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CHANGES IN THE FREQUENCY OF SHARP COLD SNAPS IN SPRING DURING THE XXI CENTURY IN UKRAINE AND THEIR IMPACT ON AGRICULTURAL PRODUCTION

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Aim. Identification of trends in the frequency of sharp inter-day decreases in the average daily air temperature of varying intensity in spring in the agroclimatic zones of Ukraine and their likely change by the end of the twenty-first century for climate scenarios of representative concentration pathways of greenhouse gas emissions RCP4.5 and RCP8.5. **Methods.** Solving the set tasks envisaged the application of both conventional scientific and specialized research methods: analytical and synthetic – to analyze the current state of research, statistical – to assess the intensity and significance of changes in the frequency of sharp inter-day air temperature drops of varying intensity, comparative analysis – to identify their specificities in agroclimatic zones of Ukraine, climatic – to characterize extreme temperature conditions, modeling – to assess their changes in the short, medium and long term under the implementation of RCP4.5 and RCP8.5 scenarios. **Results.** The current state of changes in the extremes of temperature conditions in spring, in particular, sharp inter-day changes in air temperature of varying intensity (severe, very severe, extremely cold snaps) in the agroclimatic zones of Ukraine, is considered. Sharp cold snaps aggravate agricultural production since the decrease in temperature by 4–10 °C or more often leads to light frosts, which may cause partial or complete death of plants. The specificities of their frequency and intensity in 1981–2020 were determined. It was found that in spring, the sharpest cold snaps of 4–6 °C in Ukraine occur 2–4 times per season; they are most frequent (3–4 times) in the western and eastern Forest-Steppe and Polissia. Very severe cold snaps of 6–10 °C are observed 2–3 times less – from 6–8 cases in 10 years in the southern Steppe to 13–16 cases in Polissia, in the western and eastern Forest-Steppe. The extremely cold snaps of 10 °C and more are rare in spring in Ukraine – from 2–3 to 8–9 cases in one hundred years. Only several regions can be isolated in Ukraine, where the phenomenon of such intensity can happen in spring most often. These are Ivano-Frankivsk, Chernivtsi, Zhytomyr, and Odesa regions. In these regions, the inter-day changes in spring air temperature of 10 °C or more occur 7–9 times in 100 years, whereas in Kherson and Zaporizhzhia regions, they occur twice in 100 years. This unevenness of spatial distribution of extremely cold snaps is conditioned by various factors, conditioning them. The trends in the frequency of sudden cold snaps in Ukraine are determined, and the speed, direction, significance, and reliability of their change during the study period are defined. The regions with the most significant changes in the frequency of these phenomena are specified. Despite the significant increase in air temperature during the spring season, especially in March, the frequency of severe cold snaps in 1981–2020 in the central, western, eastern Forest-Steppe, Chernihiv, and Novgorod-Siverskyi Polissia is increasing, and in the northern Steppe, it is decreasing throughout the season, except for March. In contrast to severe cold snaps, the frequency of very severe and extremely cold snaps increases the most in the Steppe and the eastern Forest-Steppe zones, especially in March. Significant variability of air temperature in March, with a general tendency to increase, indicates a significant change in atmospheric circulation during this period, in particular, an increase in the meridional nature of atmospheric processes. The data on the probable change in the frequency of severe cold snaps in 2021–2040, 2041–2060, 2081–2100 relative to the current climate period (1991–2010) for the RCP4.5 and RCP8.5 scenarios are presented.

It was determined that in the course of the twenty-first century, the frequency of sharp cold snaps in a considerable territory of Ukraine may decrease, especially under the implementation of RCP8.5 scenario. These changes will be enhanced with the increase in the phenomenon intensity. Such tendencies are notable for severe and very severe cold snaps. The greatest changes in the frequency of cold snaps under scenario RCP4.5 are probable in Polissia (14.7–18.3 % in the middle of the century and 14.7–21.3 % at the end of the century in comparison to 1991–2020); however, they will decrease further south, reaching 6–12 % in the southern Steppe. The volume of extremely cold snaps will also decrease considerably in the Steppe zone and the eastern Forest-Steppe (down to 70 % and more at the end of the century), but in Polissia, in the western and central Forest-Steppe, their volume may increase at the end of the century compared to its beginning (1991–2020). The greatest changes are probable in Polissia, in particular, in Rivne region, which may encounter almost 1.3 times more extremely cold snaps. Under the implementation of RCP8.5 scenario, in spring, the frequency of severe and very severe cold snaps will decrease in the entire territory of the country both in short- and mid-term perspective, even in Polissia (from 8 to -28 % in 2021–2040 to 8–19 % in 2041–2060). By the end of the century, there may be 1.8–9.3 % fewer cold snaps in the entire region. The frequency of very sharp decreases in air temperature may decrease almost by 23 % in Chernihiv region. In the rest of the territory, their frequency will not change considerably, and in Rivne region and Volyn, it may increase by 10.3–17.2 %. There may be almost 1.5 times more extreme cold snaps in Polissia by the end of the century compared to 1991–2020, except for Chernihiv region, where their frequency will continue decreasing to 37.7 %. These changes may be extremely dangerous for agriculture since, under such a cold spell, the minimal air temperature may drop below 0 °C, and the occurring light frosts may damage the crops considerably, especially if the air temperature increases significantly by the end of the century in this region, and the vegetation period starts sooner. **Conclusions**. It was determined that despite a considerable increase in air temperature in Ukraine, Europe, and Arctic latitudes, the earlier beginning of the warm season and vegetation season, the number of spring days with severe, very severe, and extremely severe cold snaps is increasing in almost the entire territory of Ukraine. The north-eastern and eastern regions of the country are most vulnerable due to the registered highest increase in air temperature and frequency of sharp cold snaps. There may be fewer sharp cold snaps in the short- and long-term perspective in Ukraine as compared to the current climatic period. Still, the frequency of extremely cold snaps (over 10 °C a day) will increase by the end of the century, especially in Polissia, and the western and central Forest-Steppe. These changes may result in premature termination of the vegetation period, damage to primordia and fruits, impairments to normal plant development, and a significant effect on crop productivity.

Key words: climate change, extreme air temperature, cold snaps, light frosts, climate change projections, scenarios of representative concentration pathways RCP4.5 and RCP8.5.

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INTRODUCTION

A considerable increase in air temperature, observed on our planet in recent decades, causes ever-increasing human, financial, and ecological losses. The changes in the temperature regime, frequency, and intensity of extreme temperatures triggered considerable changes not only in the atmosphere but also in hydrosphere, cryosphere, lithosphere, and biosphere and became a challenge for sustainable society development (IPCC, 2021). According to the data of the World Meteorological Organization (WMO, 2021), in the last 50 years, 11,000 natural disasters have been caused by dangerous weather, climate, and water-related phenomena, due to which 2 million people died, and there has been economic loss in the amount of USD 3.6 trillion. From 1970 till 2019, 1,672 registered dangerous phenomena in Europe led to the death of 159,438 people and economic loss in the amount of USD 476.5 billion (WMO, 2022). In 2021, only in Asia, the danger due to weather and water caused damage for a total amount of USD 35.6 billion, impacting almost 50 million people (WMO, 2022).

The number of sharp cold snaps decreases with the increase in temperature. Still, their intensity does not change much in considerable territories in Europe, the USA, and northern-eastern Asia despite rapid warming in the Arctic regions, which brings the risks related to short-term decreases in the air temperature. For instance, in 2021, only in France, light frosts caused damage to agriculture in the amount of over USD 4.6 billion (WMO, 2022; Devot et al, 2023; Lamichhane, JR, 2021).

Many scientific works both abroad and in Ukraine are dedicated to the study of sharp changes in air temperature, especially warming and heat waves. Still, sharp cold snaps, especially in the current climatic period, are underinvestigated and require attention, and their impact is extremely important, especially in the agrarian sector

(Zampieri et al, 2017; Parry et al, 2013; Cohen et al, 2021; Veron et al, 2015, Polevoy et al, 2021; Polevoy, 2017).

Severe cold snaps in winter and transition periods impact human health, especially respiratory and cardiovascular systems, cause an increase in the number of respiratory diseases, lead to hypercooling of the organism and even death of people (Stellman,1998; Haman et al, 2022; López-Bueno et al, 2021). Sharp cold snaps, especially if accompanied by precipitation, are also of serious consequences for transportation, infrastructure, and energetics since flights are cancelled, airports are closed, there are longer lines on the roads, there is a much higher demand for electricity to ensure heating of buildings (Marengo et al, 2023; Añel et al, 2017; Saad et al, 2022).

Spring cold snaps are a limiting factor for crop development and may have a destructive effect on agriculture and the production of food products in the entire world. It will affect not only plants but agricultural infrastructure and economy of local districts as well as entire countries. The losses and expenses, related to sharp cold snaps, are complex since they depend on the intensity and duration of the weather phenomenon (Hatfield et al, 2011; Jendritzky, 1999; Wei, 2024).

The impact of sharp inter-day changes in air temperature becomes evident even when their values exceed 4 °C in one day. The organism of a healthy person adapts to inter-day temperature flexibility within 4 °C easily, without any apparent burden for the adaptation mechanisms (Stellman, 1998). However, a change in temperature by 4–6 °C is already notable, and above 6 °C, it irritates the human organism and promotes the aggravation of current diseases. The most dangerous inter-day change is the decrease in the average daily air temperature by 10 °C or more, since it affects not only the human organism, but also the energetics, transport, agriculture, construction, infrastructure, and other branches (Motha, 2011; Forzieri et al, 2018).

