The atmospheric circulation patterns during dry periods in Lithuania*

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Abstract

This paper reveals the atmospheric circulation patterns during dry periods in Lithuania. The research covers the period from 1961 to 2010. Atmospheric circulation features were analysed using the Hess and Brezowski classification of macro-circulation forms, NAO and AO indices, a 500 hPa geopotential height field and the Tibaldi-Molteni blocking index. Different phases of the dry period (developing, persisting and attenuation) were evaluated individually. Also, the regional differences of dry period formation were investigated. In general dry periods are determined by a decrease in zonal and an increase in meridional circulation forms as well as the atmospheric blocking process over the Baltic region

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longitudinal belt 0–20 days prior to the start of the dry period. An especially strong shift from general circulation patterns are observed during the developing phase of a dry period. Drought persistence in the Baltic region is almost always predetermined by strong anticyclonic circulation. Most drought development stages are associated with negative NAO/AO phases

1. Introduction

The climatic features of a particular region depend primarily on latitude, land-sea interactions and the annual cycle (seasons), whereas intra-seasonal variations of climate are determined mostly by atmospheric circulation. In temperate climates, prolonged 'steady states' of atmospheric conditions usually give rise to extreme events such as floods, droughts, thaws, and frosts. In boreal zones of excessive moisture, extreme droughts are not a very common phenomenon (Lloyd-Hughes & Saunders 2002); all four categories of drought (Mishra & Singh 2010) have nevertheless been identified. First of all, droughts have a major impact on agriculture as well as on the increasing number of forest fires and the decrease in river runoff (Hisdal & Tallaksen 2003). Moreover, droughts can seriously affect the regional economy, human social life and wildlife (Thorsteinsson & Björnsson 2011, Rimkus et al. 2013). Recent studies have indicated that the number of droughts has not been increasing in northern Europe (Bordi et al. 2009); nonetheless, droughts are still expected to be common in the future (Kjellström et al. 2007).

Every regional scale of drought has its own, unique, developing scenario because of the very complex nature of droughts. Lack of precipitation is well-known as the main factor contributing to drought occurrence, while other factors either have a too 'long memory', such as soil moisture in deeper layers, or large spatial variability in land use and vegetation cover, or very special preconditions such as snow water equivalent, the rate of snow melt and the thickness of frozen soil.

Earlier studies showed that there is no typical chain of processes linked to summer drought occurrence either in northern Europe (Parry et al. 2010, Kingston et al. 2013) or in northern North America (Girardin et al. 2006, Cook et al. 2011). However, some circulation indices are still useful diagnostic tools for the large-scale atmospheric circulation impact on regional hydro-thermal anomalies (Zveryaev 2004, Samaniego & Bardossy 2007, Ignacio et al. 2008, Parry et al. 2010). Also, 'weather type' techniques could help in identifying atmospheric circulation patterns associated with droughts in Europe (Malone 2007, Fleig et al. 2011).

In recent years extreme event analysis has generated greater scientific interest in the eastern Baltic (Jaagus 2006, Tammets 2007, Avotniece et al. 2010, Kažys et al. 2011). Drought dynamics over the Baltic Sea region

(Rimkus et al. 2012) and the Neman river basin (Rimkus et al. 2013), as well as drought analysis in Lithuania using SPI and HTC indices (Valiukas 2012), have been carried out. Also, the impact of atmospheric circulation on extreme precipitation (Rimkus et al. 2011) and snow cover variability (Rimkus et al. 2014) have been analysed using macro-circulation form classification.

In this study we tried to discover the main atmospheric circulation patterns during dry periods in Lithuania between 1961 and 2010. The subjective Hess and Brezowski macro-circulation form classification (Werner & Gerstengarbe 2010) was used for identifying weather type. The main objective of our work was to characterise the atmospheric circulation during the development, persistence and attenuation phases of dry periods in Lithuania. The atmospheric circulation patterns during dry events were analysed using composite 500 hPa geopotential height field analysis. The clustering of NAO and AO indices prior to positive/negative phases were performed during dry periods. In addition, blocking episodes during drought phases were identified using the Tibaldi and Molteni blocking index (TMI) (Tibaldi & Molteni 1990).

