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Quasi-biennial oscillation effect on climate indicators: Lithuania's case

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Abstract The quasi-biennial oscillation (further – QBO) is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 26 to 29 months. Together with other circulation mechanisms, the QBO comprises a global climate system which affects the climate indices of different regions of the globe including Lithuania. The authors of the present paper chose to address the issue of the anomalies of precipitation in Lithuania. The research encompasses the time frame from 1953 to 2009: relationship between the periods without precipitation for 10 and more days, monthly precipitation sum and different phases of QBO. The highest statistically significant precipitation deviations according the QBO phase at the 30 hPa level were established to be in May, September and November. The anomalies of precipitation were found to be predetermined by the atmospheric circulation patterns.

Keywords • *atmospheric circulation • quasi-biennial oscillation (QBO) • periods without precipitation • precipitation amount*

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INTRODUCTION

The quasi-biennial oscillation (QBO) of the winds in the equatorial stratosphere was detected in the 1950s of the 20th century due to the establishment of a global, regularly measuring radiosonde network. This significant physical discovery belongs to Graystone and Ebdon from the UK and Reed from the USA. Analysing the data transmitted by radiosondes they found that equatorial stratosphere winds are characterised by periodically recurring easterly and westerly phases (Graystone 1959; Ebdon 1960; Reed *et al.* 1961). These air flows are generated at 30 km (isobaric surface13 hPa) above sea level and descend through the stratosphere at 1 km month^{-1}. The wind direction is changing every 13–14 months simultaneously over the entire equatorial zone. The complete cycle of the oscillation embraces 26–29 months. Later it was established by other researchers that QBO may not only affect the equatorial atmospheric circulation but also the atmospheric circulation of higher latitudes and formation of long-lasting weather anomalies (Naujokat 1986; Paluš, Novatna 2006).

Investigations of the influence of the easterly and westerly QBO phases on the precipitation amounts in different European regions showed a strong signal in the region of the British Isles, Central Europe and Belarus in September and October and in the southern part of the Ukraine in August and October. It was observed that the easterly phase generates greater unchangeable amounts of precipitation in September whereas in October the changeability increases. A contrary situation occurs in the eastern part of the Ukraine and in the adjacent part of Russia where a strong signal yet of different character was observed in May: greater amounts of precipitation and their lower changeability were recorded during the westerly phase. The difference can be accounted for by diverse circulation patterns during the different QBO phases (Brazdil, Zolotokrylin 1995). The results obtained by measurements of maximal temperatures, NAO index and QBO in the North Atlantic using different statistical methods provide basis for assumption that these oscillations are interrelated what is proved by the high correlation coefficient. On the other hand, this is not a resolute statement because the strong relationship might be screened by local factors and more powerful factors of global circulation (Paluš, Novatna 2006).

Longer data sets may show a closer relationship between the tropical cyclones in the Atlantic and QBO yet they may include plenty of other factors. The solar activity cycle and volcanic activity predetermine the relationship deformations bearing in mind that before 1984 the relationship between the QBO and the tropical cyclones in the Atlantic had been statistically significant (95 %). Also there is one more possibility of intermingling unknown factor in the hurricane system. The impossibility to base the relationship on the statistical data does not necessarily mean that it does not exist or that the correlation before 1984 had been casual (Camargo, Sobel 2010).

The possibility of the QBO influence on the Arctic Polar Vortex has been considered since long ago (Holton, Tan 1980) and the relationship between these two atmospheric mechanisms has been addressed by many researchers. The specific patterns of the atmosphere dynamics have been studied employing empirical orthogonal functions to express the variability of the stratosphere and wave processes in order to link them with the easterly and westerly QBO phases. It has been determined that the Arctic Polar Vortex is weaker during the easterly QBO phase than during the westerly phase. Yet the authors of these studies point out that this mechanism of effect has not been sufficiently well investigated (Garfinkel *et al.* 2012; Watson, Gray 2014). Other authors have found that the Arctic Oscillation (AO) index of the Northern Hemisphere in cold season (November–April) tends to positive values during the westerly QBO phase whereas negative AO values are dominant during the easterly QBO phase. In both cases, the pattern has been established for QBO at 30 hPa yet in warm season (May–October) in the Northern Hemisphere this link discontinues (Lu, Pandolfo 2011). In recent years, the aspects of QBO seasonal variations and their effects on the stratosphere chemistry have been increasingly investigated using digital climate models (Hurvitz *et al.* 2013; Krismer *et al.* 2013).

The effects of QBO on the climate indices in Lithuania have been scantily investigated. The last hundred years in the East Baltic countries was marked by many long-lasting droughts related to the strong anticyclone circulation (Jaagus *et al.* 2010; Rimkus *et al.* 2013). It has been established that droughts in warm seasons can be generated by the Arctic and Azores anticyclones as well as the distribution of atmospheric activity centres and damping processes (Trigo *et al.* 2008; Krichak *et al.* 2014) whereas precipitation anomalies of cold season may be predetermined by intensifying or damping of the westerly flow and other advective factors (Bukantis 2002; Bukantis, Bartkeviciene 2005). The dominance of zonal circulation increases in the winter but decreases in the summer during heavy precipitation events (Rimkus *et al.* 2011). The summer and winter precipitations are strongly influenced by NAO, but the NAO impact is weak during the autumn. The snow cover duration in Lithuania is strongly influenced by NAO. In the negative NAO phase, the snow cover lasts longest, while in the positive phase it is the shortest (Mickevičius, Bukantis 2013).

The aim of this study was to analyse if there exists in Lithuania a relationship of precipitation anomalies and long-lasting periods without precipitation (PWP) with quasi-biennial oscillation (QBO) and whether the damping of the westerly transport and intensity of cyclonic processes in the Scandinavian–Baltic region are affected by the QBO. The knowledge of the link between the precipitation amount anomalies and QBO would contribute to improvement of the methods for prediction of long-lasting precipitation anomalies (droughts or high rainfall spans).

