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MESOCLIMATIC ANALYSIS OF NON-PRECIPITATION PERIODS IN LITHUANIA

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Highlights

- In general, non-precipitation periods (NPP) of various durations (≥5 days) recurred on average 123 times per decade during the study period.
- NPP recurred most often in the spring months, as this is associated with a higher number of days with anticyclonic processes.
- Based on the growth trend of NPP of various durations in Lithuania from 1990 to 2020, in the last decade NPP have become more frequent.

Abstract. In this paper, climatic analysis of non-precipitation periods (NPP) in Lithuania was performed, assessing their recurrence and trends from 1991 to 2020 using two criteria – when precipitation was <0.1 mm per day all year round and when precipitation was <1 mm per day during the warm period – and analysing typical atmospheric circulation in the middle troposphere and sea level during the longest NPP (≥20 days). From 1990 to 2020, NPP were most frequent in the Middle Lithuania lowland (according to both criteria), in Southern and South-western Lithuania (daily precipitation <0.1 mm) and in part of Eastern Lithuania (daily precipitation <1 mm), and least frequent in part of the Samogitian highland and in part of the Baltic Highlands (according to both criteria). NPP recurred most often in the spring months, as this is associated with a higher number of days with anticyclonic circulation and powerful anticyclones recorded. Based on the growth trend of NPP of various durations in Lithuania from 1990 to 2020, in the last decade NPP have become more frequent, but only a few stations have shown reliable trends. Analysis of the atmospheric circulation during the longest NPP (≥20 days) showed that NPP were mostly determined by the Azores anticyclone ridge or anticyclone over Northern, Central or Eastern Europe regardless of the time of year. The atmospheric circulation conditions for the formation of long NPP varied more in the cold period than in the warm period, but NPP often lasted ≥20 days only at one or a few stations.

Keywords: daily precipitation, dry period, atmospheric circulation, warm period, cold period, geopotential height, sea level pressure.

Introduction

The water balance of soil is mainly determined by the amount of precipitation and the intensity of evaporation, which becomes particularly significant during long periods without precipitation. They involve intense drying of the soil profile, which may lead to meteorological drought and, subsequently, soil drought (Gomboš et al., 2019; Biniak-Pierog et al., 2020). Processes in which the soil absorbs moisture directly from the atmosphere can only partially compensate for the lack of precipitation (Dawid & Janik, 2018).

Various factors affecting droughts and dry periods also lead to different trends in their recurrence. According to the data of 1950–2015, humidity changes in Europe have been ambiguous: in southern Europe, there has been a tendency towards increasing drought, while in northern Europe, there has been a tendency towards increasing humidity (Spinoni et al., 2017). Considering the period of 1902–2010, the Mediterranean had 10 out of the 12 driest winters in the cold season in the last 20 years alone (Hoerling et al., 2012). In the southern European countries, the number and intensity of droughts have also increased (Brunetti et al., 2002; Güner Bacanli, 2017). Droughts during the period between 1951 and 2012 were most frequent in northern and eastern Europe from the early 1950s to the mid-1970s, and in southern and southwestern Europe between 1990 and the present (Spinoni et al., 2015).

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In the Baltic Sea region, the number of wet periods and days with precipitation has increased, while the average amount of precipitation over a certain period of time has decreased (Rutgersson et al., 2014).

Due to climate change and other natural and anthropogenic factors, changes in the distribution of precipitation over time and space will inevitably become even more pronounced in the near future. Changes in humidity in Europe have different trends. Drought is projected to increase in southern Europe and parts of eastern and central Europe, and humidity is expected to increase in northern Europe and parts of western and central Europe (Spinoni et al., 2017). In the Baltic Sea region, precipitation is expected to increase in the cold period of 2071–2100, and although it is expected to increase in the northern part of the region in the summer, it will decrease in the southern part (Kjellström & Ruosteenoja, 2007; Christensen & Kjellstrom, 2018). In the last decades of this century, further drought growth in the Baltic Sea region is modelled, and territorial disparities between the wetter north and the drier south will widen further (Rimkus et al., 2012). In the 21st century, the Nemunas River basin will become wetter in April–May and drier in June–August, with the largest increase in drought in the southern and central part of the basin (Stonevičius et al., 2018). Although the humidity in Lithuania and part of the Baltic Sea region will increase, the probability of short-term droughts will remain high in the summer. The uneven distribution of precipitation in Lithuania will increase even more in the future, especially during the warm season, which will increase the probability of recurrence of droughts, long dry periods and long rainy seasons (Rimkus et al., 2020).

Precipitation deficit is one of the main causes of meteorological droughts (Dai & Zhao, 2017). It can be caused by a variety of factors, both natural and anthropogenic. Droughts and dry periods are closely linked to changes in atmospheric circulation: the El Nino–Southern oscillation (ENSO) (Dai, 2011; Dai & Zhao, 2017) in the Northern Hemisphere, and mainly the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO) (Hurrell, 1995; López-Moreno & Vicente-Serrano, 2008; Rimkus et al., 2014) atmospheric circulation patterns in the Scandinavian region (SKAND) (Sousa et al., 2011). The various phases of these oscillations lead to long-term regional precipitation anomalies, with some regions suffering simultaneously from droughts and others from heavy rains and floods.

High-pressure baric formations are most commonly associated with droughts and long dry periods (Fleig et al., 2011). Droughts in the Baltic Sea region are usually caused by anticyclonic circulation and are associated with negative NAO/AO phases (Rimkus et al., 2014). In the last decades of the 20th century and at the beginning of the 21st century, the world started experiencing sudden global warming. The amount of water vapor in the atmosphere has increased (Hodnebrog et al., 2019), however, the impact of global warming on precipitation is unclear. The amount of precipitation has declined in tropical and subtropical latitudes and has increased at high latitudes; this trend is particularly pronounced in the Northern Hemisphere (Intergovernmental Panel on Climate Change, 2021). Although the amount of precipitation is not significantly affected by global warming, the rising temperature increases the proportion of liquid and decreases the proportion of solid (crystalline) precipitation. Global warming is increasing climate extremes, and the distribution of precipitation over time is changing, with many regions experiencing an increase in the proportion of heavy rainfall (Shen et al., 2018; Asmala et al., 2021; Chen et al., 2021).

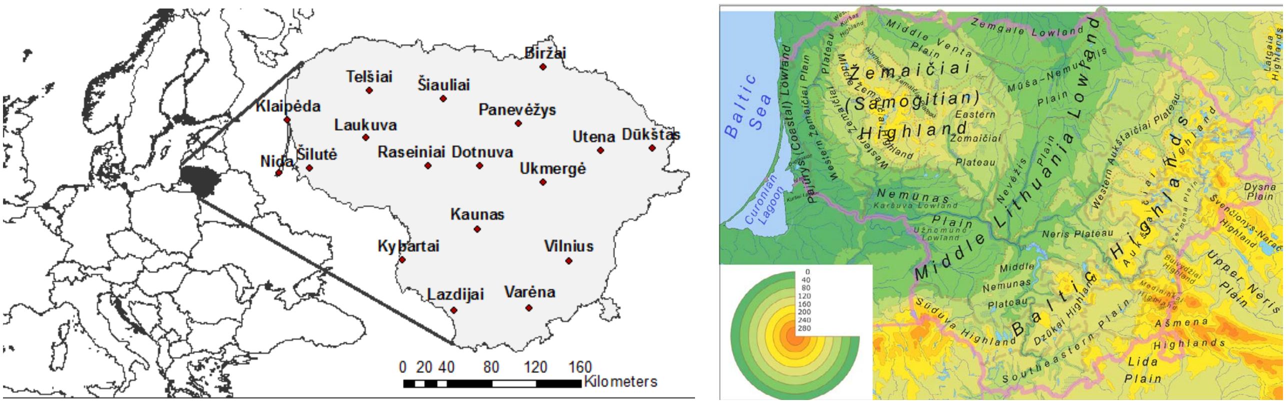
Drought has become particularly important in recent decades in the face of climate change. Climate extremes increase with increasing air temperature, with more precipitation during rainfall, leading to longer dry periods (Rahmstorf & Coumou, 2011). Thus, precipitation extremism is increasing in both directions of the precipitation distribution: both drier and rainier years have become more frequent than before (Christensen & Kjellström, 2018; Hänsel, 2020). Therefore, it is important to determine not only the extremes of precipitation, but also the recurrence of NPP and other climatic indicators. This would allow adequate decisions to be made for the management and development projects of various water-intensive industries, water management and the environment.

