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The Climate Change Impact on the Development of Droughts in Ukraine

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ABSTRACT

The paper considers the peculiarities of the climate change influence on the dynamics of drought development in Ukraine. The analysis was performed for average long-term climatic conditions during the growing season (1981–2020) and under climate change scenarios RCP 4.5 and RCP 8.5 for the period of 2021–2050 (for the period as a whole and by the decades: 2021–2030, 2031–2040, 2041–2050). The drought development was studied over relatively short periods of time (ten days) at the main agroclimatic regions of Ukraine (Polissia, Forest-Steppe, Northern and Southern Steppe). The assessment of the aridity of ten-day periods was accomplished by means of a set of aridity indicators by Selyaninov, Shashko, Budagovskiy and Bova, which corrects and supplements each other; this made it possible to consider in detail the genesis of climate-induced drought in the agroclimatic regions of Ukraine. Analysis of the study results showed that the development of drought conditions in all agroclimatic regions is expected as early as in the first decade (2021–2030). According to both scenarios, from 4–6 in Polissia to 16–17 severe and very severe droughts in the Southern Steppe are expected. In the second decade (2031–2040), under RCP4.5, improvement in moistening conditions is expected in Polissia and Forest-Steppe and under RCP8.5, an increase in the level of aridity is expected in these agroclimatic regions. In the Northern Steppe and Southern Steppe the number of moderately, very and extremely dry ten-day periods will increase (from 9 to 17). In the third decade (2041–2050), under the RCP4.5 scenario, very severe aridity conditions are assumed in all agroclimatic regions. Under RCP8.5, good moistening conditions and, according to both criteria, a small number of dry ten-day periods are expected in Polissia and Forest-Steppe. As for the conditions at the Northern and Southern Steppes very severe drought conditions are expected (from 8 to 17 ten-day periods with moderate, severe and very severe drought). For 2021–2050 on the whole, there will be an increase in aridity during the growing season in all agroclimatic regions of Ukraine.

Keywords: climate, temperature, precipitation, drought, evaporation, drought indicators, 'dry' ten-day period, growing season.

INTRODUCTION

The territory of Ukraine is characterized by various climatic conditions – from the zone of excessive and sufficient moistening in Polissia to the zone of insufficient moistening in the Southern Steppe. In relation to finding solution to the problem of assessment of drought phenomena, many diverse drought criteria have been developed and proposed with the selection of its types, including atmospheric, soil and mixed drought.

Among the reviews of methods for studying drought phenomena, the review by Buchinsky [1970] performed in the 1970s should be noticed. An up-to-date analysis of the methods used in these drought studies is performed in the monograph by Semenova [2017]. It is also necessary to refer to the 'Handbook on Indicators and Indices of Aridity' published by the World Meteorological Organization in 2016 [WMO and GWP, 2016].

Global climate changes have led to a substantial increase in air temperature, a change in the precipitation regime, and an increase in the occurrence of drought phenomena in Ukraine. Ukrainian climatologists, Krakovska and Balabukh [2020] stated, that aridity will only increase in the future.

In the last two decades, a series of papers dedicated to solving the problem of drought assessment in Ukraine has been performed.

Among these studies, the paper by Khokhlov et al. [2011], in which spatiotemporal peculiarities of the distribution of droughts on the territory of Ukraine for the period from 1943 to 2002 are studied by means of the Palmer drought intensity index. The recurrence of drought months and droughts themselves, as well as their intensity and duration, are analysed. It is shown that there were changes in the climate aridity (or moistening) on the territory of Ukraine, and these changes occurred differently in different regions. This study was continued in papers [Khokhlov et al., 2012], in which the spatiotemporal variability of diverse categories of droughts is defined by means of the standardized precipitation index and total evaporation with time scales of 1, 3, 6, 12, 24 months for the territory of Eastern Europe during 1951–1980 and 1981–2010. It was revealed that the maximum number of droughts was recorded during the period of global warming, that is, during 1981–2010.

Fundamental research on aridity in Ukraine for 2020–2050 were performed in the papers by Semenova [2015; 2017], in which the peculiarities of the evolution of droughts on the territory of Ukraine in current and future climatic conditions and their influence on the crop productivity are studied. A catalogue of seasonal droughts by agroclimatic zones of Ukraine for the period of 1995–2012 was compiled on the basis of five drought indices. The spatiotemporal distribution of seasonal droughts in 2020–2050 was obtained for various climate scenarios. These studies were further developed in the paper by Semenova and Polovyi [2020], which presents the results of the analysis of the spatiotemporal distribution of droughts in the warm seasons of 2021–2050 on the territory of Ukraine obtained by means of climate modelling data under the framework of the RCP4.5 and RCP6.0 climate scenarios. The assessment of drought events and their intensity is based on the SPEI standardized drought index on a scale of 7 months, which covers the warm season from April to October. Calculation of the drought index was based on monthly meteorological information. However, as noticed by Polevoy [2012], the vegetation of plants does not fit into calendar months, and critical periods in the development of plants in relation to moisture can minimally approach a period lasting 10 days, which leads us to the necessity of considering dry periods during shorter periods of time (ten days), i.e. consideration of the so-called 'dry ten days'. Despite the availability of papers on the analysis of droughts in Ukraine, analysis of the development of drought events was not considered in a more detailed temporal context (for ten-day periods).

The paper is aimed at assessment of the peculiarities of climate change impact on the process of development of aridity in Ukraine in 2021–2050, with the detailed consideration of drought over the time span of a ten-day period.

