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Agricultural drought assessment on the base of Hydro-thermal Coefficient of Selyaninov in Poland

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Abstract. Climate change on the globe has been manifested over the past few decades by, among other things, an increase in the frequency of extreme weather events, such as droughts. Drought affects millions of people around the world every year. Its effects usually appear after a long period of rainfall deficit. Based on climate projections, it is emphasized that water scarcity will be one of the most important problems in the future. Due to the importance of the increasing problem of drought, the analysis of this phenomenon in Poland was undertaken in the context of agriculture. The aim of this study was to assess the course of drought in the vegetation period during years 2001-2020 for Poland based on the Selyaninov's coefficient (HTC). As shown in this study, the western and central parts of the country, dominated by arable land, are particularly vulnerable to drought. Due to the cyclic nature of periods classified by HTC as dry, it can be concluded that the problem of precipitation deficit for crops in Poland could get worse.

Keywords: climate change, drought index, growing season, yields.

INTRODUCTION

Climate change on the globe has been highlighted for several decades by, among other things, an increase in the frequency of extreme weather events, such as droughts (Kociper *et al.,* 2019; IPCC, 2021). According to research published in the United in Science 2021 report, the period from 2014 to 2020 was the warmest in the history of measurements (Christensen *et al.,* 2021). The alarming reports have increased interest in the topic of water scarcity among many researchers, including climatologists, hydrologists, and agrometeorologists. Kadbhane and Manekar (2021) and Kociper *et al.* (2019), among others, pointed out the problem that agriculture is much more impacted by climate change than any other sector, because agricultural production is highly dependent on weather. Additionally, Yeşilköy and Şaylan (2000) emphasize that water scarcity will be one of the most important problems in the future, especially due to fact that agricultural activities consume almost 70% of global water resources. Problem of droughts and water scarcity concerns many countries, regardless of geographic location (Communication..., 2007). Falzoi *et al.* (2019) additionally point to the global links between the occurrence of drought in one region and the price of consumer goods in another. For example, in 2012 an increase in food price was caused by a simultaneous drought in USA and Russia. Additionally, extreme hot and dry periods in recent years, have occurred not only in summer, but also in early fall and winter. Hanel *et al.* (2018) point out that air temperatures over Europe during the autumn of 2006 and winter of 2007, were ranked as the warmest in the last 500 years. In their publication, Vlăduţ *et al.* (2017) emphasized that precipitation in Southern Europe, including Romania and Bulgaria, will decrease of about 10-20% for the 2081–2100 period, in relation to 1986-2005. Moreover, Ionita and Nagavciuc (2021) based on the analysis of the standardized precipitation index (SPI) trends from 1902-2019 showed that SPI exhibits negative, statistically significant trends (increasing drought frequency) over Central Europe region (e.g., the Czech Republic, Slovakia, Hungary, Belarus, and Poland) and over South Europe, as well as Mediterranean region (e.g., Italy, southern Spain, Albania, and Greece). The positive trend (increased frequency of wet periods) was observed only over North Europe.

Hari *et al.* (2020) further suggest in their work, that the recent Arctic warming is possibly the main factor behind more frequent extreme weather events in mid-latitude regions of the northern hemisphere. The main dynamic characteristics of the mid-latitude weather change due to arctic amplification are the position and structure of the jet stream and the activity of planetary waves. Nevertheless, studies by Barnes and Polvani (2015) indicate that the reaction of the atmospheric circulation is still largely misunderstood. Additionally, in their work, the authors indicated that the 27 state-of-the-art climate models analysed by them, often do not even agree as to the sign of the answer. Therefore, there is still great uncertainty about the correctness of these assumptions. Addressing the mechanism of the drought phenomenon itself in 2001–2020, in Poland, is a line of research that requires a comprehensive analysis and goes beyond the scope of this study.