STUDY AREA AND DATA

The quasi-biennial oscillation (QBO) data were taken from the database of the Institute of Meteorology, Freie Universität Berlin (Freie Universität Berlin 2013). The data of the stratospheric winds (direction and velocity, m s^{-1}) for 1953–2009 are analysed. From January 1953 to August 1967, the variations of zonal wind were measured in the Canton Island (2° 46′, 171° 43′) of the Republic of Kiribati. The meteorological station of the Canton Island registered the wind velocity in the isobaric surfaces 70, 50, 40, 30, 20, and 15 hPa. The 10 hPa parameters have been monitored since January, 1956. From September 1967 till December 1975, a monitoring station operated in the Gan Island of the Maldives (0° 41′, 73° 9′), and since January 1976 the stratospheric wind parameters have been monitored in Singapore (1° 22′, 103° 55′). It is worth pointing out that since January 1987 the wind parameters have been recorded in detail: in 90, 80, 70, 60, 50, 45, 40, 35, 30, 25, 20, 15, 12 and 10 hPa isobaric surfaces, but in this paper were used only 50 and 30 hPa isobaric surfaces. All stations are close to the equator where QBO stratospheric oscillation develops.

The measurements are made by radio sounding. The system records the velocity and direction of stratospheric winds. The present study represents an analysis of mean monthly wind parameters in the 30 hPa isobaric surface where the oscillation amplitude of wind velocities is highest. For the relationship between the amount of precipitation and QBO, the monthly and daily precipitation data for 01 01 1953 to 30 12 2009 from three Lithuanian Hydrometeorological Service meteorological stations (Lazdijai, Vilnius and Šiauliai) were analysed. The chosen meteorological stations represent the greater part of Lithuania's territory and are located in different physical geographical regions (Fig. 1).

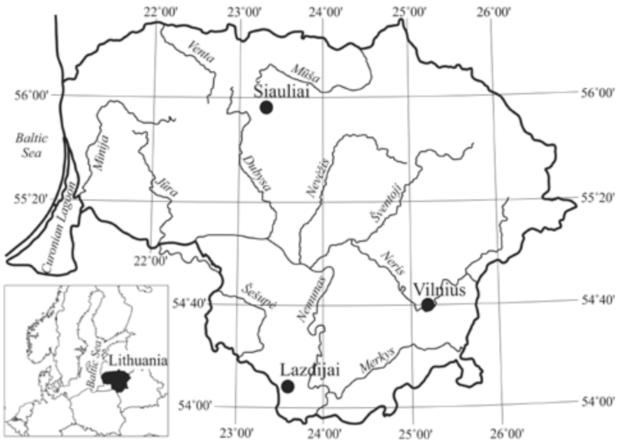

Fig. 1 Locations of meteorological stations from which the data were used in the present study. Compiled by A. Bukantis, 2015

METHODS

A time limit of 10 days was chosen for identification of periods without precipitation (PWP). This means that PWP is a time span more than 10 days without precipitation in at least two meteorological stations. The meteorological stations were chosen so as to avoid the effects of local conditions, which, for example occur in the coastal area or windward slopes of the Žemaičiai Uplands. The criterion of two meteorological stations was applied for identification of PWP which may have been related with large-scale (not local) processes of atmospheric circulation. For determining the relationship between QBO (in 50 and 30 hPa isobaric surfaces) and PWP, all PWP were bound to respective months as the data of quasi-biennial oscillations are represented by monthly means. Thus the PWP is ascribed to that month which includes more than a half of the days without precipitation. Also the empirical PWP recurrence probability for respective QBO phases was calculated, i.e. the number of PWP during the westerly QBO phase was counted and then subtracted by the sum of westerly QBO months. The same principle was applied in calculating the probability of recurrence during the easterly phase. For determining the relationship between the QBO oscillation and the sum of monthly precipitation, each month was ascribed to the westerly (positive) or easterly (negative) QBO phase. The deviation of precipitation from the mean value for the entire period is then calculated for the both phases. In total, 20 easterly and westerly QBO events for each month were analysed. For evaluation of the statistical validity of conclusions, the Wilcoxon rank-sum test was used; WRST (Fay, Proschan 2010).

The WRST is a nonparametric test of the null hypothesis that two populations are the same against an alternative hypothesis especially that a particular population tends to have larger values than the other. The distributions of both groups are equal under the null hypothesis, so that the probability of an observation from one population (*X,* precipitation amount during the westerly QBO phase) exceeding an observation from the second population (*Y,* precipitation amount during the easterly QBO phase) equals the probability of an observation from *Y* exceeding an observation from *X.* The same method was applied for analysis of the effects of QBO on the precipitation amounts in cold and warm seasons. The warm season referred to in the present study lasted from April till October and the cold season from November till March. Only the seasons with all months included either in the westerly or easterly QBO phases were analysed.

The compositional maps of precipitation anomaly and sea level pressure during the westerly and easterly QBO phases were compiled for Baltic region by using the interactive website *Monthly/Seasonal Climate Composites* (source: http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl) based on the reanalysis data from NCEP and developed by NOAA Earth System Research Laboratory (NOAA, 2014).

RESULTS

QBO and periods without precipitation

PWP is a time span more than 10 consecutive days without precipitation or precipitation being no more than 0.0 mm in at least two meteorological stations. The absence of precipitation for so long usually is related with a large-scale anticyclone circulation in the Baltic Sea region which is unfavourable for production of precipitation (Pankauskas, Bukantis 2006; Jaagus *et al.* 2010; Rimkus *et al.* 2012). Droughts not always fall under the category of PWP as there remains a possibility of local convective precipitation. The periods without precipitation in Lithuania were established and analysed according to the daily precipitation data from the Lazdijai, Vilnius and Šiauliai meteorological stations. During the analysed period, the average PWP recurrence was 2.46–2.92 events per year. Usually, the PWP lasted 10–14 days (the average of 1.93–2.26 events per year). The PWP with duration of more than 14 days only occurred in some years (Table 1).