According to the estimates of the working group of the Intergovernmental Panel on Climate Change (IPCC), by the end of the twenty-first century, the air temperature will keep increasing, the frequency and duration of heat waves will be higher, and extreme phenomena, related to low temperatures, will occur (IPCC, 2021). Therefore, the frequency and intensity of extreme events, related to air temperature, will increase further, which requires elaborating strategies and plans for adapting to climate change, and thus information about the regional specificities of the formation of these phenomena, their dynamics, possible changes in the mid- and long-term perspective and the development of the operating system of warning about extreme weather conditions.

The aim of the study is to determine trends in the change in the frequency of sharp inter-day decreases in the average daily air temperature of varying intensity in spring in the agroclimatic zones of Ukraine and their likely change by the end of the twenty-first century for climate scenarios of representative pathways of greenhouse gas emissions RCP4.5 and RCP8.5.

MATERIALS AND METHODS

The study on the frequency and dynamics of sharp inter-day changes in air temperature was conducted using daily data about the average daily air temperature from the network of hydrometeorological monitoring of Ukraine for 1981–2020. Only the data for 1981–2013 were used regarding the AR of Crimea and parts of Donetsk and Luhansk regions, occupied since 2014.

Considering the impact of sharp inter-day changes in air temperature (SCT) on economy branches and human organism for the identification of the degree of their intensity and danger, the following quantitative criteria were accepted: SCT $\leq$ 4 °C in 24 h and less – *the changes are insignificant*; 4 < SCT $\leq$ 6 °C in 24 h and less – *severe sharp cold snaps;* 6 < SCT $\leq$ 10 °C in 24 h and less – *very severe cold snaps;* SCT > 10 °C in 24 h and less – *extremely sharp cold snaps.*

The statistical evaluation of the time-wise change in the frequency of sharp cold snaps of different intensity was conducted using the analysis of time series: the form and the direction of the time series trend was determined using the regression analysis, and its statistical significance (p) was evaluated. Considering the recommendations of the IPCC, the following criteria were used to assess the share of uncertainty regarding the change in the frequency of sharp cold snaps (IPCC, 2013): the change is practically undoubted ($p \leq 0.01$, probability 99–100 %); very probable ($0.01 < p \leq 0.1$, probability 90–99 %); probable ($0.1 < p \leq 0.34$, probability 66–90 %); the change is equally probable and improbable ($0.34 < p \leq 0.67$, probability 33–66 %); hardly probable ($0.67 < p \leq 0.90$, probability 10–33 %); very hardly probable ($0.90 < p \leq 0.99$, probability 1–10 %); extremely hardly probable ($p > 0.99$, probability 0–1 %).

The results obtained helped determine the most vulnerable regions, where these phenomena may cause considerable risks for the life and activity of people and sustainable work of economy branches.

The probable change in the frequency of sharp cold snaps in the agroclimatic zones of Ukraine was evaluated using the data from 14 regional climate models of the EURO-CORDEX project (Hennemuth, 2017; Jacob et al, 2020; Jacob et al, 2023). The evaluation of climate change involves two scenarios (RCP4.5 and RCP8.5), which describe different pathways of greenhouse gas emissions, their concentration in the atmosphere, and changes in land use in the XXI century. These were used in the fifth assessment report (AR5) of the IPCC and called the Representative Concentration Pathways (RCPs) of greenhouse gas emissions (IPCC, 2013). RCP scenarios define the total volume of the additional radiation exposure by 2100 as compared to the pre-industrial period (1750) due to higher anthropogenic impact: 4.5 Wt/sq.m. and 8.5 Wt/sq.m. for scenarios of RCP4.5 and RCP8.5, respectfully. In all the RCP scenarios, by 2100, the concentration of CO_2 in the atmosphere will be higher compared to the current period due to a long-term increase in CO_2 released into the atmosphere in the 21st century. Considering the concentration of CH_4 and N_2O, the total equivalent concentrations of CO_2 by 2100 will be 630 ppm (RCP4.5) and 1,313 ppm (RCP8.5) (IPCC, 2013). The increase in the global average annual air temperature by the middle of the 21st century for RCP4.5 is expected to be 0.9–2.0 °C, and for RCP8.5 – 1.4–2.6 °C. By the end of the century, these changes may be within 1.1–2.6 °C and 2.6–4.8 °C, respectively (IPCC, 2013).

The climate forecasts for the change in the frequency of sharp cold snaps were obtained by the ensemble data of 14 climate models regarding the average monthly and seasonal values of the number of cases of sharp inter-day temperature changes in 2021–2040, 2041–2060, 2081–2100 regarding the current climatic period (1991–2010) for scenarios RCP4.5 and RCP8.5.

RESULTS OF INVESTIGATIONS

The analysis of the number of cases with sharp changes in the average daily air temperature of over 4 °C a day demonstrated that in Ukraine, in 1981–2020, the highest frequency (73 %) was registered for severe sharp changes in temperature from 4 °C to 6 °C in 24 h and very severe ones (25 %) – from 6 °C to 10 °C in 24 h. Extreme SCT of over 10 °C are about 2 %.

The highest frequency of sharp cold snaps is noted in winter: 34.1 % – severe, 42.2 % – very severe, 75.7 % – extreme (**Fig. 1**). A considerable frequency of SCT is also remarkable for transition seasons. In autumn, severe and very severe cold snaps occur more frequently than in spring. The frequency of severe SCT in autumn is 28.6 %, while in spring – 20.3 %, very severe – 25.8 % and 20.8 %, respectively. However, extreme SCT are mostly observed in spring (11.0 %). Only 0.8 % of cold snaps of such intensity a year are noted in autumn. The lowest frequency of SCT is notable for summer: 17.2 % – severe, 11.9 % – very severe, and 0.2 % – extreme (Fig. 1).

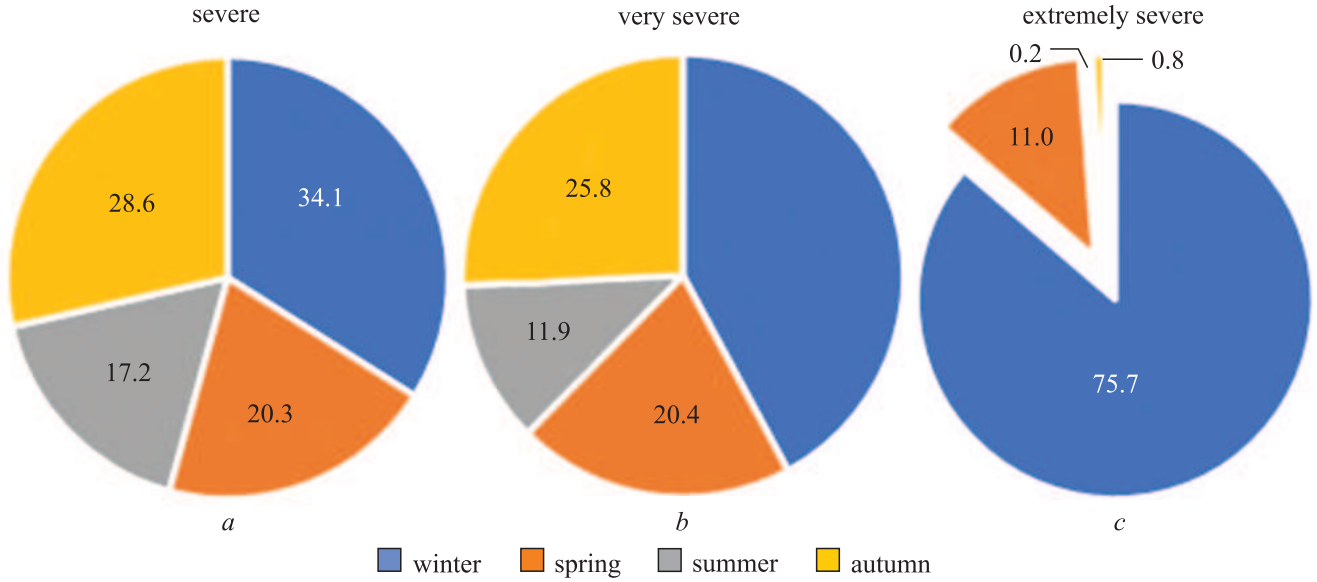


Fig. 1. The frequency (%) of sharp inter-day changes in air temperature (cold snaps) of different intensity in Ukraine in the course of the year

The significant frequency of sudden cold snaps in spring has a negative impact on agricultural production since a decrease in the average daily air temperature by 4–10 °C or more during the growing season often causes the formation of frosts on the soil and in the air, and can lead to partial or complete plant death.

