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Changes of Extreme Climate Events in Latvia

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***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.**

***Keywords* - 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. 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 the climate is changing: the global mean temperature increase over the period 1861–2000 was 0.61°C, with a 90% confidence interval of 0.45–0.77°C, while between 1901 and 2000 the observed warming was 0.57°C, with a 90% confidence interval of 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, [2]. 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, [3], [4], [5], [6], [7] and trends of their changes. Changes in extremes may be due to the mean effect, the variance effect or the structural change in the shape of distribution [8]. Determining changes in the behaviour of extreme weather events has been the topic of several international projects ECA&D [9], [10], EMULATE [11], 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 [13], [14].

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 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 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 meteorological station over the period 1852-2010 were used for the analysis of 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.

Fig. 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 I).

TABLE I

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

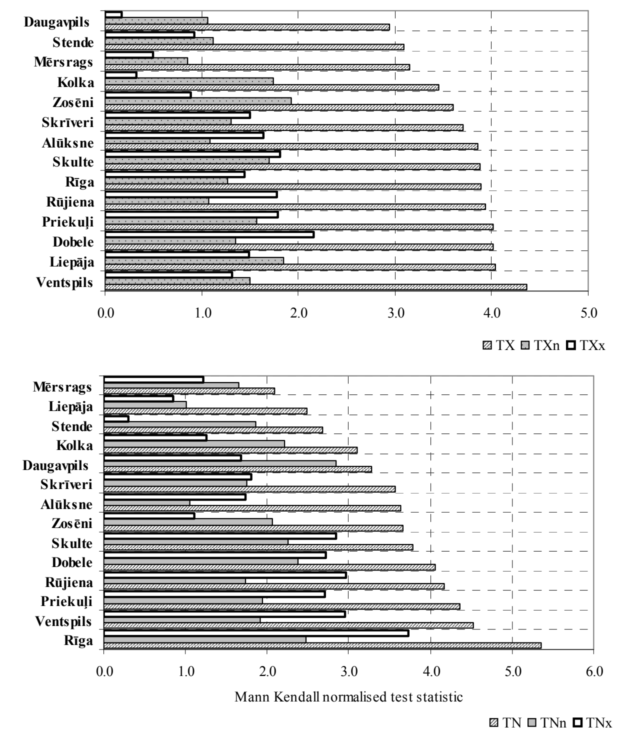

Fig. 2. Long-term trends of mean annual minimum and maximum air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics).TX - Annual or monthly mean of daily maximum temperature; TN- Annual mean of daily minimum temperature; TXn - Annual minimum value of daily maximum temperature;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

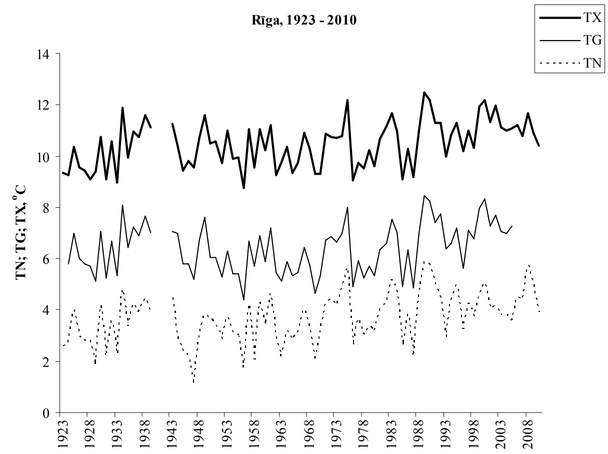

Fig. 3. Trends of annual daily maximum (TX), mean (TG) and minimum (TN) temperature in Rīga for the period from 1923 to 2010

A detailed study of the character of monthly mean of daily maximum temperature changes within a year (Table II) 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 II