Table 1 Total number and annual recurrence of periods without precipitation (PWP) of different duration in 1953–2009. Compiled by A. Bukantis, 2015

Duration of PWP, days	10–14	15–19	≥20	Total
Lazdijai N54º14' E23º31'	129 / 2.26	28 / 0.49	10 / 0.18	167 / 2.92
Vilnius N54º35' E25º26'	126 / 2.21	27 / 0.47	13 / 0.22	166 / 2.91
Šiauliai N55º56' E23º19'	110 / 1.93	21 / 0.37	9 / 0.16	140 / 2.46

Table 2 Quasi-biennial oscillation (QBO) recurrence during the westerly (W) and easterly (E) phases at 30 and 50 hPa. Compiled by A. Bukantis, 2015

QBO altitude	30 hPa		50 hPa	
QBO phase	W	E	W	E
Number of PWP events (Σ_{PWP})	55	73	80	48
Duration of QBO in months (Σ_{QBO})	330	354	420	264
Σ_{PWP} / Σ_{QBO}	1 / 6.00	1 / 4.85	1 / 5.25	1 / 5.50

The longest PWP lasted for 30–31 days in Vilnius and Lazdijai meteorological stations from 18 04 2000 to 18 05 2000. A 28 days-long PWP recorded in the Šiauliai meteorological stations occurred in August, 2002. In all three meteorological stations, the PWP not necessarily began and ended at the same time. In all meteorological stations there were 63 concurrent PWP including 55 ones lasting for 10–14 days, seven for 15–19 days and only one lasted for 25 days. In order to avoid the effects of local phenomena on formation of precipitation only those PWP were analysed which were concurrent in at least two meteorological stations. In the time span under consideration (1953–2009), there occurred 128 such events (the annual mean 2.25 PWP). The recurrence of PWP in different years was uneven: eight years had one PWP, 22 years 2 PWP, eight years 3 PWP, six years 4 PWP, and five years 5 PWP each. There were seven years without a single PWP (Fig. 2).

There were 11 years with 4–5 PWP (1969, 1975, 1979, 1982, 1983, 1984, 1996, 1999, 2000, 2003, and 2005). Analysis of the variations of stratospheric winds in the 30 hPa isobaric surface showed that the years 1969, 1975 and 1999 with 4 PWP each fell into the westerly (positive) QBO phase whereas the remaining 8 years fell into the easterly (negative) QBO phase. It is important to point out that the latter group includes the all years with the maximal number (5) of PWP each. In other words, the greater number of the years (73%) with frequent recurrence of PWP fell into the easterly (negative) QBO phase.

The recurrence of PWP according to the QBO phases is highly dependent on the altitude of QBO phase. Bearing in mind that QBO develops at a 10 hPa and changes following a regular pattern to 100 hPa, the affect on the same atmospheric circulation at different altitudes can be different (Naujokat 1986). For example, the QBO at altitudes 30 hPa and 50 hPa usually is different. The obtained results confirm the variations of QBO at different altitudes: the majority of PWP events in Lithuania occurred when the easterly phase was at 30 hPa and the westerly phase was at 50 hPa. Moreover, at different altitudes the duration of phases varies: in the 30 hPa isobaric sur-

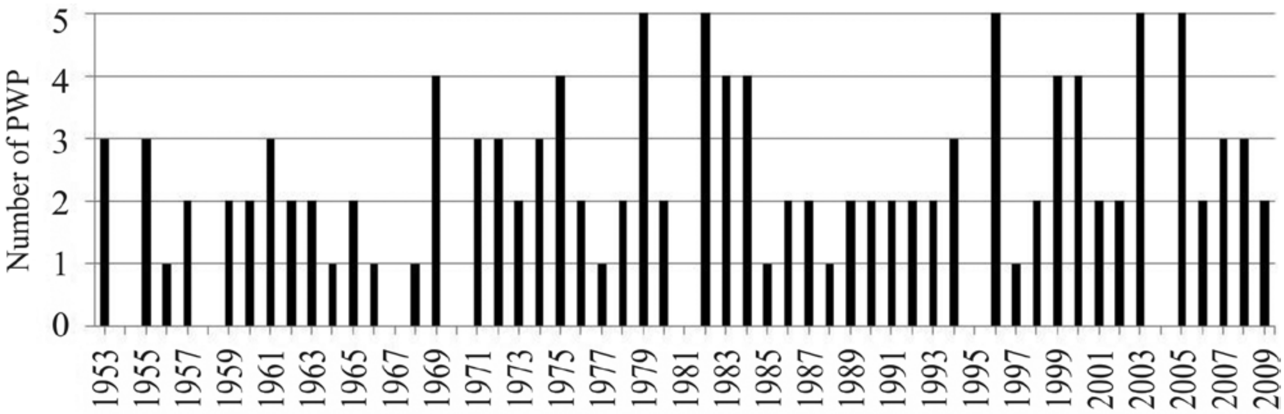

Fig. 2 The number of periods without precipitation (PWP) in Lithuania by years in 1953–2009. Compiled by A. Bukantis, 2015

face, the westerly phase lasts for 330 months whereas the easterly lasts for 354 months. At the altitude of 50 hPa, the differences are even more pronounced as the westerly phase lasts for 420 months whereas the easterly last only 264 months (Table 2).