2. Data and methods

Atmospheric circulation patterns which led to dry periods and drought formation from 1961–2010 were analysed in this study. Droughts in Lithuania are identified using the Selianinov hydrothermal coefficient (HTC) (Selianinov 1928), when for 30 consecutive days the HTC is lower than or equal to 0.5. Droughts were recorded in the entire territory of Lithuania four times (1992, 1994, 1996 and 2002) during this 50-year period. This aspect was analysed in the present study in order to determine the circulation conditions that led to the formation of drought and shorter dry periods when the HTC was less than or equal to 0.5 for 15 consecutive days. During these 50 years such dry periods were recorded 14 times in at least one third of the territory of Lithuania.

The daily air temperature and precipitation data for the growing season (May–September) from 17 meteorological stations were used (Figure 1). The HTC for each day was calculated according to the following formula:

$$\mathrm{HTC} = \frac{\sum p}{0.1 \sum t},$$

where $\sum p$ – total precipitation and $\sum t$ – sum of mean air temperatures for 30 consecutive days. The interpretation of the HTCs is as follows: < 0.5 – severe drought; < 0.7 – medium drought; < 0.9 – weak drought; > 1 – sufficient moisture; > 1.5 – excessive moisture.

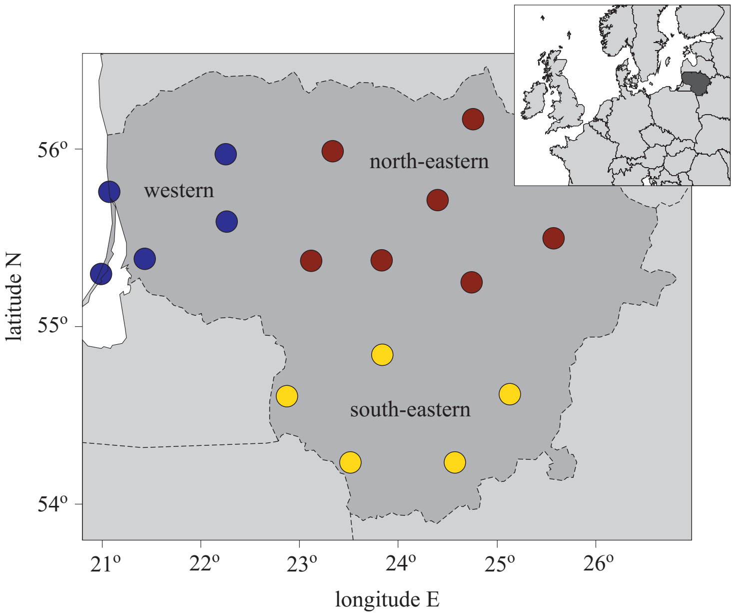

Figure 1. Locations of the meteorological stations supplying the data for this study, and the parts of Lithuania with different peculiarities of drought formation according to cluster analysis

One can start calculating HTC when the mean average air temperature is 10°C. In Lithuania this transition is most often recorded at the beginning of May. During the investigation, therefore, calculations of HTC started on May 1. In this way, the first HTCs were obtained for the beginning of June (after 30 consecutive days).

All the dry periods were divided into three phases. The first thirty-day period prior to the start of the dry period was named the 'dry period development phase'; the whole dry period (with the exception of the last five days of the dry period) was named the 'dry period persisting phase'; the last five days of the dry period and the five days after the dry period were named the 'dry period attenuation phase'.

According to the daily HTCs during all phases of the 14 dry periods, Lithuania was divided into three parts: the west, the north-east and the south-east (Figure 1). K-means clustering method was used for this purpose. The dry periods were usually determined at the same time at all the stations in these regions.