MATERIALS AND METHODS

On the basis of analysis of the current state of assessment of drought phenomena and their impact on the formation of grain crop yield, we used a set of the following indices to determine the aridity in ten-day periods under the climate change conditions [Polevoy, 2012]:

- a hydrothermal coefficient by G.T. Selyaninov (HTC);
- a moistening index by D.I. Shashko (Md);
- the evaporation deficit, proposed by A.I. Budagovskiy (ΔE) quantitatively characterizes the degree of discrepancy between the possible (optimal) and actual water consumption by plants;
- the aridity index by N.V. Bova will be used to determine the onset of drought.

The indicator by Selyaninov [1937] (a hydrothermal coefficient), which is calculated for each ten-day period of the growing season:

$$HTC = \frac{\sum P}{0{,}1 \sum t_{>10°C}}, \qquad (1)$$

where: $\sum P$ is an amount of precipitation per ten days, mm; $\sum_{t>10°C}$ is a sum of temperatures above 10 °C per ten days.

If the HTC = 0.4, it is a very severe drought; from 0.4 to 0.5 – a severe drought; from 0.5 to 0.6 – a moderate drought.

A moistening index by Shashko [1967] is determined by the following formula:

$$Md = \frac{\sum P}{\sum d}, \quad (2)$$

where: ∑P is an amount of precipitation per year, mm; ∑d is a sum of average daily air saturation deficits, mm.

Md = 0.33–0.47 means a moderate drought; *Md* from 0.20 to 0.33 means a severe drought; *Md* < 0.20 means a very severe drought.

Formula (2) is also used to define Md for each month of the growing season. The evaporation deficit by Budagovskiy [1957] is determined according to the difference between the maximum possible evaporation E_o (an evaporating capacity) and the actual evaporation E associated with soil moisture reserves. At the same time, the evaporating capacity should be understood as the maximum possible evaporation from agricultural fields with a closed grass stand during the period of its active vegetation, under optimal moisture reserves in the soil.

Knowing the value of evaporating capacity E_o and evaporation E, it is not difficult to obtain the value of the evaporation deficit

$$\Delta E = E_o - E, \quad (3)$$

which quantitatively characterizes the degree of discrepancy between the possible (optimal) and actual water consumption by plants.

Bova aridity index [Bova, 1946] is used to establish the onset of drought. It includes the main factors that determine the conditions for the growth and development of agricultural crops:

$$K_B^j = \frac{10\,(W^0 + \sum \theta)}{\sum t}, \quad (4)$$

where: K_B is Bova aridity index; W^o means the productive moisture reserves in a meter soil layer at the beginning of the growing season; ΣΘ is the amount of precipitation from the beginning of the growing season to the onset of drought; Σt is the sum of temperatures above 5 °C during this period.

The period when the value of the aridity index becomes equal to 1.5 or less is assumed as the beginning of drought.

Numerical values of these indices during the growing season (from the date of air temperature transition in spring through 5 °C to the temperature transition through this limit in autumn) were determined for Polissia (Zhytomyr Oblast), Forest Steppe (Vinnytsia Oblast), Northern (Dnipropetrovsk Oblast) and Southern (Kherson Oblast) Steppe. Average long-term climatic conditions in the vegetation season (1981–2020) and under climate change scenarios RCP 4.5 and RCP 8.5 [Stepanenko et al., 2018] for the period of 2021–2050 were considered (for the whole period and by decades of 2021–2030, 2031–2040 and 2041–2050).

RESULTS

Let us consider the results of our research by agroclimatic zones of Ukraine.

Polissia

At the beginning of the growing season (from the 13th through the 18th ten days), a higher (by 0.2–0.4 relative units) level of the expected scenario values was the common pattern of the dynamics of HTC trend (Fig. 1A). For the average long-term conditions, the evaporation deficit is at a relatively high level (6.6–15.3 mm) against the background of the general decrease in this parameter from the 13th to the 19th ten-day period, while for the scenario conditions, the difference between the values of evaporating capacity and evaporation was significantly lower, especially under implementation of the RCP 8.5 climate scenario. For the 19th and 20th ten-day periods, some abnormality of this pattern is noticed.

Starting from the 21st ten-day period and until the end of the growing season, for the scenario climate conditions, the HTC will be significantly lower than the average long-term values, and very high levels of evaporation deficit (up to 15–30 mm) will be expected. It is characteristic that almost all the time during the second half of the growing season, a mild drought will be expected (the HTC value is less than 1.0 relative unit).

The identified trend of the HTC dynamics is well confirmed by the dynamics of a moistening index by Shashko (Fig. 1B). Numerical values of this index from the 13th to the 18th ten-day period characterize the scenario climatic conditions as more provided with a high level of moistening in comparison with the long-term averages.

From the 21st ten-day period, the values of the Shashko index begin to decrease both for average long-term and scenario climatic conditions, that is accompanied by a significant increase in the evaporation deficit. At the same time, the Md index is more tough. According to the obtained assessments, even under average long-term climatic conditions, in the second half of the growing season, there are three ten-day periods (the 24th – 26th ten-day periods) with severe drought, the values of the Md index are 0.38–0.42 relative units, which is classified as drought, although the overall level of this index is higher than for scenario climatic values. For the conditions expected under the RCP 4.5 and RCP 8.5 climate scenarios, 7–8 ten-day periods of severe drought are prognosticated, and even one ten-day period of very severe drought – for the RCP 4.5 scenario.

The good consistency of all drought criteria under consideration should be noticed. The calculation of the Bova index showed that its numerical values become lower than the value of 1.5 in the 21st ten-day period, that is a sign of the onset of drought.