A drought is a weather and climate-related phenomenon of complex nature. Due to that, drought usually evolves slowly but can last for months or years and its effects occur after long periods without precipitation. Therefore, it is difficult to objectively quantify its characteristics in terms of amplitude, intensity, duration, as well as spatial extent. Its complexity is reflected in the lack of a unique definition (Spinoni *et al.,* 2018). Therefore, quantification of its characteristic is difficult. However, according to Falzoi *et al.* (2019) a drought can alternatively be defined as a temporary, recurring reduction in the precipitation in an area. Despite the difficulty of quantifying its always depends on: 1) a reference (e.g., the climatic normal) and 2) on the specific vulnerability of chosen sector to drought (an agricultural sector, an economy sector etc.). Therefore, drought is classified into four general types: meteorological, agricultural, hydrological, and socioeconomic drought (Hisdal *et al.,* 1999; Spinoni *et al.,* 2018). Further complexity is difficulty with delimitation of the exact date of the beginning and the end of drought. As mentioned above, its time span varies from weeks to years, with different intensity and sensitivity to drought of the various sectors of economy. However, undoubtedly the most sensitive is agriculture where this phenomenon causes substantial reduction of crop yield. Observed climate change and variability increases the risk of serious losses in economy, especially in the countries where the agricultural production constitutes important part of income. Based on climate projections its emphasized that water scarcity, which induces drought, will be one of the most important problems in the future (Yeşilköy and Şaylan, 2020).

In the case of Poland, apart from the ongoing climate change, the high variability of its individual elements, such as air temperature and precipitation, is also influenced by the moderate nature of the climate, with both maritime and continental elements. However, in case of Poland also the orography plays a big role for the spatial extent of droughts. The northern part of the country is situated on the Baltic Sea. Therefore, the coastal areas are characterized by higher humidity. Additionally, the southern part of the country is a mountainous region with a higher precipitation than other parts of the country. The central part of the country is most vulnerable to droughts (Pińskwar *et al.,* 2020). The worse situation is observed in central-west part of Poland, especially during the growing seasons (Łabędzki, 2007; Łabędzki and Kanecka-Geszke, 2009; Mager and Kępińska-Kasprzak, 2010; Szwed, 2015). The summer water deficit and frequency of droughts is expected to increase in the future, mainly because observed increase of evapotranspiration (Bogawski and Bednorz, 2016; Pascolini-Campbell *et al.,* 2021). Moreover, the large areas of Poland are characterized by soils derived from sands, loamy sands, boulder sands as well as loose sands of different origin, which are characterized by low water holding capacity. The negative impact of droughts in agriculture will be intensified by limitation of irrigation capacity during hydrological drought, caused by rainfall deficit (Kępińska-Kasprzak and Mager, 2010).

Issues related to water scarcity have been repeatedly addressed by Polish scientists (Szyga-Pluta, 2018; Struzik *et al.,* 2016; Toulios *et al.,* 2016; Szwed *et al.,* 2010; Łabędzki, 2007; Skowera and Puła, 2004), however, due to the importance and the growing problem of drought, an analysis of this phenomenon in Poland, in the context of agriculture, was undertaken in our study. There are several methods to identify the drought phenomenon depending on the type of drought, nevertheless in this study the attention was focused on the Hydro-thermal Coefficient of Selyaninov. Its advantage is simplicity of calculation and possibility of both monthly and decadal applications. It is particularly valuable for evaluating current crop conditions and monitoring of the agricultural drought (Bokwa *et al.,* 2021). The aim of this study was to assess the course of drought in the growing periods, during years 2001-2020, for the area of Poland based on the Selyaninov's coefficient.

MATERIALS AND METHODS

This study uses data from 2001-2020 on monthly precipitation totals and monthly mean temperature values measured at two meters by 56 synoptic stations of Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB), distributed throughout the country (Fig. 1). These data were used to calculate the Hydro-thermal Coefficient of Selyaninov (HTC) according to the formula (Taparauskiene and Miseckaite, 2017; Evarte-Bundere and Evarts-Bunders, 2012):

$$\mathrm{HTC} = \frac{\sum P_{>10^{\circ}C}}{0{,}1 * \sum T_{>10^{\circ}C}}$$

where:
Σ P>10 °C - decadal/monthly sum of precipitation (calculated from periods with daily average temperature above 10 °C),
Σ T>10 °C - decadal/monthly sum of daily average air temperature (calculated from periods with daily average temperature above 10 °C).

The Selyaninov's coefficient can be calculated for periods, when the average daily temperature exceeds +10°C. In Poland, analyses of agrometeorological indices are performed during growing season, defined usually as summer season (April 1st – September 30th) and such period for analysis is applied in this article. The authors are aware of the possibility of the occurrence of cooler periods in April, however they occur much less frequently with the progressive warming of the climate. In Polish literature, due to the inclusion of April into the vegetation period, also for this month the Selyaninov's coefficient is used as a measure for assessment of the moisture deficiency in relation to cultivated plants. However, in this study, in the case of extremely low temperature (below or close to zero), such information was excluded from the analysis due to the possibility of falsification of the results.

