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Analysis of the dynamics of the temperature regime of the North-Western Black Sea region in the context of global climate changes

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ABSTRACT

Formulation of the problem. This study aligns with UN Sustainable Development Goal No. 13 – Climate Action – by addressing key climate-related challenges impacting sustainable development in Ukraine. It focuses on analyzing the dynamics of temperature-dependent natural resource indicators in the North-western Black Sea region, a vital industrial-agricultural area. Understanding the thermal regime is essential for adapting socio-economic sectors to climate change. The research supports planning and resilience in southern Ukraine under changing climate conditions. It is part of projects at the Faculty of Hydrometeorology and Ecology, Odesa I.I. Mechnikov National University, including: 'Forecasting hazardous meteorological phenomena over the southern regions of Ukraine' (No. DR 00115U006532); 'Comprehensive probabilistic-forecasting modeling of extreme hydrological events on the rivers of southern Ukraine to ensure sustainable water use under climate change conditions' (No. DR 0121U010964); 'Zoning of Ukraine's territory based on vulnerability to climate change and selection of optimal adaptation pathways.' This work fills critical gaps in the study of regional climate dynamics.

Analysis of previous research it proves the importance of studying the climatic indicators of the temperature regime of the North-Western Black Sea region, which is a leading highly developed industrial-agricultural region of Ukraine. The underestimation of certain aspects of the dynamics of climatic characteristics of the regional climate in the context of global climate change has led to these aspects being still insufficiently studied today.

The purpose. This article aims (using the Odessa station as an example) to present the results of a physical-statistical approach to determining regional responses in the main indicators of the temperature regime of the North-Western Black Sea region to the changes occurring in the climate system of the present period.

Research methods. The implementation of the physical-statistical approach was conducted using classical methods of statistical and graphical analysis.

Presentation of the main research material. Based on long-term empirical data, it was determined that during the period from 2013 to 2023, compared to the standard climatic period (1961-1990), the average number of days with maximum air temperature above 0°C increased in all winter months. For the studied area, January remains the coldest winter month, with an average of 23,5 days with a minimum air temperature of 0°C or lower. The beginning of the 21st century is characterized by warmer winter conditions (compared to the period 1961-1990), which has led to a decrease in the number of days with low air temperature. Over the last eleven years (2013-2023), 65 thaw periods were registered. They most frequently occurred in January, in December and in February.

Research results and Practical value. The obtained results provide a basis for analyzing the dynamics of regional climate changes in the context of global climate change. The rational and timely application of the climate information presented in this article will contribute to the development of effective adaptation pathways, which, in turn, will make a significant contribution to ensuring the sustainable development of Ukraine. Future tasks will focus on researching the thermal regime indicators of other stations in the North-Western Black Sea region, involving additional empirical data.

Keywords*: climate, thermal regime indicators, calendar season, long-term characteristics, temperature variability, thaw.*

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Statement of the problem *in a general form and its connection with important scientific and practical tasks.* The processes taking place in the geographical environment are determined, first of all, by thermal conditions. Wide use of data on air temperature for scientific and practical purposes requires climatologists to study various indicators that allow to assess the peculiarities of the temperature regime of any geographical region or individual point [1].

Climatological information is the basis for the formation of rational nature management, for solving natural and ecological problems, for perspective planning and placement of various branches of the economy [1, 2]. In recent decades, the study of the climate of our planet and its variability has acquired clearly defined practical significance [3-7]. In this regard, the concept of implementation of state policy in the field of climate change for the period until 2030 [2] is aimed at developing a national climate program and preventing the reduction of risks associated with them.

According to domestic scientists [8-14], as a result of global warming, the climate on the territory of Ukraine will change dramatically, and therefore each new study in this direction will provide an opportunity to analyze climate-related natural resources in order to ensure the sustainable socio-economic development of our country.

The study of changes and fluctuations of the temperature regime as a whole, as well as its individual characteristics, in order to take them into account in the spheres of economic activity, and the development of perfect methods of its forecasting for various territories of Ukraine with great advance, are of great practical importance at the present time. Air temperature determines the state of many natural resources, which are a component of economic resources [1, 8, 9, 11, 14, 15]

Connection of the author's work with important scientific and practical tasks. The research was carried out in accordance with the goals formulated in the research works of the departments of the Faculty of Hydrometeorology and Ecology of the Odessa I.I. Mechnikov National University after on the topics: 'Forecasting dangerous meteorological phenomena over the southern regions of Ukraine' (No. DR 00115U006532); 'Complex method of probabilistic and prognostic modeling of extreme hydrological phenomena on the rivers of Southern Ukraine to ensure sustainable water use in conditions of climate change' (No. DR 0121U010964); 'Zoning the territory of Ukraine according to the degree of vulnerability to climate change and choosing optimal ways of adaptation'.