The aim of this work was to perform a climatic analysis of the recurrence of NPP in the territory of Lithuania in 1991–2020. The main tasks of the work were to compile the calendar of NPP in 1990–2020, to determine the recurrence of NPP of different durations during the research period and in different months and to evaluate their tendencies, and to analyse atmospheric circulation conditions typical for the longest NPP (≥20 days).

1. Materials and methods

1.1. Study area

Lithuania is located on the eastern shore of the Baltic Sea, in the Baltic region of Europe. Lithuania is at the edge of the North European Plain, and the country's landscape has been formed by glaciers of the last ice age. There are lowlands in the western and central parts of the country, the rest of the area is covered by highlands (Figure 1b). Lithuania has a moderately cold climate with snowy winters, as almost the whole study area belongs to Dfb type under the Köppen climate classification, only a narrow stretch near the sea belongs to Cfb type (Chen & Chen, 2013). In Lithuania the mean air temperature is about 6–7 °C, with highest values in the Curonian Spit and seashore (7,4–7,6 °C), and the lowest in the eastern part of the country (5.8 °C). The mean precipitation in Lithuania is about 675 mm, with highest values in the western part (907 mm) and lowest in the central part of the country (572 mm). Up to 50% of the annual precipitation falls during the warm season due to sudden formation of storms, squalls, thunderstorms and heavy rain events; meanwhile during cold season less intense precipitation takes



a) b)

Figure 1. a – Lithuanian meteorological stations, whose precipitation data were used in this study, b – topographic map of Lithuania (modified from Wikipedia, 2006)

place (mostly drizzle/freezing drizzle, light snow, sleet or rain). The characteristics of climate here mainly depend on atmospheric circulation patterns and advection of air masses. In Lithuania mid-latitude air masses are the most common (80%), while arctic and tropical air masses are recorded less often (respectively 18% and 2%).

1.2. Data and methods

The initial data used in the work were obtained from the archives of the Lithuanian Hydrometeorological Service (LHMT). The initial data include daily precipitation measurement data for 1991–2020 from 18 Lithuanian meteorological stations (MS) (Figure 1).

In this work, NPP (all abbreviations used in this study are listed in a Table 1) have been identified as periods of at least 5 consecutive days when precipitation did not exceed 0.1 mm per day. To assess the total recurrence of NPP and the recurrence of NPP of various durations, they were divided into periods of 5–9, 10–14, 15–19 and ≥20 days. During the warm period (April–October), NPP were identified by another criterion: when the daily precipitation did not exceed 1 mm using the same time intervals. After identifying the start and end dates and duration of NPP of different durations, their recurrence in 1991–2020 at 18 Lithuanian MS was estimated. Using the tool from ArcMap for interpolation called Spline, maps of NPP recurrence of various durations in the territory of Lithuania were created.

Recurrence of NPP of different durations in different months was also determined. If a period began in one month and ended in another, it was assigned to the month that had the most days in the period. If the NPP days were the same in both months, then it was assigned to the month in which it started. The obtained results allowed estimating which months and for how long NPP were mostly recorded at the Lithuanian MS in 1991–2020.

To determine the trends of NPP recurrence in 1991–2020, the average annual recurrence of NPP for each decade was calculated and bar charts were created according to both NPP identification criteria (<0.1 mm per day all year round and <1 mm per day during the warm period) for different decades. A chronological picture of the average annual recurrence of NPP in 1991–2020 for all stations has been compiled. The annual change and change in NPP over the 30-year study period were determined, and the statistical reliability of the trends was assessed using Student's test.

The longest NPP (≥20 days) – a total of 34 from 1991 to 2020 (https://psl.noaa.gov/data/composites/day/) – were classified according to the long-term NPP-typical atmospheric circulation processes. The 34 NPP were grouped into 4 categories according to processes at the 500 mbar level – that is, determining the baric structure influencing the territory of Lithuania. Atmospheric circulation was analysed separately for the warm (April–October) and cold (November–March) periods. If NPP continued in the transition months between the warm and cold periods, then they were assigned to the period with more days.

Table 1. Abbreviations used in this study

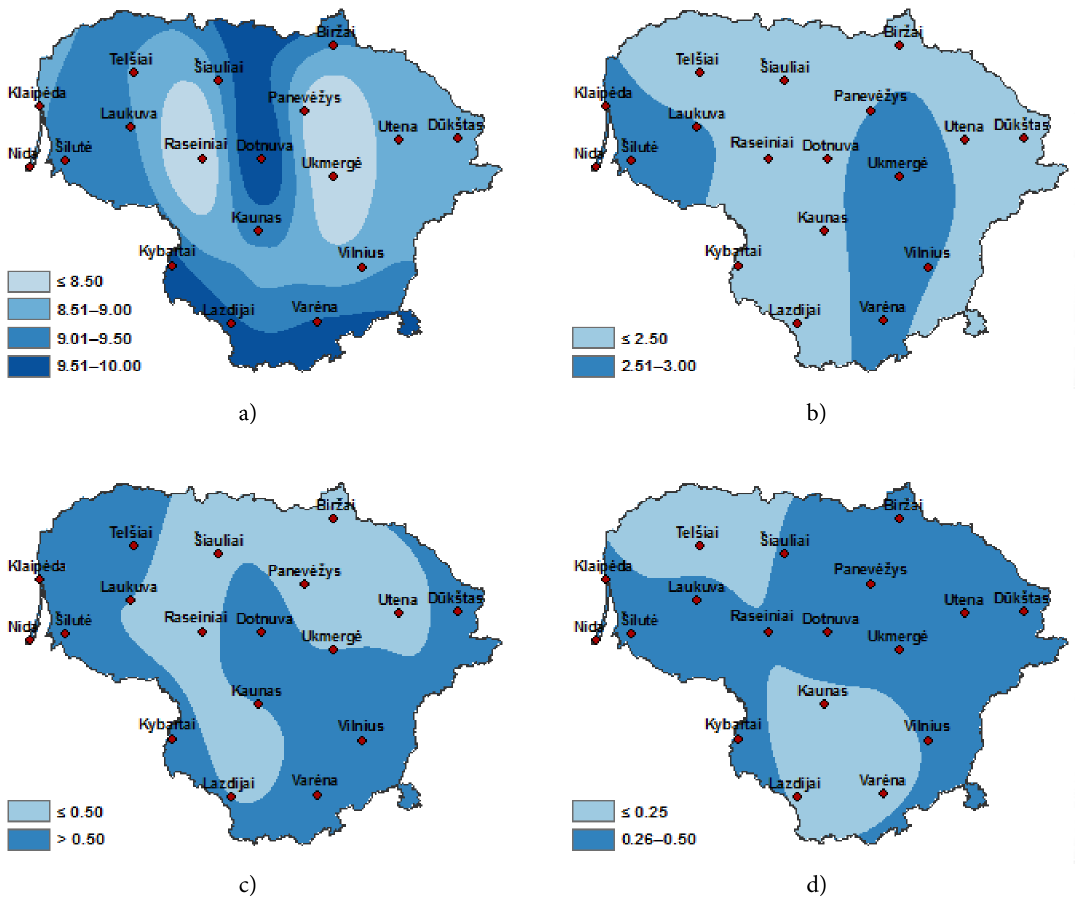
Abbreviation	Explanation
AO	Arctic Oscillation
ENSO	El Nino–Southern Oscillation
NPP	Non-precipitation period
MS	Meteorological station
NAO	North Atlantic Oscillation
SKAND	Scandinavian pattern

2. Recurrence of non-precipitation periods

2.1. Recurrence all year round

In 1991–2020, short-term (5–9 days) NPP (<0.1 mm per day) recurred most often – on average 90 times per decade (9.02 per year). Their highest recurrence was registered in Central and Southern Lithuania – on average 95–100 times per decade (Figure 2a). The recurrence of such NPP was lower than the average in most of Lithuania (the eastern outskirts of the Samogitian highland and the western part of the Baltic Highlands) – on average 80–85 times per decade. Uneven recurrence of short NPP could be caused by various factors, such as the lower average annual precipitation in the Middle Lithuania lowland, where the western air flows from the Samogitian highland are adiabatically warming, which may lead to greater recurrence of NPP. NPP of 10–14 days repeated on average 24–25 times per decade (2.45 times per year), mostly in parts of Eastern and Western Lithuania – up to 30 times per decade. These NPP were recorded least often in the Samogitian highland – on average 20–21 times per decade. As air mass transforms going from the sea into the land, convection processes intensify in the highlands and more precipitation falls; meanwhile, when the air mass descends into lowlands, the air warms adiabatically, resulting in lower precipitation (Figure 2b).