The data shown in Figure 1A and 1B give an idea on the vegetative course of aridity indices for a thirty-year period. In the context of decades (Table 1), according to the RCP 4.5 and RCP 8.5 climate scenarios, the first decade (2021–2030) is expected to be dry. The average value of the evaporation deficit will comprise 114% of the long-term value. According to the RCP 4.5 scenario, the decade of 2031–2040 is expected to be less arid, when three ten-day periods with mild and one with medium drought are expected by the HTC indicator, and three ten-day periods with moderate and four ten-day periods with severe drought are possible by the Md criterion (Table 1). The difference in values is quite natural, but the trend of the phenomenon coincides. This is confirmed by the fact that a minimal evaporability deficit (79% of the long-term value) is characteristic for the specified decade. At the same time, under the RCP 8.5 climate scenario, six ten-day periods with a mild drought are expected according to the HTC indicator, and two ten-day

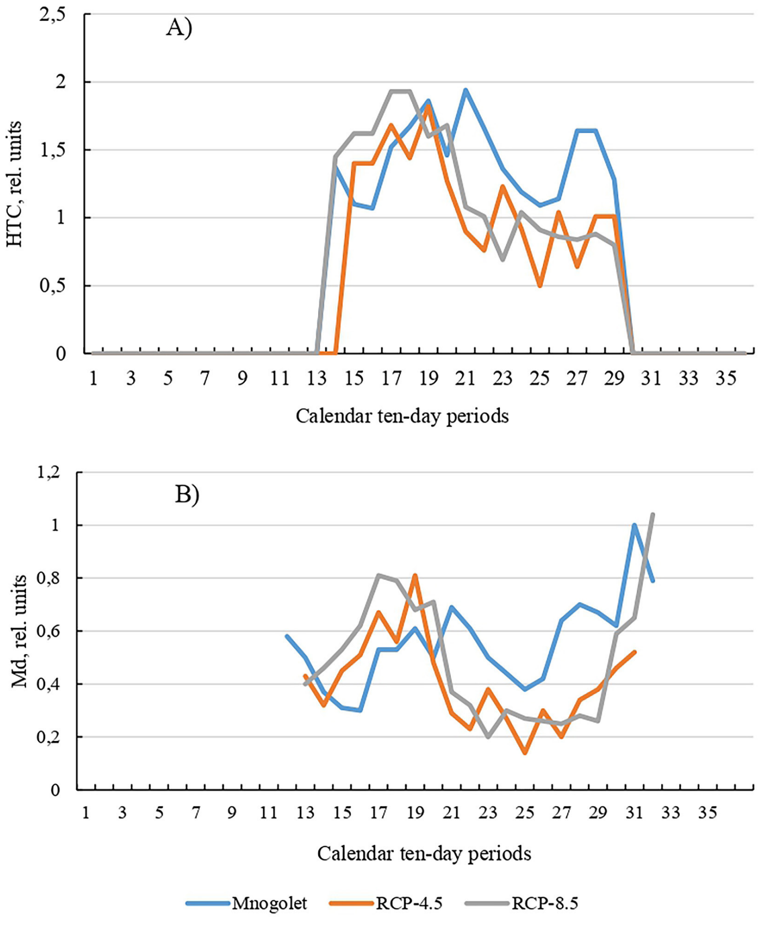

Figure 1. The dynamics for the course of scenario values of drought in Polissia compared to the long-term values of: A) Selyaninov hydrothermal coefficient (HTC); B) Shashko's moistening index (Md).

Table 1. The average number of dry ten-day periods in Ukraine during the growing season by decades (in terms of the values: HTC is a numerator, and Md is a denominator) and the average value of evaporation deficit ΔE

Characteristics of droughts	Long-term average value. 1981–2020	Period. years					
		2021–2030		2031–2040		2041–2050	
		Climate scenario					
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Polissia							
Mild drought	0/–	3/–	6/–	3/–	6/–	4/–	4/–
Moderate drought	0/4	0/8	0/6	1/3	0/2	1/7	0/4
Severe drought	0/2	1/3	0/6	0/4	0/8	1/3	0/4
Very severe drought	0/0	0/1	0/0	0/0	0/1	0/3	0/0
Evaporation deficit, mm	136	155	155	107	194	190	103
Forest-Steppe							
Mild drought	2/–	4/–	6/–	5/–	6/–	5/–	4/–
Moderate drought	0/8	1/2	0/5	0/3	1/4	0/8	1/4
Severe drought	0/3	1/4	1/5	0/6	1/5	0/4	0/3
Very severe drought	0/0	0/3	0/1	0/0	0/1	1/2	0/1
Evaporation deficit, mm	176	189	191	154	190	220	135
Northern Steppe							
Mild drought	11/–	8/–	9/–	4/–	6/–	6/–	5/–
Moderate drought	0/4	1/2	1/0	1/2	0/1	0/2	1/3
Severe drought	1/8	3/6	4/10	2/3	2/5	1/3	3/4
Very severe drought	0/5	1/8	2/7	5/9	7/11	7/10	3/7
Evaporation deficit, mm	370	466	507	488	637	608	464
Southern Steppe							
Mild drought	10/–	4/–	7/–	6/–	5/–	3/–	7/–
Moderate drought	3/1	3/1	0/1	1/3	3/2	4/4	0/2
Severe drought	2/10	1/4	0/7	1/5	1/3	2/3	1/5
Very severe drought	0/7	5/12	7/8	7/9	6/12	6/10	7/10
Evaporation deficit, mm	496	725	624	661	756	717	666

periods with a moderate drought, eight ten-day periods with a severe drought, and one ten-day period with a very severe drought are expected according to the Md indicator. The significant dryness of this ten-year period under the RCP 8.5 scenario is well confirmed by the maximum value of the evaporation deficit (143% of the long-term value). In the third decade, under the RCP 4.5 scenario, four ten-day periods of a mild drought and two ten-day periods of moderate and severe drought are expected according to the HTC indicator. According to the Md indicator, seven ten-day periods with a moderate drought and six ten-day periods with a severe and a very severe drought are assumed. Thereafter, the evaporation deficit will be 40% higher than the long-term value. Under realization of the RCP 4.5 scenario, this decade will be the least arid, and it will be distinguished by both a smaller number of dry ten-day periods according to the mentioned indices, and a minimum value of the evaporation deficit (75% of the long-term value).

