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Trends in the frequency of extreme climate events in Latvia

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Abstract This study investigated the long–term variability of extreme climate event indicators in Latvia. To assess trends in the frequency of extreme climate events, 14 extreme climate indices, such as number of extremely hot days, number of frost days or number of days with heavy precipitation, were calculated and compared with other indices characterizing mean climate. Trend analysis of long–term changes in the frequency of extreme climate events demonstrated a significant increase in the number of meteorological events associated with an increased summer temperature (for example, the number of summer days and tropical nights) and a decrease in the number of events associated with extreme temperature events in winter (the number of ice days and frost days). Due to the decreasing number of cold days, under the changing climate, the length of the growing season has increased. There were also increases in the number of days with heavy precipitation and in the intensity of heavy precipitation. Finally, influences of the large–scale atmospheric circulation on the occurrence of climate extremes are discussed.

Keywords *Climate extremes, climate change, trends, large–scale atmospheric circulation, Latvia.*

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INTRODUCTION

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 (Alcamo *et al.* 2007). Climate change can also be characterized by the changes in major indicators of the climate system: precipitation, river runoff, ice and snow cover. 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 (Karl, Trenberth 2003; Kļaviņš *et al.* 2008; Jarmalavičius *et al.* 2007). Just a few examples illustrate the threats and significance associated with extreme climate events: extreme heat events cause heat waves; extreme precipitation causes floods. As has been stated in several studies, an increase in the frequency of extreme climate events can increase the threat to society and individuals (Alexander *et al.* 2007; Beniston 2007; Kysely *et al.* 2010; Unkaševica, Tošic 2009; Jungerius 2008). Compared with existing knowledge on the long–term changes of mean climate indicators, much less is known about the changes of extremes.

Today there is a growing interest in extreme climate events (Easterling *et al.* 2000b). For many impact applications and decisions, extreme events are much more important than the climatic means. The causes of changes in the extremes may be the effects of changes in the mean values, the variance effect or structural changes in the shape of the distribution (Heino *et al.* 2008). Determining the changes of extreme weather events has been the topic of several international projects: ECA&D (Klein Tank *et al*. 2002; Klein Tank, Könen 2003), EMULATE (Moberg *et al.* 2006) and STARDEX (Haylock, Goodess 2004). Often, extreme climate events have been identified using internationally agreed, predefined indices such as number of days exceeding a fixed threshold, percentile threshold, extreme event duration, etc. (Easterling *et al.* 2000). In several studies in Europe, significant increasing trends have been found in a variety of extreme indices over the latter part of the 20th century (Heino *et al.* 1999; Wibing, Glowicki 2002; Klein Tank, Können 2003).

To date, studies of the climate change in Latvia and other Baltic countries have mostly considered changes in mean values. The aim of this study was to determine the long–term variability and trends in the time series of extreme climate events in Latvia, and analyze factors influencing climatic extremes in terms of large–scale atmospheric circulation processes.

DATA SOURCES AND METHODS

Data

The present study is based on daily air temperature and precipitation data series for five meteorological stations (Fig. 1) obtained from the Latvian Environment, Geology and Meteorology Centre[1]. The daily temperature and precipitation data of Rīga University station (observations since 1850) were used to investigate the changes in temperature and precipitation over a period of 156 years. Atmospheric circulation data were obtained from the EU COST program project COST 733 (COST733 2010).

Basic quality and homogeneity control was undertaken for all of the series. Homogeneity of the precipitation and air temperature series was tested using two statistical homogeneity tests: the standard normal homogeneity test (SNHT) (Alexandersson, Moberg 1997) for monthly, seasonal and annual data series; and multiple analysis of series for homogenisation (MASH) (Szentimerey 1996) for daily, monthly, seasonal and annual data series. Only the homogeneous data series were used in this study.

Fig. 1. Major meteorological observation stations in Latvia. Compiled by I. Kokorīte, 2010.

Methods

Trends in the meteorological event time series were analysed using the non–parametric Mann–Kendall test (Libiseller, Grimvall 2002). 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.

Ensemble climate change indices derived from daily temperature and precipitation 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 (ETCCDI 2009), with a primary focus on extreme events (Table 1).

The data on the climate change indices are available at http://eca.knmi.nl, and gaps found in the data were filled using the original observation data from the Latvian Environment, Geology and Meteorology Centre.

RESULTS AND DISCUSSION

Changes in the frequency of extreme climate events

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 highly variable weather pattern is determined by the strong cyclonic activity over Latvia.

In this study we used 14 climate indices derived from the daily temperature and precipitation series. Most of these indices measure a type of climatic extreme but a few give information about the mean conditions (for example, growing season length) while at the same time depending on extreme climate events (for example, frost).

The overall results of trend estimates for stations indicated in Fig. 1 are summarized in Figures 2 and 3, and Tables 2 and 3. Visual inspection (Fig. 2, 3) of many indicators of extreme climate events for the last ~80 years reveals clear trends. Changes related to negative temperatures (the annual number of frost days and annual number of ice days) show a decreasing trend, but many indicators describing positive temperature extremes demonstrate an increasing trend, for example the annual number of summer days (daily maximum air temperature > +25°C). Also, the number of days with heavy precipitation shows an increasing trend. Patterns of observed trends are consistent between all studied stations, and in many cases the observed trends are statistically significant (Table 2).

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[1] Electronic data base of meteorological observations CLIDATA.

Table 1. List of climate indices used in this study.