Longer (15–19 days) dry NPP in 1991–2020 recurred even less frequently – 5–6 times per decade. NPP of this duration were more frequently recorded in Western-Southwestern and Eastern Lithuania, and partly in Central Lithuania, with the highest recurrence in the Curonian Spit, reaching up to 9 times per decade (Figure 2c). This may be due to the stable stratification of the atmosphere prevailing above the sea during the warm season. NPP lasting 15–19 days were least frequent in North-eastern Lithuania and in the eastern part of the Samogitian highland – on average 3–4 times per decade. The longest NPP (≥20 days) recurred only 3 times per decade on average. However, long-term NPP recurrences were most frequent at Dotnuva MS – on average 5 times per decade – and



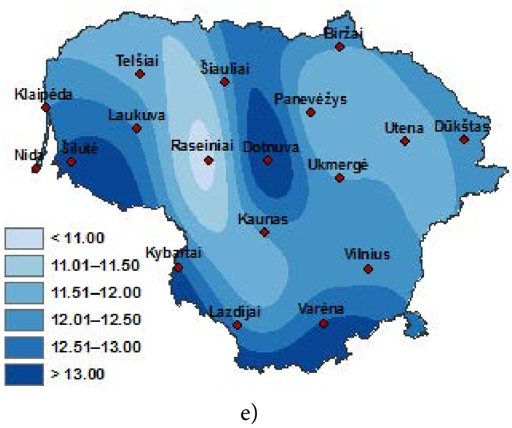
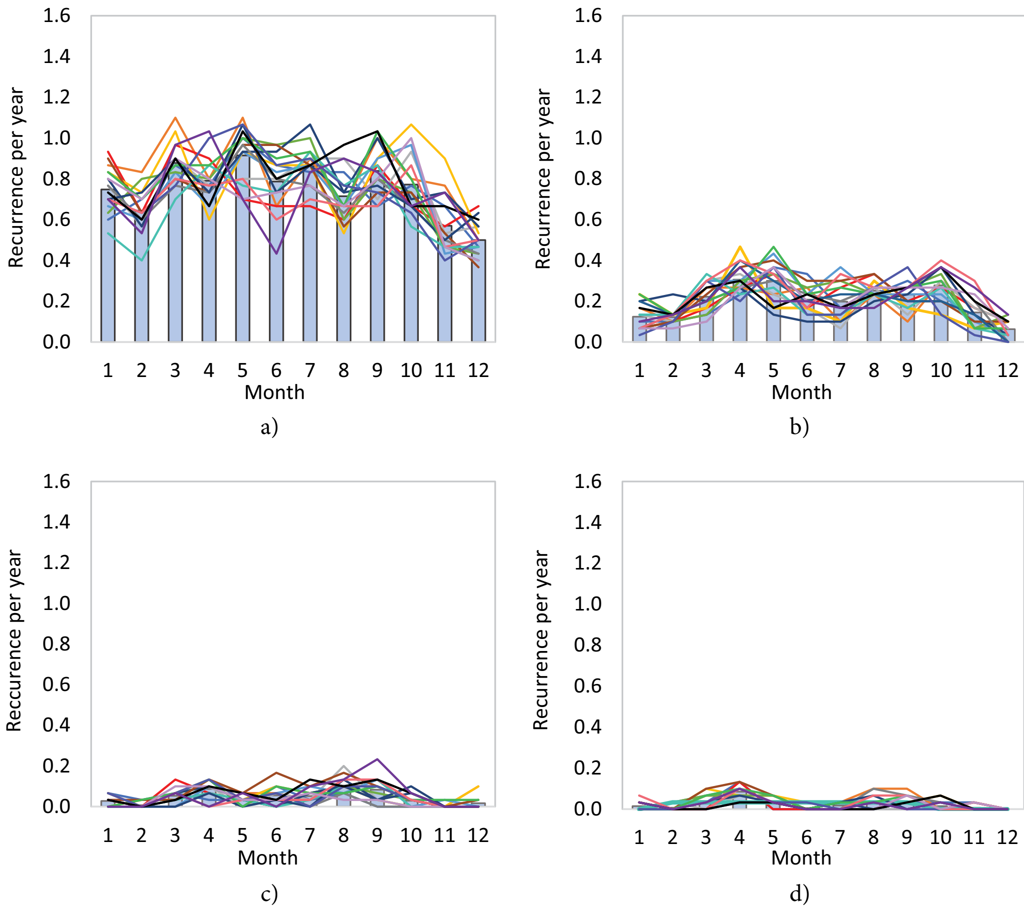


Figure 2. Average recurrence of non-precipitation periods (precipitation <0.1 mm per day) of different durations (a – 5–9 days, b – 10–14 days, c – 15–19 days, d – ≥20 days and e – the total of all durations) per year in the territory of Lithuania based on interpolated precipitation data of Lithuanian meteorological stations for all months in 1991–2020

least frequent at Telšiai and Kaunas MS – once per decade (Figure 2d). Such a rare recurrence of long NPP could be attributed to the frequent air transport from the west and north-west and the influence of the Samogitian highland. Meanwhile, in Kaunas there is less precipitation on average per year than in the surrounding hilly areas.

In general, NPP of various durations (≥5 days) recurred on average 123 times per decade during the study period. In 1991–2020, NPP of various durations were recorded most often in Central and South-western Lithuania – 130–135 times per decade (Figure 2e). The largest number of NPP at Dotnuva MS can be explained by the fact that this station is in the Middle Lithuania lowland, specifically in the precipitation shadow zone, so the air masses coming from the west and the north-west come here with altered properties. As the air mass moves farther, it transforms and its humidity decreases. Most of the precipitation falls in Western Lithuania, on the coast and in the western part of the Samogitian highland. NPP of various durations were recorded less frequently in the Samogitian highland and North-eastern Lithuania – on average 108–118 times per decade, and with lowest recurrence at Raseiniai MS.

When analysing the recurrence of NPP in different months from 1991–2020, short (5–9 days) NPP recurred most often in May – at 8 out of 18 stations (Figure 3a) – and also in the months around May at some stations. The second most common NPP recurrence was



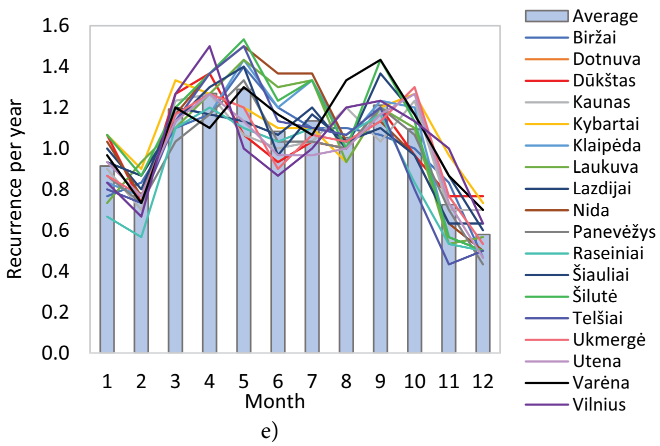


Figure 3. Distribution of the average recurrence of different non-precipitation periods (precipitation <0.1 mm per day) per year in different months of the year in Lithuanian meteorological stations: a – 5–9 days, b – 10–14 days, c – 15–19 days, d – ≥20 days and e – the total of all durations

the beginning of autumn, usually in September and October (most often in October – at 5 MS), because at that the processes of cloud formation typical of summer still prevails (as well as the intensity and duration of precipitation). In the cold season, short NPP were less common, and the fewest NPP were recorded in December at almost all MS. Although more precipitation falls during the warm season, it often falls as high-intensity convection precipitation, which results in more frequent short-term NPP in summer. There is usually less precipitation in winter, but it is more frequent and usually of low intensity; hence, there were fewer NPP recorded during the winter months (Figure 3a). Longer (10–14 days) NPP also showed several recurrence peaks – they occurred most often in April and May (at 5 and 8 stations, respectively) and October (at 7 stations) (Figure 3b). A maximum NPP recurrence in October was recorded mainly in the Middle Lithuania lowland and Southern Lithuania, with peaks in the spring months in most of Lithuania. Two recurrence maxima were recorded at 4 MS (Laukuva, Telšiai, Ukmergė and Vilnius): one in spring and the other in October. The spring NPP peaks are associated with an increase in the number of days with anticyclonic processes in the Baltic Sea region (the peak is reached in May). In October, anticyclonic activity prevails in Lithuania, the pressure peak is reached due to the influence of the Azores High, as its ridge reaches Lithuania; therefore, there are more NPP. During the cold season, the number of such NPP declines due to increased cyclonic activity.