In this paper, according to the commonly accepted classification, a division into 10 classes of the Selyaninov's coefficient was used, allowing isolation of the extreme conditions. Values of HTC as follow: extremely dry HTC <0.4, very dry HTC in range <0.4÷0.8), dry HTC in range <0.8÷1.1), quite dry HTC in range <1.1÷1.4), optimum HTC in range <1.4÷1.7), quite humid HTC <1.7÷2.1), humid HTC <2.1÷2.6), very humid HTC in range <2.6÷3.0), extremely humid HTC >3.0. The attention was focused on periods when the value of the index does not exceed 1.1. Such limit is important, because it corresponds to the minimum amount of precipitation needed for the development of selected crops (Kuś, 2016). Thus, the dry period is a potential threat to crops development and to yields reduction.

Both spatial and quantitative range of occurrence, of periods classified as dry, in April, May, June, July, August and September, which corresponds approximately to the vegetation season in Poland, was analysed. Particular attention was paid to the years, in which at least half of the analysed synoptic stations measurements indicate dry period, according to the Selyaninov's coefficient.

RESULTS

The hydrothermal Selyaninov's coefficient values shown in the maps, calculated for the growing season (2001-2020), indicate areas particularly vulnerable to crop water shortages (Fig. 2). The most drought-prone area in April was the western part of the country. The problem of precipitation deficit affected mainly Lubuskie, Wielkopolskie, Kujawsko-Pomorskie and the northern part of Dolnośląskie provinces. According to average HTC values, quite dry period concerned almost whole Poland, excluding north-eastern and southern part of the country. It is worth noting, that April is a month particularly important in agriculture, due to intensive development of crops. The highest variability of HTC values was observed in May. The areas most exposed to drought were north-western part of the country and small part of north-eastern Poland (Podlaskie province). During May, based on the Selyaninov's coefficient,

