

DYNAMICS OF FREQUENCY AND INTENSITY OF COLD WAVES IN UKRAINE UNDER GLOBAL WARMING

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Aim. Detection of spatial and temporal specificities of the frequency, duration, intensity, and magnitude of cold waves in Ukraine and determination of tendencies in their changes in 1981–2020. **Methods.** The study used modern climatological and statistical tools, including the methods of objective identification of extreme events based on daily percentiles of minimum air temperature, probability distribution analysis, and regression approaches to assess the dynamics of changes in indicators. The climate and geographical analysis of seasonal variability of indicators allowed for the detection of their spatial and temporal characteristics in different agroclimatic zones of Ukraine. **Results.** For the first time, a systematic analysis of cold waves in 1981–2020 was conducted for the entire territory of Ukraine using a unified methodology based on the threshold values of the 32nd, 5th, and 0.3rd percentiles of daily minimum air temperatures at 187 meteorological stations. Based on these indicators, a classification of cold waves of varying intensity was proposed: strong (32nd–5th percentile), very strong (5th–0.3rd percentile), and extreme (below 0.3rd percentile). It has been established that an average of 16–17 cold waves are observed in Ukraine each year, 84% of which are strong, 14% are very strong, and about 1% are extreme. A set of spatial and temporal patterns of frequency, duration, intensity, and magnitude of cold waves has been determined for all agroclimatic zones, which allows for a highly detailed characterisation of climatic risks. It has been established that the most intense and powerful cold waves are characteristic of the eastern regions (especially Luhansk, Sumy, and Kharkiv), where the minimum temperature during very strong cold waves in the winter season can drop to –20°C and below, and the magnitude of such waves can reach maximum values. The least frequency and poorly manifested cold waves are observed in western regions, in particular in the Chernivtsi region. Winter cold spells are the most intense and last the longest, while spring cold waves pose the greatest risks to agriculture. Statistically significant trends have been identified in the decrease in the frequency and intensity of cold waves in Ukraine, which correlate with current manifestations of global warming in the mid-latitude of the Northern Hemisphere. A significant weakening of cold waves in Ukraine has been observed over the last four decades. A statistically significant decrease in the recurrence of both short-term (2–5 days) and long-term (≥6 days) cold waves has been recorded throughout the country. At the same time, the decrease in long-term cold spells is more intense and more uniform in space, indicating a weakening of persistent advective intrusions of cold air. Regional anomalies in the change in cold wave characteristics have been identified, in particular, an increase in short-term spring cold spells in the Eastern Forest-Steppe, Steppe zone, and some areas of Polissia and Prykarpattia. This is a new key finding that contradicts the general trend towards weaker cold waves. It has been shown that extreme cold waves have different dynamics than strong and very strong ones — their frequency does not change significantly, and their spatial distribution is clearly associated with

local and regional circulation features. **Conclusions.** Cold waves remain a frequent phenomenon in Ukraine, despite the general warming of the climate. In 1981–2020, Ukraine experienced a statistically significant decrease in the frequency of cold waves, especially in summer and winter, which is consistent with trends in the mid-latitude of the Northern Hemisphere. The number of long-term and short-term cold spells is decreasing, with the frequency of prolonged (≥ 6 days) cold waves decreasing most rapidly, indicating a weakening of persistent Arctic air intrusions. The intensity and magnitude of cold waves tend to decrease, most noticeably in spring and autumn. Winter and summer changes are regionally heterogeneous, with local areas of intensified cold spells in eastern Ukraine. The greatest risks remain during the transitional seasons, especially in spring, when there is an increase in the recurrence of short-term but sharp cold spells in a number of regions (Eastern Forest-Steppe, Northern and Southern Steppe). This poses a threat to the early stages of crop development. Extreme cold waves in Ukraine are rare and do not change significantly in their frequency, but remain the most dangerous ones in terms of consequences. The most vulnerable regions are Polissia, Forest-Steppe, and the eastern regions. The identified spatial and temporal trends indicate a milder climate regime during the cold season, but high variability and local risks of extreme cold spells remain.

Keywords: climate change, extreme air temperature, cold wave, cold spell, light frosts, climate change projections, scenarios of representative concentration pathways RCP4.5 and RCP8.5.

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Contrary to numerous studies on heat waves and their impact on agriculture, energy sector, morbidity, and mortality of the population, cold waves remain less investigated (Carmona et al., 2015; Montero et al., 2010; Díaz et al., 2005; Donaldson et al., 2001; The Eurowinter Group, 1997). Despite relatively less attention from researchers, their impact is no less destructive than the consequences of long heat periods (Linares et al., 2015; Kysely et al., 2009; WMO, 2022; Devot et al., 2023; Lamichhane, 2021). Under an unprecedented rate of global warming, when average temperatures on the planet increase faster than ever before, cold waves and sharp cold spells remain one of the least studied, but extremely relevant climatic risks, especially for the agrarian sector (Zampieri et al., 2017; Parry et al., 2013; Cohen et al., 2021; Veron et al., 2015; Polevoy et al., 2021; Balabukh, 2017; Balabukh et al., 2024).

In conditions of global climate change and the increase in geopolitical instability, it is especially relevant to study the vulnerability of economic sectors — agriculture, energy sector, transportation, and health care — to extreme weather phenomena, including cold waves. These events may result in a considerable decrease in the yield, decline in energy safety, weaker critical infrastructure, and impact on health, work capacity, and well-being of the population (Quesada et al., 2023; Balabukh et al., 2024). The studies in Great Britain, Australia, and the Netherlands demonstrate that mortality due to the impact of low temperatures exceeds mortality due to heat several times (Vardoulakis et al., 2014; Huynen et al.,

2001). According to global estimates, the negative effect of cold waves may exceed that of high temperatures 20 times, while in Spain, this index is five times higher (Gasparrini et al., 2015).

In February 2021, a considerable part of North America suffered from Winter Storm Uri — a cold wave that lasted over a week and spread as far as Guatemala. It caused large-scale disruption of gas production, electricity generation, water supplies, transportation, and agriculture in the USA. Blackouts covered 25 states, over 4 million households, and over 150 million people, which resulted in over one hundred deaths (Ali Nejat et al., 2022; Glazer et al., 2021). Texas suffered the highest losses: damage to destroyed fields, death of cattle, and losses in agricultural production were estimated at at least USD 600 million (Veetil et al., 2022).

In recent decades, climate change has had an ever more considerable impact on the yield of crops and food safety. Optimal temperature conditions during the growth period ensure stable development and maximal performance of crops, whereas extreme phenomena — first and foremost, cold waves and sharp cold spells — lead to a decrease in the yield, damaged fields, and even death of plants (Balabukh, 2017; Balabukh et al., 2024). Both the agrarian economy and natural ecosystems become vulnerable, because different species of plants and animals have different tolerances of cold.

The number of heat waves increases, and that of cold waves decreases, but the intensity of the latter remains rather stable in considerable territories of

Europe, the USA, and North-Eastern Asia (Varfi et al., 2016; Barnett et al., 2012). It demonstrates a complicated interaction between climatic processes, when even against the background of sharp warming in the Arctic, there is a risk of short-term but sharp cold spells, which may result in considerable economic and social consequences.

Cold spells during the growth period are one of the most dangerous climatic stresses for agrarian production: they limit the growth and development of crops, decrease the yield and quality of the products, and sometimes cause a complete loss of the yield (Hatfield et al., 2011; Jendritzky, 1999; Wei, 2024). Cold waves cause the highest losses to the agrarian sector if they coincide with critical phases of crop development. Risks to farms increase during crop germination and flowering, when cold waves can weaken crops and increase their vulnerability to diseases and pests. Low temperatures approaching the biological minimum are particularly dangerous: they slow down the synthesis of organic matter, and under these conditions, very little of it is produced. Only under optimal temperature regimes is the largest reserve of organic matter formed. Spring frosts are particularly dangerous, as they limit the growth and development of crops in the early stages, which can lead to a significant reduction in food production both in Ukraine and worldwide.

Not only are plants vulnerable, but also agricultural infrastructure and the economies of local communities and states. The scale of losses depends on the intensity and duration of the cold spell (Veettil et al., 2022). The example of France is a vivid illustration: in early April 2021, frosts resulted in a decrease in the yield of peaches and nectarines by 42%, apricots — by 43%, while wine-growers lost 30–40% of their yield, and sometimes — up to 100%. The losses of the agrarian sector reached more than USD 4.6 billion (WMO, 2022; Devot et al., 2023; Lamichhane, 2021). The country had to allocate about EUR 1 billion to compensate for the agrarian losses (Vagues de gel d'avril 2021. L'État aux côtés des agriculteurs, 2021).

Thus, the impact of cold waves extends far beyond the agricultural sector. They pose threats to livestock farming, energy infrastructure, logistics systems, and the economic stability of countries. The scale of the consequences depends on the intensity and duration of the cold spells, the phase of crop development, and the level of adaptation readiness of farms, which

makes the problem extremely relevant in the context of global climate change.

According to estimates by the Intergovernmental Panel on Climate Change (IPCC, 2021), by the end of the 21st century, a further increase in the average annual global air temperature and an increase in the frequency and duration of heat waves are expected, but the probability of extreme cold waves will remain. This means that temperature extremes will intensify, posing serious challenges for the economy and society. In such conditions, it is extremely important to develop region-specific adaptation strategies based on detailed information about regional characteristics of extreme phenomena, their spatial and temporal dynamics, projected changes, and the development of effective early warning systems. This highlights the need for a detailed analysis of the spatial and temporal characteristics of cold waves and their consequences in the context of climate change.

The aim of this study is to identify the spatial and temporal characteristics of the frequency, duration, intensity, and magnitude of cold waves in Ukraine and the trends in their change in 1981–2020.

MATERIALS AND METHODS OF THE STUDIES

A comprehensive approach combining statistical, climatological, and classification analysis was used to assess the frequency, intensity, and dynamics of cold waves. The basis for the objective identification of cold waves is the use of critical percentiles of daily minimum air temperature values. These percentiles were calculated for each meteorological station in Ukraine (187 meteorological stations) and for each calendar day over a period of many years (1981–2020). Only the data for 1981–2013 were used regarding the AR of Crimea and parts of Donetsk and Luhansk regions, which have been occupied since 2014.

The application of probability distribution (Lehmann, 2013; WMO, 2015) and key indicators of cold waves allows for assessing the probability of their occurrence with varying intensity and duration, which is important for impact assessment, risk assessment, and risk management.

Since the statistical distribution of air temperature is close to normal, the three-sigma rule is used (Hansen et al., 2012):

- 68% of the values do not exceed the limits of the interval $\mu \pm \sigma$ and correspond to the climatic norm;

- 95% of the values are within the interval $\mu \pm 2\sigma$;
 - 99.7% of the values are within the interval $\mu \pm 3\sigma$,
- where μ — is the mathematical expectation (mean), σ — standard deviation of the temperature value.

Thus, the long-term mean values of the 32nd, 5th and 0.3rd percentiles of the minimal temperature for each i -th calendar year in the observation point will characterize the intensity of cold spells.

The comparison of the current value of the minimal air temperature (T_{\min_i}) of the i -th calendar day against these percentiles, one can estimate the degree of cold spell intensity (cold wave) on the i -th day of the year by the following categories:

- $T_{\min_i} > T_{\min_i}^{32\%}$ — minimal air temperature of the day corresponds to the climate norm;
- $T_{\min_i}^{32\%} \geq T_{\min_i} > T_{\min_i}^{5\%}$ — the minimum air temperature on the i -th day is classified as *cold category* (a severe cold wave, provided that its duration is two days or more).
- $T_{\min_i}^{5\%} \geq T_{\min_i} > T_{\min_i}^{0.3\%}$ — minimal air temperature of the i -th day belongs to the *very cold category* (a very strong cold wave, lasting two or more days);
- $T_{\min_i} \leq T_{\min_i}^{0.3\%}$ — minimal air temperature of the i -th day belongs to the *extremely cold* temperature (an extreme cold wave, lasting two or more days).