Longer (15–19 days) NPP were most frequent in April, August and September: the only or one of several recurrence peaks was recorded at 8, 7 and 5 stations, respectively (Figure 3c). April recurrence peaks are associated with an increase in the number of days with anticyclonic circulation and a decrease in the recurrence of deep cyclones. Due to the longer duration and infrequent recurrence, there was greater scatter of recurrence peaks of NPP lasting 15–19 days among different months, with 7 of the 18 MS having 2–3 recurrence peaks. NPP tended to be least common in the cold season, especially in the winter months. The longest NPP (≥20 days) showed the most pronounced recurrence peak in April. During the study period, long NPP were most frequent in March–May, especially in April: 14 of the 18 stations recorded the only or one of several recurrence peaks in April (Figure 3d). At several other stations in Central and Southern Lithuania, long-term NPP were often repeated in August–October. Long NPP, like shorter ones, rarely recurred in the cold season, when cyclonic processes prevail in Europe and the most active cyclogenesis centre is in Iceland. In general, NPP of various durations occurred most often from spring to autumn (March–October), and less frequently in late autumn and winter (November–February) (Figure 3e). Nevertheless, the greatest recurrence of NPP of various durations was in spring (April and May): it reached up to 15 times per decade at Nida, Telšiai, Dotnuva and Vilnius MS in May. The lowest frequency of NPP at almost all stations (17 of 18) was in December.

2.2. Recurrence during the warm period

The recurrence of NPP was also estimated when the daily precipitation was <1 mm during the warm period (April–October). Such a criterion has been applied for several reasons: 1) in the warm season there is more precipitation than in the cold season (in summer and autumn in Western Lithuania and summer in the rest of Lithuania); 2) low intensity (<1 mm) precipitation during the warm period has low ecological efficiency (Huxman et al., 2004). In 1991–2020, short NPP (5–9 days) recurred on average 67–68 (67.4) times per decade. Such periods were repeated most often in North-western Lithuania (except Klaipėda MS) and in South and South-eastern Lithuania – on average 72–74 times per decade (Figure 4a). In Western Lithuania, short NPP repeated frequently, a phenomenon related to the air mass on the seashore moving rapidly due to the high acceleration gained from the sea, which means that the rains here usually have a high intensity but a short duration during the warm season. The lowest recurrence of NPP occurred on the south-eastern slope of the Samogitian highland and in Central Lithuania – on average 62–64 times per decade. A low recurrence of short NPP in Central Lithuania may be caused by a slowdown and transformation of the air mass, which results in precipitation that is less intense, but of a longer duration.

In 1991–2020, longer NPP (10–14 days) recurred on average 24–25 times per decade in Lithuania (2.47 times per year). They recurred most often in parts of Central and North-eastern Lithuania – on average 26–28 times per decade (Figure 4b). Longer NPP in North-eastern Lithuania may recur more frequently due to the long distance from the sea, and less precipitation falls in Central Lithuania; therefore, shorter NPP are less frequent here. Such NPP were rarely recorded in Western Lithuania – on average 21–22 times per decade. The rare recurrence of 10–14-day NPP in Western Lithuania may have been determined by the influence of the Samogitian highland on the air masses coming from the west.

Even longer NPP (15–19 days) repeated on average 8 times per decade. Such NPP occurred most often in the Curonian Spit and in Central and Eastern Lithuania – on average 10–12 times per decade (Figure 4c). NPP rarely lasted 15–19 days in North-eastern Lithuania and at Telšiai MS – on average 6 times per decade. In North-eastern Lithuania, the rare occurrence of such NPP is associated with a long distance from the sea, and this may be a consequence of the predominant north-western transport at the Telšiai MS, as more frequent precipitation and, therefore, shorter dry periods prevail in this area. The longest NPP (≥20 days) repeated on average 5–6 times per decade (5.4 times a year). Such long dry periods are most common in the leeward side of the Samogitian highland and in Central Lithuania, where NPP lasting 15–19 days repeated on average 7 times per decade (Figure 4d). As there is less precipitation in the lowlands, there is no adiabatic rise in the air here: the air goes down and cools, and the amount of water vapor in it decreases. The longest NPP recurred in the Baltic Highlands and Telšiai

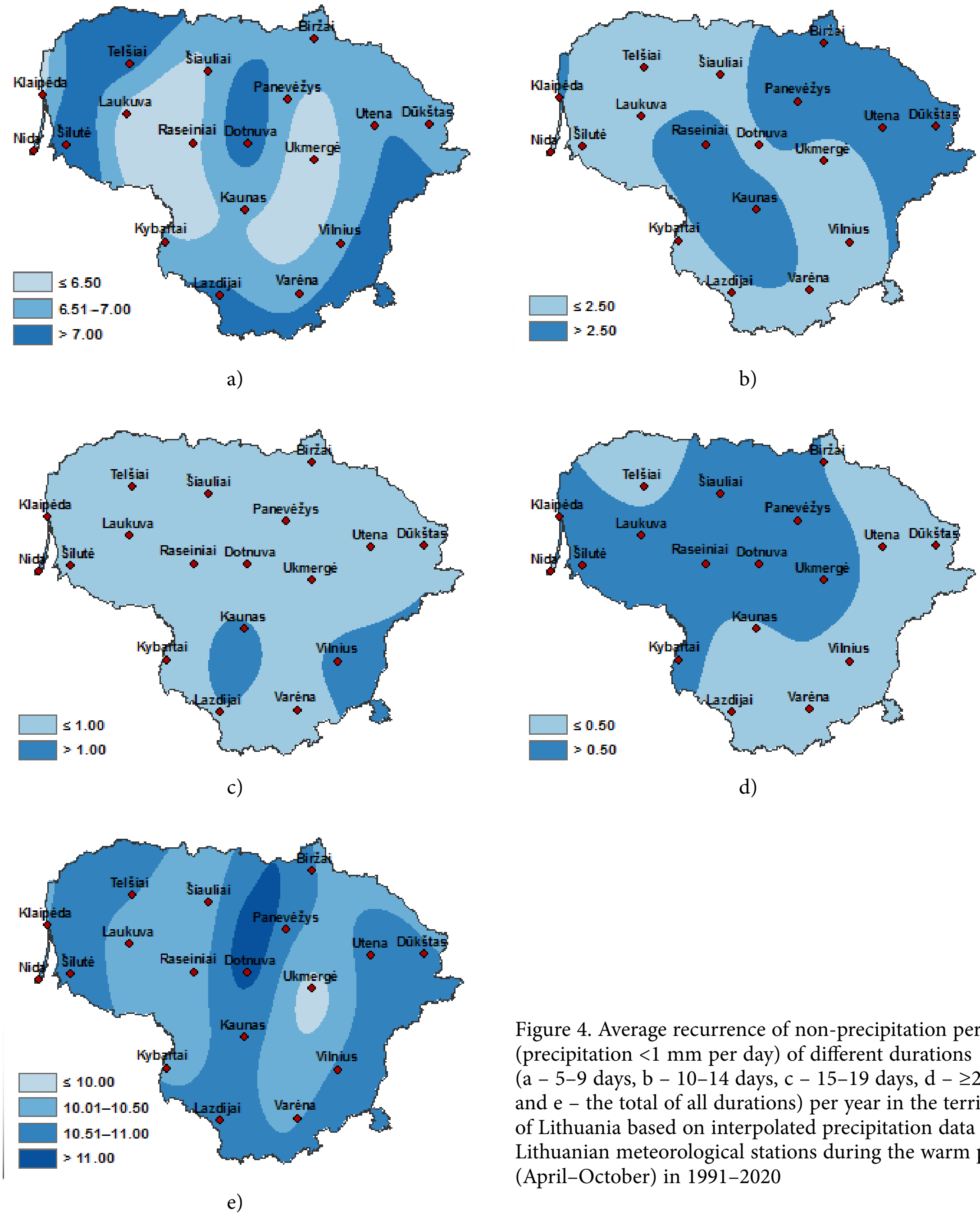


Figure 4. Average recurrence of non-precipitation periods (precipitation <1 mm per day) of different durations (a – 5–9 days, b – 10–14 days, c – 15–19 days, d – ≥20 days and e – the total of all durations) per year in the territory of Lithuania based on interpolated precipitation data of Lithuanian meteorological stations during the warm period (April–October) in 1991–2020

MS – 3–4 times per decade – because more precipitation falls here, and therefore shorter NPP are more common.