The study found a few small differences between the atmospheric circulation conditions determining the formation of dry periods in the regions.

The subjective Hess and Brezowski atmospheric macro-circulation form classification was used for the dry period analysis in Lithuania. Three circulation forms, six weather types and 29 weather condition subtypes can be distinguished according to this classification (Table 1). Subtype U is used for unidentified weather conditions. The general classification scheme, initially designed for the whole of Europe, was adapted to Lithuanian conditions (Kažys et al. 2009). The modified weather conditions patterns have already been used in analyses of heavy precipitation (Rimkus et al. 2011) and snow cover variability (Rimkus et al. 2014).

Table 1. Weather types and conditions according to the Hess and Brezowski macro-circulation classification for Lithuania (after Werner & Gerstengarbe 2005 and Rimkus et al. 2011)

Circulation form		Weather type	Weather conditions
zonal	A	western	WA, WS, WZ
mixed	B	south-western	SWA, SWZ, TRW, WW;
		north-western	HNZ, NWA;
		high pressure centre	BM, HM, SA, SEA
	C	low pressure centre	NWZ
meridional	D	northern	HB, HNA, NA, NZ
	E	north-eastern	HFNA, HFNZ, NEA, NEZ, TRM;
		eastern	HFA, HFZ
	F	south-eastern	SEZ, TB;
		southern	SZ, TM

Macro-circulation forms are divided into zonal, mixed, and meridional. During zonal circulation an air mass flows from west to east between the subtropical high pressure zone over the North Atlantic and the low pressure zone over subpolar regions. Stationary and blocking high pressure processes give rise to a meridional circulation. All north-south ridges are classified for this macro-circulation form. A mixed circulation is typical of both zonal and meridional air mass flows (Rimkus et al. 2011).

Daily NAO and AO indices obtained from the NOAA Climate Prediction Centre were used in this study. A 10-day running mean filter was applied to the NAO and AO daily indices because of the high temporal variability of these indices in summer.

Cluster analysis was applied to selected daily NAO and AO time series for periods of 30 days prior (development phase) to every drought event in order to classify synoptic preconditions, i.e. atmospheric circulation patterns during a drought development phase over the Atlantic-European domain. The hierarchical (joining tree) clustering method was carried out using the complete linkage rule and the Euclidean distance as the distance metric between clusters for determining the number of available clusters. Then k-means clustering was employed to detect the number and sequence of the members within the corresponding cluster: the cluster means were attributed to every day in the development phase.

Mean circulation patterns and their anomalies during the determined dry period events and 30 days prior to every event (dry period development phase) were identified using the NCEP/DOE Reanalysis 500 hPa geopotential height field, and averaged using composition analysis.

Blocking episodes during dry period development, persisting phases and 30 days before were identified using the Tibaldi and Molteni blocking index (TMI) for the longitudinal belt from 20W to 60E (Tibaldi & Molteni 1990). The TMI represents the reversal of the climatological meridional gradient of H500 (easterly flow) at $60\mathrm{N} \pm \Delta$. Two different gradients were used – southern (GHGS) and northern (GHGN), which are computed as follows:

$$\mathrm{GHGS} = (H(\varphi_0) - H(\varphi_S))/(\varphi_0 - \varphi_S)$$

and

$$\mathrm{GHGN} = (H(\varphi_N) - H(\varphi_0))/(\varphi_N - \varphi_0)\,,$$

where $\varphi_0 = 60 \pm \Delta$, $\varphi_S = 40 \pm \Delta$, $\varphi_N = 80 \pm \Delta$, $\Delta = (-5, 0, 5)$ degrees; H – geopotential height at 500 hPa level.

A blocking episode is identified at a given longitude if the following conditions are satisfied for at least one value of Δ:

1) $\mathrm{GHGS} > 0$;

2) $\mathrm{GHGN} < -10$ gpm/deg latitude.

Before the index calculations, the 500 hPa time series has to be smoothed using a 5-day running mean filter.