It has been established that the spatial distribution of the frequency of sharp cold snaps changes throughout the year, indicating a change in the synoptic processes that cause them. In winter, severe and, especially, very severe and extremely cold snaps are typical for the eastern regions of the country, while in the south they are much less frequent. In the spring, sharp cold snaps are most often observed in the western and northern regions of the country, particularly in Polissia, and in the east. The summer period is characterized by the highest frequency of sharp cold snaps of varying intensity in the west of the country. In autumn, severe cold snaps are most often observed in the eastern, northern, and central regions of the country, where this phenomenon is possible more than four times per season. Very severe cold snaps in autumn are possible throughout the country 1–2 times per season. They are most common in the eastern, central, and southern regions. Their frequency is twice lower in Volyn. Extreme SCTs occur rarely in Ukraine – 7 times in 100

Table 1. The number of days per year and spring with sharp changes in the average daily air temperature of varying intensity in the agroclimatic zones of Ukraine

Region	Severe sharp cold snaps		Very severe cold snaps		Extremely severe cold snaps	
	year	spring	year	spring	year	spring
Polissia						
Volyn	14.0	3.4	4.4	1.1	0.27	0.04
Zhytomyr	14.4	3.3	5.2	1.3	0.35	0.07
Rivne	14.9	3.4	5.2	1.3	0.32	0.05
Chernihiv	15.0	3.2	6.0	1.2	0.49	0.04
Western Forest-Steppe						
Ivano-Frankivsk	17.2	3.6	7.0	1.6	0.43	0.09
Lviv	14.6	3.5	4.9	1.1	0.29	0.03
Ternopil	14.5	3.4	5.2	1.3	0.26	0.03
Chernivtsi	13.9	2.8	5.2	1.2	0.37	0.08
Central Forest-Steppe						
Vinnytsia	13.8	3.1	5.2	1.2	0.35	0.06
Kyiv	14.6	3.4	5.5	1.3	0.38	0.03
Khmelnytsky	14.4	3.3	5.2	1.3	0.21	0.04
Cherkasy	14.4	2.9	5.3	1.3	0.45	0.03
Eastern Forest-Steppe						
Poltava	15.4	3.3	5.7	1.3	0.55	0.06
Sumy	15.8	3.3	6.1	1.1	0.65	0.03
Kharkiv	15.5	3.1	6.5	1.3	0.65	0.03
Northern Steppe						
Luhansk	14.9	3.0	6.9	1.2	0.78	0.01
Dnipropetrovsk	15.0	2.8	6.0	1.1	0.40	0.04
Donetsk	14.2	2.7	6.3	1.1	0.52	0.04
Kirovohrad	14.8	2.9	5.3	1.1	0.36	0.06
Southern Steppe						
Zaporizhzhia	13.3	2.1	5.2	0.8	0.22	0.02
Mykolayiv	13.4	2.1	4.5	0.8	0.28	0.04
Odesa	12.3	2.2	4.3	0.9	0.27	0.08
Kherson	12.9	2.1	4.2	0.6	0.25	0.02

years – four warmings and three coolings. Extremely sharp cold snaps are most frequent in the eastern and southern regions of the country, and the warming – in the northern and central regions.

An analysis of the spatial distribution of cold snaps of varying intensity in the country's agroclimatic zones showed that their highest frequency is characteristic of the Ukrainian Carpathians, particularly Ivano-Frankivsk region. In this region, the highest annual frequency of severe and very severe cold snaps was observed – 17.2 and 7.0 cases, respectively. This region is also characterized by the highest frequency of sharp cold snaps of varying intensity in spring: 3.6 cases of severe, 1.6 cases of very severe, and 0.9 cases of extremely cold snaps (**Table 1**). The frequency of sharp cold snaps is high in the eastern Forest-Steppe, in particular, in Sumy and Kharkiv regions, as well as in the northern Steppe, Luhansk region, where 14.9–15.8 severe cold snaps are recorded per year (3.1–3.3 cases in spring); 6.1–6.9 cases of very severe cold snaps (1.1–1.3 in spring). However, extremely cold snaps are rare (Table 1). It should be noted that a significant number of sharp drops in air temperature in spring are also characteristic of the western Forest-Steppe. The lowest frequency of severe cold snaps is in the southern Steppe, particularly in Odesa and Kherson regions: 12.3–12.9 cases per year and 2.1–2.2 in spring (Table 1).

The analysis of the dynamics in the frequency of days per year with severe SCT during 1981–2020 showed that there are heterogeneous trends in the frequency of this phenomenon in Ukraine. In the western, southern, and partially central regions of the country, their frequency is very probable (>90 %) to decrease, while in the eastern Ukraine and right-bank Polissia, it is increasing. The seasonal peculiarities of the dynamics of severe cold snaps have been identified. In winter, a decrease in the frequency of such phenomena is observed almost throughout the country, especially in the west of Ukraine and right-bank Polissia. A significant decrease in the frequency of severe SCTs is also observed in autumn, especially in the south-western, southern, and south-eastern regions of the country. In summer, and especially in spring, the number of severe SCTs increases almost throughout the country, even though during this period, there is a tendency for a significant increase in air temperature (**Fig. 2**).

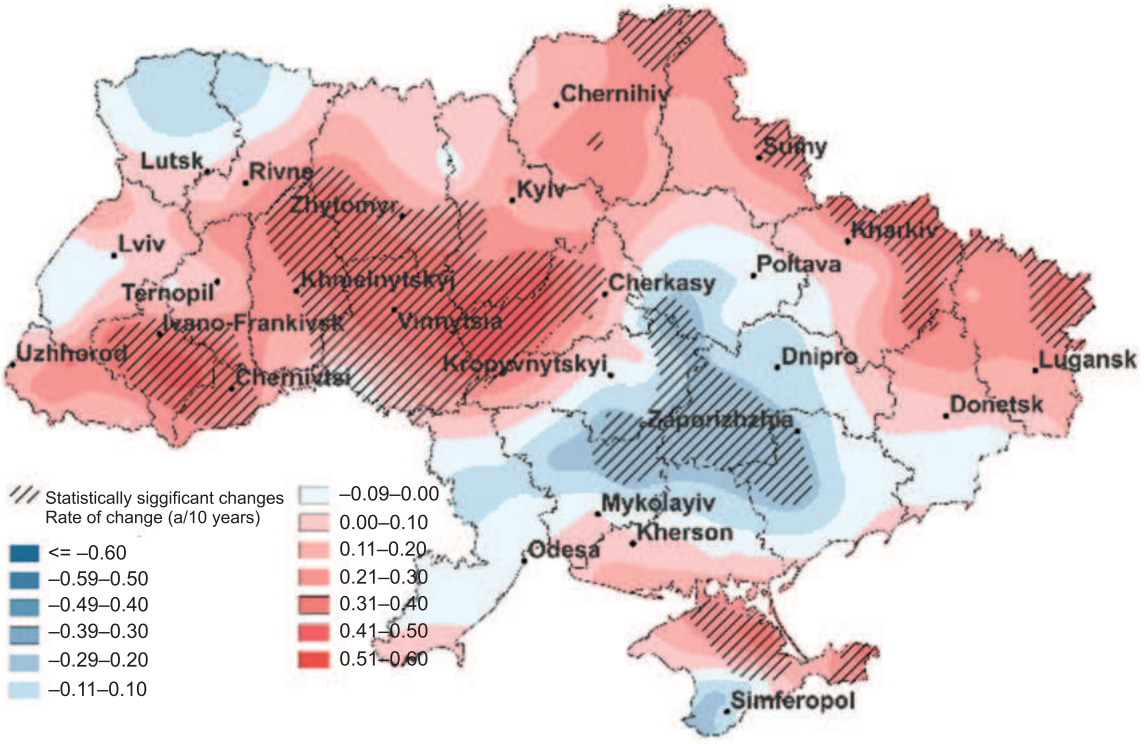
In spring, the largest increase in the number of cases of severe cold snaps during 1981–2020 was observed in the central, western, eastern Forest-Steppe, Chernihiv and Novgorod-Siverskyi Polissia. The northern Steppe during this period is characterized by a decrease in the frequency of such phenomena throughout the season, with the exception of March. It should be noted that in the western Forest-Steppe, the trends to the increase in the frequency of severe sharp drops in air temperature are notable for the entire spring season (Fig. 2).

The frequency of very severe SCTs throughout the year in Ukraine did not change considerably either. Over the course of the year, they are also characterized by a decrease in the frequency of occurrence in autumn and, especially, in winter and an increase in summer and spring over a large part of the country. In contrast to severe cold snaps, the frequency of very severe cold snaps increases the most in the Steppe and eastern Forest-Steppe zones, especially in March (**Fig. 3**). This month is characterized by their intensification throughout the country, and most significantly in the Steppe and eastern Forest-Steppe zones (Fig. 3). In April, in the western Forest-Steppe and the Volyn Polissia, there is a significant decrease in the frequency of severe cold snaps, although in the eastern Forest-Steppe their frequency increases. In May, changes in the frequency of this phenomenon are not significant almost throughout the country, with the exception of Volyn Polissia, which is notable for a tendency to the increase (Fig. 3).

For extremely cold snaps, when inter-day changes in the average daily air temperature are 10 °C or more, an increase in their frequency has been observed over the past 40 years in the Steppe zone, especially in Odesa and Mykolaiv regions and the eastern Forest-Steppe region in Kharkiv and Luhansk regions (**Fig. 4**). The increase in their frequency is most significant in March and remarkable for the entire territory of Ukraine, and most of all for the Steppe and eastern Forest-Steppe zones. In April, there is a significant decrease in the frequency of such phenomena, especially in the right-bank Polissia and the western Forest-Steppe. In the eastern Forest-Steppe, there is a tendency to their higher frequency. May is characterized by insignificant changes in the frequency of cold snaps of this intensity (Fig. 4).