Index name	Explanation	Unit
HP	Days with heavy precipitation (number of days with precipitation ≥ 10 mm)	days
VHP	Days with very heavy precipitation (number of days with precipitation ≥ 20 mm)	days
TN	Daily minimum temperature	temperature value
TX	Daily maximum temperature	temperature value
DTR	Mean of diurnal temperature range	temperature value
TG	Daily mean temperature	temperature value
FD	Frost days (number of days TN < 0 °C)	days
ID	Ice days or days without defrost (number of days TX < 0 ºC)	days
CSDI	Cold-spell days	days
CFD	Maximum number of consecutive frost days (TN < 0 °C)	days
TR	Tropical nights (number of days TN > 20 °C)	days
SU	Summer days (number of days TX > 25 °C)	days
GSL	Growing season length (count of days between first span of at least 6 days TG > 5 °C and first span in the second half of the year of at least 6 days TG < 5 °C	days
GD4	Growing degree days (sum of days with TG > 4 °C)	temperature value

In all of the meteorological observation stations there has been an increase in the number of days with heavy precipitation (daily precipitation total ≥ 10 mm), though only in Rīga, Liepāja and Alūksne this trend was found as statistically significant. The well-expressed increase in the number of days with heavy precipitation in Rīga could be associated with the influence of the Gulf of Riga and urban climate specifics (Birkmann *et al.* 2010). The number of days with very heavy precipitation (daily precipitation total ≥ 20 mm) only shows a significant increasing trend in Saldus, while in Alūksne the trend is negative. Though

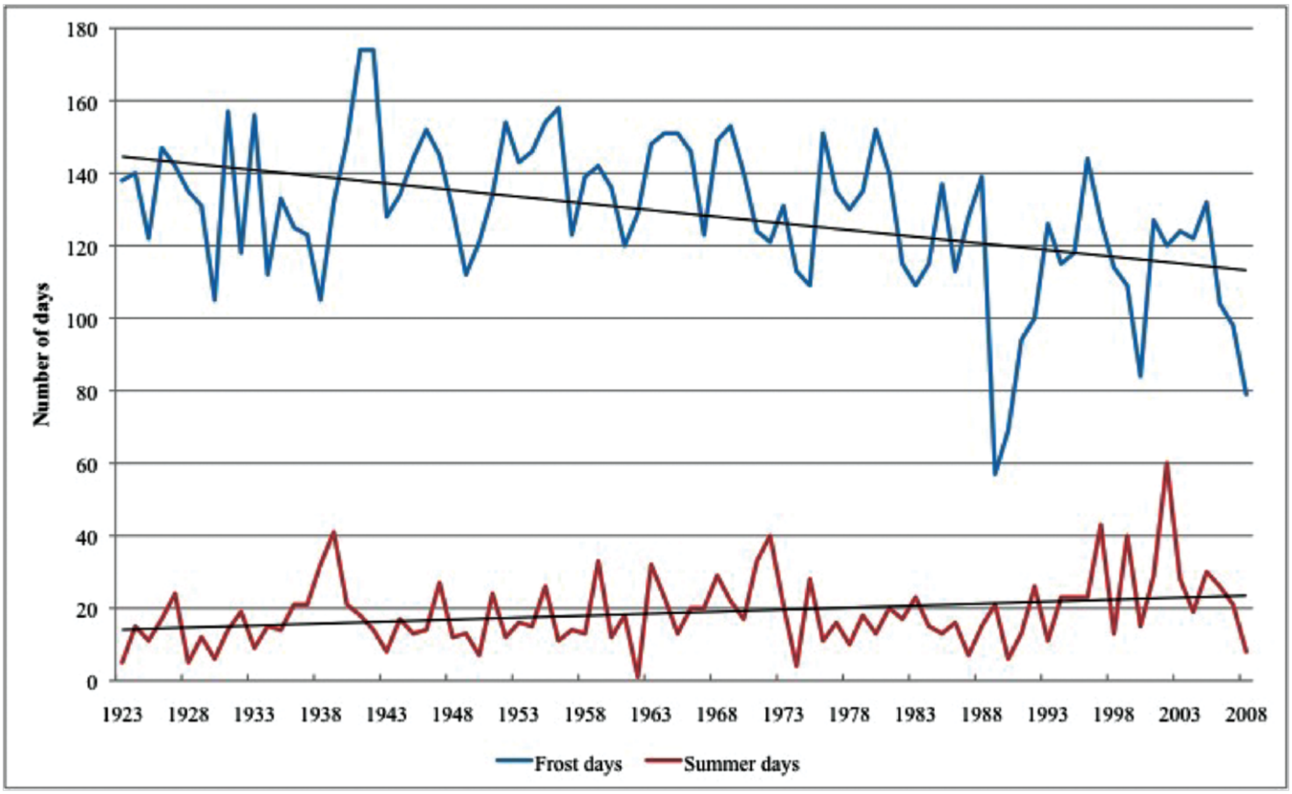


Fig. 2. Trends in the annual number of frost days (daily minimum air temperature < 0°C) and summer days (daily maximum air temperature > +25°C) in Rīga for the period 1923–2008. Compiled by Z. Avotniece, 2010.

Table 2. Long-term trends in extreme meteorological events (Man-Kendall test statistics).

	HP	VHP	FD	ID	SU	TR	CFD	CSDI
Rīga (1924–2008)	**4.16**	1.25	**-3.57**	-1.78	**2.36**	**3.62**	-0.30	**-2.27**
Liepāja (1924–2008)	**2.18**	0.14	**-3.51**	**-3.63**	0.89	**3.03**	-1.60	-1.36
Alūksne (1946–2008)	**2.86**	-0.51	**-3.98**	**-2.99**	1.92	1.72	**-3.65**	-1.58
Saldus (1946–2008)	1.80	**2.55**	**-3.04**	**-2.24**	1.84	0.43	-1.17	-1.03
Daugavpils (1946–2008)	0.93	0.13	**-2.34**	-1.89	0.49	1.90	-0.25	-1.31

HP – heavy precipitation (≥ 10mm), days; VHP – very heavy precipitation (≥20mm), days; FD – frost day (TN < 0°C), days; ID – ice day (TX < 0°C), days; SU – summer day (TX > 25°C), days; TR – tropical night (TN > 20°C), days; CFD – maximum number of consecutive frost days (TN < 0°C), days; CSDI – cold-spell days, days.
The trend was considered as statistically significant at the 5 % level if the test statistic was greater than 2 or less than -2.

studies in the United States and elsewhere in the world affirm the increase in the number of days with heavy precipitation during the 20th century (Easterling *et al.* 2000a), the strong local gradient of precipitation (Klein Tank, 2004) makes it hard to make unambiguous conclusions about the long–term trends of changes.