QBO and precipitation amount

The amount of precipitation in the territory of Lithuania was analysed based on the data on monthly precipitation from the Lazdijai, Vilnius and Šiauliai meteorological stations. The averaged data from the three meteorological stations represent the amount of precipitation in the territory of Lithuania (Fig. 3). The greatest amount of precipitation is recorded in the summer (maximum in July – 81.4 mm), the lowest in February – 31.7 mm). Grouping of months according to QBO phase at 30 hPa showed that during the westerly QBO phase in cold season (November–March) the amount of precipitation exceeds the long-term average whereas from April till September precipitation amount exceeds the average during the easterly phase (Fig. 3).

In October, the amount of precipitation during the both QBO phases is actually the same. The following step included calculation of the monthly average precipitation deviation (ΔP) from the long-term average. The highest positive ΔP percentage during the westerly QBO phase was established in September (12.3 %), November (8.1 %) and February (6.9 %). The highest negative ΔP percentage was established in July (−9.8 %), August (−5.9 %) and April (−5.6 %) (Table 3).

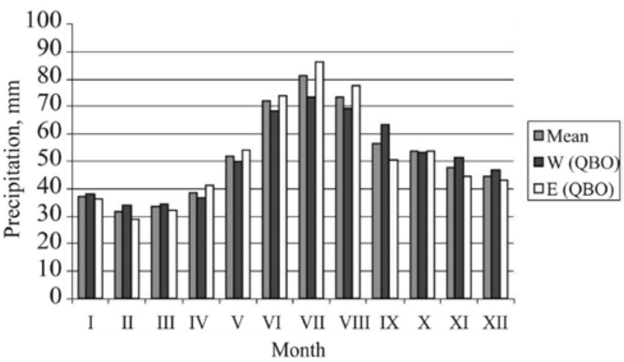

Fig. 3 The average monthly precipitation amount (mm) in Lithuania during the westerly (W) and easterly (E) quasi-biennial oscillation (QBO) phases. Compiled by A. Bukantis, 2015

During the easterly QBO phase, the deviations of precipitation had the opposite sign than the ΔP during the westerly QBO. The highest ΔP were recorded in April and July–August – 5.2–6.9 %. During the easterly QBO phase, the negative ΔP values were higher; particularly in September when this value reached 10.8 %. The maximal negative ΔP also occurred in February (−8.5 %) and November (−7.1 %). In the rest of the year, the deviations ranged from −4.1 % to +3.5 % (Table 3).

The obtained ΔP results were checked using the Wilcoxon rank-sum test in order to determine whether the precipitation amount deviations ΔP from the long-term average grouped according to QBO phases were statistically significant. Using this test, three months were established whose ΔP were statistically significant (Table 3). The statistically significant precipitation differences between the easterly and westerly QBO phases were established for May and September (90 % validity) and November (95 %). These results are the opposite of the results obtained for Central Europe and British Isles and coincide with the results obtained for the territory of Belarus in 1953–1972 (Brazdil, Zolotokrylin 1995).

By dividing the year into cold (November–March) and warm (April–October) seasons an attempt was made to determine the influence of QBO phases on the seasonal precipitation amounts. The obtained results show that in cold season the values of precipitation were higher during the westerly QBO phase: ΔP = 15.6 mm or 7.9 % from the long-term average (Table 4). Meanwhile, during the easterly QBO phase, the precipitation values were lower.

In warm season, the affects of the QBO phases were opposite. During the westerly QBO phase, the amount of precipitation was on the average by 19.5 mm lower (ΔP = 4.5 %). During the easterly phase, the effect was different, i.e. the precipitation amount increased by 19.4 mm. The obtained ΔP dif-

Table 3 Average precipitation deviation (ΔP) of precipitation amount in 1953–2009 from the average value for this period during the westerly (W) and easterly (E) quasi-biennial oscillation (QBO) phases, mm and % (month ranked in Wilcoxon rank-sum test to 90 % (*) and 95 % (**)). Compiled by V. Akstinas, 2015

Month / QBO phases	I	II	III	IV	V*	VI	VII	VIII	IX*	X	XI**	XII
ΔP mm												
W	1.0	2.2	1.0	–2.2	–2.1	–3.2	–8.0	–4.3	6.9	–0.4	3.9	2.1
E	–1.0	–2.7	–1.4	2.7	1.8	2.2	5.0	3.8	–6.1	0.3	–3.4	–1.9
ΔP %												
W	2.8	6.9	3.1	–5.6	–4.0	–4.5	–9.8	–5.9	12.3	–0.7	8.1	4.7
E	–2.6	–8.5	–4.0	6.9	3.5	3.0	6.1	5.2	–10.8	0.6	–7.1	–4.1

Table 4 The precipitation amount deviation (ΔP) in cold and warm seasons in Lithuania from the average value for 1953–2009 during the westerly (W) and easterly (E) quasi-biennial oscillation (QBO) phases, mm and %. Compiled by V. Akstinas, 2015

Season	Precipitation amount mm			ΔP mm		ΔP %	
	Average	W	E	W	E	W	E
Cold	196.8	212.4	181.3	15.6	–15.5	7.9**	–7.9**
Warm	433.2	413.7	452.6	–19.5	19.4	–4.5*	4.5*

ferences during the different QBO phases in cold and warm seasons were checked for validity using the Wilcoxon rank-sum test: ΔP 95 % and 90 % for cold and warm seasons respectively. There is a good basis for assumption that the QBO phases may have a certain effect not only on monthly but also on seasonal precipitation in the territory of Lithuania.

Sea level pressure during precipitation anomalies

After establishing the months with statistically valid precipitation deviations during the westerly and easterly QBO phases, composite maps of sea level pressure and precipitation anomalies in the Baltic region were compiled. For compilation of the maps for May, 20 % of the years with the highest negative deviations of precipitation during the westerly QBO phase and 20 % of the years with the highest positive deviations during the easterly phase were used. For the maps for September and November, 20 % of the years with the highest negative deviations of precipitation during the easterly QBO phase and 20 % of the years with the highest values during the westerly phase were used.