Therefore, a cold wave is defined as a period with minimal temperatures for the day below the 32nd percentile, which lasts at least two days in a row. The intensity of the cold wave is usually defined as the average or maximal deviation of the temperature from the climatic threshold during the entire phenomenon, it characterizes the degree, to which the air temperature dropped below the critical threshold (Radinović, Ćurić, 2012). This study assessed the average and maximum values of cold wave intensity. The danger of a cold wave depends not only on its intensity, but also on its duration. The duration allows for determining the stability of a cold wave and is calculated based on the recorded start and end times of the event. A comprehensive indicator that combines the intensity and duration of the cold spell is called the magnitude of the cold wave. It quantitatively determines the cumulative impact of extreme cold over the entire period. The lower the temperature and the longer it lasts, the greater the magnitude of the wave and the greater the damage it can cause (Forzieri, G. et al., 2015). The number of days with cold waves

of varying intensity per year and season, and the average air temperature value for the wave were also used to characterize cold waves in the study.

The calculated daily, annual, and seasonal perennial values of the 32nd, 5th and 0.3rd percentiles of the minimum temperature and the quantitative characteristics of cold waves — their frequency, duration, intensity, and magnitude— made it possible to determine the spatial and temporal specificities of the formation of cold waves and trends in their change in Ukraine during the study period. A statistical assessment of changes in cold wave characteristics was carried out by analyzing time series using regression analysis to determine the shape, direction, and statistical significance of trends (p). To interpret the degree of uncertainty, the criteria recommended by the IPCC (IPCC, 2013) were applied: 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 comparative analysis of the obtained results allowed for the detection of spatial and temporal specificities of the change in the frequency and intensity of cold waves and to determine the regions with the most significant changes in them during the study period.

THE OBTAINED RESULTS

An analysis of the frequency of cold waves in 1981–2020 showed that Ukraine experiences an average of 16–17 cold waves per year, of which 84% are severe cold waves, 14% are very severe, and 1% are extreme. Severe cold waves, when the minimum air temperature is between the 32nd and 5th percentiles, can be observed 10 to 15 times a year. The duration of such a wave averages 5–7 days per year, with the maximum in the Luhansk region. The average minimum air temperature during a severe cold spell can drop from 4.0°C in the southern Steppe of the Kherson region to zero degrees and below in the Chernivtsi and Ivano-Frankivsk regions (**Table 1**). At the same time, the Chernivtsi region has the lowest frequency of such cold spells, and severe cold waves have the lowest magnitude and insignificant intensity per year — 9.2°C and 3.4°C, respectively (**Table 1**). The frequency of cold waves in Polissia, the Forest-Steppe, and the southern Steppe does not differ sig-

Table 1. The frequency, average duration, intensity, and magnitude of severe cold waves for the year and seasons

Region	Number of CW				Duration, days				Average temperature of CW, °C				Intensity of CW, °C				Magnitude of CW, °C																
	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S
<i>Polissia</i>																																	
Volyn	14.4	2.6	3.8	4.3	3.6	5.5	5.3	5.7	5.4	5.5	1.4	-10.9	0.4	10.2	1.3	3.4	5.5	3.2	2.5	3.2	2.5	3.2	9.6	15.1	9.3	6.7	9.3	9.3	6.7	9.3	9.3	6.7	9.3
Zhytomyr	14.5	2.9	3.8	4.2	3.6	5.6	5.0	5.8	5.8	5.5	0.7	-11.6	0.2	10.2	0.8	3.6	5.4	3.4	2.6	3.4	2.6	3.4	10.1	14.4	9.9	7.4	9.7	9.7	7.4	9.7	9.7	7.4	9.7
Rivne	14.7	2.7	3.7	4.3	3.9	5.3	5.2	5.6	5.3	5.0	1.0	-11.4	0.2	10.0	1.1	3.6	5.6	3.4	2.7	3.4	2.7	3.4	9.9	15.5	9.7	7.0	9.3	9.3	7.0	9.3	9.3	7.0	9.3
Chernihiv	14.4	3.1	3.6	4.1	3.5	5.7	5.2	6.0	5.8	5.6	0.3	-13.3	0.4	10.6	0.3	3.8	6.0	3.4	2.6	3.5	2.6	3.5	10.9	16.9	10.4	7.4	10.1	10.1	7.4	10.1	10.1	7.4	10.1
<i>Western Forest-Steppe</i>																																	
Ivano-Frankivsk	14.5	2.9	3.6	4.1	3.8	5.6	5.5	5.5	5.3	6.0	-0.1	-11.8	-0.9	9.1	0.0	3.5	5.3	3.3	2.5	3.4	2.5	3.4	10.4	15.5	9.4	6.8	11.3	11.3	6.8	11.3	11.3	6.8	11.3
Lviv	14.6	2.8	3.8	4.1	3.8	5.4	5.1	5.4	5.3	5.6	0.7	-11.0	-0.1	9.5	1.1	3.5	5.3	3.2	2.5	3.3	2.5	3.3	9.5	14.6	8.7	6.5	9.6	9.6	6.5	9.6	9.6	6.5	9.6
Terнопil	14.4	2.7	3.7	4.1	3.9	5.4	5.5	5.5	5.4	5.5	1.5	-10.9	1.0	10.6	1.5	3.4	5.3	3.1	2.4	3.2	2.4	3.2	9.4	15.0	8.8	6.6	9.2	9.2	6.6	9.2	9.2	6.6	9.2
Chernivtsi	9.7	2.1	2.4	2.6	2.6	5.4	5.5	5.2	5.1	5.8	-0.6	-13.4	-0.8	9.5	-0.2	3.4	5.4	3.1	2.3	3.1	2.3	3.1	9.2	14.5	8.2	5.8	9.2	9.2	5.8	9.2	9.2	5.8	9.2
<i>Central Forest-Steppe</i>																																	
Vinnitsia	14.0	2.9	3.6	3.9	3.5	6.3	5.2	5.9	5.5	8.7	1.2	-11.0	0.8	10.9	1.4	3.4	4.9	3.2	2.5	3.4	2.5	3.4	12.1	13.5	9.4	6.9	19.5	19.5	6.9	19.5	19.5	6.9	19.5
Kyiv	14.6	3.1	3.7	4.1	3.6	5.7	5.3	5.7	6.2	5.5	1.1	-11.8	0.9	11.1	1.1	3.7	5.7	3.3	2.6	3.4	2.6	3.4	10.5	15.8	9.9	7.4	9.9	9.9	7.4	9.9	9.9	7.4	9.9
Khmelnitsky	14.6	2.9	3.6	4.2	3.9	5.6	5.3	5.8	5.5	5.7	1.3	-11.2	0.6	10.6	1.5	3.4	5.1	3.2	2.5	3.3	2.5	3.3	9.7	14.1	9.0	6.9	10.0	10.0	6.9	10.0	10.0	6.9	10.0
Cherkasy	14.6	3.1	3.6	4.1	3.7	5.5	5.2	5.7	5.5	5.7	1.3	-11.8	1.2	11.4	1.5	3.6	5.5	3.2	2.6	3.4	2.6	3.4	10.3	15.6	9.2	7.2	10.1	10.1	7.2	10.1	10.1	7.2	10.1
<i>Eastern Forest-Steppe</i>																																	
Poltava	14.5	3.1	3.4	4.1	3.8	5.8	5.5	6.1	5.9	5.6	1.5	-12.3	1.6	12.1	1.4	3.6	5.6	3.3	2.6	3.3	2.6	3.3	10.9	16.8	10.5	7.7	9.6	9.6	7.7	9.6	9.6	7.7	9.6
Sumy	14.4	3.1	3.5	4.1	3.6	5.8	5.2	6.1	6.0	5.6	0.0	-14.1	0.1	10.7	0.0	3.9	6.1	3.5	2.7	3.6	2.7	3.6	11.3	17.1	10.6	8.2	10.1	10.1	8.2	10.1	10.1	8.2	10.1
Kharkiv	14.4	3.1	3.5	4.1	3.7	6.0	5.4	5.9	6.7	5.8	0.6	-13.5	0.5	11.7	0.7	3.8	6.2	3.4	2.6	3.6	2.6	3.6	11.4	18.2	10.3	7.6	10.6	10.6	7.6	10.6	10.6	7.6	10.6
<i>Northern Steppe</i>																																	
Luhansk	13.5	2.9	3.3	3.9	3.3	7.0	6.3	10.6	5.7	5.6	0.2	-14.4	0.1	11.4	-0.1	4.0	6.5	3.6	2.7	3.9	2.7	3.9	15.1	19.6	23.8	7.6	11.1	11.1	7.6	11.1	11.1	7.6	11.1
Dnipropetrovsk	12.5	2.6	3.0	3.5	3.4	5.9	5.6	5.8	6.4	5.8	1.7	-11.7	1.6	12.4	1.5	3.7	5.6	3.2	2.6	3.6	2.6	3.6	10.7	16.6	9.3	7.6	10.3	10.3	7.6	10.3	10.3	7.6	10.3
Donetsk	13.7	2.9	3.3	3.9	3.5	6.9	6.1	9.5	6.1	5.8	1.7	-12.5	1.5	12.7	1.5	3.7	5.7	3.2	2.7	3.6	2.7	3.6	14.5	18.2	22.6	8.2	10.9	10.9	8.2	10.9	10.9	8.2	10.9
Kirovohrad	14.3	3.1	3.4	3.9	3.8	5.6	5.3	5.7	5.5	5.9	1.4	-11.4	1.3	11.9	1.6	3.5	5.3	3.1	2.6	3.4	2.6	3.4	10.2	15.5	8.8	7.2	9.8	9.8	7.2	9.8	9.8	7.2	9.8
<i>Southern Steppe</i>																																	
Zaporizhzhia	14.3	3.0	3.3	4.2	3.8	5.7	5.3	5.7	5.6	6.0	2.9	-10.3	2.2	13.3	2.5	3.5	5.3	3.0	2.6	3.5	2.6	3.5	10.3	15.4	8.6	7.4	10.9	10.9	7.4	10.9	10.9	7.4	10.9
Mykolayiv	14.7	2.9	3.6	4.1	4.0	5.5	5.3	5.5	5.4	5.8	3.0	-9.7	2.4	13.3	2.7	3.4	5.1	3.0	2.4	3.5	2.4	3.5	9.5	14.0	7.9	6.6	10.6	10.6	6.6	10.6	10.6	6.6	10.6
Odesa	14.0	3.0	3.3	3.8	3.8	6.6	5.4	7.9	6.9	6.0	3.6	-8.3	2.8	13.8	3.7	3.2	4.6	2.8	2.3	3.3	2.3	3.3	10.2	13.1	11.8	6.5	10.3	10.3	6.5	10.3	10.3	6.5	10.3
Kherson	14.3	3.0	3.4	4.1	3.8	5.7	5.3	6.1	5.6	5.8	4.0	-8.6	3.0	14.5	3.5	3.3	4.9	2.8	2.4	3.4	2.4	3.4	9.6	13.8	8.7	6.6	10.4	10.4	6.6	10.4	10.4	6.6	10.4

Note: Y — year; W — winter; S — spring; Sm — summer; A — autumn; CW — cold waves.

nificantly and ranges from 14.0 to 14.7 cases per year, reaching a maximum in the Rivne, Donetsk, and Mykolaiv regions. In the southern Steppe, the frequency of such phenomena is somewhat lower. These specificities of the spatial distribution of severe cold waves are obviously caused by various synoptic processes that affect the advection of cold in Ukraine (Climate of Ukraine).

The greatest intensity and magnitude of severe cold spells is observed in winter, especially in the Luhansk region (6.5°C and 19.6°C, respectively) and the eastern Forest-Steppe. The minimum daily air temperature can drop to -14.0°C and below. The average duration of such a cold spell can be 5–7 days and can occur up to three times per season (Table 1). In spring and autumn, the frequency of severe cold spells throughout the country is higher than in winter. In the Steppe, severe autumn cold spells occur more often than spring ones, while in the rest of the territory their frequency does not differ significantly: 3–4 such cases can be observed during the season. At the same time, the drop in air temperature in spring is usually more significant than in autumn. In summer, severe cold waves have the highest frequency but the lowest intensity and magnitude (Table 1).

The annual frequency of very severe cold waves, when the minimum daily air temperature is between the 5th and 0.3rd percentiles, is almost six times lower than the frequency of severe cold waves. During the year, Ukraine experiences 2–3 such waves. The average duration of a cold wave is 7–8 days, its average intensity per year ranges from -1.3°C to -1.8°C, and the maximum can be almost twice as high — -2.5°C to -3.1°C. The average annual intensity of a severe cold wave is 5.5°C to 8.5°C, while the maximum can reach 17.0°C to 23.3°C (Table 2).