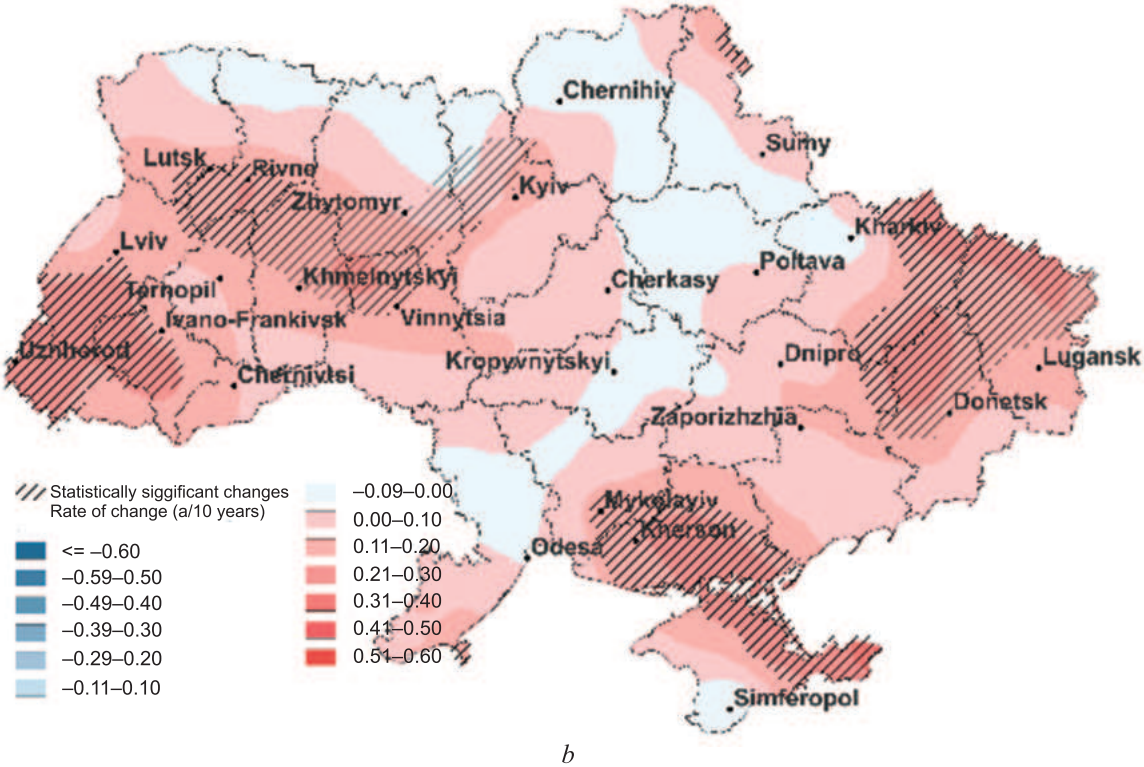
The analysis of the probable changes in the frequency of sharp changes in air temperature by the end of the century under different scenarios of greenhouse gas emissions and land use showed that both sudden warmings and sharp cold snaps will probably be less frequent in Ukraine in the short and long-term compared to 1991–2010. By the end of the twenty-first century, these trends toward a decrease in the frequency of such phenomena will intensify and be most pronounced in the northern, Polissia, and eastern regions of the coun-

severe cold snaps, spring



a

severe cold snaps, March



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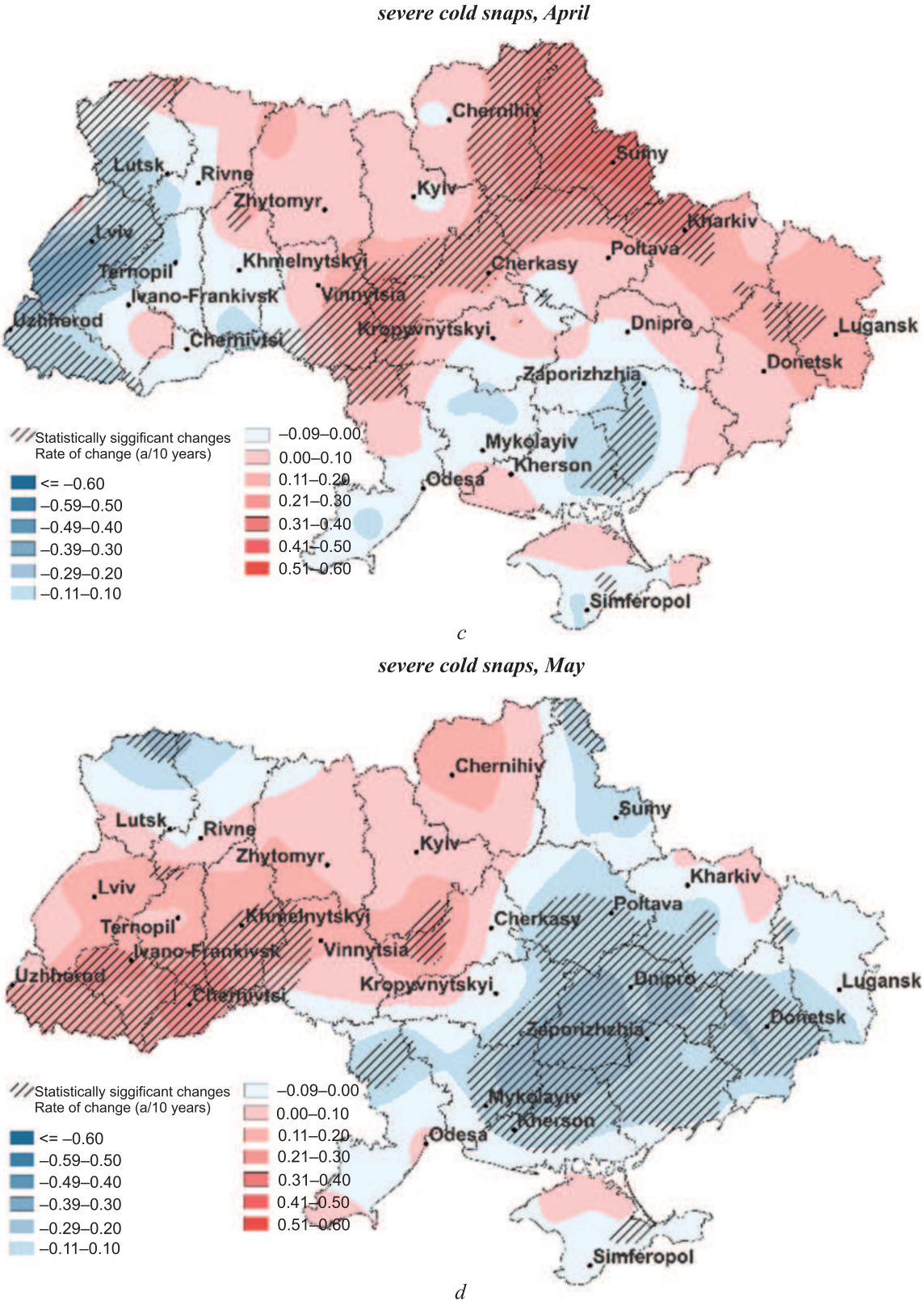
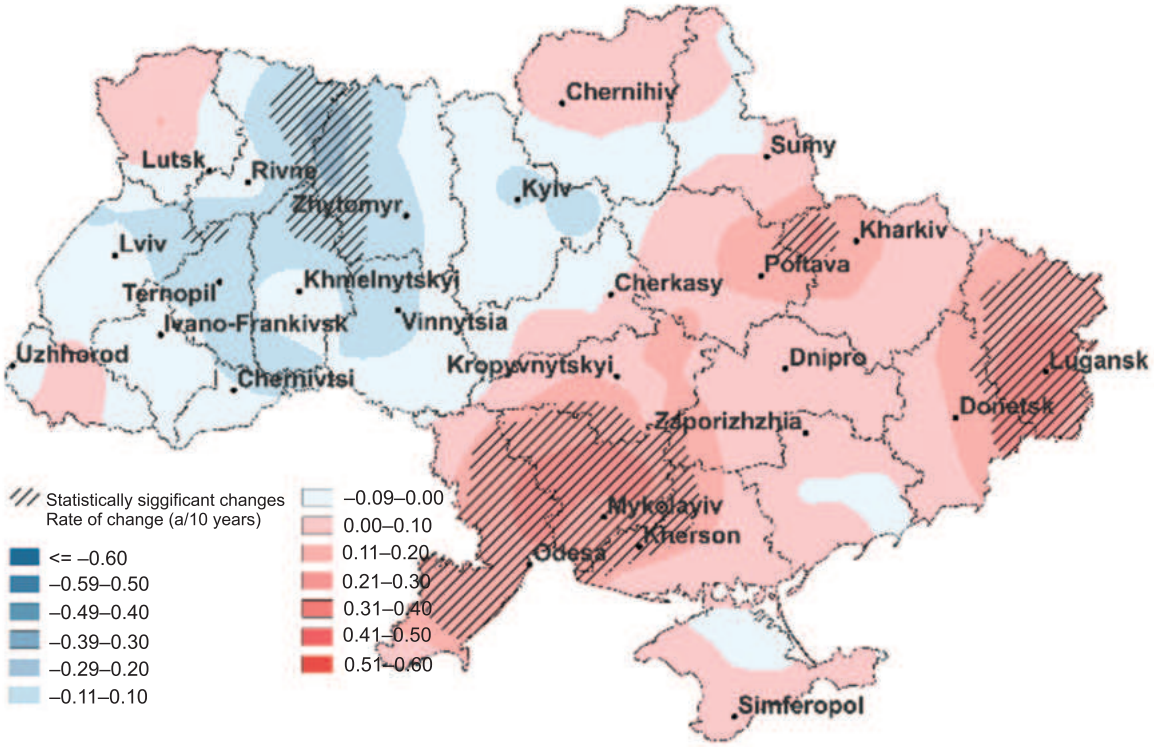