During the westerly QBO phase in May, the amount of precipitation decreased not only in the territory of Lithuania but also in the northern part of the Baltic Sea region due to the dominant high-pressure area damping the westerly transport of air masses (Fig. 4a). The highest negative precipitation anomalies embrace the area between the north-western part of Belarus and the Ladoga Lake. They reach up to −1.5 mm d^{-1} (−46 mm per month) and account for 45 % of the average monthly precipitation amount. Lithuania is included in the western part of this anomaly. Slightly lower anomalies (up to −31 mm) develop over the southern part of Sweden (50 % of the long-term average). South of the Gulf of Finland, a positive +1.3 mm day^{-1} (46 mm per month) – precipitation anomaly accounting for 46 % of the long-term average develops during the easterly QBO phase (Fig. 4b). The western part of this anomaly also includes the territory of Lithuania. A positive precipitation (10 mm per month) anomaly can be observed over Sweden. It is obvious that the pattern of atmospheric circulation markedly varies during the different QBO phases: during the westerly phase in May, the Baltic Sea region is predominated by the high-pressure area whereas during the easterly phase by the low-pressure area.

In September, the low-pressure area in the territory under consideration expands during the westerly QBO phase and is responsible for the positive precipitation anomalies (Fig. 5a). The strongest positive anomaly generates over East Poland and West Belarus. It also embraces the territory of Lithuania. The positive precipitation anomaly reaches up to +1.8 mm d^{-1} (+54 mm

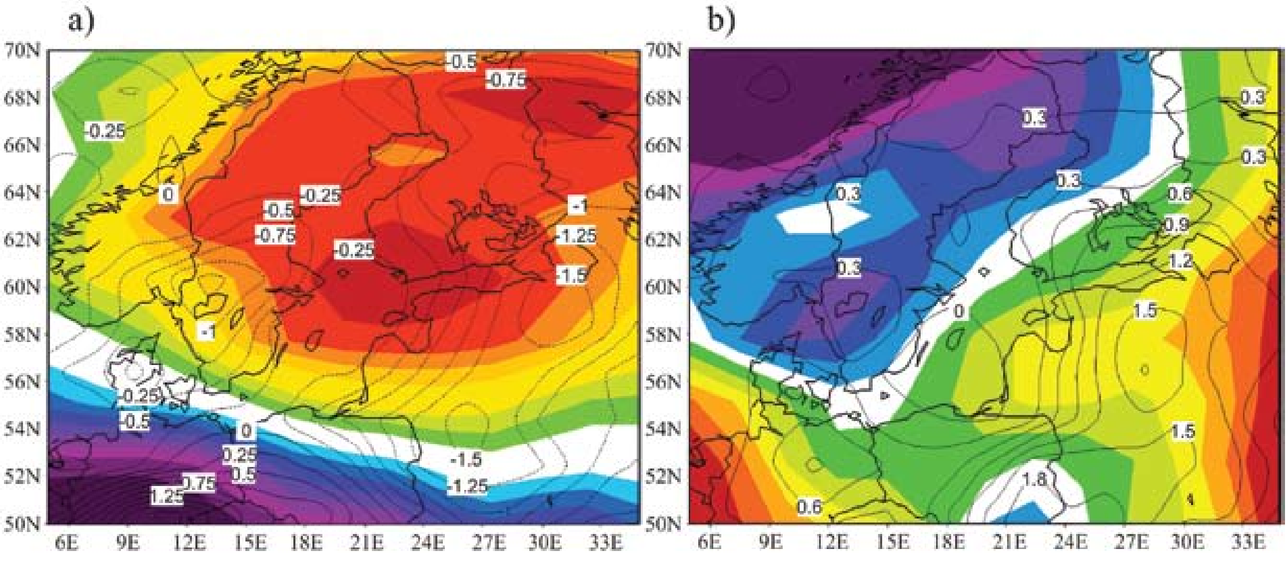

Fig. 4 Sea level pressure (red/green – high pressure, purple/blue – low pressure) and precipitation anomalies (isolines mm d^{-1}) in May during the westerly (a) and easterly (b) quasi-biennial oscillation (QBO) phases (source: NOAA, 2014). Compiled by V. Akstinas, 2015

per month) and its even 85 % of the average monthly precipitation amount. During the easterly QBO phase, the Baltic Sea region gets into the northern part of the high-pressure area what accounts for the negative precipitation anomalies (Fig. 5b). The hotbeds of anomalies are scattered over the whole Baltic Sea region yet the biggest one is in the central part of the Baltic Sea, around the Gotland Island in particular where the precipitation anomaly reaches −1.35 mm d^{-1} (−40 mm per month) accounting for 78 % of the average monthly precipitation amount.

In November, the situation is analogous to the one in September: during the westerly QBO phase, the region is predominated by the low-pressure area and positive precipitation anomalies whereas during the easterly phase by the north-western periphery of the high-pressure area and negative precipitation anomalies (Fig. 6a, Fig. 6b). During the westerly QBO phase, the highest positive 30 mm per month anomaly embraces the territories of North Lithuania and South Latvia and is extending in WE direction (Fig. 6a). The amount of precipitation exceeds the long-term value even by 80 %.

During the dominant easterly QBO phase, the highest negative precipitation anomaly (up to −27 mm per month, 51 % of the average monthly precipitation amount) is generated in the south-eastern part of the Baltic Sea. It also extends into the territory of Lithuania. The remaining part of the region is predominated by −18 mm anomaly.