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 III

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

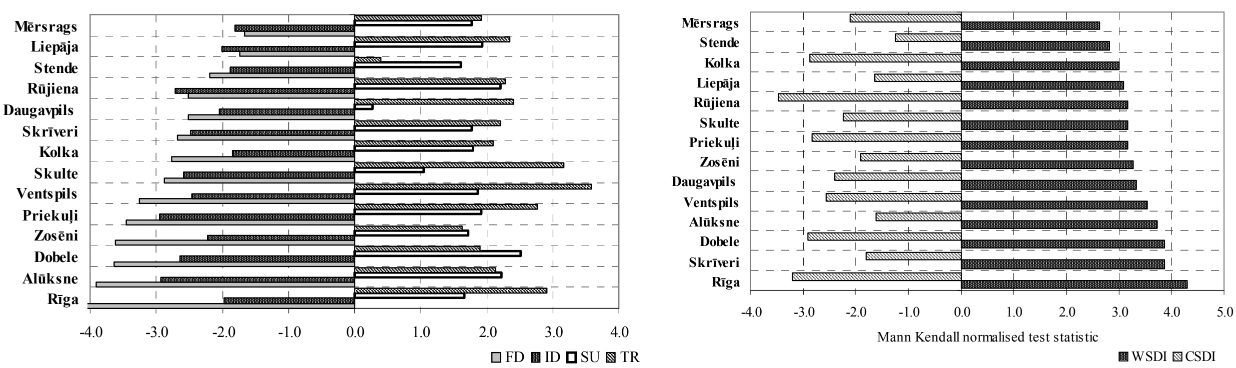

Fig. 4. Long-term trends of extreme temperature events and events of prolonged periods of extremely low and high air temperatures in Latvia over the period 1950-2010 (Mann-Kendall test statistics). FD - Frost days; ID - Ice days; SU - Summer days; TR - Tropical nights; CSDI- Cold spell duration indicator; 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 III). However trends for monthly mean of daily minimum air temperature differ, for example, in February in most of the studied meteorological stations. The trends of changes in Rīga can be considered remarkable, where statistically significant increasing trends are common for nearly the whole 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 stationRīga -University, the number of summer days was much higher in the 1850-60ies (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].

The 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 a 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 the Baltic Sea, in the more continental stations (Alūksne, Daugavpils and the capital city of Latvia – Rīga (Fig. 4)).

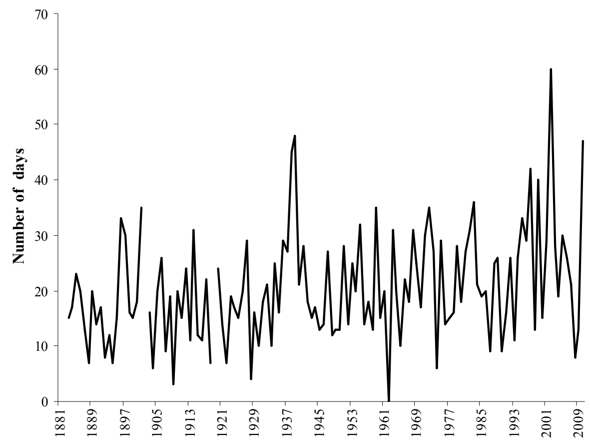

Fig. 5. The annual number of summer days in Rīga-University observation station over the period 1881-2010

On the other hand, extremes associated with negative air temperatures (despite relatively cold winters in 2009/2010, 2010/2011) have a 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].

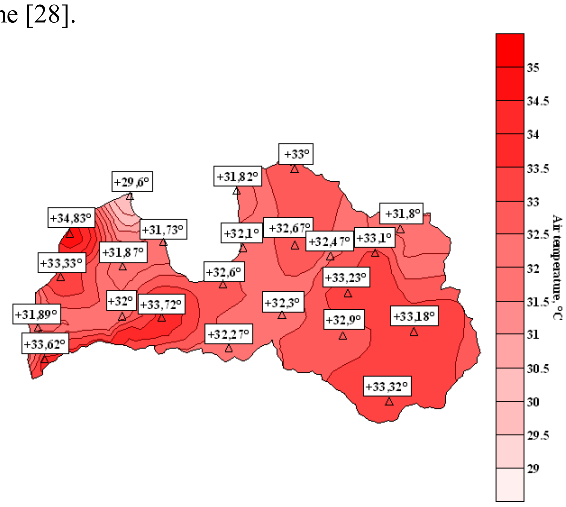

Fig. 6. The maximum values of air temperature in Latvia during the summer 2010

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

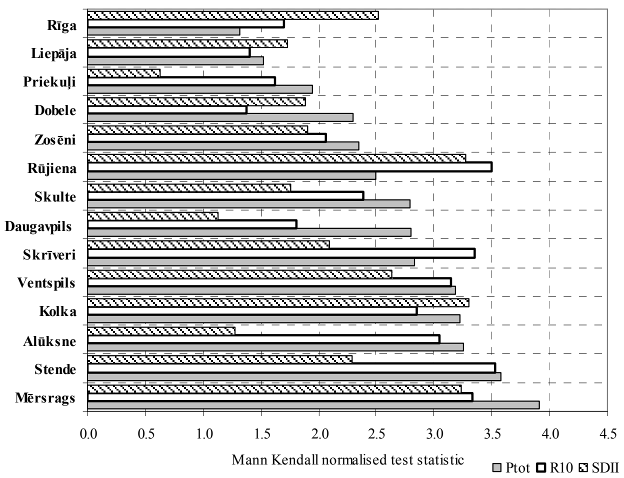

Fig. 7. Long-term trends of changes in precipitation amount and heavy precipitation events in Latvia over the period 1950-2010 (Mann-Kendall test statistics). Ptot - Annual total precipitation amount in wet days; R10 - Annual number of heavy precipitation days; SDII - Simple daily intensity index.