Very severe cold spells are observed throughout the year. Unlike severe cold waves, very severe cold waves are most often observed in winter — at least one such event is recorded in Ukraine almost every winter. During periods of intense cold spells, the average minimum air temperature can drop to -14.1...-14.6°C in the southern Steppe (Odesa and Kherson regions) and to -20.0...-21.0°C and below in the east of the country — in the eastern Forest-Steppe and northern Steppe, in particular in the Sumy, Kharkiv, and Luhansk regions. The duration of such a cold spell is 4–5 days. The average intensity of a severe cold wave ranges from -1.8°C to -2.5°C, and the maximum intensity ranges from -3.5°C to -4.8°C, in-

tenifying from south to north and northeast, reaching its highest values in the Sumy and Luhansk regions. The most powerful cold waves are recorded in the Luhansk region. In winter, their average intensity reaches 12.2°C, and the maximum can reach 32.0°C (Table 2).

Very severe cold waves are also observed in summer, but during this period, they occur least frequently — once every two to three years, most often in the eastern Forest-Steppe and southern Steppe, due to the specificities of synoptic processes. Summer cold waves are characterized by the lowest intensity and magnitude (Table 1). The most intense and powerful summer cold spells are observed in Polissia and the western Forest-Steppe, where they can last 3–4 days and the minimum air temperature can drop to 6.4–8.8°C.

During the transitional seasons, spring and autumn, the frequency of very severe cold spells is almost the same — about once every two years. Their intensity is generally similar, except in the eastern Forest-Steppe and Steppe zones, where cold spells in autumn are usually more intense and powerful than in spring. At the same time, in Polissia, in the western and central Forest-Steppe, their duration in spring is longer than in autumn, and the drop in air temperature is more noticeable and can reach -7.0°C. In the southern Steppe, the frequency of cold spells in summer, spring, and autumn is almost the same — once every two years — but their intensity and magnitude in summer is significantly lower (Table 2).

Extreme cold spells, when the minimum temperature is below the 0.3rd percentile, are rare and were not recorded across the entire territory during the study period (1981–2020). Moreover, there were too few such cases in summer and autumn to draw reliable conclusions about their frequency and intensity. It has been established that such extreme cold spells are most often observed in Polissia, where an average of four such waves were recorded over ten years, while in the Steppe and western Forest-Steppe, there are half as many during this period. The duration of such cold spells is usually 4–5 days (Table 3).

Extreme cold waves in Ukraine are most often observed in winter. During such events, the average minimum temperature can drop to -25.0°C and below in the eastern Forest-Steppe and the Luhansk region, and to -19.0°C and below in the southern Steppe. Since such cold spells are longer in the southern Steppe, they are also the most powerful. These cold

Table 2. Frequency, average duration, intensity, and magnitude of very severe cold waves during the year and seasons

Region	Number of CW				Duration, days				Average temperature of CW, °C				Intensity of CW, °C				Magnitude of CW, °C								
	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	A	Y	W	S	Sm	
<i>Polissia</i>																									
Volyn	2.2	0.7	0.5	0.4	0.6	4.2	4.5	4.0	3.8	4.1	-6.8	-18.1	-4.6	8.1	-3.5	3.0	4.5	2.5	1.6	2.5	6.8	10.9	5.0	3.1	5.7
Zhytomyr	2.3	0.9	0.5	0.4	0.6	4.2	4.6	3.7	3.7	4.3	-7.9	-18.8	-3.5	7.7	-4.8	3.0	4.3	2.1	1.6	2.5	6.9	10.5	4.4	3.1	5.8
Rivne	2.3	0.8	0.5	0.4	0.6	4.0	4.5	3.6	3.8	3.7	-7.0	-18.4	-4.9	7.7	-4.1	3.0	4.6	2.4	1.8	2.3	6.4	10.7	5.0	3.4	4.3
Chernihiv	2.4	0.9	0.7	0.4	0.5	4.2	4.8	3.8	3.5	4.4	-8.8	-20.0	-7.0	8.1	-5.5	3.1	4.4	2.7	1.5	2.8	7.4	11.2	5.5	2.8	7.2
<i>Western Forest-Steppe</i>																									
Ivano-Frankivsk	2.3	0.8	0.6	0.4	0.6	4.1	4.3	3.8	4.1	4.1	-7.9	-18.2	-7.0	6.4	-4.9	2.9	4.2	2.6	1.5	2.4	6.5	9.6	5.6	3.3	5.5
Lviv	2.1	0.8	0.5	0.3	0.5	4.1	4.3	3.7	3.8	4.2	-7.9	-18.4	-5.5	7.2	-4.0	3.1	4.6	2.5	1.6	2.4	6.8	10.3	5.0	3.0	5.8
Terнопil	2.2	0.7	0.5	0.3	0.6	4.1	4.2	3.9	4.4	4.1	-6.6	-17.9	-3.6	8.8	-4.6	2.9	4.5	2.3	1.5	2.5	6.6	10.1	5.1	3.3	5.7
Chernivtsi	1.6	0.6	0.3	0.4	0.4	3.9	4.0	3.8	3.8	4.0	-7.9	-19.1	-6.3	6.4	-6.1	2.8	3.9	2.5	1.8	2.5	6.0	8.6	5.1	3.4	5.5
<i>Central Forest-Steppe</i>																									
Vinnitsia	2.1	0.7	0.4	0.4	0.6	4.2	4.6	4.0	4.1	4.1	-7.3	-18.1	-4.9	8.8	-4.8	3.0	4.3	2.3	1.5	2.8	7.0	10.6	4.8	3.0	6.4
Kyiv	2.4	0.9	0.6	0.5	0.5	4.1	4.7	3.7	3.8	4.0	-6.9	-18.8	-3.7	8.7	-4.6	2.9	4.2	2.4	1.6	2.7	6.9	10.7	4.8	3.0	6.2
Khmelnitsky	2.3	0.7	0.5	0.5	0.6	4.1	4.5	3.8	3.9	4.1	-6.0	-18.0	-4.1	8.6	-5.3	2.9	4.2	2.5	1.5	2.8	6.4	10.1	4.9	3.0	6.2
Cherkasy	2.5	0.8	0.6	0.5	0.5	4.1	4.5	4.0	3.8	3.7	-6.7	-18.5	-4.8	9.1	-5.1	2.9	4.1	2.6	1.6	2.5	6.6	10.2	5.8	3.1	5.2
<i>Eastern Forest-Steppe</i>																									
Poltava	2.6	0.9	0.7	0.5	0.6	4.3	4.9	4.2	3.8	4.0	-6.6	-18.5	-4.3	9.4	-5.2	2.9	4.1	2.6	1.7	2.7	7.1	10.9	5.9	3.3	6.1
Sumy	2.6	0.9	0.7	0.5	0.5	4.2	4.8	3.9	3.7	4.2	-8.4	-21.2	-6.3	8.2	-5.7	3.2	4.7	2.7	1.7	2.8	7.5	11.8	6.0	3.2	6.4
Kharkiv	2.5	0.8	0.6	0.5	0.6	4.3	5.0	4.0	3.8	4.1	-7.3	-20.1	-4.0	9.1	-5.9	3.1	4.4	2.5	1.7	2.8	7.4	11.6	5.4	3.3	7.0
<i>Northern Steppe</i>																									
Luhansk	2.4	0.8	0.6	0.4	0.6	4.5	4.9	4.4	3.8	4.5	-8.8	-21.4	-4.6	8.1	-6.5	3.3	4.8	2.6	1.9	3.0	8.5	12.2	6.3	3.9	8.5
Dnipropetrovsk	2.5	0.9	0.6	0.5	0.6	4.2	4.7	4.1	3.8	3.9	-6.5	-18.2	-3.3	9.8	-5.3	2.9	4.0	2.5	1.7	2.6	6.9	10.3	5.8	3.4	5.8
Donetsk	2.5	0.8	0.7	0.3	0.6	4.4	4.7	4.3	3.9	4.4	-6.8	-18.3	-3.6	10.0	-4.4	2.8	3.7	2.5	1.6	2.7	7.1	9.7	5.9	3.2	7.2
Kirovohrad	2.6	0.9	0.7	0.5	0.6	4.2	4.6	4.3	3.7	3.9	-6.1	-17.7	-3.6	9.5	-5.2	2.8	3.9	2.5	1.5	2.6	6.6	9.8	6.2	2.8	5.6
<i>Southern Steppe</i>																									
Zaporizhzhia	2.8	1.0	0.6	0.6	0.6	4.1	4.3	4.1	3.6	4.1	-5.0	-16.4	-3.4	10.5	-3.1	2.8	3.6	2.5	1.7	2.7	6.4	8.8	5.6	3.2	6.2
Mykolayiv	2.5	0.9	0.5	0.5	0.5	4.0	4.3	4.0	3.7	3.7	-4.6	-15.7	-2.4	10.8	-3.1	2.7	3.8	2.4	1.5	2.4	6.1	8.9	5.3	2.9	5.1
Odesa	2.4	0.8	0.6	0.6	0.5	4.1	4.3	4.1	4.0	3.9	-2.1	-14.1	-0.7	11.4	-1.8	2.5	3.5	2.1	1.6	2.4	5.5	8.1	4.7	3.2	5.0
Kherson	2.7	0.9	0.6	0.6	0.6	4.0	4.2	4.1	3.9	3.8	-2.7	-14.6	-0.8	11.8	-1.4	2.5	3.5	2.1	1.6	2.5	5.7	8.4	4.8	3.3	5.1

Note: Y — year; W — winter; S — spring; Sm — summer; A — autumn; CW — cold waves.

Table 3. Frequency, average duration, intensity, and magnitude of extreme cold waves during the year and seasons

Region	Number of CW			Duration, days			Average temperature of CW, °C			Intensity of CW, °C			Magnitude of CW, °C		
	Y	W	S	Y	W	S	Y	W	S	Y	W	S	Y	W	S
<i>Polissia</i>															
Volyn	0.4	0.3	0.1	4.4	4.4	4.4	-20.0	-22.5	-14.1	4.4	4.7	3.2	10.4	11.3	7.6
Zhytomyr	0.3	0.2	0.1	4.0	4.3	4.1	-21.4	-24.2	-18.8	4.3	4.8	4.4	10.2	11.7	11.0
Rivne	0.4	0.3	0.1	4.4	4.6	4.6	-19.1	-23.8	-15.8	4.1	4.5	4.6	10.4	11.5	13.1
Chernihiv	0.3	0.2	0.0	4.5	4.4	5.4	-21.9	-25.7	-16.0	4.5	4.7	5.4	10.5	11.6	12.2
<i>Western Forest-Steppe</i>															
Ivano-Frankivsk	0.3	0.1	0.0	4.0	4.1	4.4	-18.9	-24.3	-15.5	3.8	4.0	5.0	9.2	9.7	13.5
Lviv	0.3	0.2	0.1	4.3	4.3	4.4	-20.4	-23.1	-14.6	4.8	4.8	4.6	11.4	11.0	12.6
Ternopil	0.3	0.2	0.1	4.1	4.1	4.4	-19.6	-22.1	-13.5	3.9	3.8	4.4	8.7	8.2	11.4
Chernivtsi	0.1	0.1	0.0	3.8	3.9	4.7	-20.4	-24.0	-14.7	3.8	4.2	4.4	8.3	9.2	9.8
<i>Central Forest-Steppe</i>															
Vynnytsia	0.3	0.2	0.1	4.0	3.9	5.4	-19.5	-23.0	-16.3	3.9	4.2	4.4	9.2	9.4	13.8
Kyiv	0.3	0.2	0.1	4.0	4.1	4.7	-19.2	-24.5	-14.9	4.2	4.8	5.1	9.8	11.8	12.1
Khmelnysky	0.3	0.2	0.1	4.1	4.2	4.3	-20.8	-22.9	-17.5	3.8	3.7	5.1	8.6	8.6	12.2
Cherkasy	0.3	0.1	0.1	4.2	4.4	5.8	-18.7	-24.1	-15.7	3.6	4.3	4.3	9.7	10.8	15.3
<i>Eastern Forest-Steppe</i>															
Poltava	0.2	0.1	0.1	4.2	3.6	5.6	-20.6	-24.8	-12.9	3.8	4.2	3.4	8.6	8.4	10.0
Sumy	0.3	0.2	0.1	4.1	3.9	3.8	-22.5	-25.9	-16.4	4.1	3.9	5.0	8.7	8.2	9.4
Kharkiv	0.2	0.1	0.1	4.1	3.4	5.1	-21.2	-26.1	-15.9	3.5	3.4	3.8	7.5	6.4	9.1
<i>Northern Steppe</i>															
Luhansk	0.2	0.1	0.1	4.3	3.8	5.3	-21.2	-27.3	-20.8	3.3	3.8	3.8	8.1	7.5	12.5
Dnipropetrovsk	0.2	0.1	0.1	4.7	4.2	6.1	-19.7	-23.7	-18.1	3.9	3.8	4.9	10.7	8.5	17.8
Donetsk	0.2	0.1	0.01	5.0	4.3	6.2	-19.0	-24.0	-17.3	3.5	4.2	3.5	9.5	9.8	11.9
Kirovohrad	0.2	0.1	0.01	4.6	4.9	6.0	-17.8	-23.1	-18.2	3.4	4.0	4.2	10.7	11.9	17.3
<i>Southern Steppe</i>															
Zaporizhzhia	0.2	0.1	0.1	5.4	5.3	6.6	-16.2	-20.7	-14.4	3.9	4.0	5.0	12.0	11.9	17.7
Mykolayiv	0.2	0.1	0.1	5.4	6.2	5.8	-17.7	-20.7	-15.3	3.5	4.1	3.4	10.6	13.2	10.8
Odesa	0.2	0.1	0.01	4.8	4.8	5.4	-15.9	-18.8	-12.7	3.0	3.5	2.6	8.1	9.5	7.4
Kherson	0.2	0.1	0.01	6.4	8.3	6.5	-14.5	-19.0	-13.3	4.0	4.5	4.8	15.8	21.6	17.3