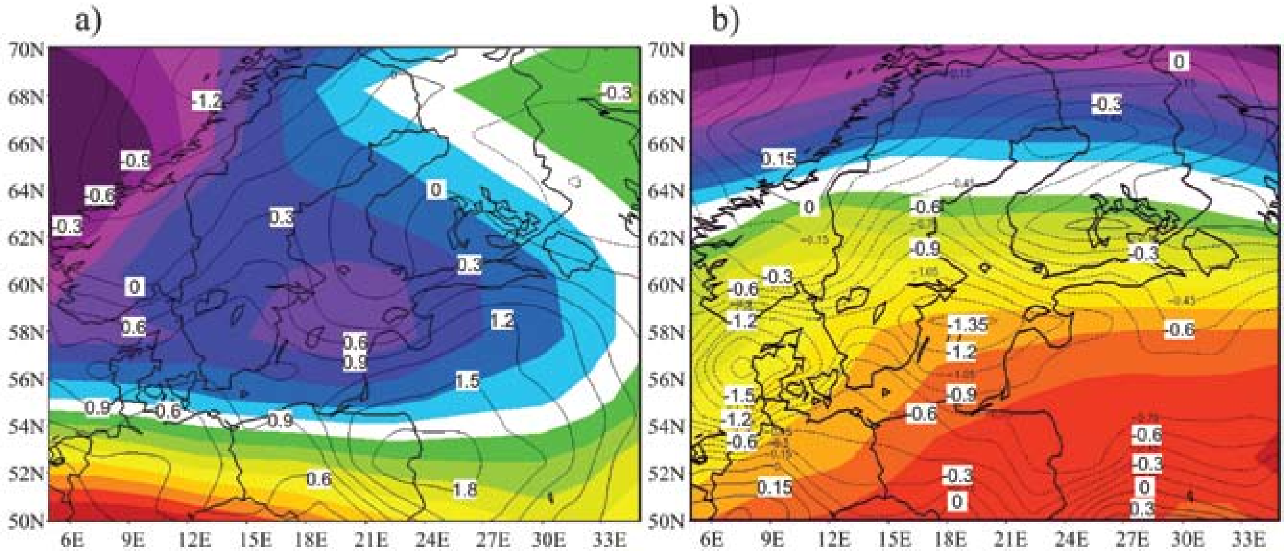

Fig. 5 Sea level pressure (red/green – high pressure, purple/blue – low pressure) and precipitation anomalies (isolines mm d^{-1}) in September during the westerly (a) and easterly (b) quasi-biennial oscillation (QBO) phases (source: NOAA, 2014). Compiled by V. Akstinas, 2015

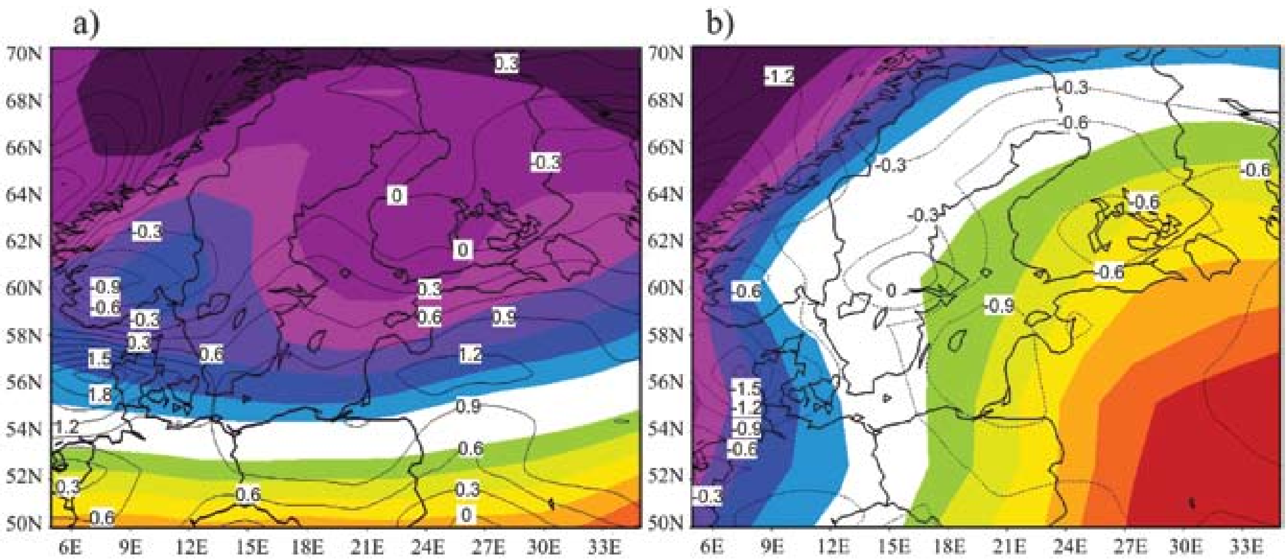

Fig. 6 Sea level pressure (red/green – high pressure, purple/blue – low pressure) and precipitation anomalies (isolines mm d^{-1}) in November during the westerly (a) and easterly (b) quasi-biennial oscillation (QBO) phases (source: NOAA, 2014). Compiled by V. Akstinas, 2015

DATA COMPARISON THROUGHOUT THE CENTRAL EUROPE

The average amount of precipitation and its dependence on the different QBO phases were studied in Eastern, Western and Central Europe (Brazdil, Zolotokrylin 1995). In most of Europe, statistically significant results were obtained in May, September and October, but these results differ pretty much from the results of this paper. In May, in the eastern part of Ukraine higher amount of precipitation was estimated during the westerly QBO phase, whereas in Lithuania 4.0 % decrease in amount of precipitation during the westerly QBO phase and 3.5 % increase of precipitation during the easterly QBO phase in the same month were determined. In September, in the British Isles, southern part of Germany, Switzerland, Slovakia and Hungary, during the easterly QBO phase greater amounts of precipitation were detected, when in this work the opposite result of –10.8 % decrease of precipitation during the easterly QBO phase and 12.3 % increase during westerly QBO phase was estimated in Lithuanian territory. Identical QBO signal was observed only in a single area of Vitebsk (Belarus).