NPP of various durations (daily precipitation <1 mm per day) recurred on average 80 times per decade during the warm period. NPP occurred most frequently in the Middle Lithuania lowland and in some parts of Western and Eastern Lithuania – 107–111 times per decade (Figure 4e). The greatest recurrence of NPP in 1991–2020 was at Dotnuva MS – 111 times per decade. Meanwhile, the rarest recurrence of NPP of various durations was on the leeward side of the Baltic Highlands and on the leeward side of the Samogitian Highland – on average 99–103 times per decade. Although the highest precipitation is in Western Lithuania and the lowest is in Central Lithuania, Western Lithuania showed greater recurrence of shorter NPP, while Central Lithuania showed fewer but longer NPP (Dotnuva MS is an exception). The general distribution of NPP of various durations in Lithuania is mainly determined by the recurrence of short NPP (5–9 days).

The recurrence of short NPP (5–9 days) in different months between 1991 and 2020 was quite even, but these events recurred most often in July at 7 of 18 stations and in April and May at 6 of 18 stations (a single peak or one of several maximum peaks). The peaks in July could be attributed to the peculiarities of summer rains – high intensity, but short duration, which creates a short NPP between rains. The lowest recurrence of NPP was in September and October – there are no fixed NPP recurrence peaks, as these months are more likely to have lower-intensity precipitation than in summer. Longer NPP (10–14 days) were more common in the spring months, with only one or one of several recurrence peaks at 7 stations in April and May, respectively (Figure 5b), as in many cases longer dry periods are due to atmospheric circulation patterns. However, in some parts of Lithuania the peaks of NPP in the summer months remained: in July at 3 stations and in August at 1 station. NPP lasting 10–14 days during the warm season repeated in many stations in June and August, when there are fewer days with anticyclonic circulation.

Even longer NPP (15–19 days) were most likely to recur in September and April, with 8 of the 18 stations having the only or one of several recurrence peaks in these months (Figure 5c). Such NPP were the least frequent in August, when there are fewer days with anticyclonic circulation and fewer powerful anticyclones. The longest NPP (≥20 days) recurred most often in the spring, especially in April – it was recorded at 11 of 18 MS. In the following months (June–October), NPP of this duration occurred less frequently, and in July there were no recurrence peaks of NPP lasting ≥20 days (Figure 5d).

In general, NPP of various durations during the warm season (precipitation <1 mm per day) repeated most often in April – on average 17 times per decade (Figure 5e). In April, a total of 14 out of 18 stations recorded NPP recurrence peaks, and the highest recurrence was recorded at Dūkštas MS, where it reached 19 times per decade. Meanwhile, during the warm period (April–October), a single NPP minimum peak or one of several minimum peaks occurred in August for 7 of 18 stations and in October for 6 of the 18 stations. Although NPP recurrence minima were recorded in most stations during the warm season in August, there was a high recurrence amplitude in this month (11–17 times per decade). For example, in August Vilnius MS was in second place in terms of NPP recurrence (1.67 times per decade).

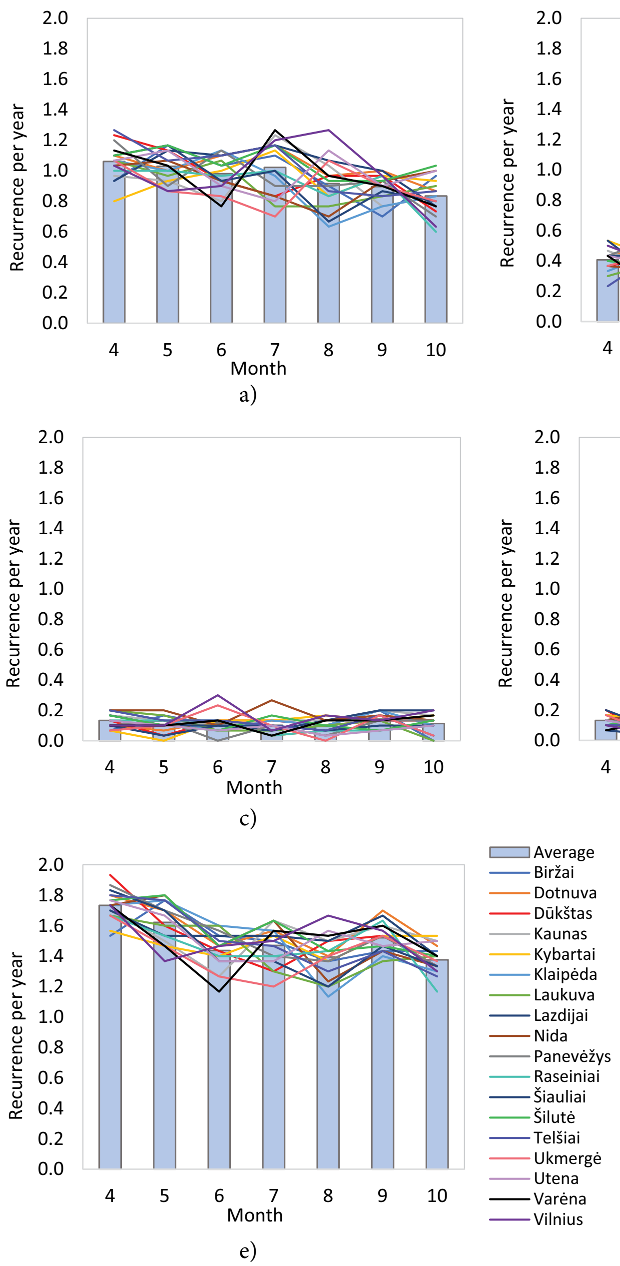


Figure 5. Distribution of average recurrence of different non-precipitation periods (precipitation <0.1 mm per day) per year during the warm period (April–October) in Lithuanian meteorological stations: a – 5–9 days, b – 10–14 days, c – 15–19 days, d – ≥20 days and e – the total of all durations

NPP recurrence considering all seasons (daily precipitation <0.1 mm) and the warm season (daily precipitation <1 mm) has several similarities. According to both criteria, there was a high recurrence of short NPP (lasting 5–9 days) and a rare recurrence of long NPP (15–19 and ≥20 days). NPP of various durations recurred on average 123 times per decade when considering all seasons (daily precipitation <0.1 mm) and 107–111 times per decade when considering the warm period (daily precipitation <1 mm). Therefore, NPP of various durations are more frequent in the warm period, as Lithuania is much more likely to be affected by anticyclonic atmospheric circulation and cyclonic circulation in the cold period. In addition, during the cold period, even in the presence of anticyclonic circulation, low-intensity precipitation from clouds situated under inversion is possible; therefore, the highest number of NPP is typical for the spring–summer months. When considering all seasons, NPP recur least frequently in the winter months, and when considering the warm period, NPP recur least frequently in August.

3. Recurrence trends of non-precipitation periods in 1991–2020

NPP (daily precipitation <0.1 mm) most frequently recurred in the last decade of the study period (2011–2020) – 131–132 cases of NPP of various durations. In 2001–2010, the number of NPP decreased compared with 1991–2000 (Table 2). Compared with the following decades, 1991–2000 had the most NPP lasting ≥20 days and the least NPP lasting 10–19 days; it also had more short NPP (5–9 days) compared with 2001–2010, but fewer compared with 2011–2020. In 2011–2020, NPP of 5–19 days recurred more frequently than in other decades, while the longest NPP (≥20 days) reached similar values as in 2001–2010. This recurrence of NPP of different durations resulted in the highest overall recurrence of NPP of various durations (≥5 days) in 2011–2020.

During the warm season (April–October), there was the same number of NPP of various durations (daily precipitation <1 mm) in 1991–2000 and 2001–2010, averaging 103.5 cases, and reaching the highest values in 2011–2020 – 109–110 cases per decade (Table 2). However, the trends of NPP of different durations in the decades of the study period are different. In 1991–2000, compared with the other decades, long-term (≥20 days) NPP were more frequent and medium-term NPP (10–19 days) were less common. In 2001–2010, 10–14-day NPP recurred more frequently than in the other decades, and the shortest NPP (5–9 days) and the longest NPP (≥20 days) were less frequent. In 2011–2020, 5–9-day and 15–19-day NPP recurred more frequently than in other decades, resulting in an overall maximum of NPP recurrence of various durations in 2011–2020.