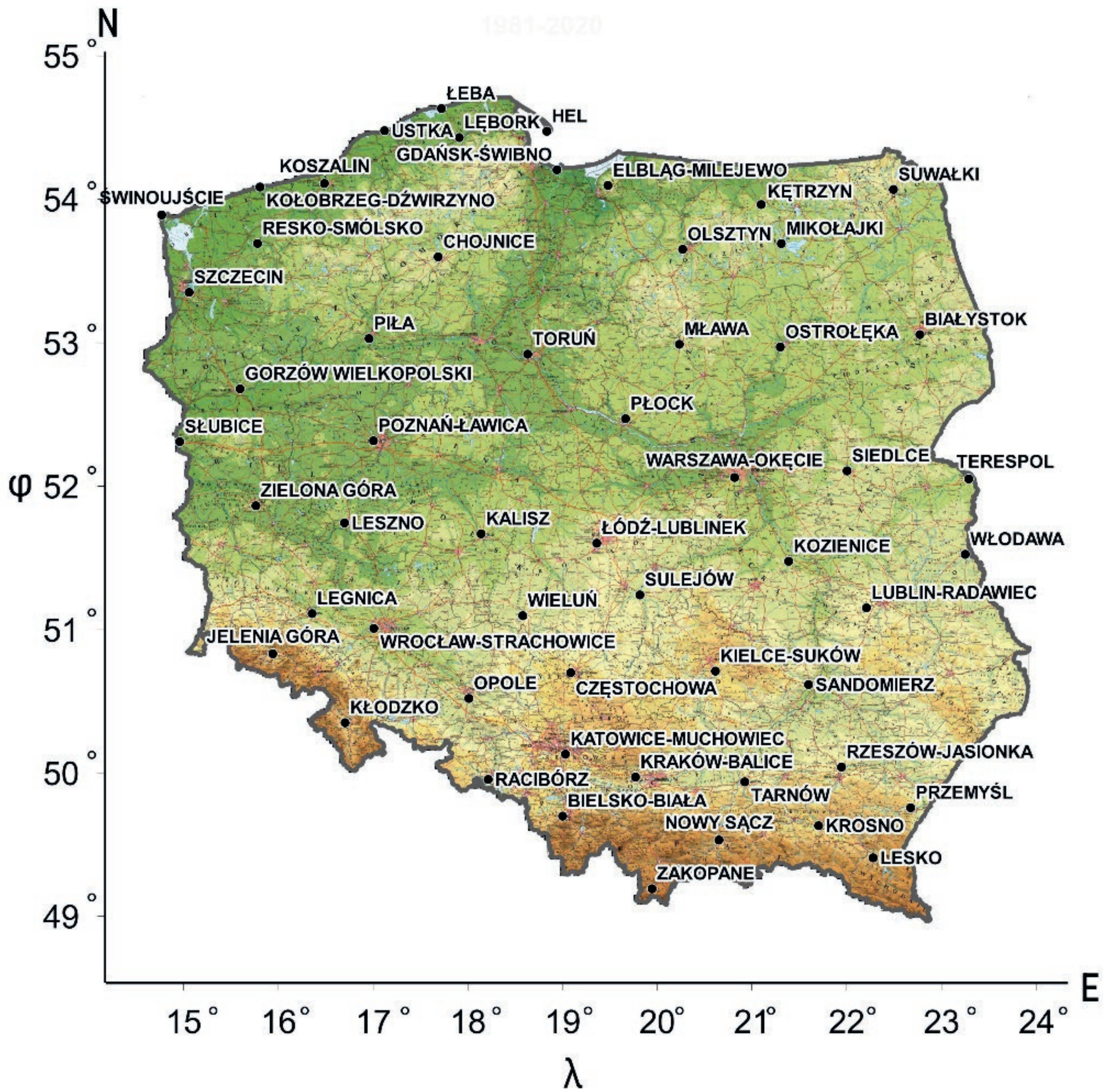

Fig. 1. Location of selected synoptic stations of IMGW-PIB.

hydrothermal conditions in the whole country were classified as humid. Extreme (extremely wet) conditions occurred especially in the northern and southern part of the country, as a direct result of orography. Increased precipitation in May improves soil moisture conditions, but their excessive amount combined with insufficient evapotranspiration and low temperatures (e.g. ground frost) may lead to the development of many fungal diseases among plants. June was another month with rather dry and barren conditions in most areas of Poland. Lack of precipitation affected mainly the western part of the country: Lubuskie and Wielkopolskie provinces. Water surpluses appeared only in the mountain areas (south Poland). In July optimal conditions prevailed, but through the centre of the country, a belt of rather dry conditions was observed. August was the month in which water deficits occurred in most parts of the country. Optimal conditions prevail only near the coast