Note: Y — year; W — winter; S — spring; CW — cold waves.

waves also become quite powerful in winter in Polissia, due to their greater intensity and significant duration (**Table 3**).

In spring, extreme cold spells occur once every ten years or less frequently, and do not cover the entire territory of the country. They are most likely to be observed in Polissia, in the Forest-Steppe, and in the Luhansk region. For the rest of the territory, the data available for 40 years is insufficient to make a reliable conclusion about their frequency. In Polissia, the average minimum temperature drop during such spring cold spells is $-14.1...-16.0^{\circ}\text{C}$, and in the Zhytomyr

region, it can reach -18.0°C and below. In the Forest-Steppe, the temperature decrease is quite uneven and varies from -12.9°C in the Poltava region to -17.5°C in the Khmelnytskyi region. The most significant cold spells are recorded in the Luhansk region, where the average minimum temperature during an extreme cold wave in spring can drop to -20.8°C .

The analysis shows that as temperatures become more extreme, their spatial distribution becomes more uneven. This is because such values are influenced not only by large-scale synoptic processes but also by regional and local characteristics.

Over the past decades, there has been a steady decline in the intensity and frequency of cold waves in the temperate latitudes of the Northern Hemisphere (Geert Jan van Oldenborgh et al., 2019). The analysis of the dynamics of these indicators in Ukraine in 1981–2020 showed that the same trends are characteristic of our country, but with regional and seasonal features. It has been established that over the last four decades (1981–2020), there is virtually no doubt (probability of about 99%) that the number of cold waves has decreased when the minimum daily air temperature is below the perennial average values of the 32nd percentile. The rate of change is, on average, two waves per 10 years (**Fig. 1**).

The decrease in the frequency of cold waves throughout the year is characteristic of the entire territory of Ukraine and is most pronounced in winter and summer. During the summer season, these changes are more intense than in winter: the decrease averages 0.6 and 0.8 cold waves per 10 years, respectively (**Fig. 1**). In addition, in summer, the decrease in the frequency of cold waves is significant and uniform throughout the country (**Fig. 2**). In winter, the greatest changes are characteristic of the Right-Bank Polissia, central and eastern Forest-Steppe, northern and

southern Steppe, with the exception of a significant part of the Odesa region and the Autonomous Republic of Crimea, where their rate is significantly lower. In the western Forest-Steppe, in particular in the Prykarpattia region, these changes are not significant in winter (**Fig. 2**). In autumn, almost throughout the country, with the exception of Luhansk region and some areas of Kyiv, Zhytomyr and Lviv regions, there is a decrease in the number of cold waves, but the rate of their change is almost half that in summer. In spring, unlike other seasons, the changes in the number of cold waves across the country are very uneven. A decrease in the frequency of cold spells is characteristic only of Podillia, Volyn, Chernihiv Polissia, and the southern Steppe. In the remaining territory, their frequency did not change considerably in 1981–2020, and in some regions, including Transcarpathian, Prykarpattia, Right-Bank Polissia, eastern Forest-Steppe, it even increased (**Fig. 2**).

As mentioned above, cold waves vary in duration. The longer such a cold spell lasts, the more dangerous it becomes and the greater the risks it poses, especially for agriculture. The studies have shown that Ukraine is experiencing a trend towards a decrease in both short-term (2–5 days) and long-term (6 days

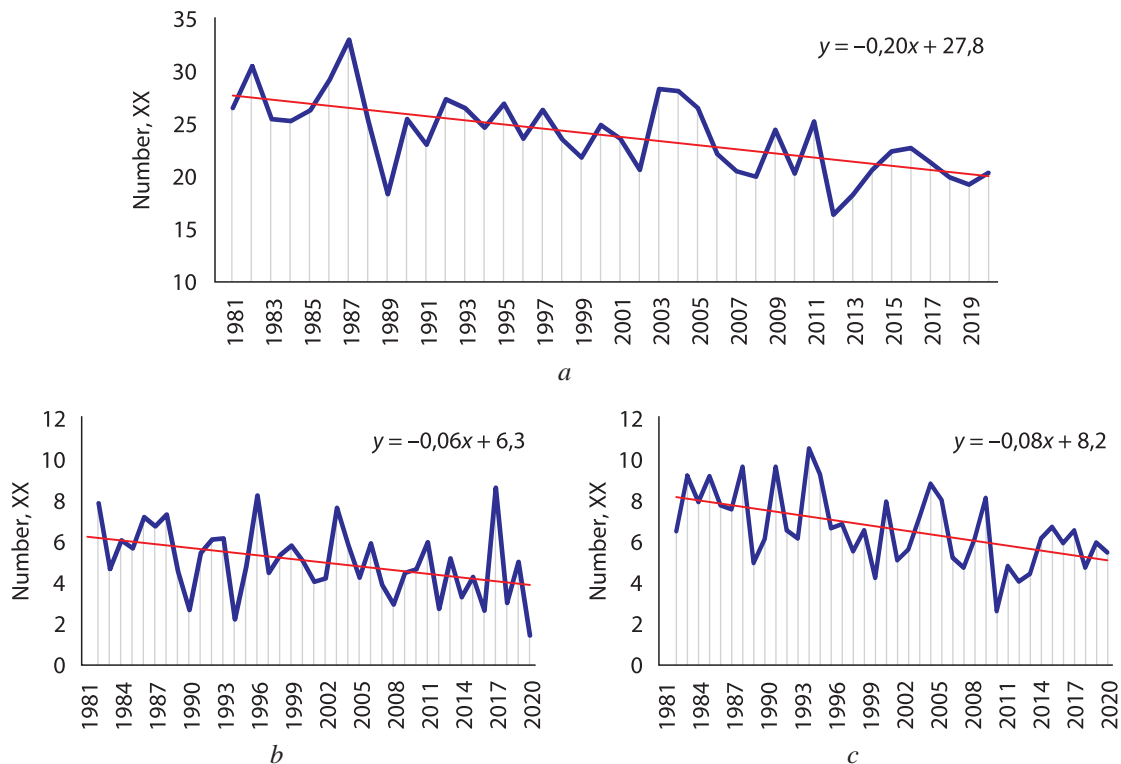


Fig. 1. The interannual variability and trends of changes in the number of cold waves per year, winter, summer in Ukraine. 1981–2020: *a* — year; *b* — winter; *c* — summer

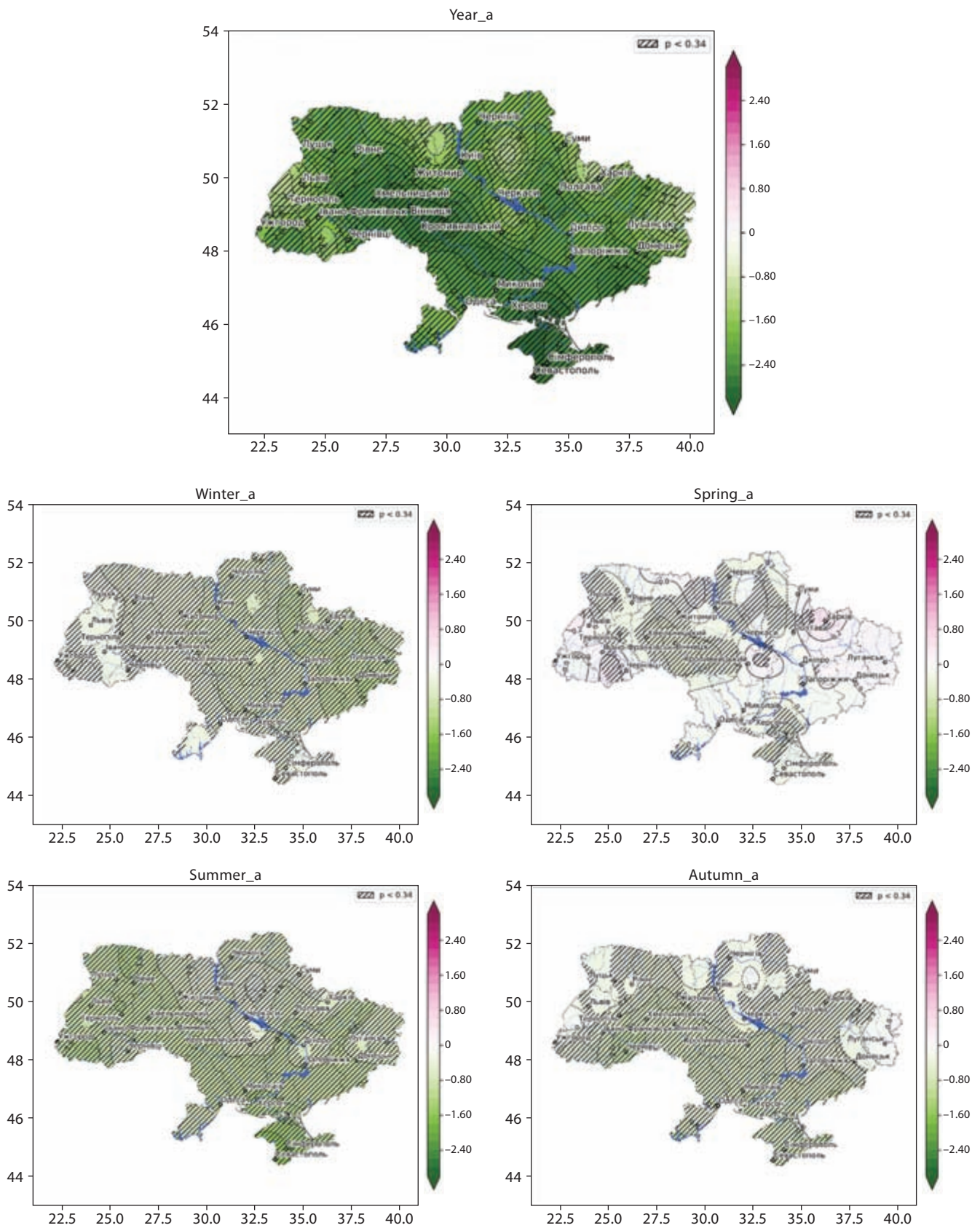


Fig. 2. The velocity and significance of the change in the average number of cold waves during the year and seasons in Ukraine. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

or more) cold waves throughout the year. The reduction in the number of long-term cold spells is more intense than that of short-term ones: 1.1 and 0.9 cold waves per 10 years, respectively (Fig. 3–5).