According to both criteria (daily precipitation <0.1 mm in all seasons and <1 mm in April–October), there is a positive trend in the number of NPP during the study period (Figure 6a and 6b). In 2020, according to both criteria, the number of NPP decreased compared with 2018–2019, but this is more reminiscent of cyclical fluctuations, as in 2016–2017 there was also a decrease in the number of NPP. Considering 2011–2020, 2018 stands out with the most NPP not only in this decade, but also in the entire study period, and the number of NPP was also high in 2013–2015 (Figure 6a). This year mainly determined the general growth trend of the number of NPP, a phenomenon is related to the previous dry summers, notably the summer of 2015, which has been analysed in previous studies (Orth et al., 2016; Ionita et al., 2017). While the change in the number of NPP during the warm period (daily precipitation <1 mm) has a smaller amplitude, but the trend is the same (Figure 6b).

Based on the average of all stations, the number of NPP in Lithuania is growing, a finding confirmed by other studies on the current and future decrease in precipitation in the southern part of the Baltic Sea region, including Lithuania (Kjellstrom & Ruosteenoja, 2007; Rimkus et al., 2012). Considering all times of the year (with daily precipitation <0.1 mm), there was an average annual decrease in the number of NPP at 6 stations (33%) and an increase at 12 stations (67%). During the warm season (with daily precipitation <1 mm), the trends are similar: at 4 stations (22%) the average annual number of NPP decreased and at 14 stations (78%) it increased. According to both criteria, there was a decrease in the number of NPP in Central and Western Lithuania (according to the <0.1 mm criterion, also at Vilnius MS, in Eastern Lithuania); elsewhere in Lithuania, the number of NPP increased.

Assessing the change in the number of NPP over the 30-year study period (daily precipitation <0.1 mm), the number of NPP increased the most in Raseiniai and Biržai

Table 2. Average annual recurrence of non-precipitation periods (NPP) of various durations (with daily precipitation <0.1 mm in all seasons and <1 mm in April–October) in different decades of the study period

Duration of NPP	Number of cases (daily precipitation <0.1 mm)			Number of cases (daily precipitation <1 mm)		
	1991–2000	2001–2010	2011–2020	1991–2000	2001–2010	2011–2020
Total (≥5 days)	12.08	11.74	13.16	10.35	10.35	10.96
5–9 days	9.28	8.24	9.54	6.85	6.37	7.01
10–14 days	1.95	2.66	2.73	2.10	2.73	2.57
15–19 days	0.44	0.60	0.63	0.66	0.87	0.90
≥20 days	0.42	0.24	0.26	0.74	0.38	0.48

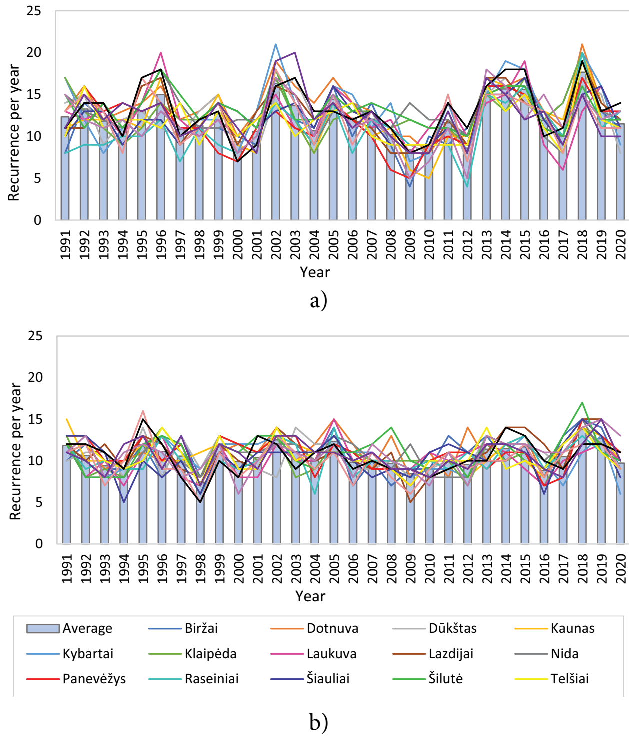


Figure 6. The total recurrence of non-precipitation periods of various durations (a – daily precipitation <0.1 mm for all season, b – daily precipitation <1 mm for April–October) in Lithuania from 1991 to 2020

(Central and Northern Lithuania) – on average by 4.6 and 2.9 cases, respectively. During the warm period (daily precipitation <1 mm), the number of NPP increased on average in about 2 cases in 30 years in Utena and Biržai (Eastern and Northern Lithuania), and decreased the most in Panevėžys, Kaunas and Kybartai (Northern and Central Lithuania) in about 1 case in 30 years. According to both criteria, there were only three Lithuanian MS in which the statistical reliability of trends reached 90%, and for one MS it reached 95%; in all cases these were negative trends. When considering daily precipitation <0.1 mm, there was a statistically significant change in the number of NPP only at Vilnius MS (–0.056). When daily precipitation was <1 mm in the warm season, there was a statistically significant change in the number of NPP at Kaunas MS (–0.037) (with 95% reliability), and at Kybartai (–0.033) and Panevėžys MS (–0.040) (with 90% reliability).

4. Analysis of atmospheric circulation for the longest non-precipitation periods

Between 1991 and 2020, there were a total of 34 long NPP (≥20 days), of which 23 were recorded during the warm period (April–October) and 11 during the cold period (November–March). Four NPP groups were distinguished according to which part of the baric structure influencing Lithuania according to the 500 mbar height maps (Table 3). The first group, which includes all cases when Lithuania was at the top or in the eastern part of the upper ridge at the 500 mbar level, accounted for 76.47% (26 out of 34) of all cases (Figure 7). The second group, which includes cases when Lithuania was in the western part of the upper ridge at the 500 mbar level, accounted for 11.77% (4 out of 34) of all cases (Figure 8). The third group, when Lithuania was in the south-western periphery of the cyclone at the 500 mbar level, included only 2.94% (1 out of 34) of all cases (Figure 9). Finally, the fourth group, which includes cases when Lithuania at the 500 mbar level was in the low-gradient baric field, accounted for 8.82% (3 out of 34) of all cases (Figure 10). In 1990–2020, dry periods recurred most often when at the 500 mbar level Lithuania was in the eastern part or at the top of the upper ridge, and at sea level the anticyclonic circulation prevailed above Lithuania, mostly related to the Azores anticyclone ridge or anticyclone in Northern, Eastern or Central Europe. Previous research has confirmed that most dry periods are associated with anticyclonic circulation (Fleig et al., 2011; Parry et al., 2013). The predictor of almost all dry periods is the strengthening and expanding eastern ridge, blocking western transport over Western Europe (Rimkus et al., 2014).

Table 3. The number and duration of cases of the longest non-precipitation periods according to the 500 mbar level height map, considering in which part of the baric structure Lithuania is located

Group	Description	Number of cases	Duration
1. Top or eastern part of the upper ridge	At the 500 mbar level, Lithuania is at the top or eastern part of the upper ridge. At sea level, Lithuania is at the top or eastern part of the Azores anticyclone ridge or in the periphery of the anticyclone situated over Northern, Central or Eastern Europe	26 (76.47%)	20–50 days
2. Western part of the upper ridge	At the 500 mbar level, Lithuania is at the western part of the upper ridge. At sea level, Lithuania is at the western part of the anticyclone which is situated over Eastern Europe (usually associated with an Asian anticyclone ridge)	4 (11.77%)	20–39 days
3. South-western periphery of the cyclone	At the 500 mbar level, Lithuania is at the southwestern part of the cyclone, which is situated above North-eastern Europe. At sea level, a ridge is formed above Northern Europe (including Lithuania) from a high-pressure centre above Iceland	1 (2.94%)	26 days
4. Low-gradient baric field	At the 500 mbar level, a low gradient baric field is above Lithuania. At sea level, Lithuania is in the periphery of the anticyclone situated above North-western and/or Eastern Europe or in the saddle point	3 (8.82%)	20–27 days

