 m over the last 800-850 years. The data obtained from long-term observation of the average sea level changes over the past more than 120 years in the Daugava River mouth show that it has risen for 0.25-0.30 m. Sinking of the Earth's crust – even if only 1 mm per year (totalling to 80-90 cm) – soil compaction and settling under buildings and artesian water withdrawal can be mentioned as the side factors which all together cause lowering of the Earth's surface.

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