Forest Steppe

At the beginning of the growing season during the 12th–15th ten-day periods under the scenario climatic conditions, the values of HTC were higher than those for the average long-term conditions (Fig. 2A). Meanwhile, the evaporating capacity deficit was 4–10 mm lower than for average long-term conditions. Then, during the next two ten-day periods, this pattern was disrupted, and starting from the 18th ten-day period, the numerical values of HTC under the long-term conditions will be higher than those under scenario climatic conditions.

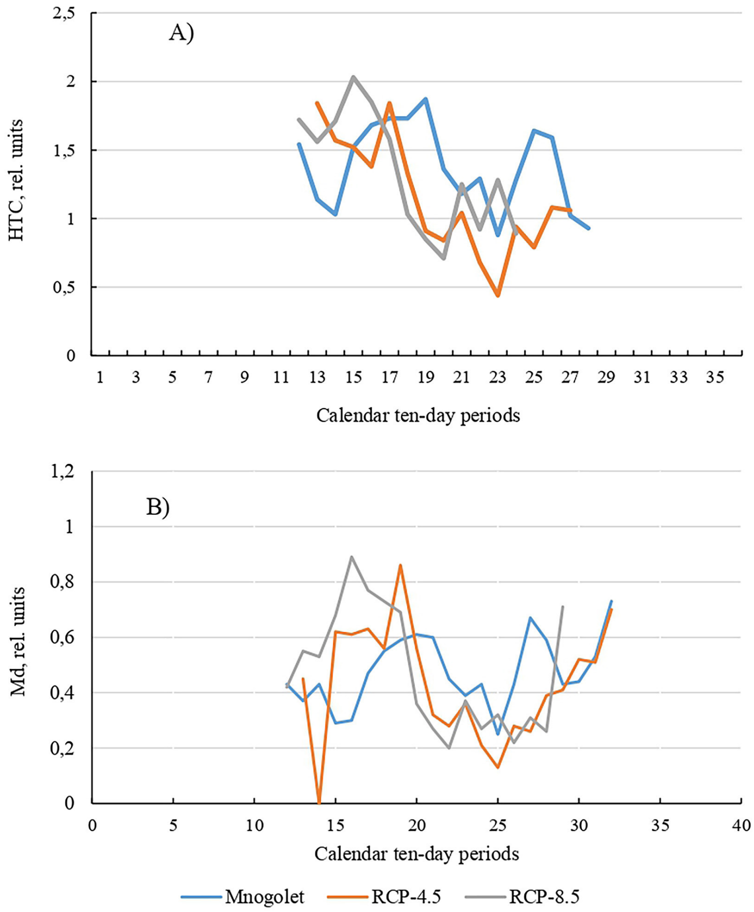

Figure 2. The dynamics for the course of scenario values of drought in the Forest Steppe compared to the long-term values of: A) Selyaninov hydrothermal coefficient (HTC); B) Shashko's moistening index (Md)

For all alternatives, there is an abrupt drop in the values of HTC and an increase in the evaporation deficit (up to 20–30 mm), which is especially significant under the scenario climatic conditions. Starting from the 19th ten-day period and during all subsequent ten-day periods for the climatic conditions under the RCP 4.5 scenario, drought is expected. Climatic conditions will be less arid during the realization of the RCP 8.5 scenario.

According to the numerical values of the Shashko moistening index, under average long-term conditions, a moderate drought will be observed during the first six ten-day periods (Fig. 2B). Md values are expected to be in the range of 0.29–0.47 relative units, that is classified as a moderate drought. For the scenario climatic conditions, Md values will be higher and, therefore, the moistening conditions will be more favourable. In addition, the evaporation deficit will be at a relatively low level.

This situation will hold out until the 19th ten-day period. Then there will be a dramatic decrease in Md values. Even for average long-term conditions, five dry ten-day periods are expected. However, almost until the end of the growing season, Md values under average long-term conditions will be higher than scenario conditions.

If the RCP 4.5 and RCP 8.5 climate scenarios are realized, according to the calculated Md values, it is predicted that there will be a severe drought, including one very severe drought.

According to the Bova aridity index, the onset of drought under average long-term conditions will occur in the 20th ten-day period, and under the RCP 4.5 and RCP 8.5 scenarios, it will occur in the 19th ten-day period.

In the annual variation by decades in the Forest Steppes (Table 1), the distribution of the number of dry ten-day periods under both the RCP 4.5 and RCP8.5 scenarios will be similar to the distribution of these characteristics in Polissia. The value of the evaporation deficit changes comparably. The largest number of dry ten-day periods under both scenarios will be observed in the first decade, under the RCP8.5 scenario – in the second decade, and under the RCP4.5 scenario – in the third decade. As in Polissia, the second decade under the RCP4.5 scenario and the third decade under the RCP8.5 scenario will be milder from the point of view of dryness.