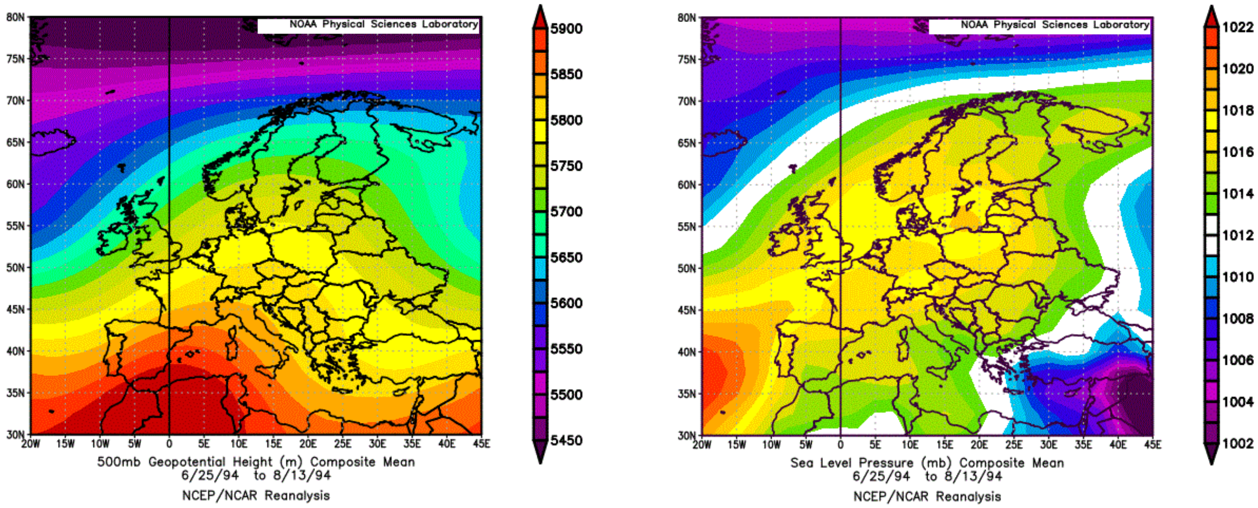


Figure 7. Composite maps of non-precipitation period, 25 June–13 August 1996, over Europe: left – at the level of 500 mbar geopotential height (The NCEP / NCAR database uses the abbreviation mb instead of mbar); right – at the sea level pressure

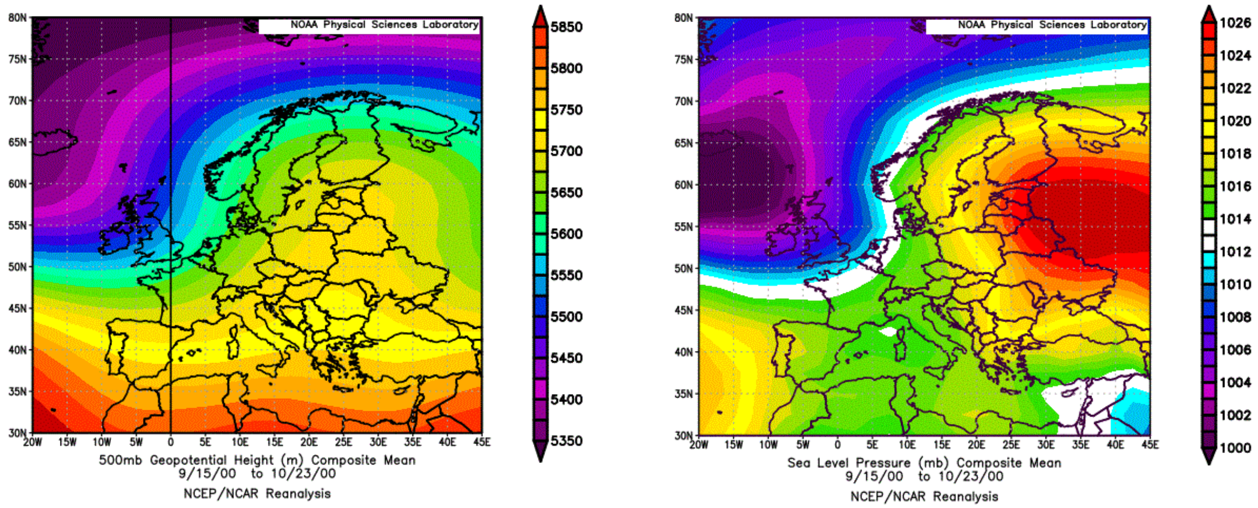


Figure 8. Composite maps of non-precipitation period, 15 September 2000–23 October 2000, over Europe: left – at the level of 500 mbar geopotential height (The NCEP / NCAR database uses the abbreviation mb instead of mbar); right – at the sea level pressure

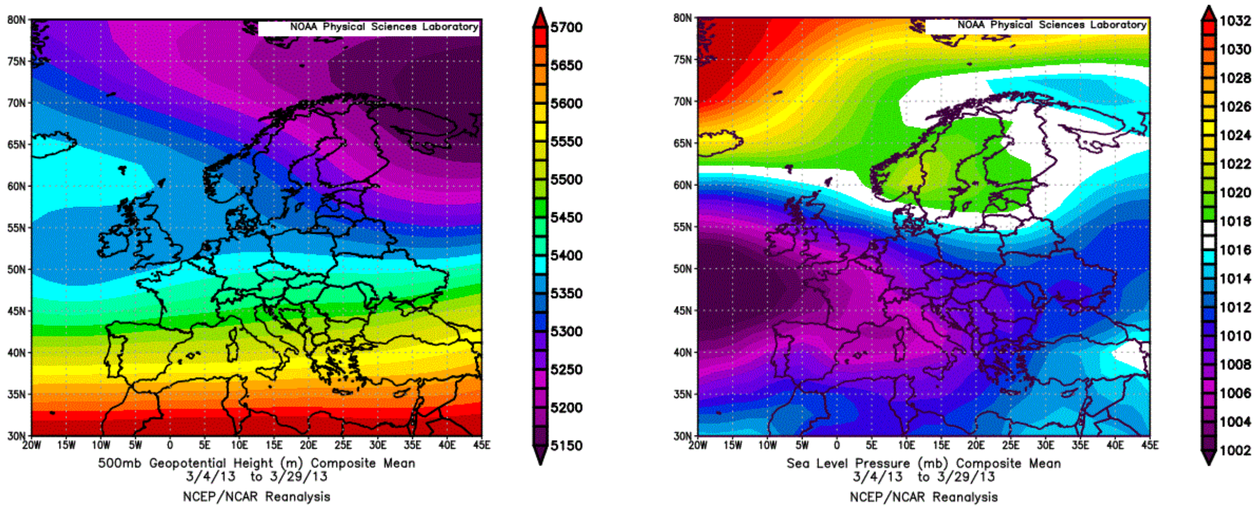


Figure 9. Composite maps of non-precipitation period, 04 March 2013–29 March 2013, over Europe: left – at the level of 500 mbar geopotential height (The NCEP / NCAR database uses the abbreviation mb instead of mbar); right – at the sea level pressure

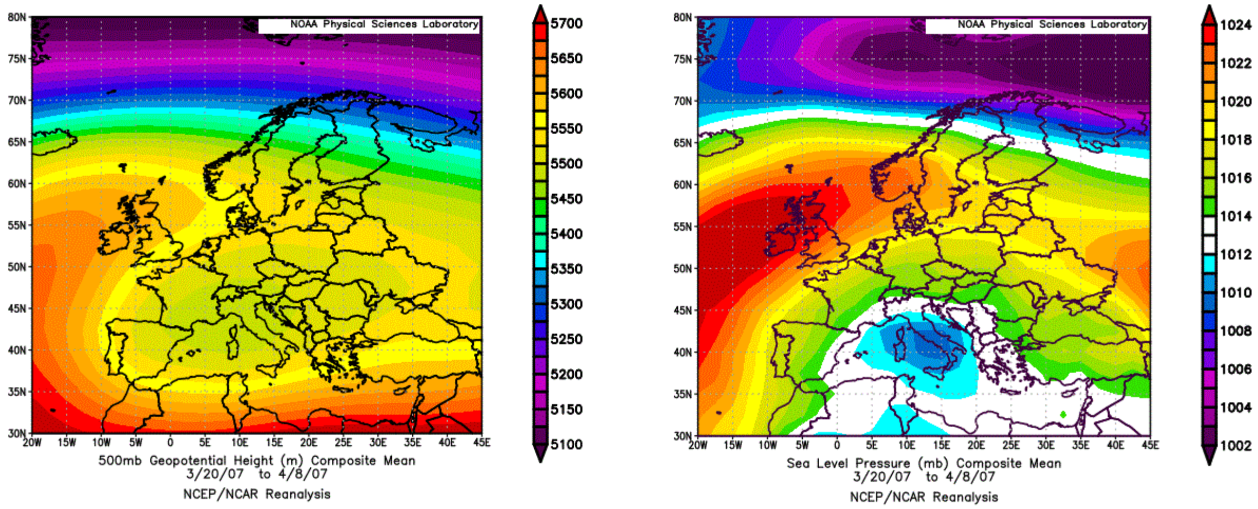


Figure 10. Composite maps of non-precipitation period, 20 March 2007–08 April 2007, over Europe: left – at the level of 500 mbar geopotential height (The NCEP / NCAR database uses the abbreviation mb instead of mbar); right – at the sea level pressure