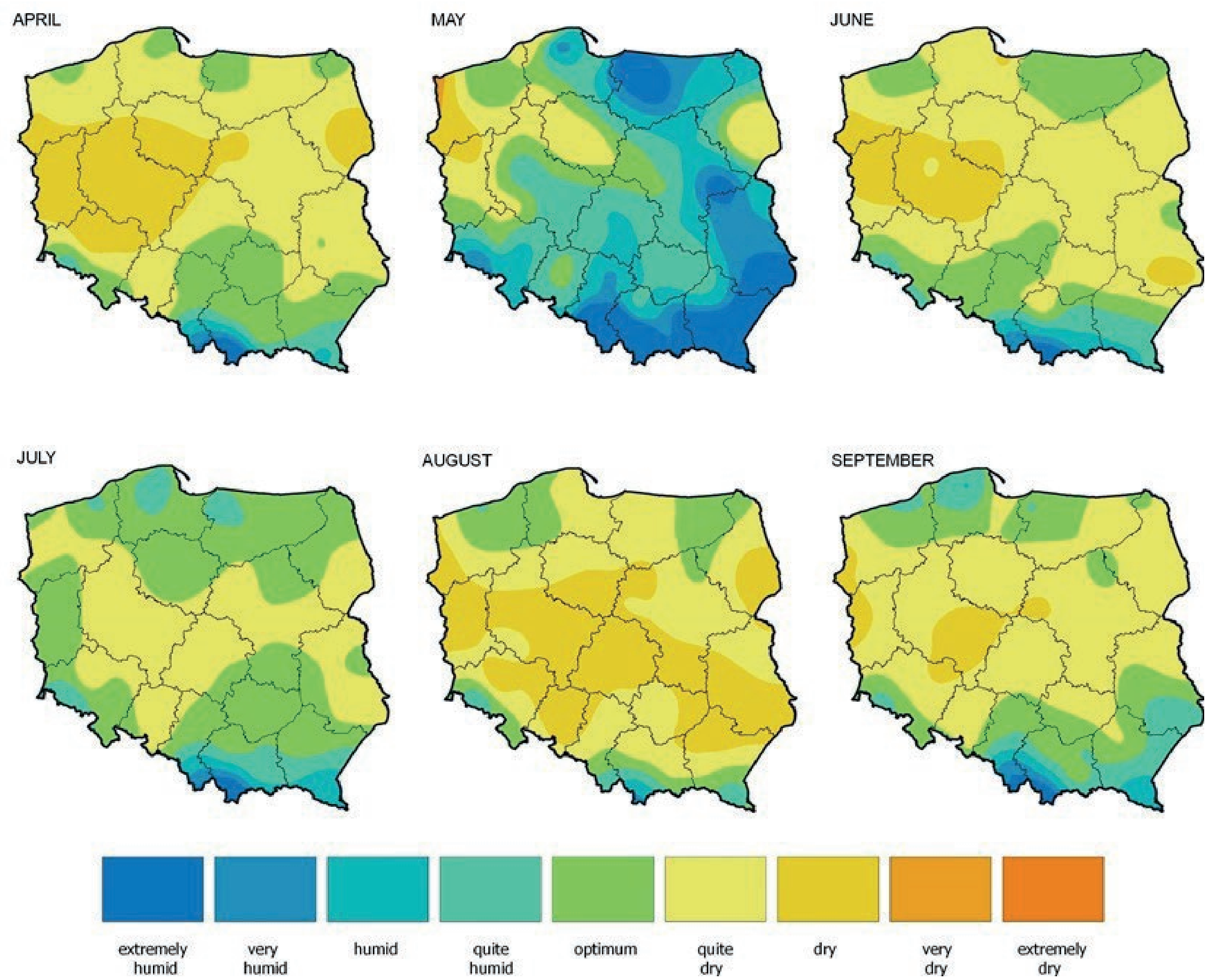

Fig. 2. Mean monthly values of HTC in Poland (2001-2020). The areas marked on the map are the province borders.

and in some mountainous areas. A similar situation occurred in September, where dry conditions prevailed in the most of central part of the country, while optimal and wet conditions prevailed in the north and south.

Due to the fact, that in Poland the north-west and west circulation is dominating, wet air masses pill up from the seaside over the windward slopes of Pomerania and Masurian Lake District on the north and over the north slopes of the mountains in the South Poland. At these places, the water vapour condenses, which cause clouds vertical development and rainfall, whereas the lowlands in central part of the country lay in the rain shadow. As a result, those mountainous and coastal areas are characterized by a higher frequency and amount of precipitation and a lower value of the potential evapotranspiration index (Fig. 3).

Described above conclusions on the areas, where low and very low values of HTC are noticed most frequently are also confirmed by the spatial distribution of Precipitation–Evapotranspiration Index (PEI) during growing season (April-September), calculated from years 2001-2020 (Fig. 3). PEI shows that the low and very low values occur in central and central-west part of the country. Totals of precipitation in the warm part of the year (April-September) are the lowest here, in comparison with other regions of the country, and the potential evapotranspiration is higher and exceeds precipitation. The spatial distribution of the greatest water shortages is quite unfavourable from the point of agriculture, because a major part of Polish agricultural potential is concentrated in those regions.

The HTC values for months and years in 2001-2020 period was presented in the form of graphs (Fig. 4). The

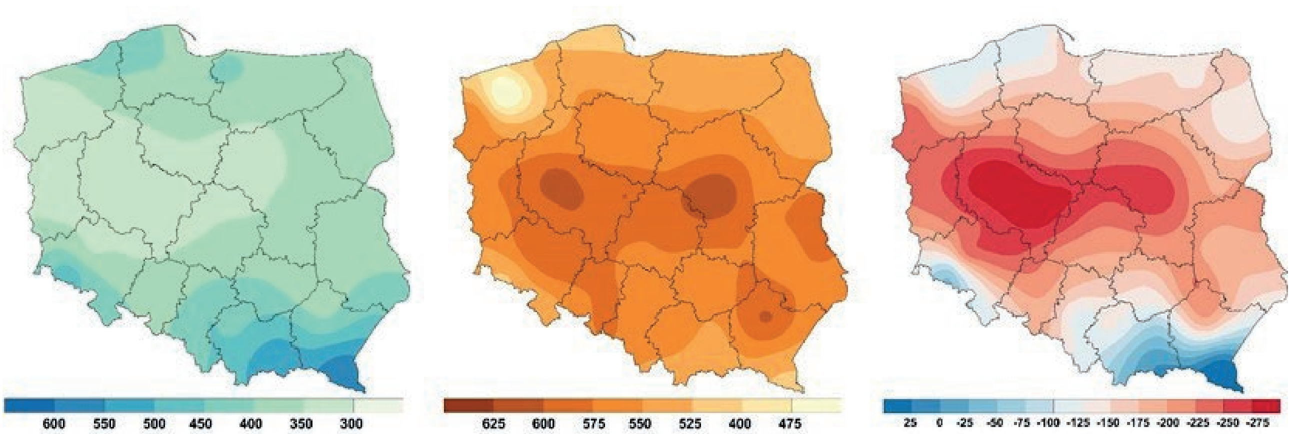

Fig. 3. Spatial distribution [in mm] of the average sums of precipitation, potential evapotranspiration and Precipitation-Evapotranspiration Index in Poland during growing season (April-September) in years 2001-2020.