The extreme values of air temperature are increasing along with the increase in the mean values, wherewith there has been an increase in the number of days with extremely high temperatures and a decrease in the number of days with extremely low air temperatures (IPCC, 2007). Trends were stronger for the climatic indices relating to the cold seasons: for example, the number of frost days (TN < 0°C) and number of ice days (TX < 0°C) both show statistically significant decreasing trends in all the studied stations. Studies brought out in Central and Northern Europe show that the decrease in the number of days with negative air temperatures since 1930 is associated with an increase in winter minimum air temperatures (Easterling *et al.* 2000), and the average decrease in the number of ice days over the period 1946–1999 has been 9.2 days (Klein Tank, 2004). The number of maximum consecutive frost days (TN < 0°C) and cold–spell days (unless the statistical significance is not so strong) also demonstrate a decreasing trend. At the same time the climatic indicators of positive temperature extremes, for example the number of summer days (TX > 25°C) and the number of tropical nights (TN > 20°C), demonstrate increasing trends. Besides in the period 1946–1999 in Europe the number of summer days has increased by 4.3 days (Klein Tank, 2004).

Many of the trends in extreme climatic indicators are much stronger in the capital city Rīga, especially in respect to the number of summer days and tropical nights, but also in the case of days with heavy precipitation. This may be due to an increasing urban heat island effect or other specific urban climate effects

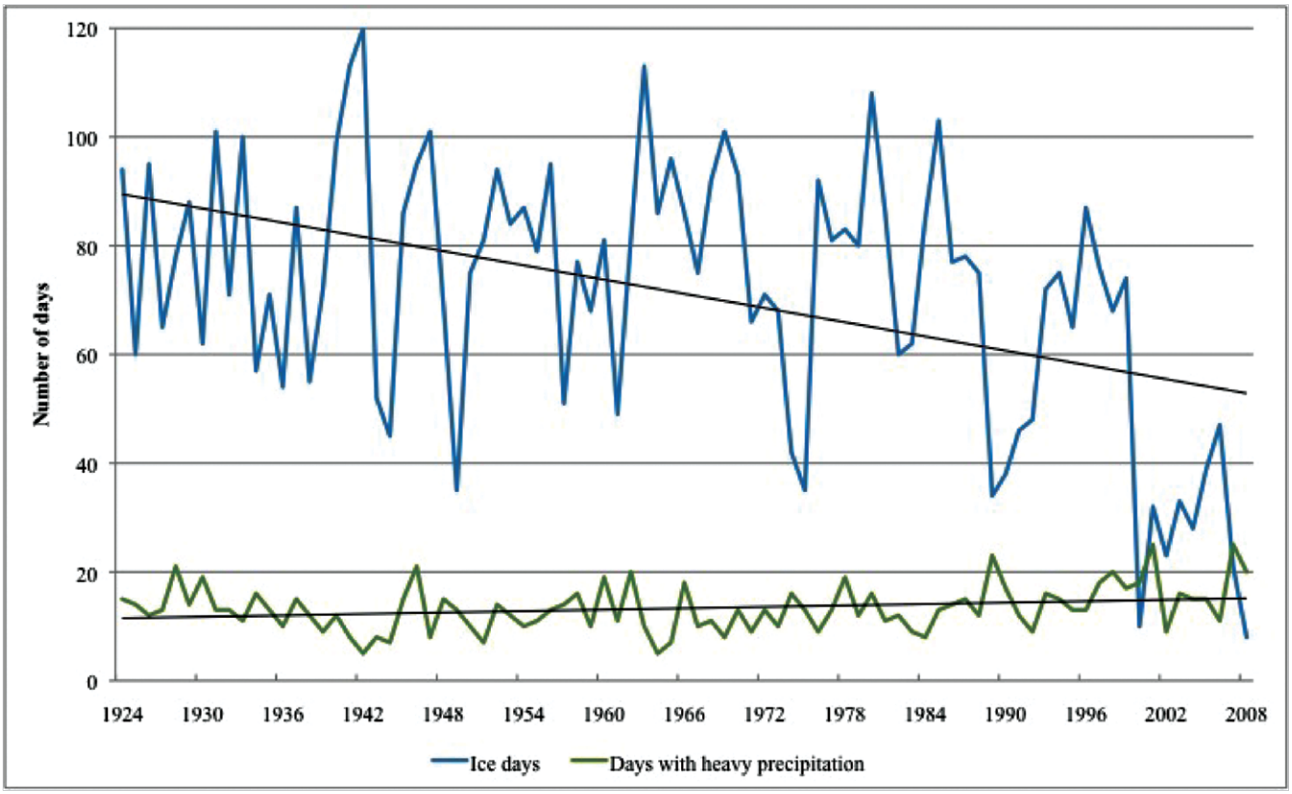


Fig. 3. Trends in the annual number of ice days (daily maximum air temperature < 0°C) and days with heavy precipitation (daily precipitation total ≥ 10 mm) in Liepāja for the period 1924–2008. Compiled by Z. Avotniece, 2010.

(Birkmann *et al.* 2010; Lee, Baik 2010; Matzarakis, Endler 2009).

As well as climate extremes, the mean daily mean temperature, the mean daily minimum temperature and the mean daily maximum temperature all showed changes over the study period. As a result of the changes in climate, the number of growing degree-days and growing season length are increasing (Table 3). There has been a statistically significant increase in the values of mean daily minimum, mean daily maximum and mean daily mean (except Daugavpils where the trend is of no statistical significance) temperatures. The significant increases in the mean values of air temperature have led to changes in the values of mean diurnal temperature range. In Liepāja and Saldus the diurnal temperature range has increased, which could be associated with a greater increase in the daily maximum air temperatures than in daily minimum air temperatures. In the rest of the stations the diurnal temperature range has decreased, besides in Alūksne and Daugavpils this negative trend is of a statistical significance. These trends of changes are in correspondence with the global decrease in the values of diurnal temperature range (Easterling *et al.* 2000). The well expressed warming observed in many countries in Europe is more associated with the increase in the number of days with extremely high air temperatures than with the decrease in the number of days with extremely low air temperatures (Klein Tank 2004).