4.1. Analysis of atmospheric circulation for the longest non-precipitation periods during warm season

During the warm period (April–October), 87% (20 of 23) of all long NPP cases in Lithuania in 1991–2020 were caused by atmospheric circulation conditions typical for group 1 – an upper ridge above Europe at the 500 mbar level associated with the Azores anticyclone ridge at sea level. Meanwhile, in the western part of the upper ridge in the warm period, Lithuania accounted for only 4.35% (1 of 23) and in the low-gradient baric field 8.69% (2 of 23) of all long NPP cases.

The phenomenon of NPP recorded at the same time in at least 50% of the area (7 out of 23 cases) during the warm period is mainly related to the effects of the Azores anticyclone or the Asian anticyclone. Such NPP were mostly determined by the formation of a high-pressure centre above the Baltic Sea, differing only in which part of the anticyclone Lithuania is located. In other cases, when NPP recurrence lasting ≥20 days in <50% of the territory or at only a few MS, the formation of NPP is determined mainly by similar conditions, but there are exceptions. For example, in the case of NPP in May 2017, most of Europe was in the area affected by anticyclonic circulation for almost an entire month, as the Icelandic minimum moved significantly south (to the south of Iceland).

The circulation of the five longest NPP in Lithuania lasting ≥20 days at the 500 mbar level is characterised by an upper ridge from the south (south-east–south-west) extending through Europe. Meanwhile, at sea level Lithuania was mainly affected by the north-eastern ridge of the Azores anticyclone or the western ridge of the Asian anticyclone, and in some cases by a secondary anticyclone centre over the Baltic region and/or Eastern Europe. Shorter NPP were also usually caused by the conditions already mentioned, but there were cases when they were caused by other anticyclonic processes. For example, NPP, recorded from 18 May 2016 to 08 June 2016, which lasted ≥20 days only at Dotnuva MS, was determined by an anticyclone located above the Norwegian Sea, which also affected Lithuania's weather.

4.2. Analysis of atmospheric circulation for the longest non-precipitation periods during the cold season

Similarly to the warm period, in the cold period (November–March) the formation of NPP is mainly related to the conditions typical for group 1. More than half (54.55%, 6 out of 11) of all cases of the cold period were due to the upper ridge above Europe, when Lithuania was at the top or in the eastern part of this ridge. Moreover, 27.3% (3 of 11) of all NPP cases recured when Lithuania was in the western part of the upper ridge, and 9.09% (1 of 11) of all long NPP were recorded when Lithuania was in the south-western part of the cyclone or in the low-gradient baric field.

During the cold period, none of the 11 NPP that lasted ≥20 days were recorded in more than 50% of the Lithuanian territory (at least in 9 out of 18 Lithuanian MS surveyed). NPP covering the largest territory (>30% of the territory) were recorded in March 2013 (38% of the territory) and March–April 2003 (33% of the territory). These long NPP, which covered the most territory, had different conditions: in the case of 2013, Lithuania's weather was determined by the anticyclone ridge, which had been located in the usual place of the Icelandic minimum. In 2003, at sea level an anticyclone formed over Central and Western Europe, and Lithuania was in its eastern periphery. Meanwhile, the recurrence of long-term NPP at one or more stations, as in most cases during the warm period, was associated with an upper ridge above Europe at the 500 mbar level and at sea level with an anticyclone above Central or Eastern Europe. However, there are exceptions, for example, in March–April 2007, NPP lasting ≥20 days were recorded at only two Lithuanian MS (Dotnuva and Kybartai) when the territory of Lithuania was in the saddle point.

During the cold period, the longest NPP were much shorter than in the warm period – the longest one lasted 26 days in March 2013. All cases had a duration of 20–26 days and had a similar circulation patterns at the 500 mbar and sea levels between 1991 and 2020. Again, the exception during the cold period, given the different duration, is the longest NPP in March 2013. Considering the shorter NPP, lasting <20 days, the exception is a case from March–April 2007, which was recorded at two Lithuanian MS. At that time, Lithuania was in a saddle point with two high-pressure areas from the west and east and the low-pressure areas from the north and south (Figure 10). Thus, in the cold period, cases classified as group 1, as in the warm period, accounted for the majority of all cases, namely 54.5% (6 of 11) of cases. However, in this case there is greater scatter among all groups, as there have been few NPP during the cold period in the last 30 years: 27.3% (3 of 11) of cases belong to group 2, 9% (1 of 11) of cases belong to group 3 and 9% (1 of 11) of cases belong to group 4.

Conclusions

In summary, NPP of various durations (daily precipitation <0.1 mm), occurred most often in the Middle Lithuania lowland and Southern and South-western Lithuania, and least frequently in the Samogitian highland and in North-eastern Lithuania. During the warm period (daily precipitation <1 mm) NPP most often occurred in the Middle Lithuania lowland and partly in Eastern Lithuania, and least frequently in the western part of the Baltic Highlands and partly in the Samogitian highland. In Lithuania, such a complete analysis of NPP had not been performed before; there are much older sources that analysed the recurrence of NPP, but not for the period considered in this study. Therefore, the obtained results are unique and important in expanding the knowledge about the typical recurrence of non-precipitation periods in Lithuania.

The highest number of NPP occurred in the spring months, which usually have more days with anticyclonic circulation. The number of NPP of various durations (1991–2020) has shown a growth trend, which has mainly been determined by the increase in climate extremes in both distribution directions (Rahmstorf & Coumou, 2011; Hänsel, 2020; Rimkus et al., 2020). However, according to other studies, the annual precipitation in the eastern part of the Baltic Sea region increased significantly throughout the year except during April and September. It should also be considered that the amount of 30–90 days precipitation can be more and more often influenced by short-term 1–5 day rain events, when the amounts of precipitation exceeding a monthly climate normal may fall over a noticeably short period of time (Jaagus et al., 2018; Mačiulytė et al., 2022). These data, as well as our data on the recurrence of NPP, confirm the increasing extremity of the temporal distribution of precipitation against the backdrop of increasing annual precipitation in the territory of Baltic states. The longest NPP during 1991–2020 was recorded when Lithuania had been affected by an anticyclone ridge of the Azores or anticyclone located above Northern, Eastern or Central Europe. This study confirms the findings of previous studies on the most frequent recurrence of dry periods with increased meridian transport and atmospheric western transport blocking processes (Jaagus et al., 2010; Rimkus et al., 2014).

To date, there is no consensus on an NPP definition due to distinctive climatic conditions in different areas, which makes it difficult to compare the results with those of other countries. Even in a relatively small area like Lithuania, NPP recur with varying frequency due to the effects of mesoclimatic factors. Therefore, it is important to consider not only macrosynoptic factors but also local geographic conditions in these studies. Some scientists believe that a day without precipitation can also be considered if more than 2 mm of precipitation does not fall per day (Byun & Wilhite, 1999; Gomboš et al., 2019), or more than 3 mm of precipitation during the vegetation period (Srdjevic et al., 2022), because this amount of precipitation has almost no effect on ecosystems. When defining the number of days without precipitation necessary for the onset of drought in our latitudes, some authors believe that there should be a period of at least 15 consecutive days (Huschke, 1970), others say that such a period should be longer than 20 days (Hlásny et al., 2015; Srdjevic et al., 2021). It seems that there cannot be unified statistical criteria for NPP, because they depend on the general climatic characteristics of the studied region and the time of year.

Drying of soil profile occurs during long rainless periods. Meteorological drought and subsequently soil drought occurs in the case of the sufficiently long rainless period (Gomboš et al., 2019). Therefore it is necessary to know the size and statistical characteristics of non-precipitation periods. As indicated in our analysis, they can be characterised by high spatial heterogeneity.

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