3. Atmospheric macro-circulation forms during dry periods

The study results show that weather type recurrence frequency during dry periods shifted from the general distribution in 1961–2010 (Table 2). In general, dry periods are determined by a decrease in zonal and an increase in meridional circulation forms. The greatest changes can be attributed to western (weather type A) and north-eastern (E) flows (Figure 2). Also, some

Table 2. Frequency [%] of different weather types over Lithuania during different phases of dry periods versus overall circulation patterns in 1961–2010

Dry period phases	Weather type	Weather type frequency [%] in Lithuania: Overall circulation	Part of Lithuania affected by dry period: Whole	Western	North-eastern	South-eastern
developing	A	23	10	12	12	10
	B	36	36	30	43	49
	C	4	3	3	2	2
	D	11	6	7	5	1
	E	19	36	37	31	31
	F	6	7	9	5	6
	U	1	2	2	2	1
persisting	A	23	16	14	8	19
	B	36	41	37	44	36
	C	4	2	0	0	4
	D	11	11	14	16	14
	E	19	24	25	24	20
	F	6	7	9	7	6
	U	1	1	1	1	1
attenuation	A	23	32	25	27	45
	B	36	23	27	36	10
	C	4	7	3	0	10
	D	11	12	18	17	24
	E	19	19	18	16	4
	F	6	6	8	3	4
	U	1	1	1	1	3

changes can be attributed to northern (D) and south-eastern (F) weather types. The greatest changes can be attributed to western (weather type A) and south (north)-eastern (E and F) flows (Figure 2). The recurrence of the most frequent (15%) weather condition, the WZ (West cyclonic), which brings moist air from the west, decreases by half during dry periods, while the recurrence of the NEZ (Northeast cyclonic) and HNFZ (Norwegian Sea – Fennoscandian high, cyclonic) weather conditions is more than twice as high as in the overall circulation. A blocking anticyclone over Fennoscandia

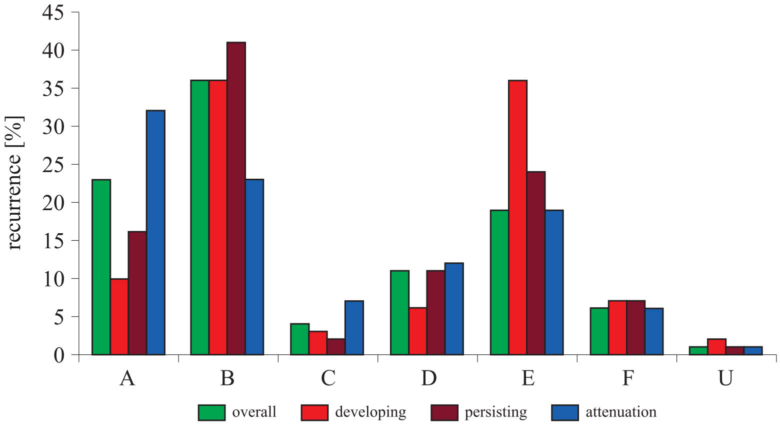

Figure 2. Overall weather type recurrence [%] over Lithuania and weather types during different phases of dry periods in May–September from 1961 to 2010

and a low-gradient pressure field over Lithuania allows warm continental air masses to flow from north to east. Also, the frequency of the weather condition BM (Central European ridge), which lets southern warm air masses enter Lithuania, is 40% higher under dry period conditions.

It is obvious that the recurrence of different weather types during dry period phases varies a lot (Table 2). A difference from the overall circulation patterns has already appeared during the first 15-day period. However, the greatest changes in circulation can be seen during the next 15 days of the developing phase. The recurrence of weather type E (eastern and north-eastern flow) almost doubles during this phase, while the frequency of zonal circulation decreases.

The circulation features of the persisting phase differ slightly from the developing phase. The recurrence of high-pressure centres (type B) increases, while the frequency of type E weather is lower than in the developing phase. Also, a slight increase in zonal circulation can be observed, although its recurrence is lower than during general conditions.