Table 3. Long-term trends in meteorological events characterizing climate variability (Man-Kendall test statistics).

	TG	TN	TX	DTR	GD4	GSL
Rīga (1924–2008)	**2.72**	**3.31**	**3.46**	-1.01	**2.33**	**2.06**
Liepāja (1924–2008)	**2.13**	**2.13**	**4.05**	0.19	0.93	1.81
Alūksne (1946–2008)	**2.66**	**2.62**	**2.59**	**-2.00**	1.34	1.03
Saldus (1946–2008)	**2.53**	**2.54**	**3.20**	0.42	1.51	0.30
Daugavpils (1946–2008)	1.61	**2.37**	**2.43**	**-3.14**	-0.23	-0.15

TG – mean daily mean temperature, °C; TN – mean daily minimum temperature, °C; TX – mean daily maximum temperature, °C; DTR – mean diurnal temperature range, °C; GD4 – growing degree days (sum of TG > 4°C), °C; GSL – growing season length, days.
The trend was considered as statistically significant at the 5 % level if the test statistic was greater than 2 or less than -2.

The long–term changes (1851–2006) of the number of frost days and summer days, with respect to the deviation from the average value for the reference period (Fig. 4), clearly indicate the increasing trend in the latter part of the observation period (1960–2006). However, at the same time the analysis of long–term changes demonstrates a significant natural variability of climate indicators for the past 150 years.

Impact of large–scale atmospheric circulation processes on extreme climatic events

The characteristics, transformation and trajectories of an air mass reaching certain locations, as well as its specific weather conditions, are mostly determined by the large–scale circulation processes in the atmosphere (Jaagus 2006). The movement of an air mass is mainly dependent on the location of large–scale synoptic systems and the corresponding air flows in the atmosphere (Moberg *et al.* 2003). For these reasons, 18 large–scale atmospheric circulation patterns for the Baltic Sea region were examined in this study. These patterns were derived from modifications of the circulation patterns created by Gerstengarbe and Werner (Hoy, Matschullat 2010) and made available for scientific research by the European Cooperation in Science and Technology Action 733 (COST733 2010). This classification approach is based on predefined circulation patterns determined according to the subjective classification of the so–called Central European *Großwettertypes*. It is assumed that these *Großwettertypes* are defined by the geographical position of major centres of action, and that the location and extent of frontal zones can be sufficiently characterized in terms of varying degrees of zonality, meridionality, and vorticity of the large–scale sea level pressure field over Europe (Beck 2008). With the help of these circulation patterns, the character of the large–scale atmospheric circulation and the types of synoptic systems determining the weather conditions over a certain area can be derived for each day from 1957 to 2002.

Over the period 1957–2002, 925 cases of summer days (daily maximum air temperature >+25°C), 27 cases of tropical nights (minimum air temperature >+20°C) and 7 cases of the mean daily temperature exceeding +25°C were found (Tables 4–6). It was stated above that any one of the circulation types used in this study could be responsible for extremely hot weather conditions in Rīga, but here we find that seven of them can be defined as dominant. Extremely high air temperatures in Rīga can be observed when the weather conditions are determined by a south–westerly and southerly anticyclonic flow, in the case of a high-pressure area being situated over the eastern part of Europe, and with the warmer air flowing into the territory from western Russia. Extremely hot weather in Rīga can also be observed when cyclonic conditions are dominant: south–westerly, southerly and westerly cyclonic flows are associated with the warm sector of a cyclone and an intensive inflow of warm air.