Analysis of recent research and publications. Climatic changes occurring during the last decades cause concern of the scientific community. The researches of Ukrainian scientists point to the restructuring of climatic components that took place during the 20th century and continues in the 21st century [1, 9, 15-20]. The dynamics of the temperature-humidity regime and the assessment of its future changes and fluctuations under various climate scenarios for Ukraine are presented in works [1, 9, 11, 19]. The results of these studies indicate significant regional changes not only in time, but also in its spatial distribution. As is known, the formation of climatic fields occurs in close connection with the processes of circulation of air masses [1, 12, 13, 21-25]. The authors emphasize that on a global scale, the weakening of the zonal circulation and the growth of the meridional southern component is noted in all seasons of the year [10, 14, 21]. The paper [13, 21], which presents the results of a statistical study of relationships in the climate system of the Atlantic-European region, is devoted to the circulation aspects of the spatio-temporal distribution of the thermal regime for the Eastern European region in the main and transitional seasons of the year.

As you know, climatic factors are of decisive importance, in particular, in the formation of the hydroecological state of water resources. Overall, warming has intensified the global hydrologic cycle by increasing globally averaged precipitation, evaporation, and runoff. Moreover, the consequences of global warming are not only changes in average values, but also a general increase in extremes. During the last thirty years, extreme events have taken place in Ukraine, primarily related to the rainfall regime. For example, in some regions, the number of abnormally dry years, winters, and summers significantly increased, and the change in the temperature regime was reflected only in the increased number of abnormally hot summers. Such changes led to the fact that, for example, during the years 1998-2007, droughts were observed almost every year in some regions of Ukraine [26]. In connection with the expected increase in air temperature in the Northern Hemisphere, the food security of Ukraine (and especially its southern regions) will depend on how effectively agriculture adapts to climate changes [1, 9].

Taking into account that the results of the research of many scientists [16-18, 22, 25, 27] indicate particularly significant climate changes over the last decades in the temperate latitudes of the Northern Hemisphere, the authors [13] investigated the current dynamics of the temperature regime of the Eastern European region in the sector 40-60°N. and 20-44° east. Based on the reanalysis of «ERA-INTERIM» data for the period 1979-2013 average monthly values of surface air temperature and atmospheric pressure in 144 nodes of a regular grid of points 2°×2° were analyzed. A comparison of multi-year air temperature regimes in January and July for different averaging periods shows that the contribution of temperature changes in these months to climate continentality changes in different parts of the sector is ambiguous.

Analysis of the dynamics of the temperature regime during the winter season allows us to state that the air temperature near the surface of the earth in almost the entire territory increased by 1°C on average. In the summer season, the average monthly air temperature in most of the territory increased (compared to the long-term average value) and the highest temperature anomalies were observed in the period 2001-2010 (up to 2 °C). Analysis of the dynamics of the temperature regime in the transitional seasons of the year also indicates an increase in air temperature near the surface of the earth in the studied region [13].

As is known, the climate is formed under the influence of closely related factors, which have their own characteristics in each specific region of Ukraine. First of all, it is solar radiation, the nature of the underlying surface and atmospheric circulation. The interaction of these factors, their intensity and specific effects are characterized by a certain territorial individuality. In turn, each of the listed factors is formed under the influence of elements that also have their own individual geographical features [1].

The study of changes and fluctuations in the distribution of temperature characteristics and in the regime of precipitation (because they are one of the main indicators of the state of the climate system) for the purpose of taking into account in the spheres of economic activity, the development of perfect methods of their forecasting for various territories of Ukraine with great advance, have at the present time extremely important value [1, 11, 12, 16-19, 24].

The peculiarities of atmospheric circulation, the influence of the Black and Azov seas separate the south of Ukraine according to climatic characteristics into a separate area that requires research of its climate-related natural resources. Due to its geographical location and the state of the environment, the south of Ukraine is the territory for which the socio-economic consequences of climate change may be irreversible. Therefore, the scientific community is faced with the task of studying the reasons that lead to these changes, in order to predict the future state of the physical parameters of the most mobile links of the climate system.