A decrease in the frequency of long-term cold waves has been observed throughout the entire territory of Ukraine and is fairly uniform, indicating that these changes are caused by the same process. Only in the Luhansk region is the rate of change slightly slower, although it is still significant (Fig. 4). These trends are observed throughout the year. The most intense changes are observed in winter and summer in the central Forest-Steppe, southern Steppe, and in the west of the northern Steppe. During the transitional seasons, these changes were much slower, and in the eastern and north-eastern regions, they were insignificant (Fig. 4).

The change in the frequency of short-term cold waves during the year was not as uniform as that of long-term cold waves (Figs. 4, 5).

There are some regions where these changes were insignificant or even had the opposite trend (Fig. 5). A decrease in the frequency of short-term cold spells was observed throughout most of the year, except for spring. Despite a significant increase in air temperature during the spring season (Balabukh et al., 2024), the number of short-term cold intrusions is increasing, especially in the eastern and central Forest-Steppe, the northern and southern Steppe, the Prykarpattia, and the Right-Bank Polissia (Fig. 5). This increase is accompanied by higher recurrence of severe and very severe cold spells (Balabukh et al., 2024), which poses risks for agriculture.

In winter, a decrease in the frequency of short-term cold waves is observed almost in the entire territory of the country, with the exception of the western Forest-Steppe and south-western region, where these changes are insignificant. At the same time, in the eastern Forest-Steppe, the frequency of such cold waves is decreasing at the fastest rate (Fig. 5).

In summer, a decrease in the frequency of such cold spells is observed throughout almost the entire country, with the exception of the eastern Forest-Steppe and some regions (Fig. 5). In autumn, these changes are quite heterogeneous: in Polissia and the southern Steppe, they are insignificant, and in some regions, the frequency of such cold waves is even increasing. At the same time, most of the country's territory shows a tendency towards a decrease in their frequency, especially in the western Forest-Steppe and in the west of the southern Steppe (Fig. 5).

It has been established that a decrease in the frequency of cold waves per year is accompanied by a decrease in their intensity, both average and maximum — 0.2 and 0.3°C per 10 years (Figs. 6, 7).

These changes are observed throughout the country, with the exception of the Luhansk region and the eastern areas of the Kharkiv region. Such trends are characteristic of autumn and, especially, winter. In summer, a decrease in the intensity of cold waves is characteristic of the southern, central, and western regions, while in the northern and eastern regions, an increase in their intensity is observed. Heterogeneous changes are also characteristic of the spring season: in the southern, eastern (except for the Kharkiv region), central, and partly western regions, the intensity of

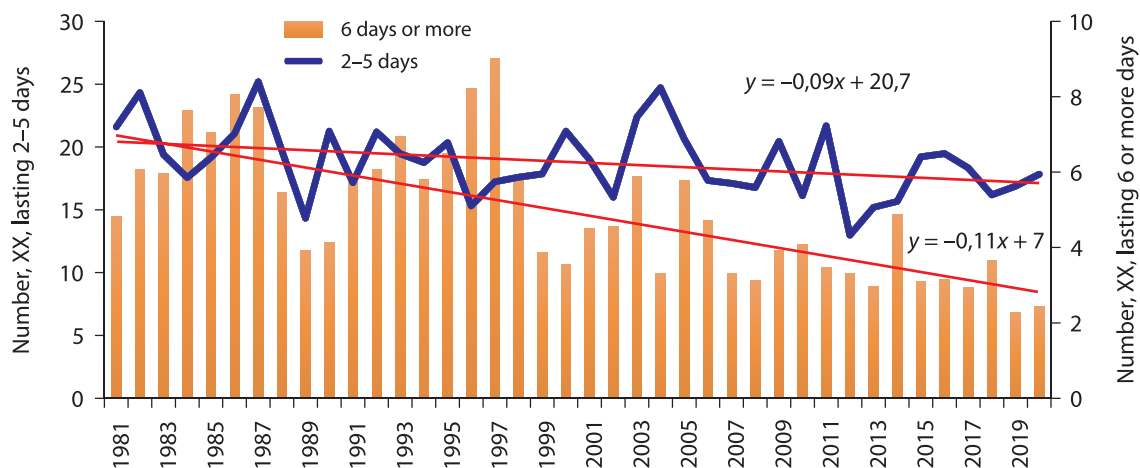


Fig. 3. The interannual variability in the frequency of short-term (2–5 days) and long-term (6 days or more) cold waves in Ukraine. 1981–2020

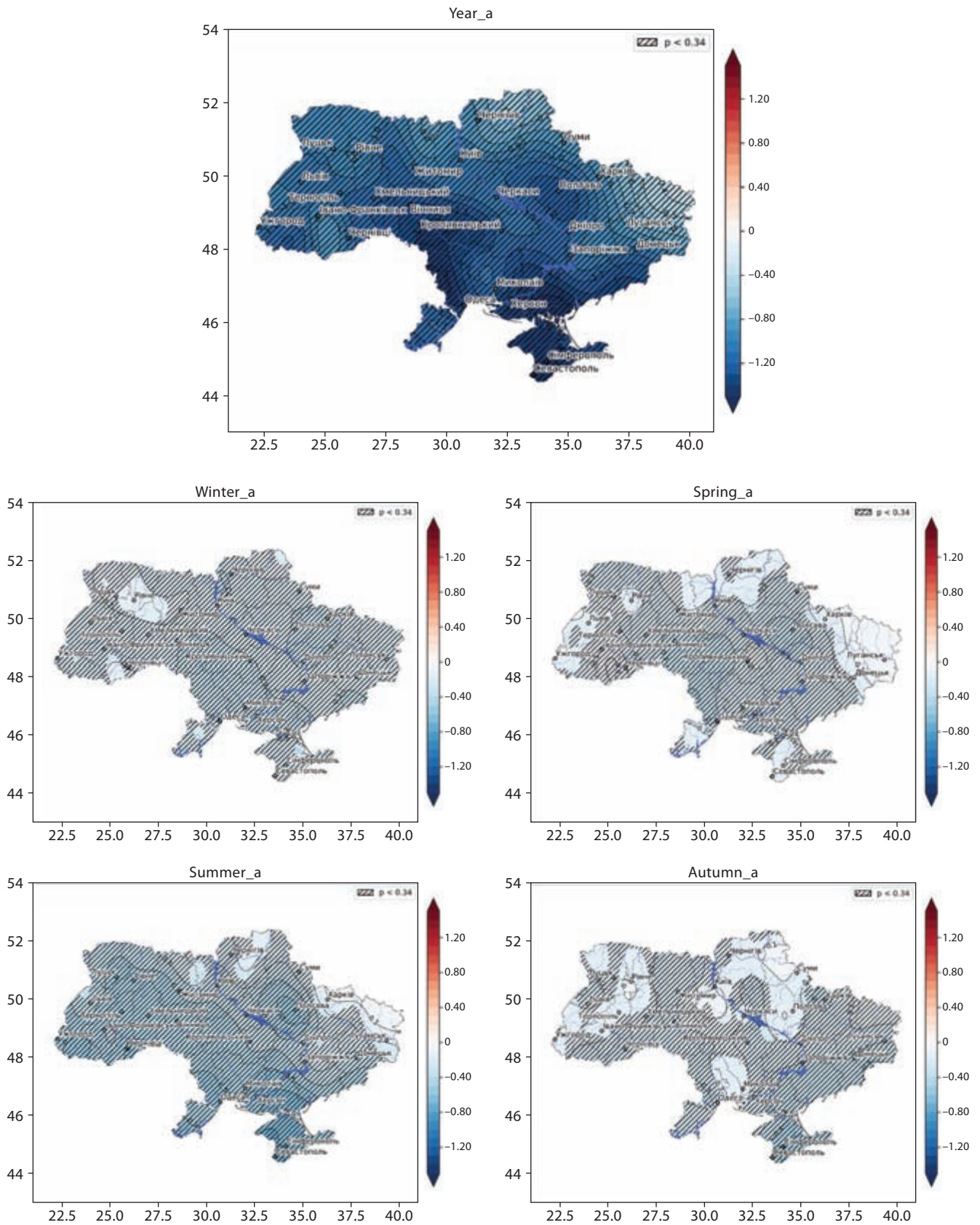


Fig. 4. The velocity and significance of the change in the average number of cold waves which last 6 days or more during the year and seasons. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

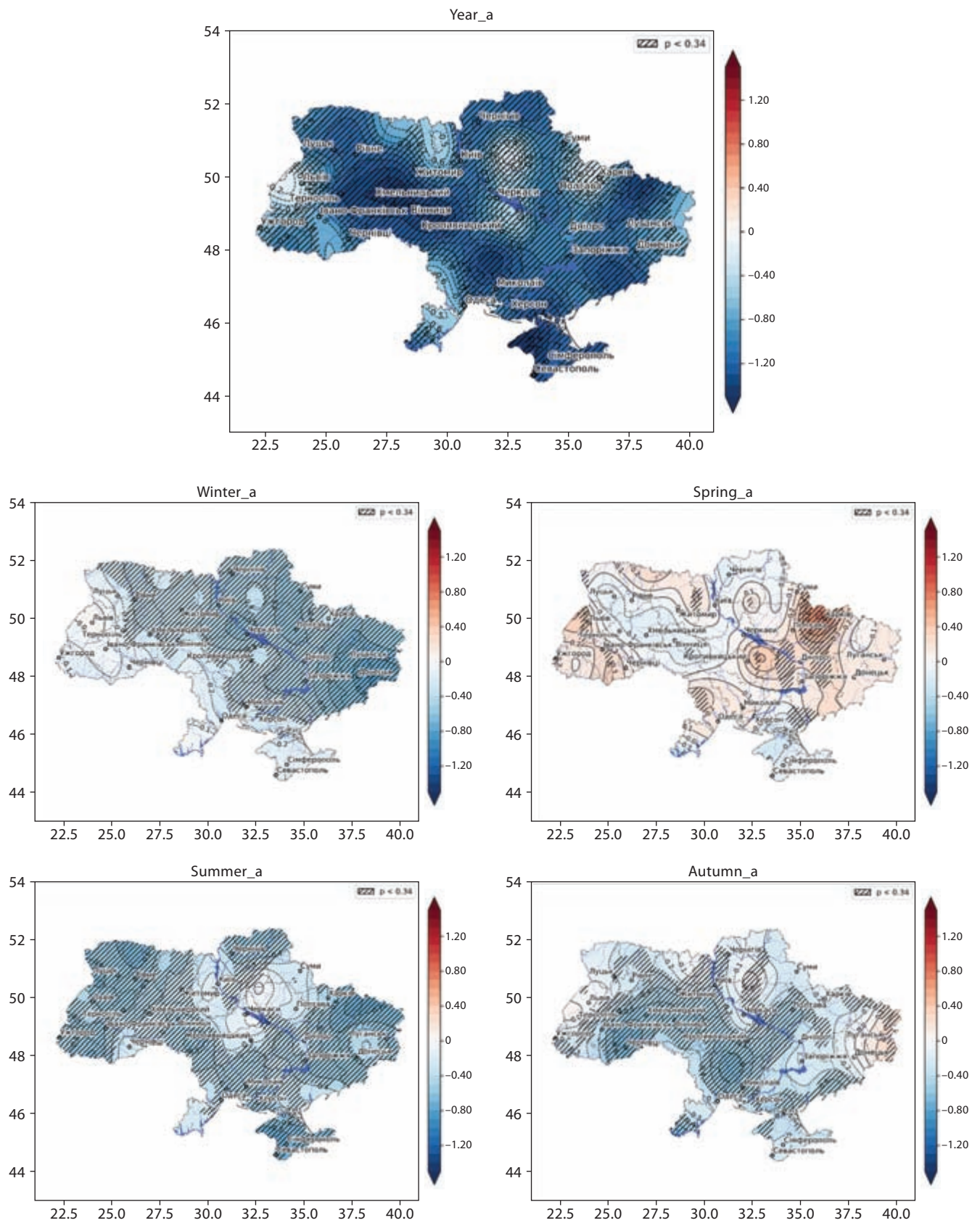


Fig. 5. The velocity and significance of the change in the average number of cold waves, lasting 2–5 days, during the year and seasons in Ukraine. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

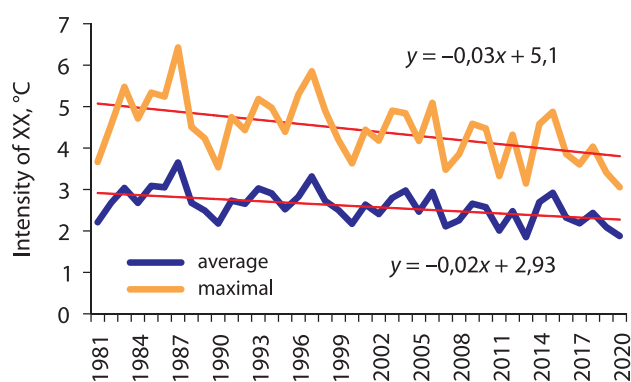


Fig. 6. The interannual variability and trends of changes in the average and maximal intensity ($^{\circ}\text{C}$) of the cold waves for the year

cold waves decreases, while in the Right-Bank Polissia it increases (**Fig. 7**).