Northern Steppe

In the dynamics of HTC at the beginning of the growing season (until the 17th ten-day period), more favourable climatic conditions under the RCP 4.5 and RCP 8.5 scenarios are less expressed, although the level of HTC is predominately somewhat higher under the scenario conditions (Fig. 3A). There is a slight (by 5–10 mm) decrease in the value of the evaporating capacity deficit. Starting from the 17th ten-day period up to the 26th ten-day period, there will be a dramatic decrease in the scenario values of HTC compared to the average long-term conditions, although even under the average long-term conditions from the 19th through the 25th ten-day periods, a mild drought is observed (with the HTC being less than 1, that is classified as a mild drought). Under the scenario climatic conditions, 5 ten days of mild and moderate drought will be observed during this period, and from the 20th through the 23rd ten-day period, the development of severe and very severe drought is expected. The maximum value of evaporation deficit will exceed the long-term level by 40–50 mm.

The dynamics of the moistening index Md is similar to the dynamics of HTC, but it provides a stricter assessment of the moistening conditions (Fig. 3B). Until the 16th ten-day period, the assessment of conditions according to climate scenarios was somewhat higher, although the moistening conditions for all variants are characterized as a moderate drought.

However, if immediately after the 16th ten-day period the average long-term conditions are assessed as a moderate to severe drought, and in the following four ten-day periods – as a very severe drought, then for the scenario climate conditions, a period of very severe drought is expected during the ten-day periods 10–12. During this period, it is difficult to distinguish the advantages of one of the scenario variants, although for the climatic conditions under the RCP 4.5 scenario, several ten-day periods with a higher moistening index are expected.

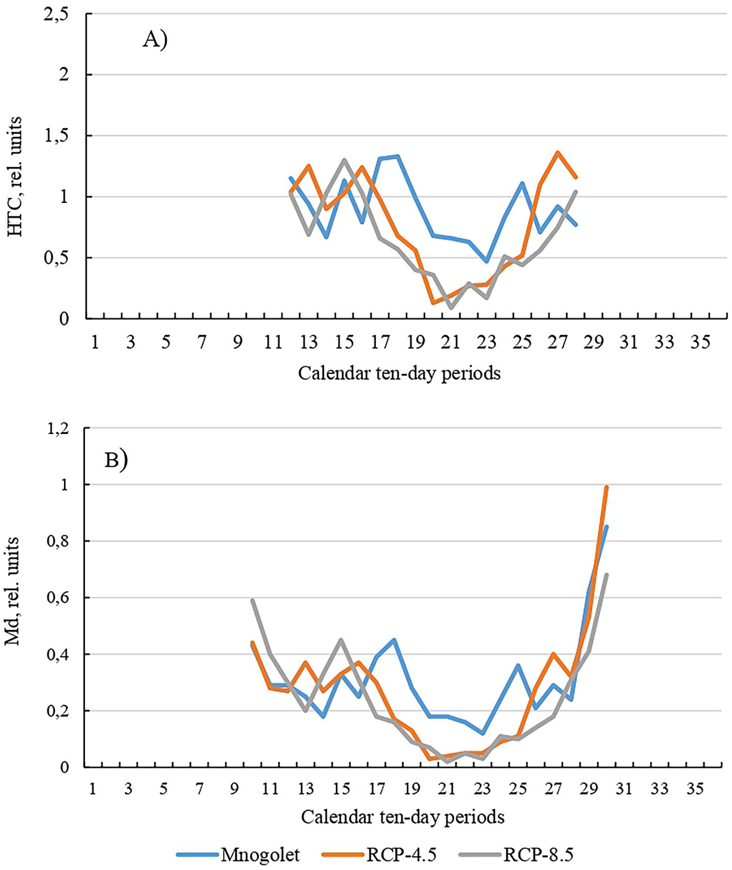

Figure 3. The dynamics for the course of scenario values of drought in the Northern Steppe compared to the long-term values of: A) Selyaninov hydrothermal coefficient (HTC); B) Shashko's moistening index (Md).

According to the Bova aridity index, the onset of drought under average long-term conditions will occur in the 18th ten-day period, and under the RCP 4.5 and RCP 8.5 scenarios – in the 17th ten-day period, that is in good agreement with the results of the assessment of drought development by the criteria of HTC, Md and evaporation deficit. The last index indicates a dramatic increase in the values of the evaporation deficit.

Aridity in the Northern Steppe is expected to increase significantly (Table 1). In the decade of 2021–2030 under the RCP 4.5 scenario, the number of dry ten-day periods by the HTC indicator will comprise: 8 ten-day periods with a mild drought, 1 – with a moderate drought, 4 – with a severe and very severe drought, while by the Md indicator, 16 ten-day periods with a moderate, severe and very severe drought are expected. At the same time, the evaporation deficit will exceed the long-term value by 26%. The realization of the RCP 8.5 scenario will exacerbate the aridity of this period: the number of dry ten-day periods will increase according to both indices. In both cases, an increase in the number of ten-day periods with severe and very severe drought is mostly expected. The evaporation deficit will increase by 37%.