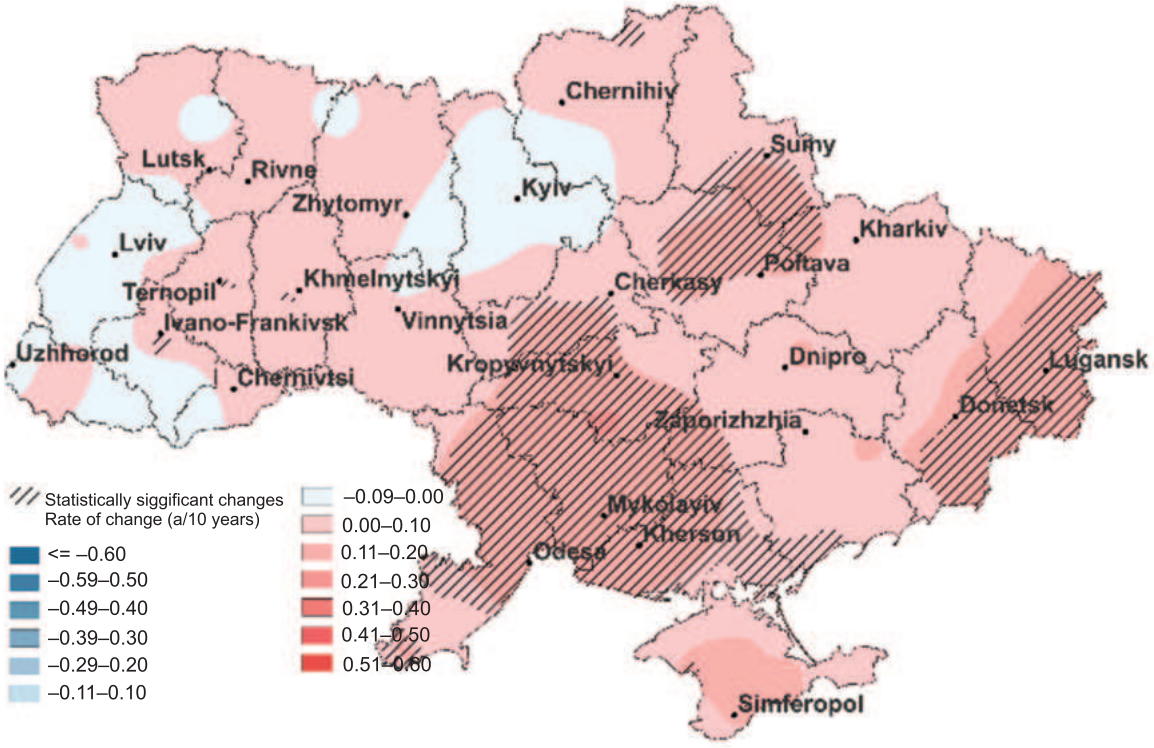
Fig. 2. The velocity of the change in the number of cases of severe sharp cold snaps in spring and their significance 1981–2020

very severe cold snaps, spring



a

very severe cold snaps, Match



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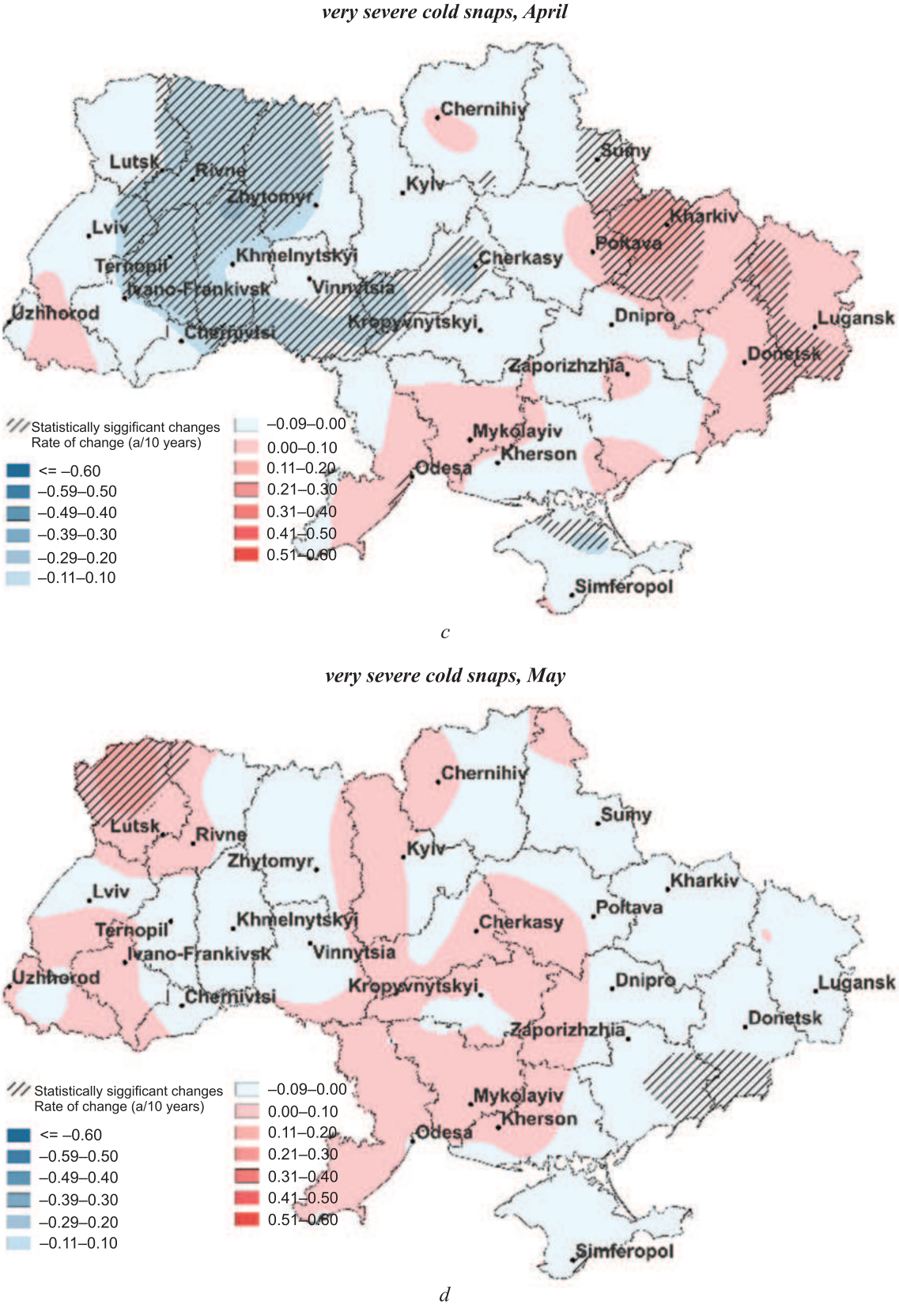
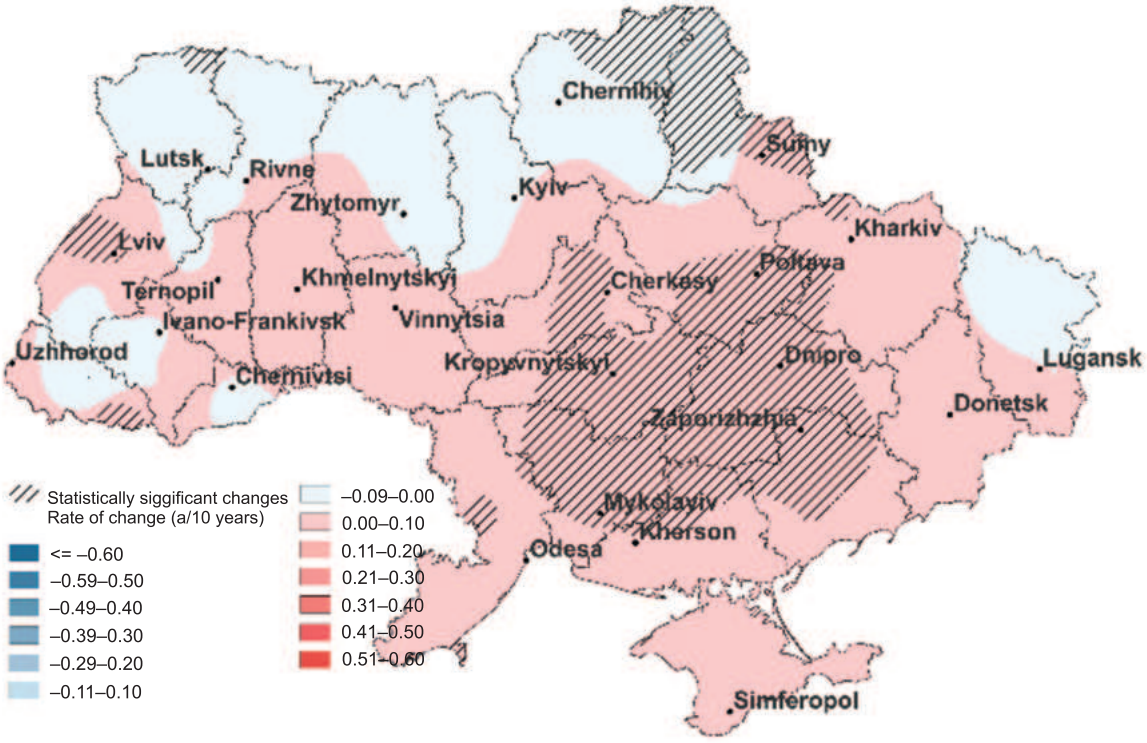