The magnitude of cold waves in Ukraine decreases as well (**Figs. 8, 9**). These changes are observed almost in the entire territory of the country and fluctuate from 1.5 to 3.0 $^{\circ}\text{C}$ or more in 10 years (**Figs. 8, 9**). The highest decrease in the magnitude of cold waves is observed in the transitional seasons. In spring, the velocity of these changes averages 3.7 $^{\circ}\text{C}$ in 10 years.

The most intense changes (over 6.0 $^{\circ}\text{C}$ in 10 years) are observed in the north-eastern and central regions of the country. Autumn in Ukraine is also characterized by a significant decrease in the average intensity of cold waves — 3.2 $^{\circ}\text{C}$ in 10 years. The analysis of their interannual variability in autumn showed that since the beginning of the 21st century, there has been a sharp (2–3 times) decrease in the intensity of cold waves compared to the 1980s and 1990s. Such changes indicate a change in the atmospheric processes that cause this phenomenon during this period. The most heterogeneous changes are characteristic

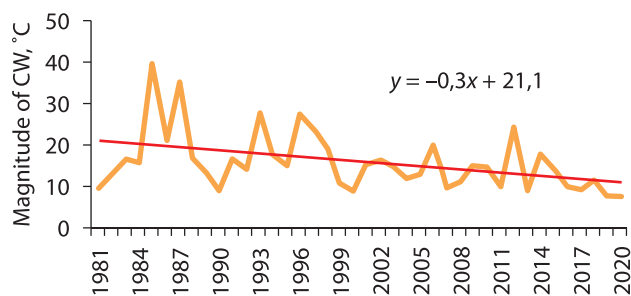


Fig. 8. The interannual variability and trends of changes in the average magnitude of the cold waves for the year. 1981–2020

of the north-eastern and central regions of Ukraine, where the magnitude of cold waves both decreases and increases. In the rest of the territory, changes in the intensity of cold waves amount to 1.0–2.0 $^{\circ}\text{C}$ over 10 years. The same changes are characteristic of the summer season for almost the entire territory of the country. The exceptions are Polissia and the Kharkiv region and, especially, the Luhansk region, where cold waves became more intense in summer during 1981–2020. The winter season is characterized by very heterogeneous changes in the intensity of cold waves. The Pryazovia and Prykarpattia stand out, where there has been a significant decrease in the intensity of cold waves, and the Luhansk region, where they have increased significantly. However, across a large part of the country, changes in the intensity of cold spells in winter were insignificant.

The analysis of changes in the frequency of cold waves of varying intensity showed that during the study period, the number of severe and very severe cold waves decreased most intensively. The rate of decrease in the frequency of such phenomena was three times higher than that of extreme cold waves (**Fig. 10–13**).

Thus, in 1981–2020, the frequency of extreme cold waves in Ukraine did not change significantly, while the frequency of severe and very severe cold waves decreased.

The increase in the frequency and intensity of heat waves and the decrease in the frequency and intensity of cold waves in winter cause a significant increase in air temperature during this season, both maximum and minimum ones. The number of winter days, days with frost and sharp changes in temperature during the day, is decreasing, especially in the east of the country. However, the number of days with severe frost in 1981–2010 remained unchanged, and the maximum duration of the period with such conditions probably increased by 1 day per 10 years in the western and eastern regions of the country (Balabukh et al., 2017).

DISCUSSION

The study found that cold waves remain an important climatic factor for Ukraine's territory, despite the persistent manifestations of global warming. An important result is the identified spatial-temporal structure of the frequency, intensity, and force of cold waves. The most intense cold spells are observed in the eastern regions, primarily in the Luhansk, Sumy,

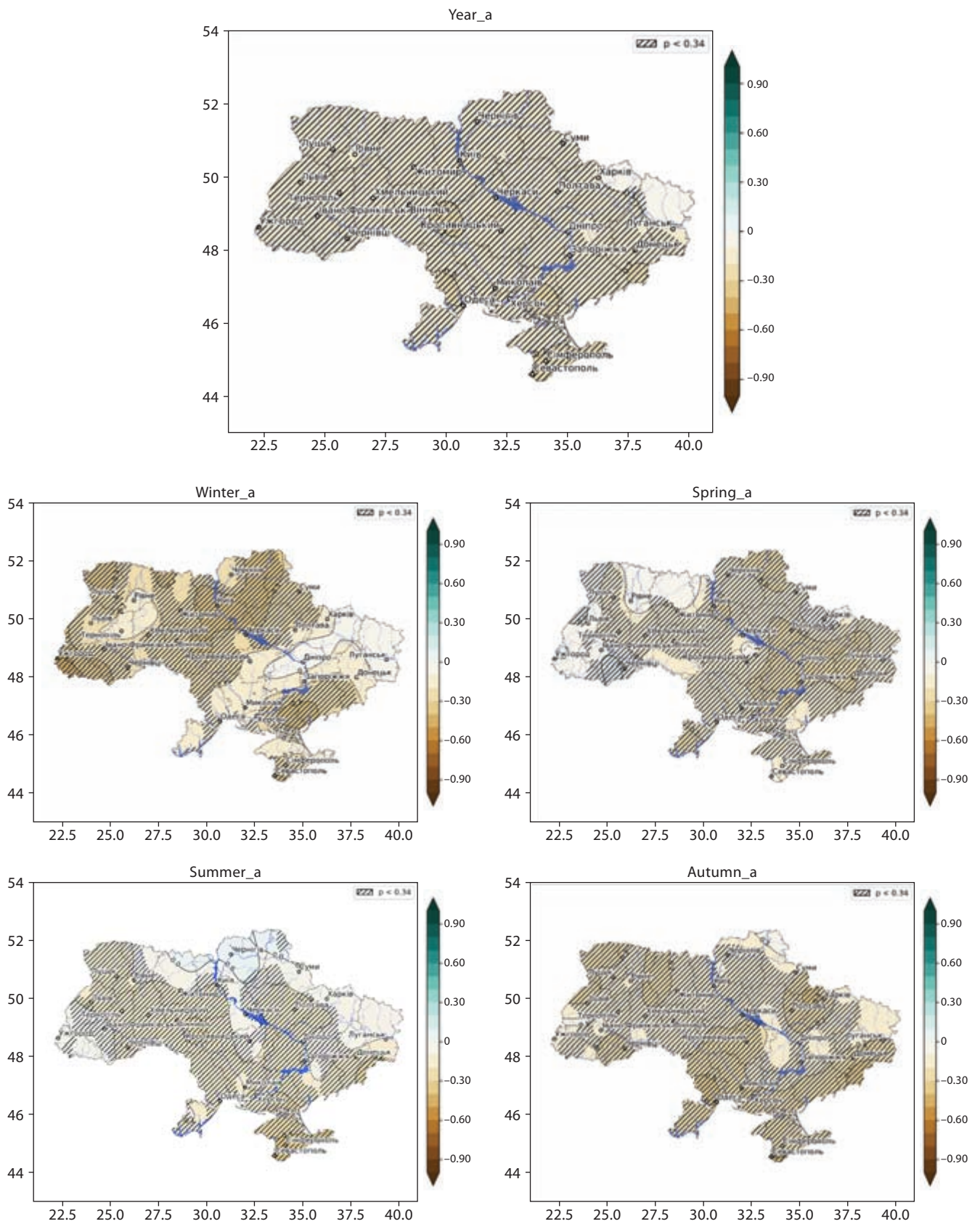


Fig. 7. The velocity and significance of the change in the average intensity of cold waves during the year and season. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

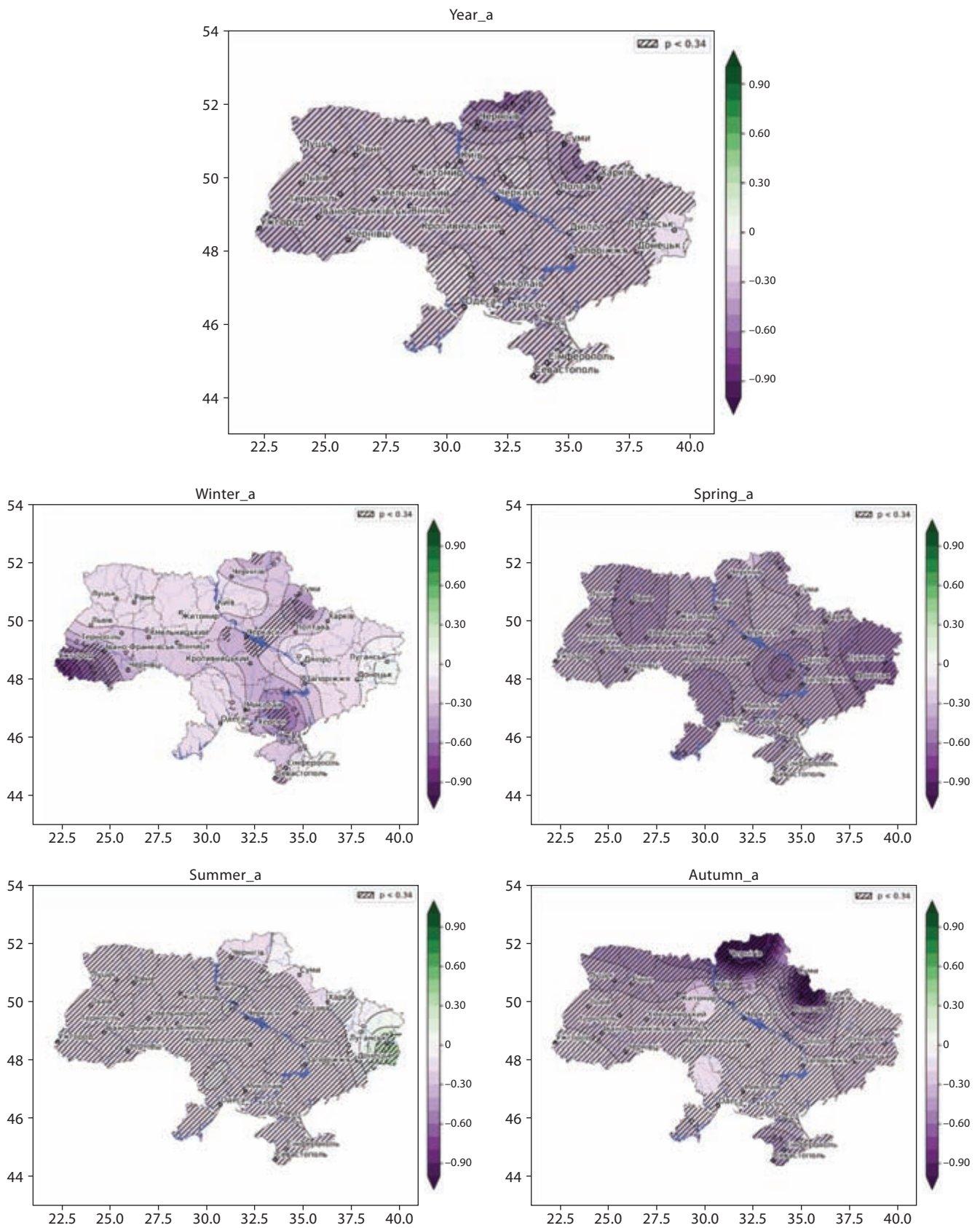


Fig. 9. The velocity and significance of the change in the average magnitude of cold waves during the year and season in Ukraine. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

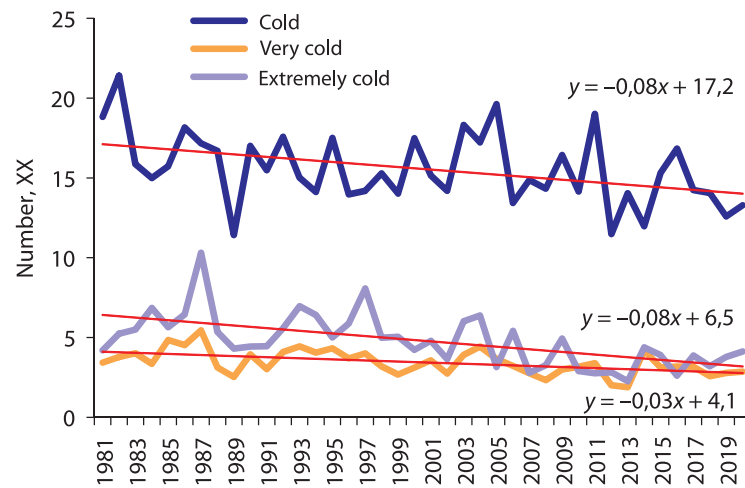


Fig. 10. The interannual variability and trends of changes in the frequency of cold waves of different intensity. 1981–2020

and Kharkiv regions, confirming the role of the eastern area of the country as the one most vulnerable to cold intrusions. Cold waves are least pronounced in the western regions, where the continental climate is mitigated by the influence of the Atlantic and the orographic features of the Carpathians.