thermometer mark has been placed on those years, in which at least half of analysed synoptic stations indicated minimum one of these categories the values of HTC as follow: extremely dry HTC <0.4, very dry HTC in range <0.4÷0.8) or dry HTC in range <0.8÷1.1). For the analysed multi-annual period, in April, the situation of possible water shortages occurred in nine years, twice of it occurred in the years 2009-2011 and 2018-2020. In the case of May, the dry index for at least 50% of the stations occurred in six years, among them continuously from 2016 to 2018. In June, a similar situation occurred in 10 years, of which in four cases the problem occurred year after year (2005-2006, 2010-2011, 2015-2016, 2018-2019). In July, as in May, the problem of water shortages affected six years, of which occurred in 2013-2015 and 2019 and 2020. The worst situation was in August, where the problems of water shortages appeared for five consecutive years in a row (2015-2019). Moreover, the dry period recorded by at least 50% of synoptic stations, was found 12 times in August. In September, the problem of precipitation scarcity affected 10 years, of which four years of dry periods in a row occurred from 2003 to 2006.

DISCUSSION

Based on the HTC, it has been shown that the problem of precipitation deficit leading to potential drought stress for crops, occurs during almost the entire growing season. Extremely dry periods covering the whole country occurred mainly in April, but their intensification in recent years is also seen in other months. Studies conducted by Szyga-Pluta (2018) indicated that extremely dry periods occur mainly in August and September. However, the author analysed a much longer period (1966-2015). Importantly, in the case of the very dry period, the results of the present study confirm those obtained by Szyga-Pluta. The very dry index occurs most frequently in September and August. Bartczak *et al.* (2014) found that a characteristic feature is the clustering of dry periods into periods of several or more years, which was also confirmed in the present study. In most cases, especially in the last years of the analysed 20-year period, dry months occurred cyclically.

Considering the water requirements of crops, the problem of water scarcity seems to be getting worse. Since 2011, the number of months characterized by precipitation scarcity has been increasing. At the very beginning of the twentieth century, dry months did not occur very often in succession. The last years of analysis show whole sequences of months, considered as dry according to HTC. Moreover, research conducted by Diakowska *et al.* (2018) indicated that in the near future, the highest probability of drought will occur in central part of Poland. This analysis indicates that the existing water problems in central Poland will get worse. It is important because this region is characterized by the largest share of agricultural land.

A study by Hari *et al.* (2020) found that Europe was affected by drought three times between 2001 and 2020. The first time, such a large-scale event occurred in 2003. This problem has been extensively discussed, among others, in the publication by Rebetez *et al.* (2006). The authors showed that the monthly mean temperature deviations of August 2003 reached +6°C at many meteorological stations in southwestern Germany, eastern France and western Switzerland. Also in our analysis, August 2003 was classified as very dry at more than 70% of synoptic stations. July was less extreme than