The attenuation phase (10 days) can be characterised by the restoration of the overall circulation frequency with even more intense western (32% compared to 23% for the overall circulation) flows (type A), which bring cooler and moister air. The northern flow (type D) is also very favourable for dry period attenuation, while the recurrence of the high-pressure centre (type B) decreased (Figure 2).

The regional differences are not so specific, although some peculiarities can be identified. The influence of the meridional flows (types E and F) on dry period development and a persisting phase is higher in the west than in the other regions, whereas in south-eastern and north-eastern Lithuania high-pressure centres (type B) are a more frequent cause of dry periods.

The largest regional difference is determined during the attenuation phase. A very strong shift from meridional to zonal circulation (Table 2) in south-eastern Lithuania is observed. Meanwhile, a strong increase in the northern flow (type D) during the attenuation phase is common to all parts of the country.

4. Atmospheric circulation patterns during dry periods

The NAO and AO indices for the periods 30 days prior to dry period events have been grouped into three different clusters. The first group indicates a prevailing negative NAO/AO phase during these periods, the second a stepwise weakening of the positive NAO/AO phase, and the third a different mean course for the NAO and AO indices. A strong positive NAO index after the first 15 days drops close to zero, while the AO index shows a permanent strengthening of the positive AO phase during the first 20 days, followed by a slight weakening (Figure 3).

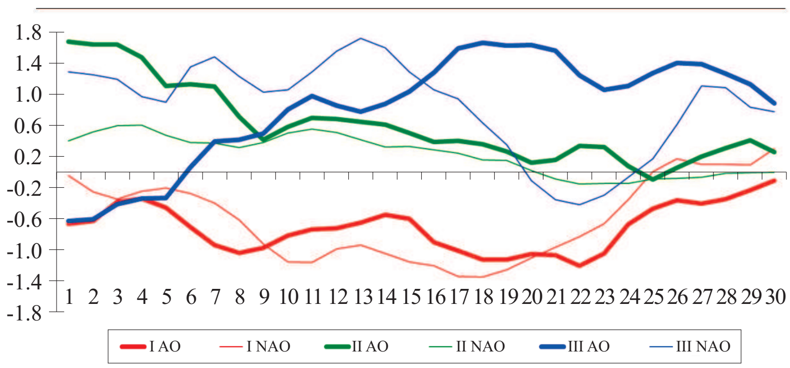

Figure 3. Plot of the means of each cluster of the daily NAO and AO indices for the development phase (30 day period) of every dry period. The standardised NAO and AO indices are shown on the y-axis and the sequence of days in the development phase on the x-axis

The first cluster aggregates the highest number of dry period preconditions – 55%, the second – 25%, and the third – 20%. The AO index in most of the cases shows a greater magnitude than the NAO, and also the number of members in every cluster is distributed more evenly in the case of AO than in the NAO. For this reason all composites for every cluster were made only for AO cluster members.

Composite analysis of 500 hPa height anomalies calculated as a mean field for every AO index time series cluster reveals three different preconditioning circulation patterns before dry period events.

The first one resembles a typical summer western European blocking pattern, which tends to propagate further eastwards. However, this mean field aggregates different synoptic development patterns (Figure 4a). Many of the events included in this pattern represent the slow movement of an upper high from the mid-Atlantic to western Europe, while others depict the slow development of a cut-off-low over the western Mediterranean, or the retreat of an upper low from Scandinavia to northern Asia.