A comparison of seasons shows that temperature extremes respond unevenly to global warming. The greatest decrease in intensity is observed in autumn and, especially, in winter. Winter cold spells show a more complex regional structure: in the west, the changes are weak or insignificant, while in the east and center of the country, cold spells are significantly weaker. This is consistent with conclusions about the weakening of the East European anticyclone and changes in the trajectories of cold intrusions.

The identified patterns are consistent with current trends in the Northern hemisphere, where there has been a gradual decrease in the frequency and intensity of extreme cold spells, but their high spatial and temporal variability remains (Geert Jan van Oldenborgh et al., 2019; IPCC, 2021). Similar to other regions of Europe, Canada, and the United States (Varfi et al., 2016; Barnett et al., 2012), Ukraine has seen a decrease in the frequency and intensity of cold waves, but with distinct regional specificities related to local and regional atmospheric circulation. Global studies (Geert Jan van Oldenborgh et al., 2019; IPCC, 2021) show that, against the backdrop of a general increase in temperature, there is still the possibility of short-term but intense cold waves associated with changes in atmospheric circulation, weakening of the polar vortex, and changes in the baric field. The trends

observed in Ukraine are generally consistent with these global processes, but have distinct regional and seasonal characteristics.

The established decrease in the frequency of cold waves, both short-term and long-term, indicates a weakening of persistent advective intrusions of Arctic air, which is particularly evident in summer and winter. This is consistent with the current stratification of the thermal regime in Eurasia, where a gradual weakening of cold intrusions during the warm season is observed. It is notable for Ukraine that summer cold waves demonstrate the most uniform decrease among all seasons, while spring changes are the most complex, heterogeneous, and regionally contrasting.

The increase in the frequency of short-term but intense spring cold spells in the eastern Forest-Steppe, the northern and southern Steppe, as well as in Polissia and some western regions, is one of the key new findings of this study, which indicates local specificities of atmospheric circulation that may be associated with more frequent waves of Arctic air and regional baric anomalies. These results are particularly important for the agricultural sector, as cold waves are one of the most dangerous abiotic stresses for agricultural crops. These changes are particularly dangerous for grain crops, fruit and berry plantations, corn, sunflowers, and vegetable crops, as even a short period of temperature reduction from -2 to -5°C during critical phases of development can cause massive damage, crop loss, fungal diseases, and reduced resistance to pests (Lamichhane, 2021; Balabukh et al., 2024). They are also capable of disrupting critical phases of plant development — germination, budding, flower-

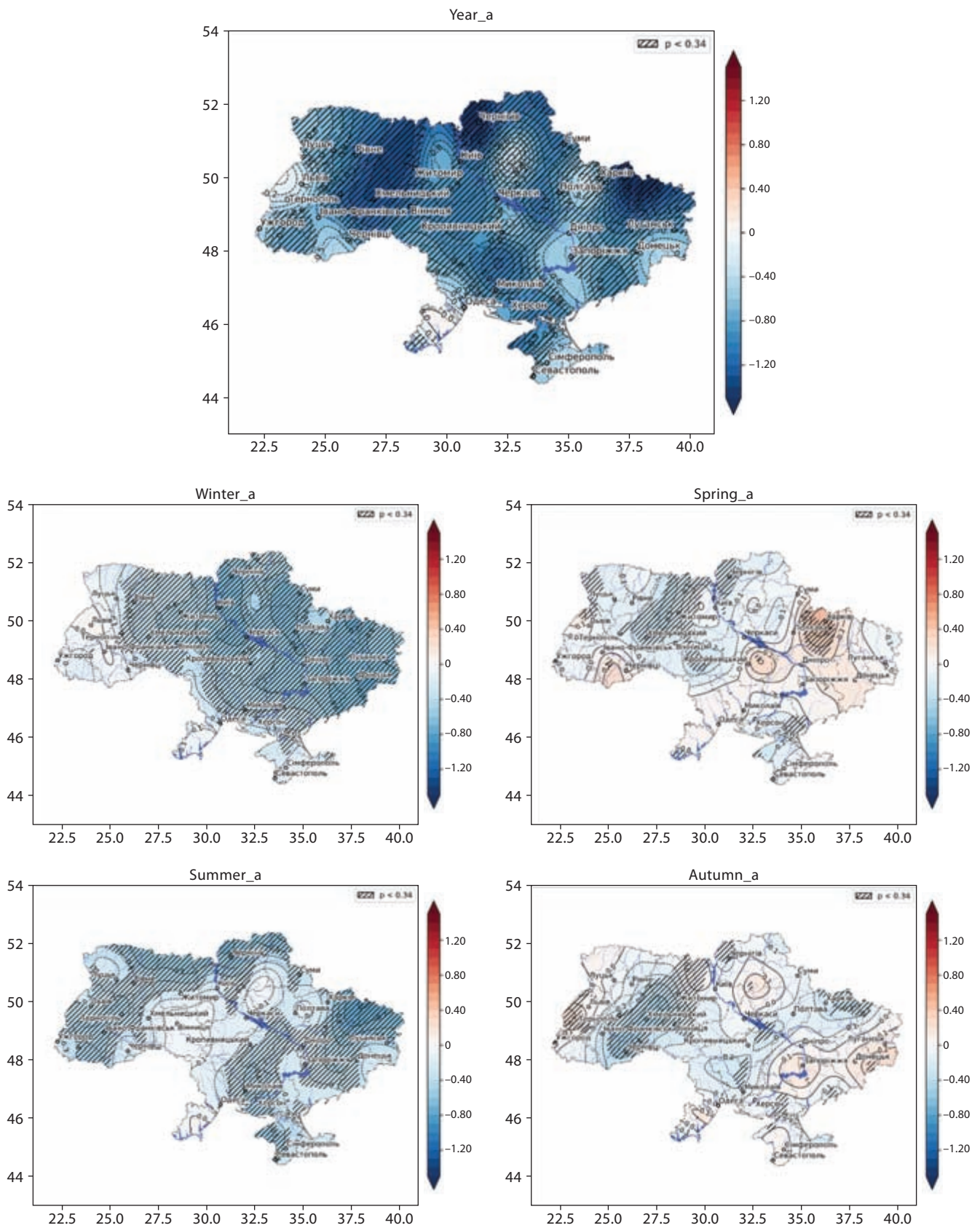


Fig. 11. The velocity and significance of the change in the average number of severe cold waves during the year and season. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

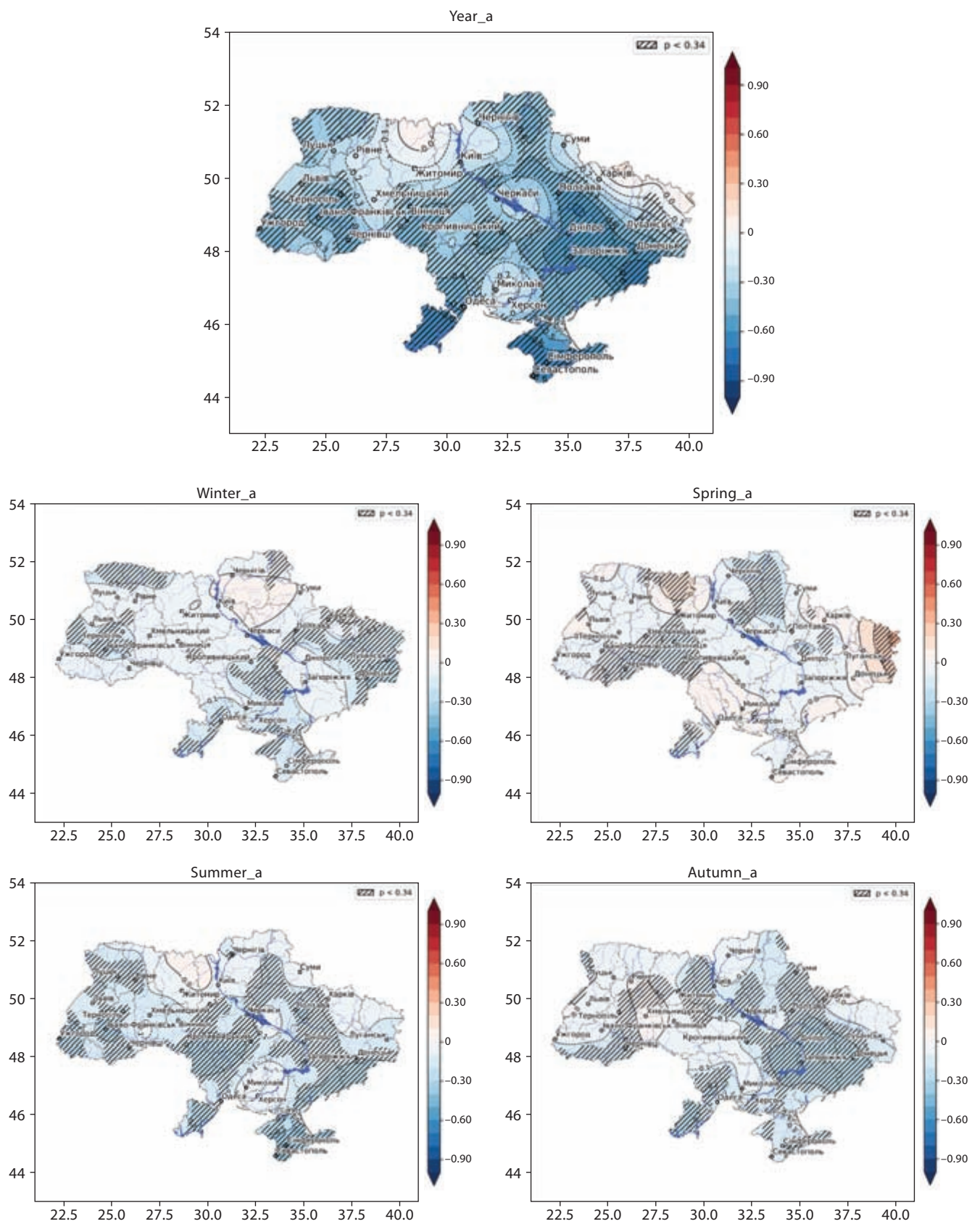


Fig. 12. The velocity and significance of the change in the average number of very severe cold waves during the year and season. 1981–2020: *a* — year; *b* — winter; *c* — spring; *d* — summer; *e* — autumn