In the second decade, under the RCP 4.5 scenario, the number of ten-day periods with a severe and a very severe drought increases (up to seven) according to the HTC indicator, the number of ten-day periods with a very severe drought according to the Md indicator increases to nine, and the evaporation deficit exceeds the long-term one by 32%. Under realization of the RCP 8.5 scenario, an even greater increase in the number of ten-day periods with severe and very severe droughts is expected according to both indices. Such conditions will form a very tough and dry period. The evaporation deficit will be 172% of the long-term level.For the third decade, under the RCP 4.5 scenario, rather harsh conditions, accompanied by a large number of ten-day periods with a severe and a very severe drought according to both indices, will also be formed. The excess of the evaporation deficit over the long-term value will amount to 64%. It should be noticed that, as in the case of the Forest-Steppe, under realization of the RCP 8.5 scenario, milder conditions are expected from the point of view of aridity assessment; this will be reflected in a decreased number of ten-day periods with a severe and a very severe drought and a decreased evaporation deficit, which will be only 125% of the long-term value.

Southern Steppe

Under average long-term conditions, the first two ten-day periods of the growing season (the 12th and 13th ten-day periods) are in more favourable moistening conditions in comparison with the scenario data (Fig. 4A).

Over the next three ten-day periods, the moistening conditions worsen, and a slight drought is observed (the HTC values range from 0.61 to 0.81 relative units). For the scenario climatic conditions, especially for the RCP 8.5 scenario, the moistening conditions will be more favourable. From the 17th up to the 25th ten-day period, the average long-term conditions are classified as a slight drought, and during three ten-day periods – as a moderate drought. In the same period, according to scenario data, severe and very severe drought is expected. The maximum values of the evaporation deficit will comprise 64–72 mm. In the 26th–28th ten-day periods for the RCP 4.5 scenario, the moistening conditions will improve, the HTC values will be higher than the long-term averages, while for the RCP 8.5 scenario they will be significantly lower.

Under realization of the RCP 8.5 climatic scenario, the moistening conditions according to the moistening index Md in the period (the 9th–16th ten-day periods) will be partially characterized as a moderate drought, while under the RCP 4.5 scenario, the moistening index corresponds to the definition of a severe drought (Fig. 4B).

For average long-term conditions, this assessment will be even tougher. For these conditions, severe drought will be observed from the 17th to the 28th ten-day periods, and a very severe drought – for three ten-day periods. Under the scenario conditions, a very severe drought is expected during this period; from the 28th ten-day period it transitions to a severe and then to a moderate drought.

For the assessment according to the Bova aridity index, the onset of drought under average long-term conditions will occur in the 16th ten-day period, and according to the RCP 4.5 and RCP 8.5 climate scenarios – in the 15th and 16th ten-day periods, respectively, that is in good agreement with the results of the assessment of the drought development according to the criteria of the HTC, Md and evaporation deficit.

Under the conditions of the Southern Steppe (Table 1), for the first decade, in case of the RCP 4.5 scenario, three ten-day periods with a moderate drought, one ten-day period with a severe

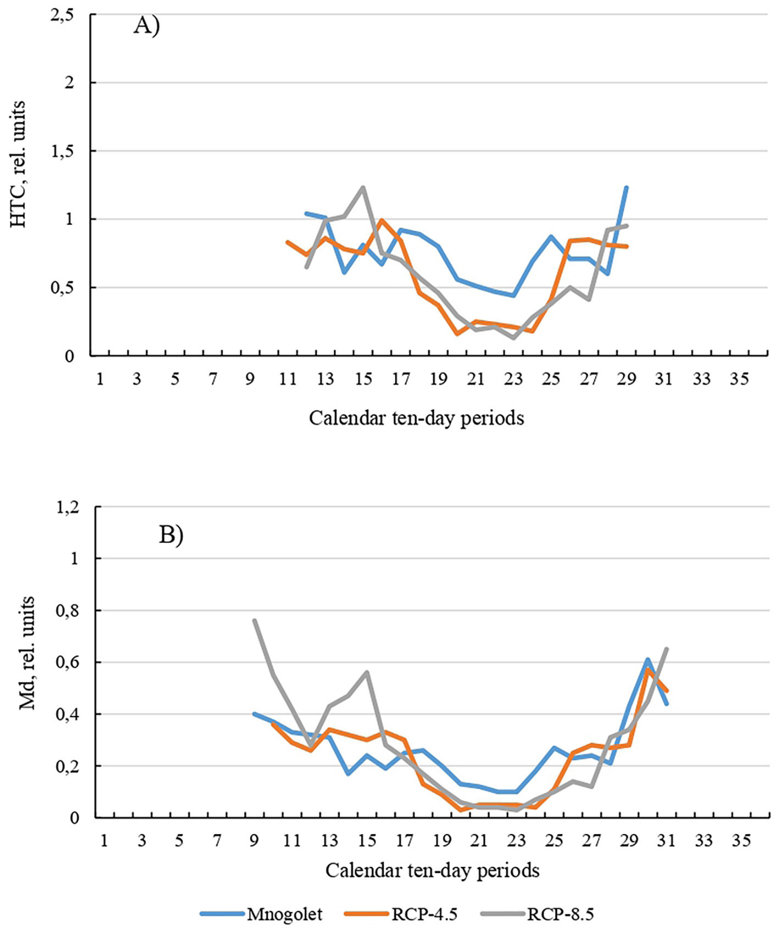

Figure 4. The dynamics for the scenario values of drought in the Southern Steppe compared to the long-term values of: A) Selyaninov hydrothermal coefficient (HTC); B) Shashko's moistening index (Md).

drought, and five ten-day periods with a very severe drought will be observed according to the HTC indicator. The assessment of the expected conditions according to the Md criterion shows that one ten-day period with a moderate drought, four ten-day periods with a severe drought and twelve ten-day periods with a very severe drought are possible. The evaporation deficit will exceed the long-term level by 46%. In such a situation, the first decade will be characterized as one of the driest in the entire fifty-year period. For the RCP 8.5 scenario, the number of ten-day periods with a severe and a very severe drought will slightly decrease, and the excess of the evaporation deficit will be 24%.