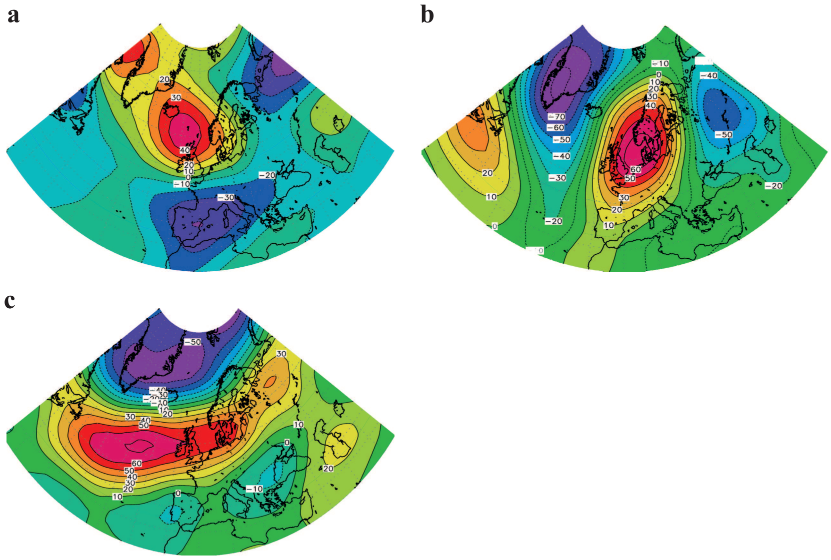

Figure 4. Composites of 500 hPa geopotential height anomalies of 30-day periods prior to dry period events for every AO index time series cluster: a) first cluster, b) second cluster, c) third cluster. Anomalies are extracted from long-term means based on the 1961–2010 period. The images were constructed using GrADS software. For further explanations, please refer to the text

The second cluster's composite involves the most stable drought development conditions: an upper high developing not far from the drought location (southern Scandinavia), and subsequently developing into the central European blocking pattern. The intra-seasonal variation of the blocking index over the European domain during the analysed dry periods gave a clear sign of blocking over the Baltic region longitudinal belt 0–20 days before the dry period started. Also, these blocking patterns were identified as being the strongest between dry periods attributed to other clusters (Figure 4b). The most extreme drought in the summer of 1992 had the strongest blocking signal, which was related to the more extended blocked circulation to the west, while other droughts were related only to regional, short-lived blocking episodes. Moreover, blocking tended to recur during the drought development phases of the three severe droughts analysed: 1994, 1996 and 2002 (Figure 5).

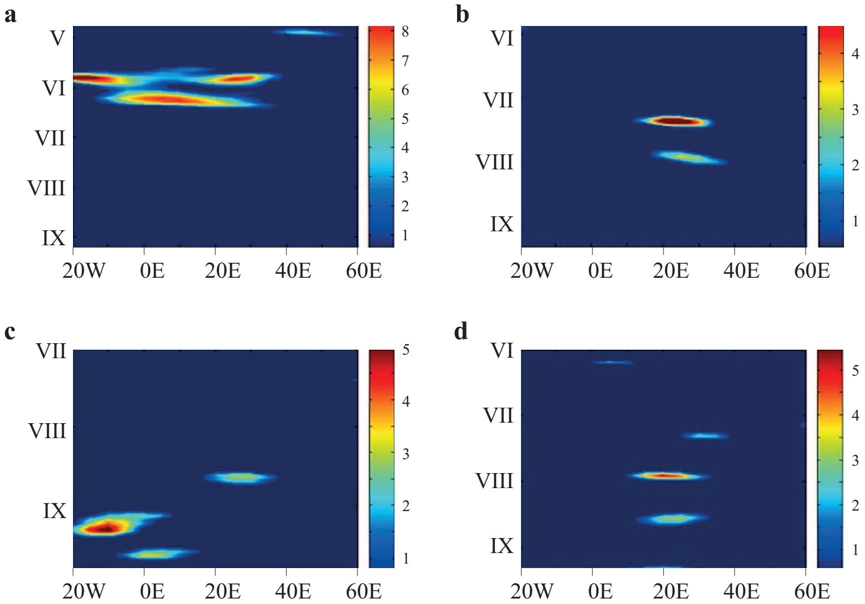

Figure 5. Hovmoller diagrams of the TMI blocking index for the droughts involved in the drought development cluster II (see explanations in the text): 1992 (a), 1994 (b), 1996 (c) and 2002 (d). The y-axis in the diagrams represents seasonal length, which corresponds to the individual drought occurrence and development periods. The units are gpm deg^{-1} latitude