In Central Europe statistically significant results were obtained in October and QBO signal was identical for September, but in Lithuania in October it did not show statistically significant results. And finally, in November in Lithuanian territory during the westerly QBO amount of precipitation increased by 8.1 %, while during the easterly QBO phase amount of precipitation decreased on average by 7.1 %. Such uneven distribution of amount of precipitation in different areas shows localized impact of westerly and easterly QBO phase signal.

When investigating relations between QBO and a pressure at sea level in the Baltic Sea region, it is important to pay attention to atmospheric circulation of the whole North Hemisphere. It is estimated that QBO affects Arctic atmospheric circulation from November to April (Hurvitz *et al.* 2013). The research showed that the polar vortex is weaker in the easterly QBO phase than in the westerly phase, but the authors themselves emphasize that the mechanism of impact is not well studied (Watson, Gray 2014). Some authors have shown a close relationship between the Arctic Oscillation (AO) and QBO atmospheric indices, when during the cold season (from November to April) in the Northern Hemisphere the AO index often takes positive values during the westerly QBO phase, while negative values of AO dominate during the easterly QBO phase.

In the Northern Hemisphere during the warm season (from May to October) this relations is broken (Lu, Pandolfo 2011). In this case it is important to draw attention to conditions of formation of AO. During the positive AO phase in the Arctic region low pressure field forms, while in the Subtropics high pressure field is observed. Such a pressure field distribution determines mid-latitude jet-stream, which is associated with decrease of pressure and increase of precipitation in Northern Europe (Hansen *et al.* 2010). This investigations revealed, that during the westerly QBO phase in September and November over the Baltic Sea region the low pressure fields formed together with the positive precipitation anomalies. This well illustrates impact of westerly QBO phase on positive AO values. During the negative AO phase in the Arctic region high pressure field is observed, it provides favourable conditions for anticyclone formation over the Baltic Sea region (Hansen *et al.* 2010).

The analysed investigations stated that during the easterly QBO phase the AO index gets negative values. This coincides with the results of this research, where in September and November during the easterly QBO phase over the Baltic Sea region high pressure field together with negative anomalies of precipitation was formed. This explains the higher rate and frequency of periods without precipitation (PWP) during the easterly QBO phase. Thus it can be assumed that the effect of QBO on the pressure and precipitation anomalies in Lithuania and the Baltic Sea Region reveals itself by interaction between QBO and Arctic Oscillation (AO).

CONCLUSIONS

In the analysed time frame 1953–2009, the average recurrence of periods without precipitation (PWP) amounted to 2.46–2.92 events per year. Usually, the PWP lasted for 10–14 days (1.93–2.26 events per year on the average). The longer periods only occurred in some years. Analysis of the relationship between the recurrence of PWP in Lithuania and quasi-biennial oscillation (QBO) showed that higher recurrence of PWP was characteristic of the easterly QBO phase at 30 hPa and that namely during this phase, the events of PWP occurred even 4–5 times per year.

The statistically valid (according to Wilcoxon rank-sum test) QBO effect on the precipitation amount in Lithuania was established in May, September and November. In May, by 4 % lower precipitation was established during the westerly QBO phase and by 3.5 % higher during the easterly phase. The lower values of precipitation in September (−10.8 %) and November (−7.1 %) were established during the easterly QBO phase and the higher values 12.3 % in September and 8.1 % in November were observed during the westerly phase. During the easterly QBO phase in cold season (November–March), the average amount of precipitation in Lithuania is by 15.5 mm (7.9 %) lower, whereas during the westerly phase in warm season (April–October), it is by 19.4 mm (4.5 %) lower than the climate normal.

During the different QBO phases at 30 hPa, the patterns of atmospheric circulation vary considerably: during the westerly QBO phase in May, the Baltic Sea region is predominated by the high-pressure area, damping the western transport of air masses, whereas during the easterly phase over Scandinavia is dominated the low-pressure area. This is why during the westerly QBO phase in May, the negative precipitation anomalies occur not only in Lithuania but also in other parts of the Baltic Sea region and during the easterly phase; the precipitation amount exceeds the long-term average. In September and November, the low-pressure area in the territory under consideration expands during the westerly QBO phase and is responsible for the positive precipitation anomalies whereas during the easterly phase, the Baltic Sea regions finds itself in the northern part of the high-pressure area and is subject to the negative precipitation anomalies.

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REFERENCES

Brazdil, R., Zolotokrylin, A. N., 1995. The QBO signal in monthly precipitation field over Europe. *Theoretical and Applied Climatology 51 (1)*, 3–12. http://dx.doi.org/10.1007/BF00865535

Bukantis, A., 2002. Application of factor analysis for quantification of climate-forming processes in the eastern part of Baltic Sea region. *Climate Research 20 (2)*, 135–140. http://dx.doi.org/10.3354/cr020135

Bukantis, A., Bartkevičienė, G., 2005. Thermal effects of the North Atlantic Oscillation on the cold period of the year in Lithuania. *Climate Research 25 (3)*, 221–228. http://dx.doi.org/10.3354/cr028221

Camargo, S. J., Sobel, A. H., 2010. Revisiting the influence of the quasi-biennial oscillation on tropical cyclone activity. *Journal of Climate 23 (21)*, 5810–5825. http://dx.doi.org/10.1175/2010JCLI3575.1

Ebdon, R. A., 1960. Notes on the wind flow at 50 mb in tropical and sub-tropical regions in January 1957 and January 1958. *Quarterly Journal of the Royal Meteorological Society 86*, 540–542. http://dx.doi.org/10.1002/qj.49708637011