Large–scale atmospheric circulation processes in-

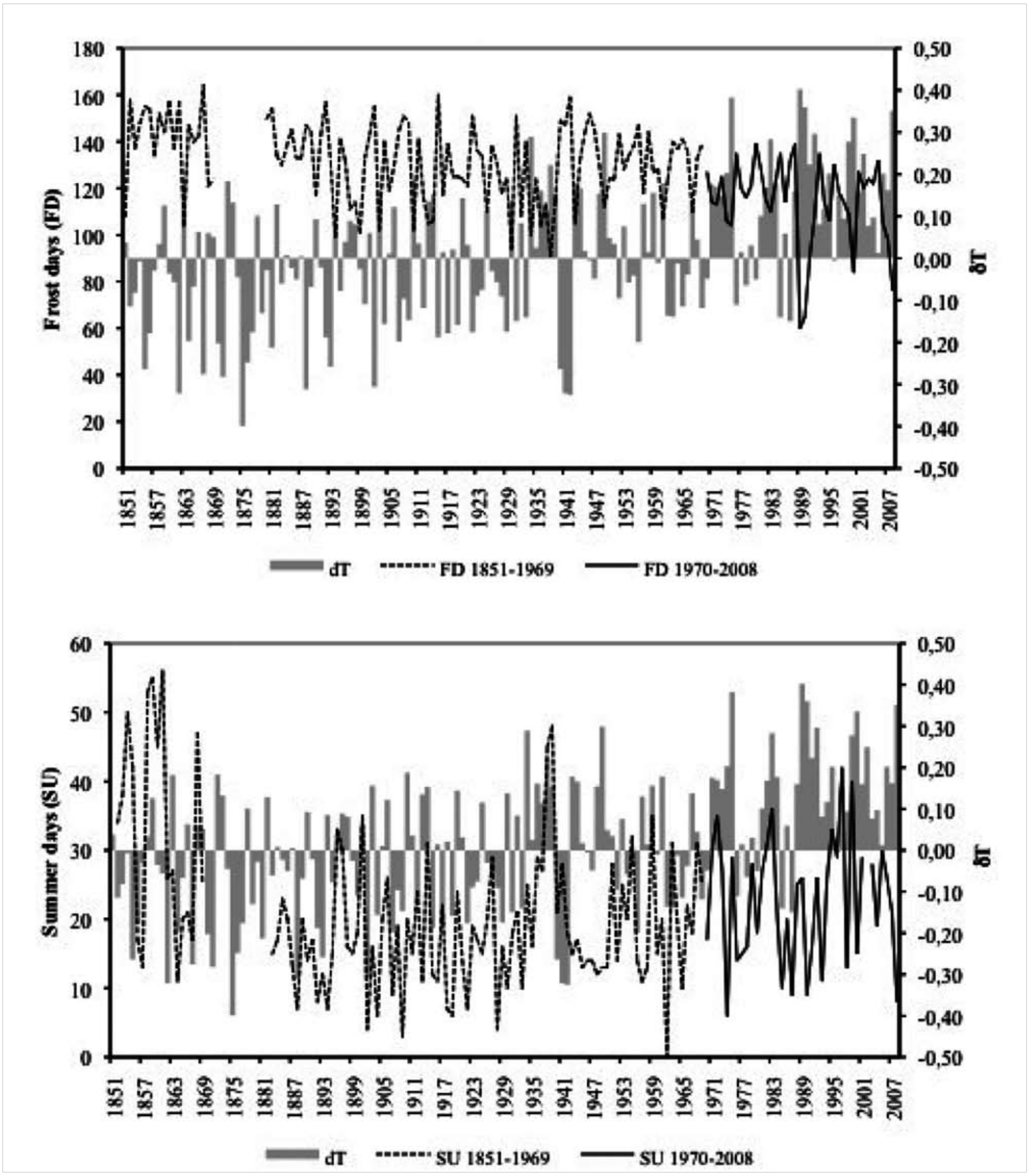


Fig. 4. Long–term trends in the numbers of frost days (FD) (number of days TN < 0 °C) and summer days (HD) (number of days with TX > 25 °C) expressed as their deviations from the average value for the reference period 1960–1990 at Rīga University (1851–2008). Compiled by V. Rodinov, 2010.

fluence extreme precipitation processes (Katz 1999). In the period 1957–2002 there were 732 cases of heavy precipitation (daily precipitation total ≥ 10 mm) in Rīga. The days with heavy precipitation were mainly associated with cyclones, however there were some differences between the synoptic processes responsible for heavy precipitation in the cold and in the warm times of the year: in the summer, heavy precipitation events were mainly associated with convective processes and the cold fronts of cyclones; in winter these events were mostly the result of prolonged precipitation associated with a warm front (Jakimavičius, Kovalenkovienė 2010; Kriaučiūniene *et al.* 2008). However, when the centre of a low-pressure area was situated over Latvia, heavy precipitation was observed at any time of the year (Table 7).

Table 4. Large-scale circulation types during summer days (daily maximum air temperature > +25°C) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	64	6.92
2	West anticyclonic	85	9.19
3	Southwest cyclonic	97	10.49
4	Southwest anticyclonic	104	11.24
5	Northwest cyclonic	29	3.14
6	Northwest anticyclonic	35	3.78
7	Central Low	24	2.59
8	Central High	47	5.08
9	North cyclonic	15	1.62
10	North anticyclonic	23	2.49
11	Northeast cyclonic	16	1.73
12	Northeast anticyclonic	28	3.03
13	East cyclonic	41	4.43
14	East anticyclonic	66	7.14
15	Southeast cyclonic	38	4.11
16	Southeast anticyclonic	78	8.43
17	South cyclonic	50	5.41
18	South anticyclonic	85	9.19

Table 5. Large-scale circulation types during days with the daily mean air temperature > +25° in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	2	28.57
3	Southwest cyclonic	4	57.14
16	Southeast anticyclonic	1	14.29

Table 6. Large-scale circulation types during tropical nights (daily minimum air temperature > +20°C) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	2	7.41
3	Southwest cyclonic	3	11.11
4	Southwest anticyclonic	1	3.70
6	Northwest anticyclonic	1	3.70
7	Central Low	1	3.70
12	Northeast anticyclonic	1	3.70
13	East cyclonic	1	3.70
14	East anticyclonic	7	25.93
15	Southeast cyclonic	1	3.70
16	Southeast anticyclonic	4	14.81
17	South cyclonic	4	14.81
18	South anticyclonic	1	3.70

Table 7. Large-scale circulation types during days with heavy precipitation (daily precipitation total ≥ 10 mm) in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	75	10.25
2	West anticyclonic	16	2.19
3	Southwest cyclonic	64	8.74
4	Southwest anticyclonic	19	2.60
5	Northwest cyclonic	59	8.06
6	Northwest anticyclonic	21	2.87
7	Central Low	81	11.07
8	Central High	7	0.96
9	North cyclonic	96	13.11
10	North anticyclonic	28	3.83
11	Northeast cyclonic	70	9.56
12	Northeast anticyclonic	30	4.10
13	East cyclonic	50	6.83
14	East anticyclonic	24	3.28
15	Southeast cyclonic	31	4.23
16	Southeast anticyclonic	10	1.37
17	South cyclonic	44	6.01
18	South anticyclonic	7	0.96

Table 8. Large-scale circulation types during days with heavy summer (June–August) precipitation in Rīga for the period 1957–2002.

Circulation type	Description	Number	%
1	West cyclonic	31	10.37
2	West anticyclonic	6	2.01
3	Southwest cyclonic	27	9.03
4	Southwest anticyclonic	9	3.01
5	Northwest cyclonic	25	8.36
6	Northwest anticyclonic	7	2.34
7	Central Low	42	14.05
8	Central High	2	0.67
9	North cyclonic	29	9.70
10	North anticyclonic	6	2.01
11	Northeast cyclonic	36	12.04
12	Northeast anticyclonic	9	3.01
13	East cyclonic	23	7.69
14	East anticyclonic	13	4.35
15	Southeast cyclonic	10	3.34
16	Southeast anticyclonic	7	2.34
17	South cyclonic	14	4.68
18	South anticyclonic	3	1.00

Due to the differences in the processes determining the weather conditions favourable to the formation of heavy precipitation (Jakimavičius, Kovalenkovienė 2010) it was necessary to choose a definite season for the analysis. For this purpose the number of days with heavy precipitation for each month during the period 1957–2002 was calculated. The number of days with heavy precipitation was considerably greater in June,