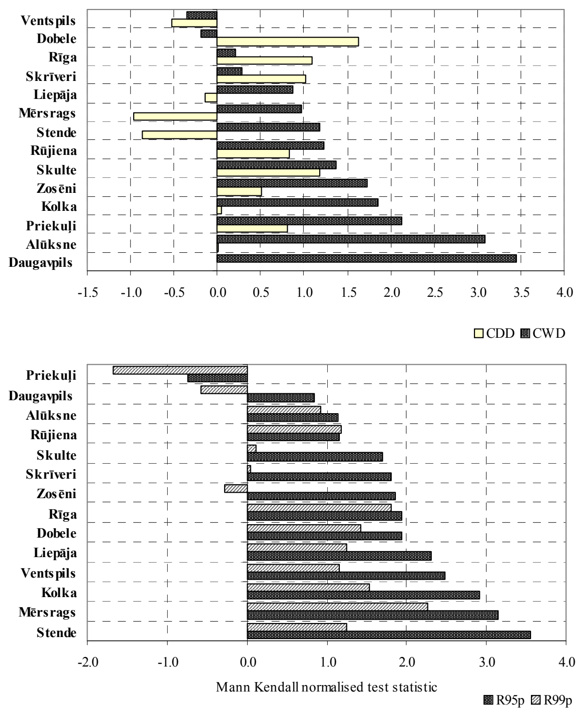

Fig. 8. Long-term trends of prolonged dry and wet periods and extremely heavy precipitation in Latvia over the period 1950-2010 (Mann-Kendall test statistics).CDD - Consecutive dry days; CWD - Consecutive wet days; R95p - Very wet days; R99p - Extremely wet days.

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 significant changes in the precipitation intensity character and consecutively in the damaging potential of the heavy precipitation events. At the same time, the 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 the 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).

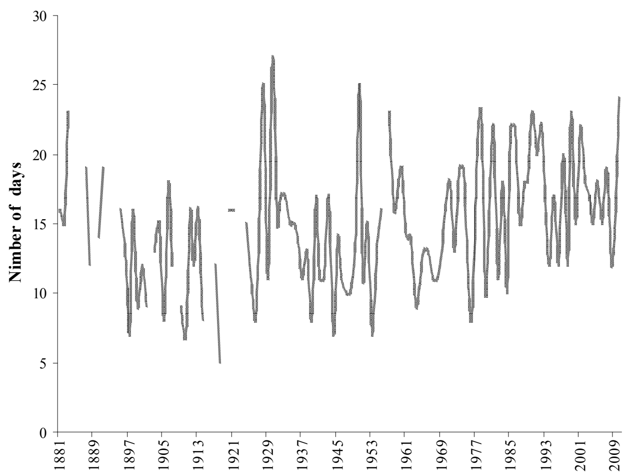

Fig. 9. Long-term trends in the number of days with heavy precipitation (daily precipitation amount ≥ 10 mm) in Rīga-University observation station over the period 1881-2010

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. Thus, 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].

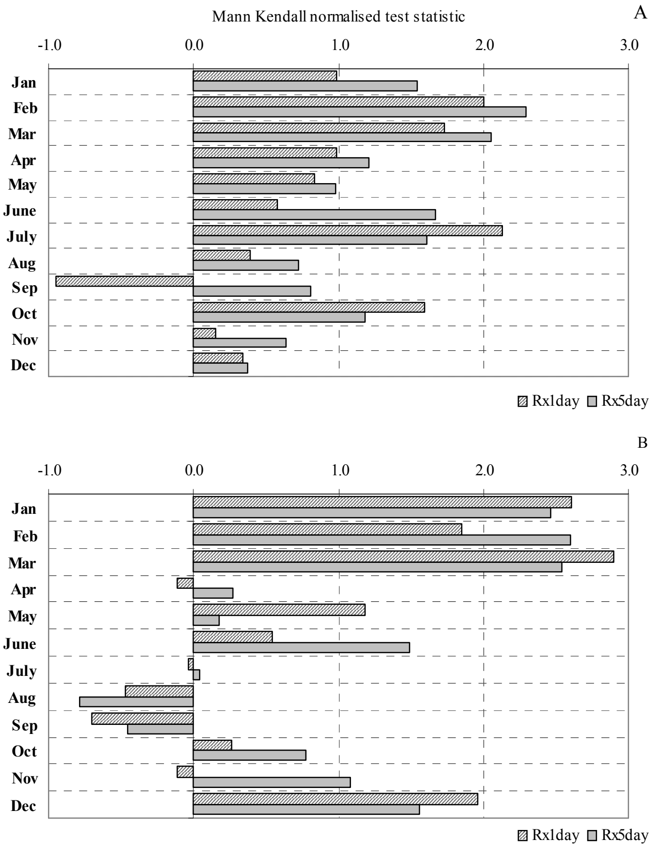

Fig. 10. Long-term trends of monthly maximum 1-day and 5-day precipitation amount in Mērsrags and Priekuļi observation stations over the period 1950-2010 (Mann-Kendall test statistics).Rx1day - Max 1-day precipitation amount (monthly maximum 1-day precipitation); Rx5day - Max 5-day precipitation amount (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 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 future climate change will result in a further increase in both extreme precipitation and heat events in Latvia.

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