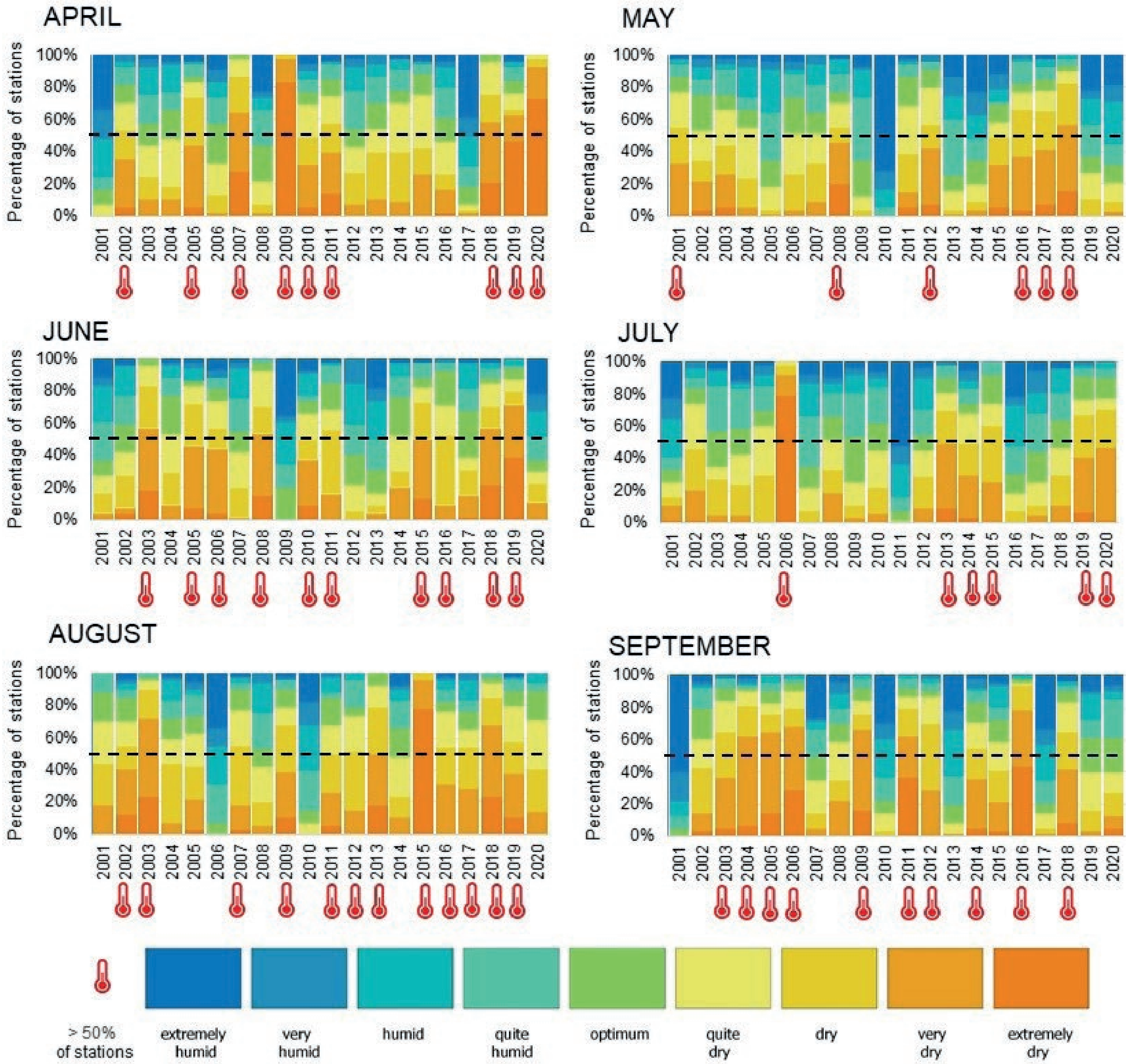

Fig. 4 Mean monthly values of HTC in Poland (2001-2020).

June and August, except in Sweden, Finland and Norway, which is also evident in our study. For 2003, from May to August, monthly minimum and maximum air temperatures were consistently above normal from Portugal to Hungary and from Great-Britain and Denmark to Sicily and Greece. In contrast, virtually all of Europe struggled with heat in 2018. Based on Hari *et al.* (2020), temperature anomalies were +2°C and precipitation anomalies showed a deficit of over 20%. Also in our study, it was shown that drought occurred in Poland for almost the entire growing season in 2018. In addition, Hari *et al.* (2020) using multi-year observations, showed that the occurrence of a summer (consecutive) drought in 2019 was unprecedented in the last 250 years. However, Ionita *et al.* (2021) have shown that the droughts, which occurred in 2003, 2018 as well as 2019 are within the historical variability and they are not unprecedented over the last millennium. Nevertheless, the combined impact of both the 2018 and 2019 droughts on vegetation activity was stronger in comparison to the 2003 European drought. Thus, determining future drought risk of in our region, droughts seem to be a key issue for many researchers, including climatologists, hydrologists, and agrometeorologists.