Fay, M. P., Proschan, M. A., 2010. Wilcoxon-Mann-Whitney or *t*-test? On assumptions for hypothesis tests and multiple interpretations of decision rules. *Statistics Surveys 4*, 1–39. http://dx.doi.org/10.1214/09-SS051

Freie Universität Berlin Meteorological Institute 2013. The Quasi-Biennial-Oscillation (QBO) Data Serie. *Source: http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/*

Garfinkel, C. I., Shaw, T. A., Hartmann, D. L., Waugh, D. W., 2012. Does the Holton-Tan mechanism explain how the quasi-biennial oscillation modulates the Arctic Polar vortex? *Journal of the Atmospheric Sciences 69 (5)*, 1713–1733. http://dx.doi.org/10.1175/JAS-D-11-0209.1

Graystone, P., 1959. Meteorological office discussion on tropical meteorology. *Meteorological Magazine 88*, 117.

Hansen, J., Ruedy, R., Sato, M., Lo, K. 2010. If It's That Warm, How Come It's So Damned Cold? *Source: http://www.columbia.edu/~jeh1/mailings/2010/20100115_Temperature2009.pdf*

Holton, J. R., Tan, H. C., 1980. The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *Journal of the Atmospheric Science 37*, 2200–2208. http://dx.doi.org/10.1175/1520-0469-(1980)037<2200:TIOTEQ>2.0.CO;2

Hurwitz, M. M., Oman, L. D., Newman, P. A., Song, L. S., 2013. Net influence of an internally generated quasi-biennial oscillation on modelled stratospheric climate and chemistry. *Atmospheric Chemistry and Physics 13 (5)*, 12187–12197. http://dx.doi.org/10.5194/acp-13-12187-2013

Jaagus, J., Briede, A., Rimkus, E., Remm, K., 2010. Precipitation pattern in the Baltic countries under the influence of large-scale atmospheric circulation and local landscape factors. *International Journal of Climatology 30 (5)*, 705–720.

Krichak, S. O., Breitgand, J. S., Gualdi, S., Feldstein, S. B., 2014. Teleconnection – extreme precipitation relationships over the Mediterranean region. *Theoretical and Applied Climatology 117*, 679–692. http://dx.doi.org/10.1007/s00704-013-1036-4

Krismer, T. R., Giorgetta, M. A., Esch, M., 2013. Seasonal aspects of the quasi–biennial oscillation in the Max Planck Institute Earth System Model and ERA-40. *Journal of Advances in Modeling Earth Systems 5 (2)*, 406–421. http://dx.doi.org/10.1002/jame.20024

Lu, B. W., Pandolfo, L., 2011. Nonlinear relation of the Arctic oscillation with the quasi-biennial oscillation. *Climate Dynamics 36 (8)*, 1491–1504. http://dx.doi.org/10.1007/s00382-010-0773-7

Mickevičius, V., Bukantis, A., 2013. Effects of the North Atlantic oscillation on Lithuanian climate. *Water Management Engineering 42 (62)*, 5–13. [In Lithuanian].

Naujokat, B., 1986. An update of the observed Quasi-Biennial Oscillation of stratospheric winds over the tropics. *Journal of the Atmospheric Sciences 43 (17)*, 1873–1877. http://dx.doi.org/10.1175/1520-0469-(1986)043<1873:AUOTOQ>2.0.CO;2

NOAA Earth System Research Laboratory Physical Sciences Division 2014. Monthly/Seasonal Climate Composites. *Source: http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/ printpage.pl*

Paluš, M., Novotna, D., 2006. Quasi-biennial oscillations extracted from the monthly NAO index and temperature records are phase – synchronized. *Nonlinear Processes in Geophysics 13 (3)*, 287–296. http://dx.doi.org/10.5194/npg-13-287-2006

Pankauskas, M., Bukantis, A., 2006. The dynamics of the Baltic Sea region climate humidity in 1950–2004. *The Geographical Yearbook 39 (1)*, 5–14. [In Lithuanian].

Reed, R. J., Campbell, W. J., Rasmussen, L. A., Rogers, R. G., 1961. Evidence of a downward propagating annual wind reversal in the equatorial stratosphere. *Journal Geophysical Research 66 (3)*, 813–818. http://dx.doi.org/10.1029/JZ066i003p00813

Rimkus, E., Kažys, J., Bukantis, A., Krotovas, A., 2011. Temporal variation of extreme precipitation events in Lithuania. *Oceanologia 53 (1-TI)*, 259–277. http://dx.doi.org/10.5697/oc.53-1-TI.259

Rimkus, E., Valiukas, D., Kažys, J., Gečaitė, I., Stonevičius, E., 2012. Dryness dynamics of the Baltic Sea region. *Baltica 25 (2)*, 129–142. http://dx.doi.org/10.5200/baltica.2012.25.13

Rimkus, E., Stonevičius, E., Korneev, V., Kažys, J., Valiuškevičius, G., Pakhomau, A., 2013. Dynamics of meteorological and hydrological droughts in the Neman river basin. *Environmental Research Letters 8 (4)*, 5014, 10 pp.

Trigo, R. M., Valente, M. A., Trigo, I. F., Miranda, P., Ramos, A. M., Paredes, D., Garcia-Herrera, R., 2008. The impact of North Atlantic wind and cyclone trends and their impact in the European precipitation and Atlantic significant wave height. *Annals of the New York Academy of Sciences 1146*, 212–234. http://dx.doi.org/10.1196/annals.1446.014

Watson, P. A. G., Gray, L. J., 2014. How does the quasi-biennial oscillation affect the stratospheric polar vortex? *Journal of the Atmospheric Sciences 71 (1)*, 391–409. http://dx.doi.org/10.1175/JAS-D-13-096.1