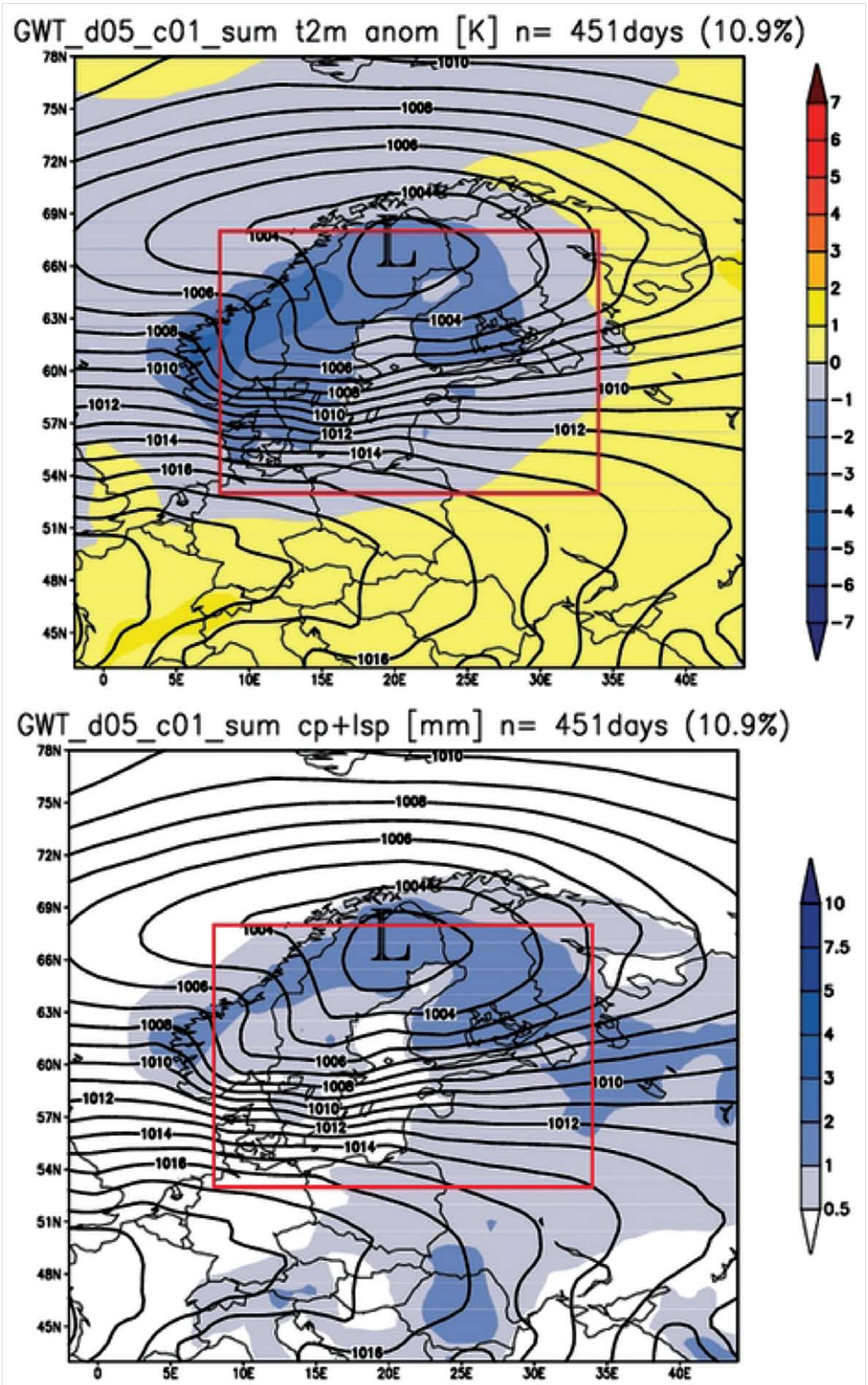


Fig. 5. Circulation type No 1 — westerly cyclonic air flow.