If the first two composites correspond to weak AO circulation (a positive geopotential anomaly over the European Arctic), then the third one resembles a more intense zonal circulation over subpolar latitudes and is similar to a north-shifted NAO-like pattern. Actually, the periods involved in this cluster represent the most unstable development: transient synoptic scale waves cross the north-eastern Atlantic and northern Europe, while other cyclonic systems develop over southern Europe and the Mediterranean. So drought development is initiated by transient ridges crossing Great Britain, southern Scandinavia and the Baltic Sea, while frontal activity is shifted northwards from this track (Figure 4c).

Composite analysis of the 500 hPa height anomalies for the dry periods shows a very diverse picture: from the weak gradient in the upper high pressure field to the weak cyclonic circulation over the southern Baltic region. The composite field of the persisting phase of the four longest dry episodes in Lithuania shows a very distinctive dipole pattern at the 500 hPa level with a positive anomaly centre located over Scandinavia, and a negative centre (negative anomaly belt) over western Europe, the Mediterranean and the Balkans (Figure 6). This points to the generation of anticyclones over Scandinavia, which give rise to the persistent rainfall deficiency in Lithuania. Also, this pattern resembles the summer Scandinavian blocking high (Cassou et al. 2005) and the positive phase of the Scandinavia teleconnection pattern (Bueh & Nakamura 2007), which is less prominent in summer than in other seasons.

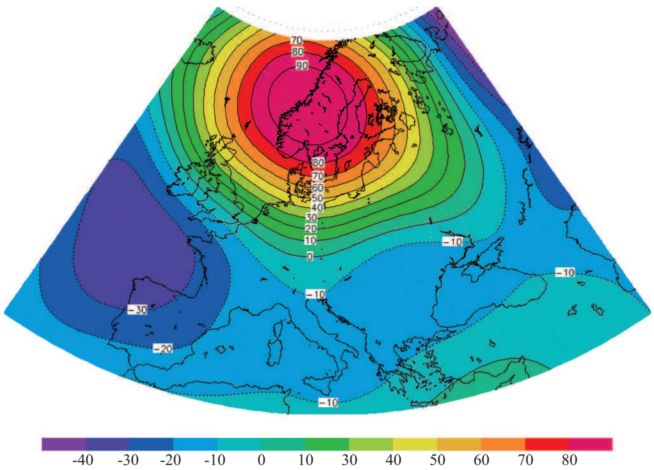

Figure 6. Composition of the 500 hPa geopotential height anomalies [gpm] for the persisting phase of the four longest dry periods in at least one part of Lithuania (1992, 1994, 2002 and 2006). The different length of the persisting phases is standardised to a period of 35 consecutive days with the lowest HTC values in each period. The contour interval is 10 gpm. Anomalies were calculated according to the 1961–2010 reference period. The images were constructed using GrADS software

5. Discussion and conclusions

An analysis of the Hess and Brezowski macro-circulation forms shows that dry periods are determined by a decrease in zonal and an increase in meridional circulation form patterns in Lithuania. This corresponds to other findings (Jaagus 2006, Avotniece et al. 2010, Kažys et al. 2011) in the eastern Baltic region. Even though dry periods are very hard to define by atmospheric circulation patterns (Kingston et al. 2013), this research revealed some significant differences during its persistence. An especially strong shift from general circulation patterns is observed during the developing phase of a dry period. The domination of meridional vs. zonal circulation patterns remains during the persisting phase, while ‘extra’ zonal circulation patterns occur during the attenuation phase of a dry period. Prolonged dry anomaly alterations to humid periods are very common in May–September in Lithuania. Moreover, the findings are confirmed by analyses of the atmospheric circulation and extreme conditions in the region (Rimkus et al. 2011, Rimkus et al. 2013).