For the second decade under the RCP 4.5 scenario, nine ten-day periods with a moderate, a severe and a very severe drought are expected according to the HTC criterion, and according to the Md criterion, their number will be seventeen. The hardest conditions are formed under the RCP 8.5 scenario. They will be distinguished by the occurrence of ten ten-day periods with a moderate, a severe and a very severe drought according to the HTC indicator and seventeen similar ten-day periods according to the Md indicator. The evaporation deficit will comprise 152% of the long-term value.

Under realization of the RCP 4.5 scenario, the third decade is characterized by twelve ten-day periods with a moderate, a severe and a very severe drought according to the HTC indicator, and according to the Md indicator – by seventeen similar ten-day periods with an evaporation deficit comprising 145% of the long-term value. In case of realization of the RCP 8.5 scenario, the conditions will be somewhat less harsh.

The characteristic circumstance is the fact that according to both indices (HTC and Md) in all three decades, under both the RCP 4.5 scenario and the RCP 8.5 scenario, there is a significant increase in the number of ten-day periods with severe and very severe droughts, which form extremely arid conditions.

Let us consider the average (for the growing season) values of the hydrothermal coefficient HTC by Selyaninov [1937], the moistening index Md by Shashko [1967], the evaporation deficit Δ*E* by Budagovskiy [1957], as well as a Bova [1946] aridity index, which is used to determine the ten days when the dry season begins (Table 2). As it should be expected, the average long-term values of HTC and Md indices for the growing season decrease from Polissia to the Southern Steppe (from 1.44 to 0.75 relative units and from 0.56 to 0.27 relative units, respectively), and there is an increase in evaporation deficit (from 136 to 495 mm) and a shift in the terms of the onset of drought to earlier periods (from the 21st ten-day period to the 16th ten-day period).

Under climate change scenarios, the Selyaninov hydrothermal coefficient will decrease by 15–23% in Polissia. In the Forest Steppe, the coefficient values will decrease by 5–17%. At the same time, the moistening conditions in the Forest Steppe under the RCP 8.5 scenario will be 8–12% better than those under the RCP 4.5 scenario. This situation is also clearly visible in the values of Shashko moistening index: its changes for both climate scenarios are insignificant (2–8%), under the RCP 8.5 scenario they will amount to only 2%. It is interesting to notice that the evaporation deficit will not undergo significant changes. It is expected to decrease by 5%.

The moistening conditions in the Northern and Southern Steppes are characterized as mild and moderate droughts according to the HTC criterion and as a severe drought according to the Md criterion. The evaporation deficit will increase by 60–69% in the Northern Steppe, and by 14–16% in the Southern Steppe.

DISCUSSION

Various indicators are used to obtain aridity estimates. The paper [Khokhlov et al., 2011], based on the use of the standardized precipitation index, concludes that there has been a trend towards an increase in the number and intensity of droughts since the second half of the 1990s.

The paper [Semenova, 2015] considers the temperature and humidity conditions in Ukraine in the future for 2020-2050 based on CMIP5 climate modelling data. Analysis of the spatiotemporal distribution of droughts was performed by means of the SPI index. According to the RCP2.6 and RCP8.5 climate scenarios, the maximum increase in surface air temperature can reach +2.1 °C and +3.1 °C, respectively. The amount of precipitation will also increase, but it will not be enough to avoid the formation of droughts. It is expected that under both mild and severe climate scenarios in the period of 2020–2050, almost every third warm season will be with a mild drought throughout the country. During this period, from 1 to 3 seasons with moderate and severe drought upon average and no more than 1 to 2 seasons of extreme drought are prognosticated. Drought periods will alternate with humid periods of comparable intensity, with the period from 2034 to 2040 predicted to be the most humid, and the most significant drought periods will be observed in the 2020s and 2040s. The most severe drought reaching extreme intensity will be observed in 2042–2045, and in the south it will last until 2050. The studies performed in [Semenova et al., 2020] demonstrate the results of the analysis of the spatiotemporal distribution of droughts in the warm seasons of 2021–2050 on

Table 2. Comparison of aridity indices for the average long-term conditions and those expected under climate change scenarios for the growing season

	Indices											
	HTC. relative units			Md. relative units			Δ*E*. mm			The ten-day period of the onset of drought from 1 January		
	Climatic period. years											
Agroclimatic zone	Long-term 1981–2020	RCP 4.5 2021–2050	RCP 8.5 2021–2050	Long-term 1981–2020	RCP 4.5 2021–2050	RCP 8.5 2021–2050	Long-term 1981–2020	RCP 4.5 2021–2050	RCP 8.5 2021–2050	Long-term 1981–2020	RCP 4.5 2021–2050	RCP 8.5 2021–2050
Polissia	1.44	1.11	1.22	0.56	0.41	0.49	136	198	177	21	21	21
Forest-Steppe	1.39	1.15	1.32	0.49	0.45	0.48	176	167	168	20	19	19
Northern Steppe	0.88	0.68	0.58	0.31	0.28	0.24	370	594	626	18	17	17
Southern Steppe	0.75	0.54	0.54	0.27	0.24	0.25	495	577	566	16	16	16

the territory of Ukraine based on climate modelling data under the framework of climate scenarios RCP4.5 and RCP6.0. Assessment of drought events and their intensity was performed on the basis of the SPEI standardized drought index on a scale of 7 months, which covers the warm season from April to October. The analysis of the prognostic time dependence of the drought index in the regions of Ukraine showed that, according to both scenarios, a trend of transition from moderately humid conditions in 2021–2035 to dry conditions in 2037–2050 will be observed. At the same time, under the framework of the RCP6.0 scenario, a longer transition is prognosticated during the 2030s with high spatial variability of the drought index during this period. The driest years under both scenarios are expected in 2044–2048, when in several regions the seasonal drought may reach extreme intensity.