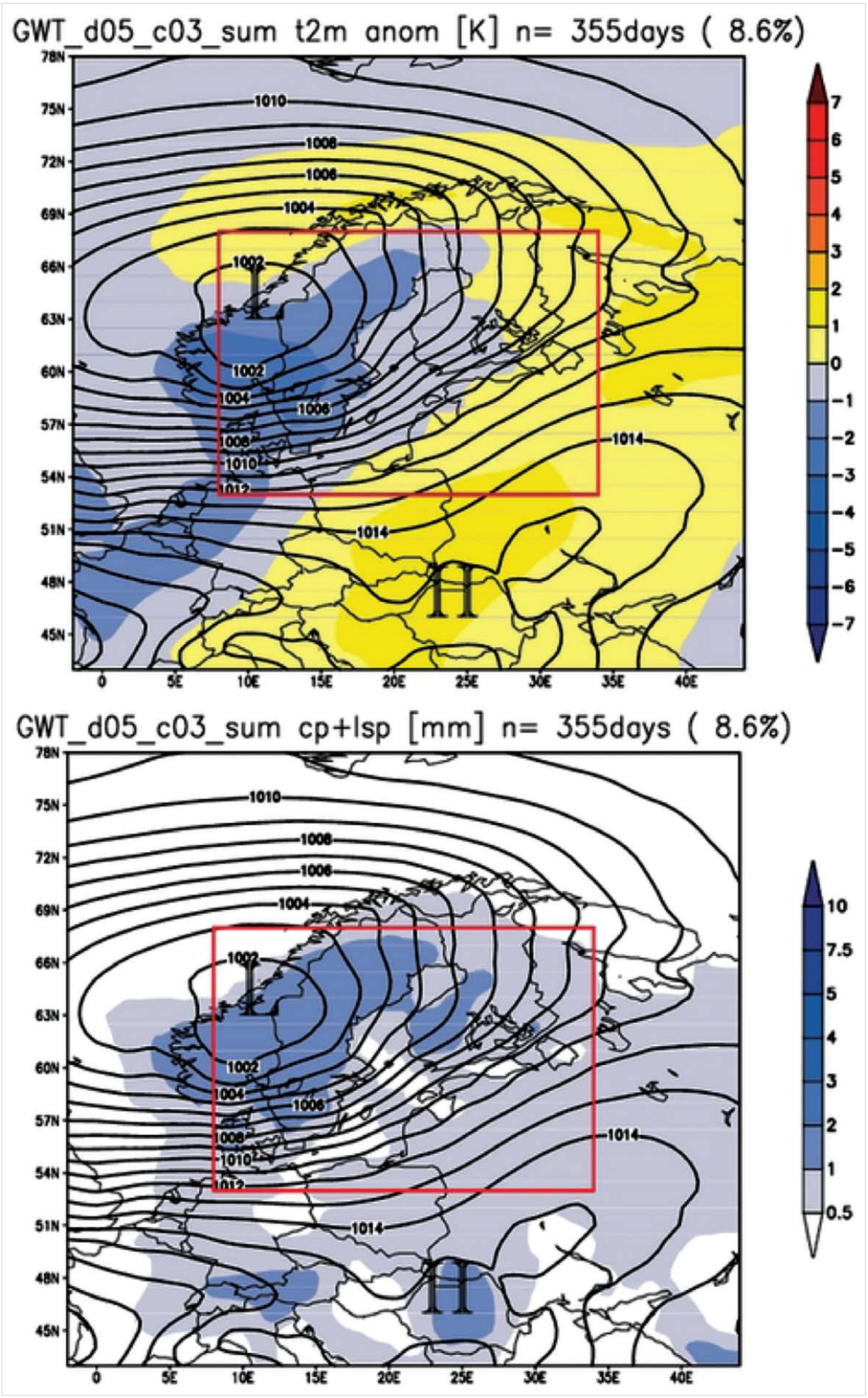
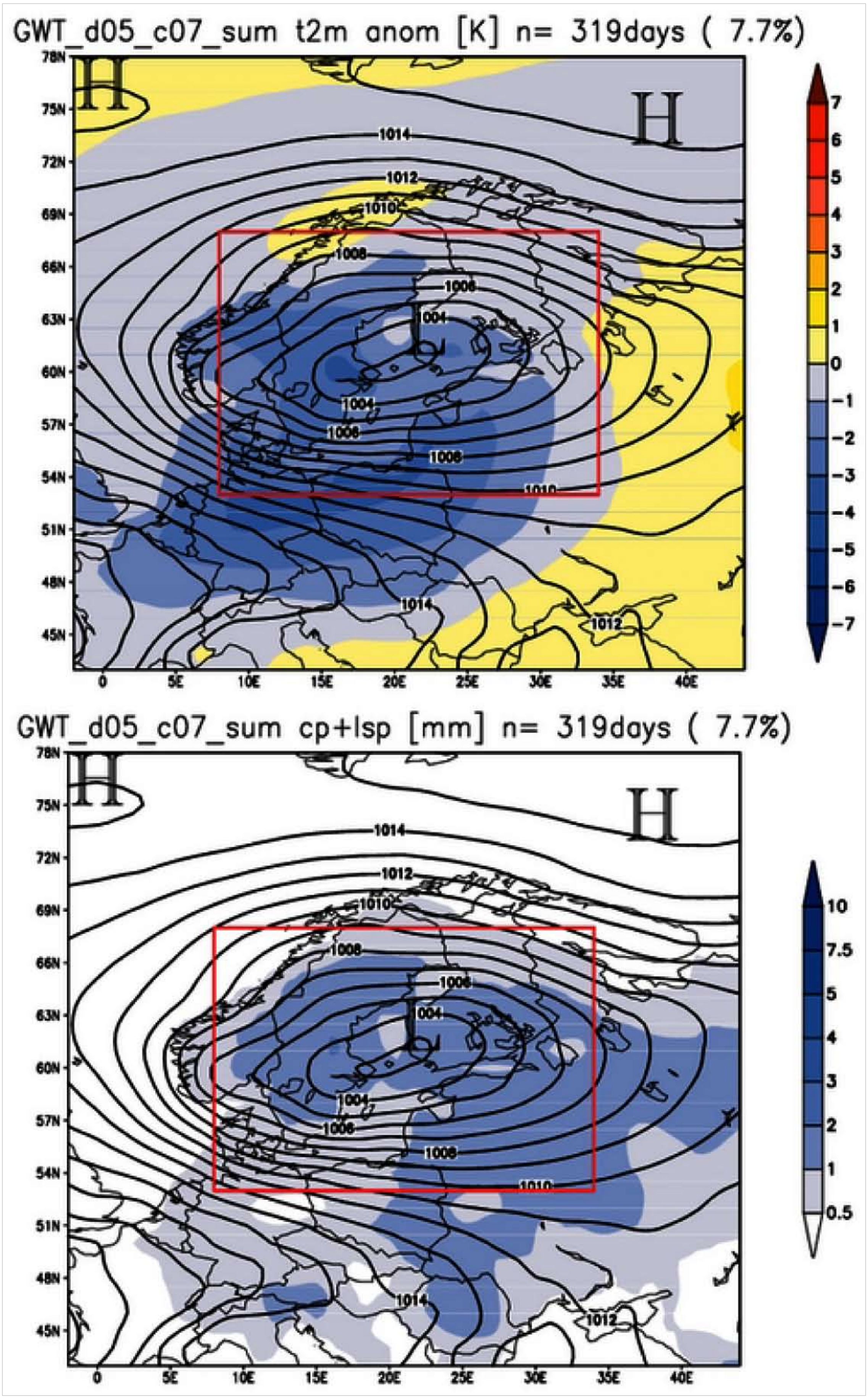


Fig. 6. Circulation type No 3 — southwesterly cyclonic air flow.



GWT_d05_c07_sum t2m anom [K] n= 319days (7.7%)

GWT_d05_c07_sum cp+lsp [mm] n= 319days (7.7%)

Fig. 7. Circulation type No 7 – air flow in the centre of a low.