The analysis of 14 cases when HTC was less than or equal to 0.5 for 15 consecutive days revealed the fact that the frequency of weather types in the whole of Lithuania is significantly different from the respective values in the various regions (Table 2). Even though Lithuania is not a large country (ca 65 300 km^2) this can be explained by different climatic features (Figure 1). The whole country lies in the air mass transformation zone between oceanic and continental climates: it is a hemiboreal climate (type Dfb) according to the Köppen-Geiger climate classification (Peel et al. 2007). Particularly significant differences between the western and southern parts of the country have already been observed in dryness analyses for the Baltic Sea region (Pankauskas & Bukantis 2006, Rimkus et al. 2012) and the Nemunas river basin (Rimkus et al. 2013). Another possible reason is methodological. We use the subjective (Werner & Gerstengarbe 2010) vs. objective (Fleig et al. 2011) Hess and Brezowski atmospheric macro-circulation form classification. Although the classification has been modified for Lithuania, there are shifting possibilities of weather patterns because of geographical features and long dry period phases (>2 weeks). Different weather conditions could be identified using both methods, especially at the beginning and end of dry phases.

A previous study by Bukantis & Valiuškevičienė (2005) showed that extreme air temperatures are mostly determined by meridional, and extreme precipitation – by zonal circulation forms. However, extreme weather events are generated by diverse circulation forms if the whole country was used for determining circulation forms. Drought formation cluster analysis (Figure 1) explains clearly that circulation forms should be analysed for different parts of the regions, even though the territory is not that big. This statement was already endorsed by Rimkus et al. (2011, 2012). Another possible reason for the variance is the inequality of dryness trends (Rimkus et al. 2013) in different parts of Lithuania. The dryness frequency remains practically the same in the western part of the country, while in other parts dryness tends to decrease.

Dry periods usually correspond to high pressure fields (Parry et al. 2010, Fleig et al. 2011). Hence, drought persistence in the Baltic region is almost always predetermined by a strong anticyclonic circulation above, in the middle troposphere, while the centre of such a circulation is situated on average to the north-west of the drought region, and favours the advection of warm and dry air. The North Atlantic oscillation and the Arctic oscillation are not very active large-scale phenomena in the warm season (Parry et al. 2010, Kingston et al. 2013). However, three different AO and NAO index course clusters were extracted from daily data in the 30-day periods prior to every drought event. Most of the development stages before dry periods appear to be linked with the negative NAO/AO phase.

Almost all the dry periods studied have a precursor – an enhancing and eastwards propagating ridge with the possibility of blocking westerly flow over western Europe. Moreover, such blocking ridges prior to the most extreme drought events tend to develop over central Europe accompanied by deep upper troughs upstream and downstream from them. Only a few dry periods were initiated by a zonal flow slowly retreating to the north and later replaced by a upper level ridge. These conditions (third cluster) lead to a shortage of precipitation primarily in south-eastern Lithuania, whereas the first two clusters have the same effect in western and north-eastern Lithuania.The persisting phase of dry periods seems to be less dependent on anomalous atmospheric circulations. Only the four longest dry periods were associated with a persistent geopotential height anomaly centred over Scandinavia, while the others showed a wide range of available weather regime sequences: a surface anticyclone over Russia slowly retreating to the south-east, an upper level ridge over the Balkans, Ukraine and Belarus, a stable upper level high over northern Russia, a cut-off-low over the Balkans and the Black Sea etc. However, all this list of available regimes does not mean their persistence in space and time, or their persistent influence in maintaining dry periods in Lithuania. Direct forcing on the dryness of circulation processes appears to take place only at the beginning of the persisting phase, while inertia plays an important role in the remainder of this phase, particularly because of the slow recovery of soil moisture. This problem is beyond the scope of the present paper, however.

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