A comparison of the spatiotemporal distribution of droughts under the RCP4.5 and RCP6.0 scenarios with the results of another scenarios RCP2.6 and RCP8.5 showed [Semenova et al., 2020] the general similarity of the drought index trends, which indicate a gradual transition from moderately humid conditions in the 2020s (with one significant drought in the middle of the period) to mostly dry conditions in the 2040s, with the frequency of seasonal droughts being almost the same in all scenarios, although episodes of prolonged droughts occur at different time intervals in different scenarios.

A comparison of the data obtained by us with those presented above shows a general coincidence of the trend of arid phenomena development by decades and over a thirty-year period as a whole. However, consideration in the context of dry decades displays an increase in aridity as early as in the period of 2021–2030 in all agroclimatic zones, that is not entirely consistent with the results [Semenova et al., 2020], although one significant drought in the middle of the period is expected there. The results of calculations show that both scenarios assume from 4–6 in Polissia to 16–17 severe and very severe droughts in the Southern Steppe, that is also confirmed by the excess of the evaporation deficit by 14 to 46%, respectively.

For the second decade, a decrease in the intensity of the thermal regime and an improvement in moistening conditions are expected in Polissia and Forest Steppe under RCP4.5. This will lead to a significant reduction in the number of dry ten-day periods and a decrease in the evaporation deficit. At the same time, an increase in the level of aridity in these agroclimatic districts is assumed under RCP8.5. In the Northern Steppe and the Southern Steppe, according to both criteria (HTC and Md), the number of moderately dry, very dry and extremely dry ten-day periods will increase (from 9 to 17).

In the third decade (2041–2050), under realization of the RCP4.5 scenario, very severe drought conditions are expected in all agroclimatic zones, however, compared to the rest of the agroclimatic zones, arid conditions in the Forest Steppe will be somewhat milder (the evaporation deficit here will make up 125% of the long-term value compared to 140–164% in other zones). This is in good agreement with the results of [Semenova et al., 2020], in which it is noticed that, according to both scenarios, the mid-decade will be the driest, the drought will reach extreme intensity, and in the south, it will last until 2050. However, in our case, not everything is so clear. Under RCP8.5, good moistening conditions and, according to both criteria (HTC and Md), a small number of dry ten-day periods are expected in Polissia and Forest Steppe, that is not entirely consistent with the conclusions obtained in [Semenova et al., 2020]. As for the conditions at the Northern and Southern Steppe, our conclusions on the increase in aridity completely coincide. According to both criteria (HTC and Md), 8 to 17 ten-day periods with moderate, severe and very severe drought are expected.

CONCLUSIONS

Thus, consideration of the aridity development in the context of a ‘dry ten-day period’ according to P.I. Brounov [Polevoy, 2012] by means of a set of aridity indices, which supplement each other, made it possible to study in detail the genesis of climate change-induced drought in the agroclimatic regions of Ukraine over small time periods.

It was established that the development of dry conditions in all agroclimatic zones is assumed as early as in the first decade (2021–2030). According to both scenarios, from 4–6 in Polissia to 16–17 severe and very severe droughts in the Southern Steppe are expected, that is confirmed by an excess of evaporation deficit by 14 to 46%, respectively.

In the second decade (2031–2040), under RCP4.5, an improvement in moisture conditions is expected in Polissia and Forest Steppe, that will lead to a significant reduction in the number of dry ten-day periods and a decrease in evaporation deficit, and under RCP8.5, an increase in the level of aridity is expected in these agroclimatic areas. In the Northern Steppe and the Southern Steppe, according to both aridity criteria (HTC and Md), the number of moderately dry, very dry and extremely dry ten-day periods will increase (from 9 to 17).

In the third decade (2041–2050), under realization of the RCP4.5 scenario, very severe drought conditions are expected in all agroclimatic zones. Against this background, the arid conditions will be somewhat milder in the Forest Steppe, where the evaporation deficit will comprise 125% of the long-term value compared to 140–164% in other zones. Under RCP8.5, good moisture conditions and, according to both criteria, a small number of dry ten-day periods are assumed in Polissia and Forest Steppe. As for the conditions at the Northern and Southern Steppe, according to both criteria (HTC and Md), very severe drought conditions are expected (from 8 to 17 ten-day periods with moderate, severe and very severe drought). Overall, for 2021–2050, there will be an increase in aridity in all agroclimatic zones during the growing season.

Thus, the realization of climate change scenarios in Ukraine will lead to an increase in aridity in the future, an increase in evaporation deficit and a general increase in the number of ten-day periods within the growing season, the conditions of which will be characterized as a mild, a moderate, a severe and a very severe drought. In terms of moistening, more favourable conditions are assumed under the climate scenarios in Polissia and Forest Steppe, and the most severe conditions – in the Southern Steppe.

The results, which we obtained, specify the process of development of arid phenomena under the climate change in Ukraine, and provide a quantitative assessment of their intensity. They can be used under planning the allocation of areas under crops in agroclimatic zones of Ukraine, and adaptation of crop production to changing conditions through alteration of the structure of sown areas in order to mitigate the impact of adverse conditions.

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