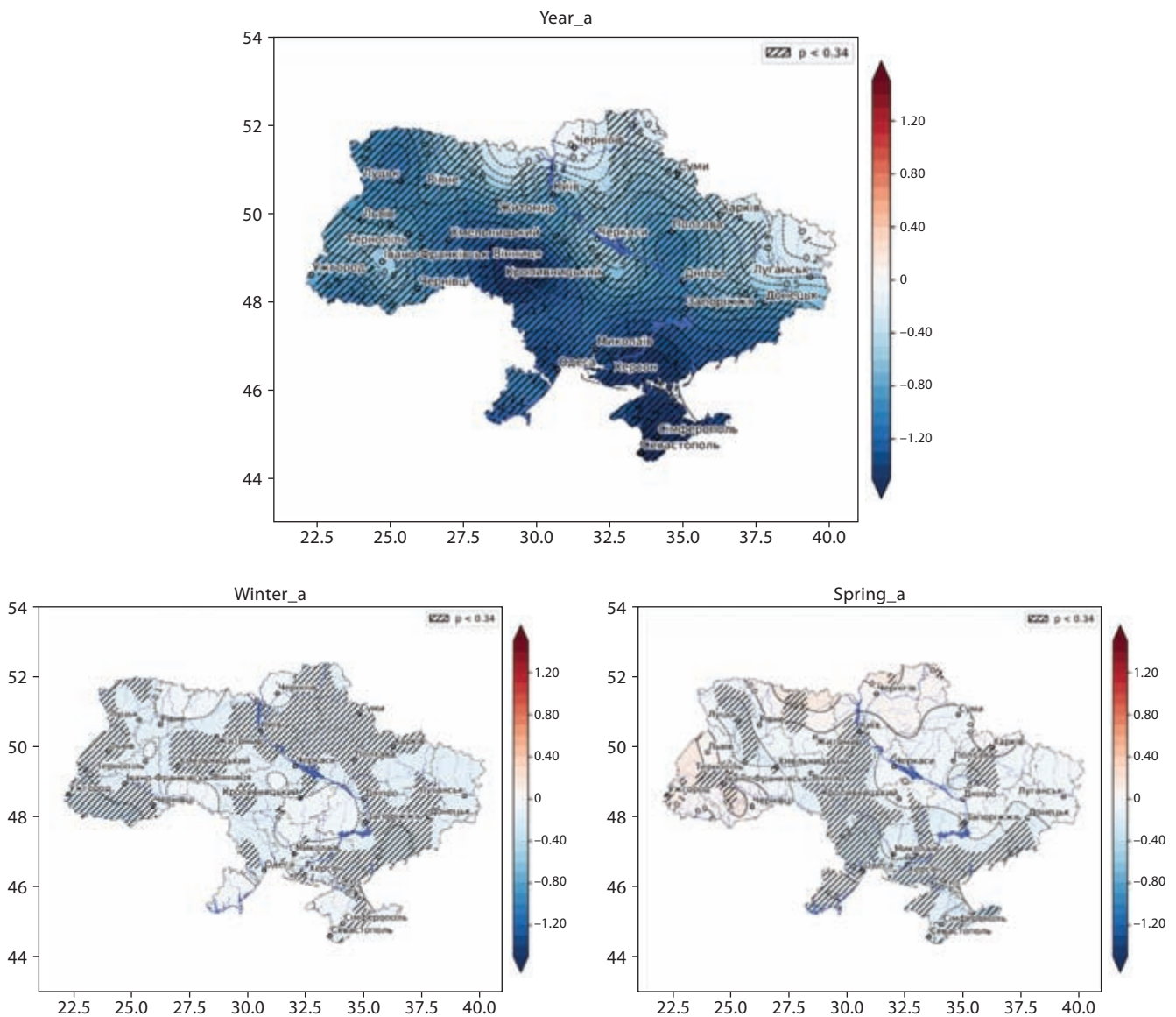


Fig. 13. The velocity and significance of the change in the average number of extreme cold waves during the year and season. 1981–2020: *a* — year; *b* — winter; *c* — spring

ing, and fruit set — leading to a sharp decline in productivity (Hatfield et al., 2011; Jendritzky, 1999; Wei, 2024). This is consistent with our findings that spring cold waves, although generally less frequent than winter ones, pose the greatest risk to agriculture, especially in the eastern Forest-Steppe, northern, and southern Steppe.

Although the total number of cold waves is decreasing, the increase in the frequency of sudden short-term cold spells during transitional seasons may increase the number of injuries (glaze, black frost), acute respiratory diseases, and additional burden on health care systems (Quesada et al., 2023).

The difference in the dynamics of extreme cold waves deserves special attention. Unlike severe and very severe cold spells, their frequency has remained practically unchanged over a 40-year period, and their spatial distribution is determined mainly by local circulation conditions. This confirms the assumption that the most extreme manifestations of cold are caused not by a general change in the climatic background, but by rare yet potentially dangerous circulation anomalies. The fact that extreme cold waves are most prevalent in Polissia and eastern Ukraine corresponds to the location of these regions along the typical trajectories of Arctic air.

The obtained results demonstrate that even with a decrease in the number of cold waves in Ukraine, high climatic instability persists, and there are local areas of increased risk, especially in the spring season. This points to the need to improve early warning systems for cold spells, adaptation strategies for agricultural production, and further research into the analysis of circulation mechanisms that cause extreme cold spells. The use of multifactorial models capable of taking into account regional circulation patterns, changes in snow cover, local orographic effects, and long-term indices of atmospheric variability is promising.

CONCLUSIONS

Cold waves remain a relevant weather phenomenon in Ukraine's territory, despite the global tendency towards temperature increase. Based on the analysis of the period of 1981–2020, significant spatial and temporal changes in their frequency, duration, and intensity have been identified. In most regions of Ukraine, there is observed tendency towards a decrease in the number of cold waves, both short-term and long-term ones. The most uniform decrease occurs in summer, while in spring and autumn the changes are more complex and regionally contrasting.

Spring cold waves show an increase in frequency in a number of regions, in particular in the eastern Forest-Steppe, northern and southern Steppe, and some areas of Polissia. It is these cold spells that remain the most dangerous for both agriculture and public health.

Extreme cold waves remain stable in frequency and intensity, indicating that they depend on individual circulation anomalies rather than the general warming trend. The highest intensity of such events is observed in the eastern regions, which are typical areas of Arctic air advection.

The established spatial and temporal structure of cold waves is of great agroclimatic importance. Cold spells during critical phases of crop development can cause significant crop losses, increase the risk of plant diseases, and affect the stability of agricultural production. Early and mid-season crops are most vulnerable to such events.

Cold waves pose a serious risk to public health. They increase mortality from cardiovascular and respiratory diseases, increase the number of injuries, and place an additional strain on the health care system, especially during transitional seasons.

Seasonal and regional specificities of cold wave dynamics reflect complex changes in atmospheric circulation in Eastern Europe, in particular, the weakening of the Eastern European anticyclone and the restructuring of cold intrusion trajectories.

The obtained results of a comprehensive analysis of the spatial and temporal characteristics of cold waves in Ukraine form the basis for the development of regionally oriented strategies for adaptation to extreme cold spells in agriculture, the energy sector, transportation, and life support systems. The identified trends and maps of changes in the frequency and intensity of cold waves can be used to improve early warning systems, predict risk situations, and increase the resilience of critical infrastructure. The results of the study are important for the agricultural sector, as they allow the identification of regions with the highest risks of spring and autumn cold spells, which negatively affect crop yields. The information about the reduction of long-term cold waves and regional specificities of their intensity is useful for optimizing energy planning, in particular for forecasting peak loads during cold periods. The methodological approach can be integrated into climate assessments for local communities, vulnerability assessments, and climate risk management plans. The data obtained form a scientific and applied basis for long-term planning in agricultural and infrastructure policy, as well as for developing health care recommendations regarding the impact of low temperatures.

Further research prospects include analyzing the relationship between cold waves and large-scale atmospheric circulation, and studying the sensitivity of various sectors of the economy and public health to extreme cold spells.

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ДИНАМІКА ПОВТОРЮВАНOSTІ ТА ІНТЕНСИВНОСТІ ХВИЛЬ ХОЛОДУ В УКРАЇНІ В УМОВАХ ГЛОБАЛЬНОГО ПОТЕПЛІННЯ

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Мета. Виявлення просторово-часових особливостей повторюваності, тривалості, інтенсивності та потужності хвиль холоду в Україні, а також визначення тенденцій їхньої зміни протягом 1981–2020 рр. **Методи.** У роботі використано сучасний кліматологічний та статистичний апарат, зокрема методи об'єктивної ідентифікації екстремальних подій на основі добових процентилів мінімальної температури повітря, аналіз розподілу ймовірностей та регресійні підходи для оцінки динаміки зміни показників. Кліматогеографічний аналіз сезонної мінливості показників дав змогу виявити їхні просторово-часові особливості у різних агрокліматичних зонах України. **Результати.** Уперше для всієї території України проведено систематизований аналіз хвиль холоду протягом 1981–2020 рр. із застосуванням єдиної методики, заснованої на порогових значеннях 32-го, 5-го та 0,3-го процентилів добових мінімальних температур повітря 187 метеорологічних станцій. На основі цих показників запропоновано класифікацію хвиль холоду різної інтенсивності: сильні (32 — 5-й перцентиль), дуже сильні (5 — 0,3-й перцентиль) та надзвичайні (нижче 0,3 перцентилію). Встановлено, що на території України щороку спостерігається в середньому 16–17 хвиль холоду, 84% з яких становлять сильні, 14% — дуже сильні та близько 1% — надзвичайні. Визначено комплекс просторово-часових закономірностей повторюваності, тривалості, інтенсивності та потужності хвиль холоду для всіх агрокліматичних зон, що дає змогу охарактеризувати кліматичні ризики з високою деталізацією. Встановлено що найінтенсивніші та найпотужніші хвилі холоду характерні для східних областей України (особливо Луганської, Сумської та Харківської), де мінімальна температура під час дуже сильних хвиль холоду у зимовий сезон може знижуватися до -20°C і нижче, а потужність таких хвиль досягати максимальних значень. Найменша повторюваність і слабо виражені хвилі холоду спостерігаються у західних регіонах, насамперед у Чернівецькій області. Зимові похолодання проявляються найінтенсивніше та тривають найдовше, тоді як весняні хвилі холоду створюють найбільші ризики для сільського господарства. Установлено статис-

тично значущі тенденції зменшення повторюваності та інтенсивності хвиль холоду в Україні, які корелюють з сучасними проявами глобального потепління в помірних широтах Північної півкулі. Виявлено суттєве ослаблення хвиль холоду в Україні протягом останніх чотирьох десятиліть. На всій території країни зафіксовано статистично значуще зменшення повторюваності як короткотривалих (2–5 днів), так і довготривалих (≥ 6 днів) хвиль холоду. Водночас зменшення довготривалих похолодань відбувається інтенсивніше та більш однорідне в просторі, що свідчить про ослаблення стійких адвективних вторгнень холодного повітря. Виявлено регіональні аномалії у зміні характеристик хвиль холоду, зокрема посилення короткочасних весняних похолодань у східному Лісостепу, степовій зоні, окремих районах Полісся та Прикарпаття. Це є новим ключовим результатом, який суперечить загальній тенденції до ослаблення хвиль холоду. Показано, що надзвичайні хвилі холоду мають іншу динаміку, ніж сильні та дуже сильні — їхня частота суттєво не змінюється, а просторовий розподіл чітко асоційований з локальними та регіональними циркуляційними особливостями.

Висновки. Хвилі холоду залишаються частим явищем на території України, попри загальне потепління клімату. Протягом 1981–2020 рр. в Україні відбувалося статистично значуще зменшення повторюваності хвиль холоду, особливо влітку та взимку що відповідає тенден-

ціям у помірних широтах Північної півкулі. Кількість довготривалих та короткотривалих похолодань скорочується, причому повторюваність тривалих (≥ 6 днів) хвиль холоду зменшуються найшвидше що свідчить про ослаблення стійких вторгнень арктичного повітря. Інтенсивність і потужність хвиль холоду мають тенденцію до зниження, найбільш виражену навесні та восени. Зимові та літні зміни є регіонально неоднорідними, з локальними зонами посилення похолодань на сході України. Найбільші ризики зберігаються у перехідні сезони, насамперед навесні, коли фіксується зростання повторюваності короткочасних, але різких похолодань у низці регіонів (східний Лісостеп, північний і південний Степ). Це створює загрозу для ранніх фаз розвитку сільськогосподарських культур. Надзвичайні хвилі холоду в Україні трапляються рідко та суттєво не змінюють своєї частоти, однак залишаються найнебезпечнішими за наслідками. Найвразливішими до них є Полісся, Лісостеп та східні регіони. Виявлені просторово-часові тенденції свідчать про пом'якшення кліматичного режиму в холодний період року, однак збереження високої мінливості та локальних ризиків екстремальних похолодань.

Ключові слова: зміна клімату, екстремальна температура повітря, хвиля холоду, похолодання, заморозки, проєкції зміни клімату, сценарії РТК4.5 та РТК8.5.