Fig. 3. The velocity of the change in the number of cases of very severe sharp cold snaps in spring and their significance 1981–2020

extremely cold snaps, spring



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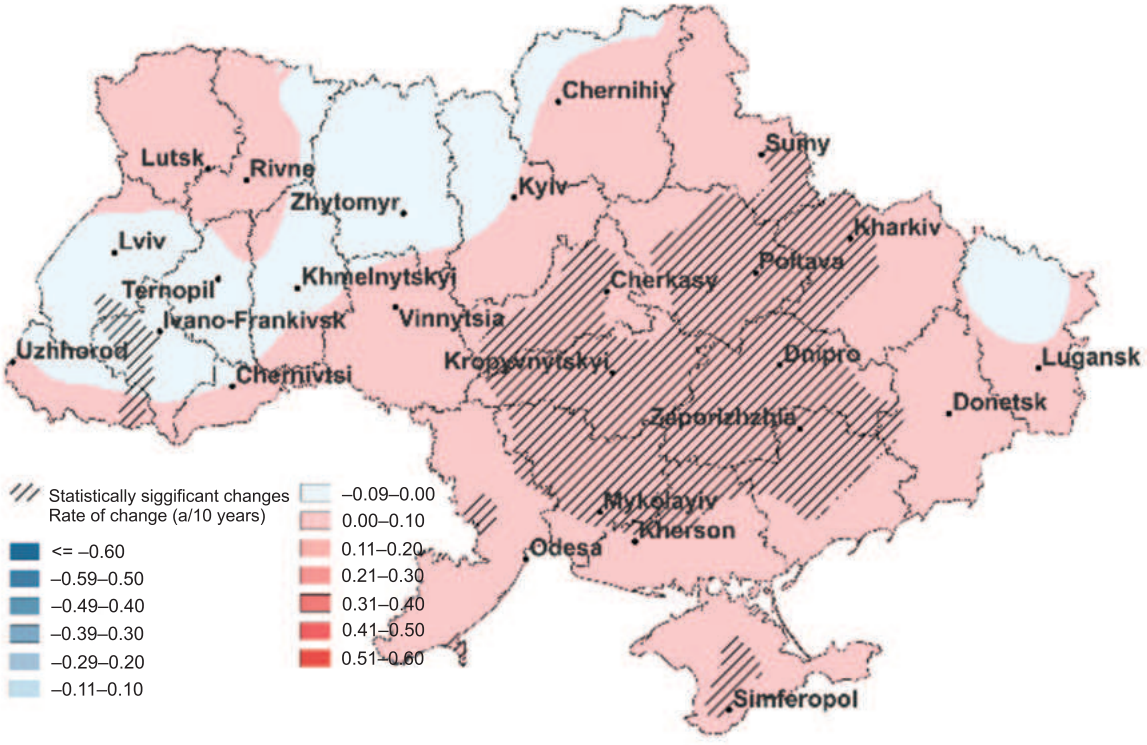
extremely cold snaps, March



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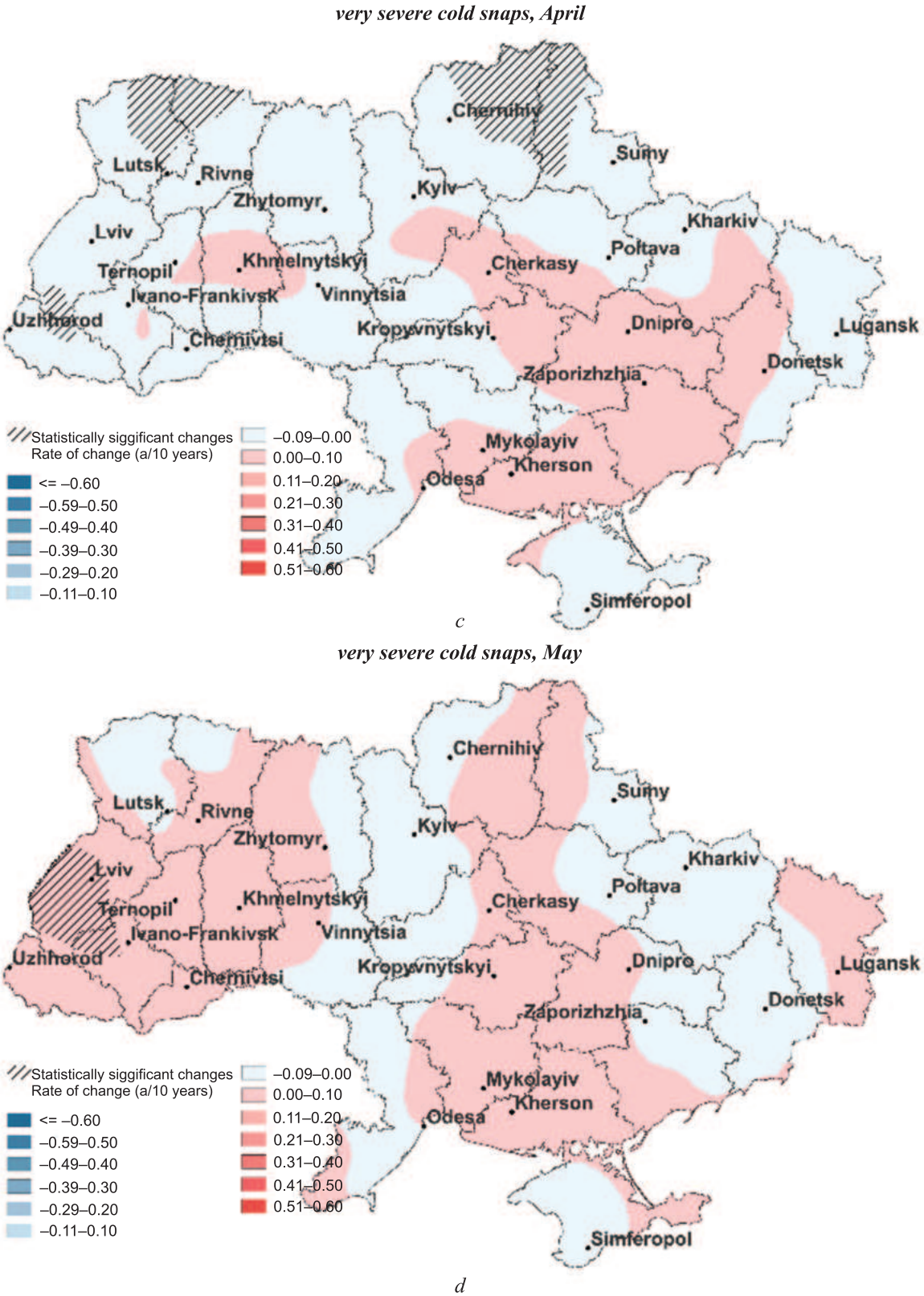

Fig. 4. The velocity of the change in the number of cases of extremely sharp cold snaps in spring and their significance 1981–2020

try. Such trends are typical for RCP4.5 scenario and especially for RCP8.5 scenario, under which this decrease is expected to be more significant. It has been established that the greatest changes will probably be observed in winter, especially in the northern, north-eastern, and eastern regions of the country, where the frequency of sharp temperature changes will decrease by the end of the century. In summer, sharp temperature changes, especially sharp warmings, will probably increase, especially in the southern and south-eastern regions under RCP8.5 scenario.

It was established that in spring, under RCP4.5 scenario, the frequency of sharp cold intrusions will decrease throughout the country in the twenty-first century (**Table 2**). These changes will be enhanced with the increase in the phenomenon intensity. Such tendencies are notable for severe and very severe cold snaps. It should be noted that the

Table 2. The projection of the change in the number of spring days (%) with a sharp drop in the average daily air temperature in 2021–2040, 2041–2060, 2081–2100 compared to 1991–2010 under RCP4.5 scenario

Region	Severe cold snaps 4–6 °C in 24 h			Very severe cold snaps 6–10 °C in 24 h			Extremely cold snaps over 10 °C in 24 h		
	2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Polissia									
Volyn	–12.1	–18.3	–15.5	–16.6	–24.1	–15.4	–37.6	79.5	44.3
Zhytomyr	–11.9	–14.9	–14.7	–13.2	–22.4	–22.7	–12.0	5.9	45.3
Rivne	–10.2	–17.5	–17.0	–16.6	–27.2	–16.8	3.6	118.6	134.1
Chernihiv	–10.6	–14.7	–21.3	–23.8	–32.2	–30.3	–37.8	–25.3	–40.4
Western Forest–Steppe									
Ivano–Frankivsk	–10.3	–15.4	–14.0	–5.2	–12.7	–1.2	–29.8	–49.6	1.5
Lviv	–9.0	–13.9	–14.9	–7.4	–19.2	–0.3	–25.3	18.5	22.4
Ternopil	–8.3	–17.3	–14.2	–5.6	–17.4	–6.4	–10.2	–3.3	18.8
Chernivtsi	–7.3	–12.9	–10.2	–5.4	–13.9	–7.7	–28.3	–14.3	1.8
Central Forest–Steppe									
Vinnytsia	–3.1	–12.8	–11.1	–20.3	–20.9	–26.3	–19.7	–10.4	7.5
Kyiv	–9.8	–13.4	–18.1	–19.2	–25.1	–26.0	19.3	23.2	33.8
Khmelnytsky	–7.8	–14.3	–15.0	–7.0	–19.5	–10.0	–14.7	13.3	11.5
Cherkasy	–6.7	–13.0	–15.9	–25.8	–25.8	–31.8	13.3	24.0	–41.3
Eastern Forest–Steppe									
Poltava	–6.3	–8.2	–14.5	–23.8	–27.3	–34.8	–20.9	–36.1	–43.2
Sumy	–8.4	–12.9	–17.3	–27.7	–34.0	–36.7	–40.7	–42.9	–38.4
Kharkiv	–4.2	–10.8	–14.7	–26.7	–27.5	–30.5	–42.2	–55.2	–53.2
Northern Steppe									
Luhansk	–7.2	–11.6	–18.9	–22.5	–31.0	–32.5	–47.0	–45.5	–63.2
Dnipropetrovsk	–1.0	–5.5	–9.1	–23.2	–22.7	–23.5	–37.1	–45.5	–68.5
Donetsk	–5.6	–11.6	–14.8	–15.8	–20.8	–22.8	–28.2	–31.8	–69.1
Kirovohrad	1.0	–5.7	–8.9	–30.0	–29.5	–35.4	–18.3	–36.9	–63.9
Southern Steppe									
Zaporizhzhia	–5.3	–11.9	–9.6	–11.1	–13.8	–23.5	–13.6	–38.1	–77.2
Mykolayiv	1.7	–6.0	–7.7	–30.6	–27.6	–34.0	5.8	–46.8	–75.4
Odesa	–1.6	–8.0	–9.9	–25.2	–22.9	–24.4	–43.3	–50.5	–64.0
Kherson	–2.5	–12.0	–9.9	–20.9	–17.9	–27.0	–17.9	–58.9	–96.3