Widely reported climate change is highlighted by the increasing likelihood of extreme events, including both droughts and heavy rainfalls. Based on Nikolaev (2020), the excessive rainfall in Russia causes 10 to 15% greater yield losses than rainfall deficiency in extremely dry years. Frequent occurrence of heavy rainfall in autumn makes harvesting difficult or completely impossible. Additionally, the excessive precipitation creates unsuitable conditions for winter crops. According to the climate change scenarios for East part of Europe, the further increase in annual precipitation totals, as well as annual air temperature is predicted (Nikolaev, 2020). However, predictive analyses by Hari *et al.* (2020) showed, that anthropogenic warming will lead to an intensification of droughts in Europe. Thus, the probability of biennial droughts may increase significantly. The authors highlight that such events have significant implications for many sectors, including impacts on agrophenology, crop water demand, and vegetation health activities. Nevertheless, the authors showed that the occurrence of subsequent droughts, as well as their impact on crops and pastures, can be significantly reduced if mitigation strategies are adopted that lead to changes in global warming. These observations seem to confirm the study by Ionita and Nagavciuc (2021). Authors showed that most of the countries in South Europe and Mediterranean region, as well as Central Europe show a significant trend of increasing drought frequency in the last 120 years, while countries of Northern Europe show a significant trend of increasing the frequency of wet periods. Therefore, water shortages as well as surpluses could be even more common and more severe in the future (Szwed, 2010; Ziernicka-Wojtaszek and Kopcińska, 2020).

Year by year, agriculture in Poland is becoming more and more heavily affected by climate change. Natural disasters, such as drought, are becoming more frequent and thus decrease the crop production. It seems to be necessary to improve knowledge on climate and weather, as well as to draw up plans to both identify and mitigate risk in agriculture.

CONCLUSIONS

Based on analyses of spatial and temporal distribution of Selyaninov's coefficient (HTC) for Poland in years 2001-2020, it has been found, that droughts have been noticed already in April, i.e., from the beginning of the vegetation season, at the most parts of the country. The biggest area of the country covered by dry conditions was noticed in August and September, while the smallest - in May. May was also a month, with the highest variability of HTC values in vegetation seasons of analyzed period. In July, optimal conditions prevailed in the North and South Poland, but the quite dry conditions were dominating in the belt over the center of the country.

The drought-prone area for the most of vegetation seasons of 2001-2020 was the belt of lowlands, from western to eastern border of Poland, but most often the lowest values of Selyaninov's coefficient in the western part of this area were noticed. From the economical point of view, it is unfavorable, because most of the agricultural lands are located in this area.

As this study shows, the three most dry HTC categories occur cyclically over the past two decades. Water shortages could be even more common and more severe in the future. Additionally, since 2011, the number of months characterized by precipitation scarcity has been increasing. At the very beginning of the twentieth century, dry months did not occur very often in succession, but last years of analysis show the whole sequences of months, considered as dry according to HTC. Therefore, it can be concluded that the problem of precipitation deficiency for crops in Poland could get worse.

Year by year, agriculture in Poland is becoming more heavily affected by climate change. Natural disasters, such as droughts, are becoming more frequent and thus decrease the crop production. It seems to be necessary to improve knowledge on climate and weather, as well as to draw up plans to both identify and mitigate risk in agriculture.

As shown in a study by Ionita *et al.* (2021) the occurrence of drought, year by year has much more severe effects on crops than a single event such as the drought in 2003. The results presented in this article let us believe that in the nearest future the amount of water available for plants during growing season in central Poland, may decrease even more. Published by Eitzinger *et al.* (2012) analyses, emphasize that crops, especially in the warm and dry lowland regions, will need more water to maintain their production potential. However, the similar situation may also occur in the areas like Polish lowlands, where increasingly frequent droughts are a serious problem for agriculture. Recommendation given by Eitzinger *et al.* (2012), e.g. need of efficient management of water resources used for irrigation and improved efficiency of irrigation methods, are especially necessary in the areas like Poland, where resources of surface water per capita are very low.

Due to the growing threat of negative effects of droughts, especially on agriculture, monitoring of this phenomenon is particularly important. Among other indicators, it seems that the Selianinov's coefficient can be used for such monitoring. HTC integrates the main factors of drought: temperature and precipitation and therefore it is a useful tool in agriculture practice. The HTC is easy to calculate and is based on commonly, publicly available data. In this study were used monthly period for analyses, but HTC, in contrary to other coefficients, gives possibility to calculate for also decadal periods, important in farmers activity.

However, the indicator also has limitations. First of all, the the HTC should be calculated for periods with average daily air temperature higher than 10°C. In Polish conditions, the average values of air temperature in April are sometimes lower, so especially in mountain regions the result can be distorted by periodically occurring temperatures below zero degree Celsius. Moreover, it does not consider the water and soil balance. Therefore, this index should be interpreted with caution and in relation to other agrometeorological indices. Nevertheless, despite these limitations, the HTC can be useful for tracking the extent to which crop water needs are being met in a given area.

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