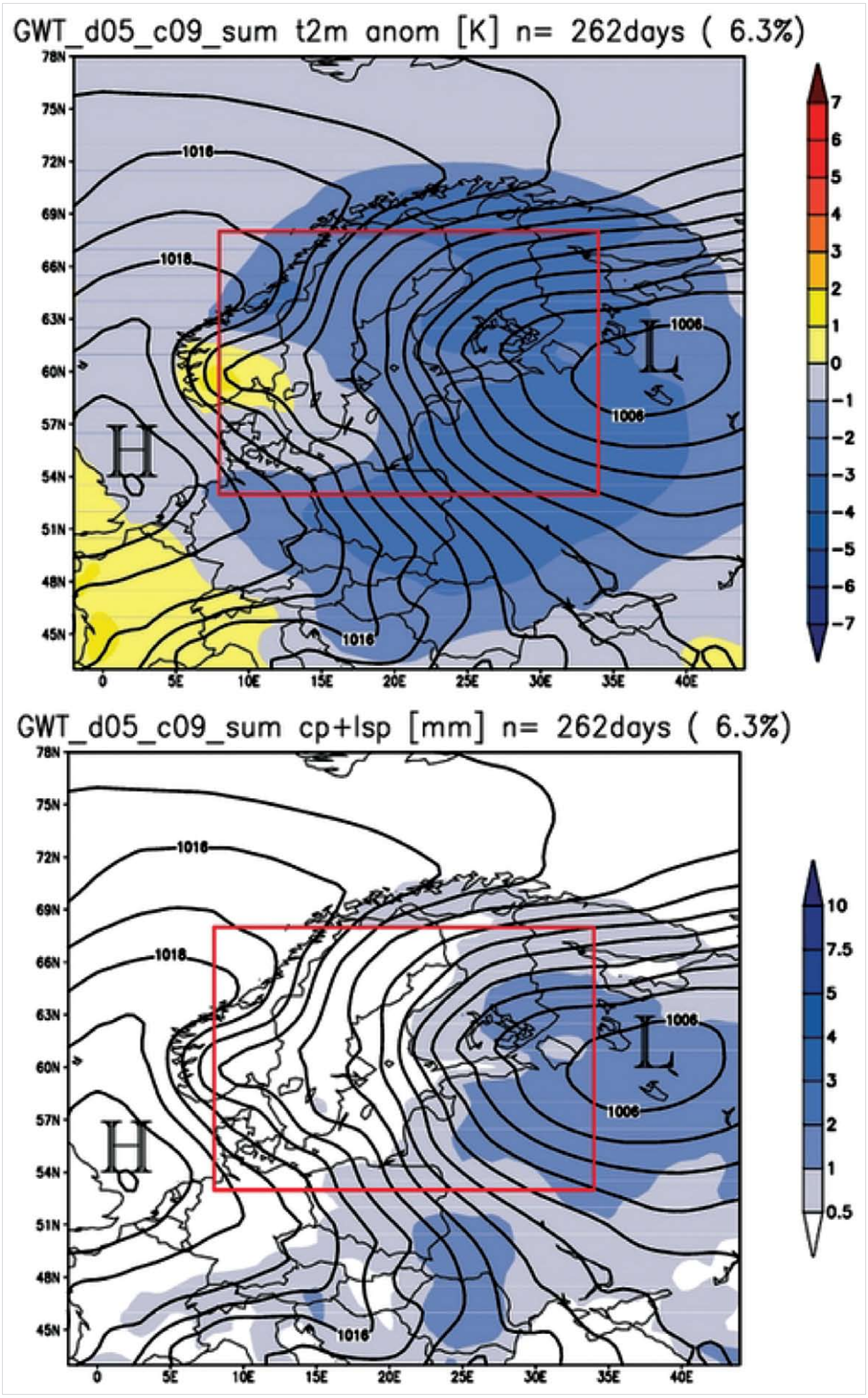


Fig. 8. Circulation type No 9 – northerly cyclonic air flow.

July, August, September and October and therefore summer season was chosen for further analysis.

Conditions favourable for the occurrence of heavy precipitation in summer were also mostly associated with cyclonic activity (Table 8). The dominant synoptic conditions characterising days with heavy precipitation in Rīga were westerly, south–westerly (see Figs 5, 6) north–easterly and northerly (Fig. 8) cyclonic flows, and additionally the circulation of air in the centre of a low-pressure area (Fig. 7). In the cases of westerly and south–westerly flows the centre of the low was situated over Scandinavia, and heavy precipitation in Rīga was brought by the weather fronts, especially the cold front. When there was a northerly and north–easterly cyclonic flow, the centre of the low was situated over the western part of Russia, and precipitation in Latvia was associated with the convection caused by the advection of cold air. However, the predominant conditions for the occurrence of heavy precipitation in Rīga occurred when the centre of a low was situated over the region, when the strong convective updrafts intensify the formation of clouds and precipitation.

CONCLUSIONS

There have been significant changes in the extreme climate events in Latvia in the past ~80 years. The trend analysis of extreme climate event indicators showed a significant increase in the number of meteorological events associated with an increased summer temperature (for example, the number of summer days and tropical nights) and a decrease in the number of events associated with extreme temperature events in winter (number of ice days and frost days). Due to the decreasing number of cold days under a changing climate, the length of the growing season has increased. There were also increases in the number of days with heavy precipitation and in the intensity of heavy precipitation. In this study we found the trends of extreme climate event indicators to be much stronger in the capital city Rīga, which could be associated with the impact of the urban heat island and the effects of the specific urban climate.

As a driving factor associated with extreme climate events, large–scale atmospheric circulation processes were identified and the dominant circulation types influencing extreme precipitations and summer temperature extremes were found. Weather conditions are mainly dependent on the location of large–scale synoptic systems and the corresponding air flows in the atmosphere, wherewith during the analysis we found some regularities between the large–scale atmospheric circulations and the weather conditions on the boundary layer. Though any of the 18 atmospheric circulation types can be the cause of extremely high temperatures and heavy precipitation in Rīga, the most common synoptic situations for the occurrence of extremely high air temperatures can be found in the conditions of south–westerly, southerly anticyclones flows causing the advection of warm air from western Russia and in the cases of the warm sector of a cyclone being situated over the territory – in the conditions of westerly, south–westerly cyclonic flows. Extreme precipitation events during the summertime were mainly associated with cyclonic activity, and the predominant conditions of the occurrence of heavy precipitation were found during the days when the centre of a low-pressure area was situated over the region.

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