highest changes in the cold snaps are probable in Polissia (14.7–18.3 % in the middle of the century, and 14.7–21.3 % at the end of the century), but they will decrease further south, reaching 6–12 % in the southern Steppe. As for very severe cold snaps, the greatest changes are remarkable for the eastern Forest-Steppe, where they will vary within 27–34 % in the middle of the century, and, at the end of the century, will amount to 30–35 % compared to the current climate period. The volume of extreme cold snaps will also decrease considerably in the Steppe zone and the eastern Forest-Steppe (down to 70 % and more at the end of the century), but in Polissia, in the western and central Forest-Steppe, their volume will increase at the end of the century compared to its beginning (1991–2020). The greatest changes are probable in Polissia, in particular, in Rivne region, which may encounter almost 1.3 times more extremely cold snaps (Table 2). These changes may be extremely dangerous for agriculture, since under

Table 3. The projection of the change in the number of spring days (%) with a sharp drop in the average daily air temperature in 2021–2040, 2041–2060, 2081–2100 compared to 1991–2010 under RCP8.5 scenario

Region	Severe cold snaps 4–6 °C in 24 h			Very severe cold snaps 6–10 °C in 24 h			Extremely cold snaps over 10 °C in 24 h		
	2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100	2021–2040	2041–2060	2081–2100
Polissia									
Volyn	–11.6	–8.0	–7.3	–14.0	–7.7	17.2	14.6	87.2	154.3
Zhytomyr	–7.9	–2.4	–1.8	–17.8	–15.1	–0.7	–64.4	22.0	26.9
Rivne	–10.0	–3.9	–5.1	–16.2	–11.8	10.3	–16.9	12.3	172.4
Chernihiv	–10.9	–13.5	–9.3	–27.5	–19.0	–22.9	–13.0	–9.9	–37.7
Western Forest–Steppe									
Ivano–Frankivsk	–9.4	–3.5	0.4	–19.6	–2.3	35.1	2.4	–7.0	104.3
Lviv	–10.4	–4.8	–0.3	–17.3	2.0	25.9	–48.4	–22.6	9.6
Ternopil	–11.2	–7.1	1.4	–20.1	–3.0	25.8	–8.4	27.2	57.4
Chernivtsi	–8.1	–1.8	3.1	–18.3	–4.4	30.3	23.9	44.4	174.1
Central Forest–Steppe									
Vinnytsia	–5.1	–1.0	4.7	–16.5	–9.9	7.9	–50.0	25.7	29.2
Kyiv	–6.6	–6.9	–3.6	–22.9	–15.8	–8.4	–57.8	–16.6	–60.3
Khmelnytsky	–9.1	–1.6	2.9	–16.3	–6.7	16.1	–15.5	45.2	100.0
Cherkasy	–6.0	–3.5	–0.8	–24.2	–18.7	–8.9	–43.2	–32.3	15.8
Eastern Forest–Steppe									
Poltava	–7.5	–5.8	–6.4	–32.7	–24.6	–18.3	–31.5	–32.7	–4.1
Sumy	–11.1	–11.0	–10.8	–33.9	–27.2	–27.4	–20.4	–23.7	–30.9
Kharkiv	–13.1	–7.9	–12.1	–32.2	–20.0	–25.0	–52.3	–72.2	–40.5
Northern Steppe									
Luhansk	–12.7	–8.8	–8.6	–26.4	–14.9	–30.4	–76.4	–78.4	–53.6
Dnipropetrovsk	–7.9	–1.8	–1.1	–29.7	–18.1	–14.8	–67.0	–67.6	–44.9
Donetsk	–15.4	–11.2	–10.4	–25.5	–14.8	–22.5	–63.7	–58.8	–54.4
Kirovohrad	–3.1	0.7	5.7	–29.5	–17.0	–12.8	–54.6	–65.1	–24.1
Southern Steppe									
Zaporizhzhia	–13	–8.9	–8.1	–23.5	–16.0	–11.8	–86.0	–74.6	–24.7
Mykolayiv	–5.3	1.0	4.9	–29.2	–18.2	–10.1	–73.9	–111.2	–41.2
Odesa	–5.5	0.3	7.1	–27.9	–12.6	3.8	–61.2	–81.8	–21.8
Kherson	–10.4	–5.2	–0.7	–25.4	–17.6	–11.5	–84.9	–129.9	–36.4

such a cold intrusion, the minimal air temperature may drop below 0 °C, and the occurring light frosts may damage the crops considerably.

Under RCP8.5 scenario, in spring, the number of cases with severe and very severe cold snaps per season will decrease in the entire territory of Ukraine both in short-, mid-, and long-term perspective. The change in their frequency will be enhanced by the increase in the phenomenon intensity by the end of the century (**Table 3**). For instance, in 2021–2040, in Polissia, the number of this phenomenon occurrences is expected to decrease by 7.9–27.5 %, in 2041–2060 – by 8.0–19.0 % as compared to 1991–2020. The changes in the frequency of extreme cold snaps will be more significant and fluctuate in 2021–2040 from -64.4 % in Zhytomyr region to +14.6 % in Volyn. In the middle of the century, there will probably be a considerable increase in the frequency of such dangerous phenomena from 12.3 % to 87.2 % almost in the entire territory of Polissia, except Chernihiv region. By the end of the century, there may be almost 1.5 times more extremely cold snaps in the region compared to the current climate period, except for Chernihiv Polissia, though the air temperature will increase considerably. These changes are especially dangerous, since, due to the changes in the temperature mode and moisturization mode, favorable conditions were formed in Polissia for the cultivation of oil crops and cereals, the so-called oil-grain belt (Tarariko et al, 2024). These plants are highly vulnerable to such drops in air temperature, especially at the beginning of their development, which may cause a considerable yield loss.

The same tendencies were noted for the western and central Forest-Steppe (Table 3). However, in the Steppe and eastern Forest-Steppe, the number of sharp cold snaps will decrease by the end of the century. These changes will be enhanced with the increase in the phenomenon intensity (Table 3).

DISCUSSION

Agricultural production is one of the economy branches, most vulnerable to climate change. Changes in environmental factors, including air temperature, precipitation, and wind speed, affect crop growth cycles, the frequency of extreme weather phenomena, and the emergence of pests and diseases, which ultimately affects crop yields and quality (Lesk, 2016; Devi et al, 2023, Miedema, 1982; Polevoy et al, 2004; Polevoy, 2013).

Cold spring weather has a negative impact on crops, especially those that were sown earlier than usual in the hope of an early harvest. Low temperatures slow down germination, emergence, and vegetative growth, and can lead to freezing of plants, seedling death, or significant damage.

In case of negative air temperatures, the water in plant cells begins to freeze, which can lead to cell damage due to the formation of ice, which destroys their membranes and kills the plants (Miedema, 2008). Cereals are the most vulnerable to sharp cold snaps, especially corn, which is sensitive to frost at all stages of its growth cycle (Barlow et al, 2015; Grotjahn, 2021; Elmore, 1995).

Vegetables, especially heat-loving ones, such as peppers, eggplants, and tomatoes, are also sensitive to frost. Frosts can damage not only the crops but also the seeds in the fruit, which can lead to reduced germination and problems with future crops (Bozhko, 2013). For example, tomato or pepper seeds may become unusable for future harvests after an autumn frost. If the temperature drops to critical levels, it can slow down the growth of crops or even lead to their death. Plants that have already begun to blossom may lose their ability to fertilize, which reduces yields. For such crops as wheat, corn, and soybeans, this can have catastrophic consequences (Brown & Blackburn, 1987). On the other hand, for fruit trees such as apples, pears, apricots, cherries, and other trees, a sharp cold snap can damage flowers or primordia, significantly reducing future yields. Even short-term spring frosts can have a decisive negative impact on certain fruit trees (Bozhko, 2013; Brown & Blackburn, 1987). In addition, cold weather may have a significant negative impact on different stages of plant growth, causing substantial losses with different economic consequences. Premature blossoming, fruiting, and fruit loss are very difficult to assess and quantify in terms of yield loss, depending on the growth stage.

Very severe and extreme drops in air temperature in the spring also cause damage to agricultural infrastructure. They may damage irrigation systems by freezing water in the pipes, making it difficult to provide plants with the necessary moisture after the frost (Perry, 1994; Brown & Blackburn, 1987). Severe cold snaps may damage the structure of greenhouses, especially if they have not been properly prepared for the cold.

Extreme temperatures may also affect plant phenology, including shifting planting and harvesting dates.

Farmers may be forced to change their usual sowing or harvesting dates to avoid the risk of frost damage, which requires additional effort and planning (Bozhko, 2013).

Several mechanisms influence the cold advection and decrease in air temperature in Europe and Ukraine: blocking processes, changes in the position of the jet stream, stratospheric warming and weakening of the polar vortex, the negative phase of the North Atlantic Oscillation, etc. (Martazinova & Ostapchuk, 2004; Bartholy & Pongrácz, 2006; Shabbar et al, 2001; Luo et al, 2014; Yiou et al, 2004, Balabukh et al, 2016). These factors act both individually and in combination, causing cold snaps of varying intensity and duration.

CONCLUSIONS

Severe cold snaps may have serious consequences for agriculture, reducing the quantity and quality of crop yields, damaging plants and infrastructure. Frosts in spring and autumn are particularly important, as they can lead to premature termination of the growing season, damage to primordia and fruits, and disruption of normal plant development.

It has been established that over the past 40 years, there has been a tendency in Ukraine to the increase in the frequency of sharp cold snaps of varying intensity in spring despite the increase in surface air temperature during this period. The greatest changes are remarkable for March. This poses threats to agricultural production, as due to rising air temperatures and shorter cold periods, the timing of sowing spring crops is shifted to earlier dates and often begins in the Steppe zone in March.

The analysis of the probable change in the frequency of sharp cold snaps in spring by the end of the 21st century showed that the number of severe and very severe cold snaps will probably decrease by the end of the century, but the number of extremely cold snaps will increase, especially in Polissia, the western and central Forest-Steppe.

To combat these negative effects, it is important to develop adaptation methods, such as the use of resistant plant varieties, covers for crops, or the introduction of new technologies to reduce the impact of frosts.

Further research is needed to assess the impact of sharp inter-day changes in air temperature and its variability on crop yields. A more detailed consideration of their spatial and temporal variability when developing recommendations for adapting agricultural practices under climate change will help reduce crop shortfalls caused by changes in agroclimatic conditions. The synoptic conditions, causing the formation of sharp temperature changes of varying intensity, also need to be studied. The identification of such processes will promote the development of methods for early warning about these dangerous weather phenomena.

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Зміна повторюваності різких похолодань у весняний період впродовж XXI століття в Україні та їхній вплив на сільськогосподарське виробництво

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Мета. Виявлення тенденцій зміни повторюваності різких міждобових знижень середньої за добу температури повітря різної інтенсивності весною в агрокліматичних зонах України та їхньої ймовірної зміни до кінця XXI століття для кліматичних сценаріїв репрезентативних траєкторій концентрацій викидів парникових газів РТК4.5 і РТК8.5. **Методи.** Для вирішення поставлених завдань застосовували як загальнонаукові, так і спеціалізовані методи досліджень: аналітико-синтетичний –

для аналізу сучасного стану досліджень, статистичний – для оцінки інтенсивності та значущості зміни повторюваності різких міждобових знижень температури повітря різної інтенсивності, порівняльний аналіз – для виявлення їхніх особливостей в агрокліматичних зонах України, кліматичні – для характеристики екстремальних умов температурного режиму, моделювання – для оцінки їхньої зміни у коротко-, в середньо- та довгостроковій перспективах за реалізації сценаріїв РТК4.5 і РТК8.5. **Результати.** Розглянуто сучасний стан зміни показників екстремальності температурних умов весною, зокрема різких міждобових змін температури повітря різної інтенсивності (сильні, дуже сильні, надзвичайні по-холодання) в агрокліматичних зонах України. Різкі похолодання весною погіршують сільськогосподарське виробництво, оскільки зниження температури на 4–10 °С і більше під час вегетації часто призводить до заморозків, що можуть викликати часткову або повну загибель рослин. Встановлено особливості їхньої повторюваності та інтенсивності у 1981–2020 рр. Виявлено, що весною сильні різкі похолодання 4–6 °С в Україні бувають 2–4 рази за сезон, найчастіше (3–4 рази) – у Лісостепу західному, східному та на Поліссі. Дуже сильні похолодання 6–10 °С спостерігаються у 2–3 рази рідше – від 6–8 випадків за 10 років у Степу південному до 13–16 випадків на Поліссі, у Лісостепу західному і східному. Надзвичайні похолодання 10 °С і більше весною в Україні бувають рідко – від 2–3 до 8–9 випадків за сто років. На території України можна виділити лише декілька областей, де явище такої інтенсивності весною буває найчастіше: Івано-Франківська, Чернівецька, Житомирська та Одеська області. У цих регіонах весною міждобові зміни температури повітря на 10 °С і більше бувають 7–9 разів за 100 років, у той час як у Херсонській та Запорізькій областях вони спостерігаються 2 рази за 100 років. Така неоднорідність просторового розподілу надзвичайних похолодань зумовлена різними чинниками, що їх зумовлюють. Встановлено тенденції зміни повторюваності різких похолодань в Україні та визначено швидкість, напрям, значущість і достовірність їхньої зміни впродовж досліджуваного періоду. Уточнено регіони де відбуваються найбільш значущі зміни повторюваності цих явищ. Незважаючи на суттєве підвищення температури повітря протягом весняного сезону, особливо у березні, повторюваність сильних різких похолодань впродовж 1981–2020 років у Лісостепу центральному, західному, східному та на Чернігівському і Новгород-Сіверському Поліссі зростає, а в північному Степу зменшується впродовж усього сезону, за винятком березня. На відміну від сильних похолодань, повторюваність дуже сильних та надзвичайних різких знижень температури найбільше зростає в степовій зоні та Лісостепу східному, особливо у березні. Значна мінливість температури повітря у березні, при загальній тенденції до її підвищення, свідчить про суттєву зміну атмосферної циркуляції у цей період, зокрема, посилення меридіанальності атмосферних процесів. Надано дані щодо ймовірної зміни повторюваності різких похолодань у 2021–2040, 2041–2060, 2081–2100 рр. відносно сучасного кліматичного періоду (1991–2010рр.) для сценаріїв РТК4.5 та РТК8.5. Встановлено що впродовж XXI століття на значній території України повторюваність різких похолодань, ймовірно, зменшуватиметься, особливо за реалізації сценарію РТК8.5. Ці зміни посилюватимуться із зростанням інтенсивності явища. Такі тенденції характерні для сильних і дуже сильних різких похолодань. Найбільші зміни повторюваності сильних похолодань за сценарію РТК4.5 ймовірні на Поліссі (14,7–18,3 % в середині століття і 14,7–21,3 % в кінці століття відносно 1991–2020 рр.) і зменшуватимуться у південному напрямку, досягаючи 6–12 % у Степу південному. Кількість надзвичайних похолодань також суттєво зменшуватиметься у степовій зоні і Лісостепу східному (до 70 % і більше у кінці століття), проте на Поліссі, у Лісостепу західному та центральному їхня кількість у кінці століття ймовірно зросте, порівняно з його початком (1991–2020 рр.). Найбільші зміни ймовірні на Поліссі, зокрема у Рівненській області, де надзвичайних похолодань може стати майже у 1,3 разів більше. Весною за реалізації сценарію РТК8.5 повторюваність сильних та дуже сильних похолодань зменшуватиметься на всій території країни як у коротко- так і середньостроковій перспективі, навіть на Поліссі (від 8 до –28 % у 2021–2040 до, 8–19 % у 2041–2060 рр.). До кінця століття сильних похолодань може бути менше у всьому регіоні на 1,8–9,3 %. Повторюваність дуже сильних різких знижень температури повітря може зменшитись майже на 23 % на Чернігівщині. На решті території їхня повторюваність суттєво не зміниться, а на Рівненщині та Волині може збільшитись на 10,3–17,2 %. Надзвичайних похолодань до кінця століття на Поліссі може бути майже у 1,5 рази більше, ніж у 1991–2020 рр., за винятком Чернігівської області, де їхня повторюваність продовжить зменшуватиметься до 37,7 %. Такі зміни можуть бути вкрай небезпечними для сільського господарства, оскільки мінімальна температура повітря при такому вторгненні холоду може опускатись нижче 0 °С і заморозки, що виникатимуть, можуть завдати значних збитків сільськогосподарським культурам, особливо якщо температура повітря до кінця століття в цьому регіоні суттєво підвищиться, а вегетаційний період починатиметься раніше. **Висновки.** Встановлено, що, незважаючи на значне підвищення температури повітря в Україні, Європі та арктичних широтах, більш ранній початок теплого періоду і періоду вегетації, кількість днів із сильними, дуже

сильними та надзвичайними похолоданнями весною зростає майже на всій території України. Найбільш вразливими є північно-східні і східні регіони країни, де відмічається найбільший ріст температури повітря і найбільша повторюваність різких похолодань. Різких похолодань весною, у коротко- та довгостроковій перспективах в Україні, ймовірно, буде менше порівняно з сучасним кліматичним періодом, але повторюваність надзвичайних похолодань (понад 10 °С за добу) до кінця століття зростатиме, особливо на Поліссі, у західному та центральному Лісостепу. Такі зміни можуть призвести до передчасного припинення вегетаційного періоду, пошкодження зав'язей і плодів, порушення нормального розвитку рослин та суттєво вплинути на врожайність сільськогосподарських культур.

Ключові слова: зміна клімату, екстремальна температура повітря, похолодання, заморозки, проєкції зміни клімату, сценарії репрезентативних траєкторій концентрацій РТК4.5 та РТК8.5.

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