For the territory of the Odesa region, a number of works [15, 20, 25, 27] were devoted to the study of the spatio-temporal dynamics of long-term indicators of the temperature and humidity regime. Based on a comparison of climate characteristics calculated for different averaging periods, the authors obtained results indicating regional scale variations, which are particularly noticeable at the current stage of global climate change.

Thus, as evidenced by the results of the above publications, it is extremely important to study the quantitative indicators of natural factors that influence the formation of the climate, which will allow predicting their future changes, and this, in turn, will help to timely assess meteorological and environmental risks in solving social problems, in order to ensure sustainable development of our country and especially its southern regions.

Highlighting previously unsolved parts of the general problem, to which the specified article is devoted. Now the issues of further socio-economic development of the state caused by changes in the earth's climate system are extremely urgent for Ukraine. Due to its geographical location and the state of the environment, the south of Ukraine is the territory for which the socio-economic consequences of climate change may be irreversible. It should be taken into account that global warming has sharply expressed regional features, namely – for some regions it brings favorable changes, for others – these changes are negative and can lead to economic losses in various sectors of the economy and aggravation of ecological tensions [1, 26].

In order to solve natural and ecological problems, prospective planning and adaptation of various branches of the economy of the southern region, in connection with global climate changes, a resource approach to the study of such changes is important. For this, further comprehensive research of hydrometeorological processes, increase of the information base using modern methods is necessary physical and statistical analysis [28]. Agriculture, fuel and energy, water and other sectors of the economy, health and tourism are related to the state of the natural environment. The temperature regime is changing: spatial and temporal distribution. Therefore, the use of climate resource - information about the atmosphere, its thermal state can be taken into account to solve specific socio-economic problems.

The purpose of this article, using the example of the Odesa station, is to present the results of a statistical approach to the determination of regional responses in the main indicators of the temperature regime of the North-Western Black Sea region to those changes that occurred in the climate system during the period of the second global warming, which began in the 70s x years of the last century and continues to the present time.

In accordance with the stated objective, the study includes the following tasks, the resolution of which will allow for determining the dynamics of specific temperature indicators in the North-western Black Sea region: analysing the average daily, maximum, and minimum air temperatures for the period 1991-2023, as well as inter-daily variability and the diurnal aperiodic amplitude of air temperature; determining the number of days and the duration of periods with low air temperatures (-10.0°C and below). Identifying the number of days and the duration of thaw periods.

The subject of the study is the database of empirical data on the average daily, maximum and minimum air temperature at St. Odesa for 2790 winter calendar days of the period 1991-2023 [29]. *The main task* is to determine regional temperature changes in the North-Western Black Sea region during the last decade of the 20th century and two decades of the 21st century and to determine trends in temperature indicators of the modern period, compared to the climatic norm of 1961-1990 [30]. The period of research of the thermal regime of the North-Western Black Sea Coast, the results of which are presented in this article, falls on the secondary global warming (the end of the 70s of the 20th century to the present), during which there is an intense global temperature increase, compared to the climatic norm of 1961-1990. The period of research of the thermal regime of the North-Western Black Sea Coast, the results of which are presented in this article, falls on the secondary global warming (the end of the 70s of the 20th century to the present), during which there is an intense global temperature increase.

Presentation of the main material *of the study with a full justification of the obtained scientific results.* As the data of meteorological observations show, in the last decades of the 20th and at the beginning of the 21st centuries, significant drops in the average daily air temperature became more frequent in Ukraine, the repeated occurrence of which during the month is almost always accompanied by dangerous and spontaneous meteorological phenomena, which requires the scientific community to study and forecast them.

In accordance with the set goal, the study covers the last three decades, which are characterized by intense global warming. In order to determine the climatic responses in the North-Western Black Sea region, at the first stage, a study of ***long-term changes in the average daily air temperature*** was carried out, which reflects the peculiarities of the temporal distribution of air temperature in more detail than the monthly average. Using the series of observations of this meteorological quantity in the period 1991-2023 [29], its long-term average values were calculated and the largest and smallest of them were determined, which are listed in the table 1.

Table 1

Long-term values of average daily air temperature at St. Odesa in three periods
(I – 1991-2000; II – 2001-2010; III – 2013-2023)

Month	Average daily temperature, °C						Average monthly, °C		
	minimal			maximum					
	I	II	III	I	II	III	I	II	III
December	-9,0	-6,4	-3,8	8,5	9,0	9,3	0,6	1,6	2,9
January	-9,0	-11,0	-9,5	4,5	7,3	7,1	-1,1	-0,2	-0,2
February	-7,5	-6,9	-5,3	6,4	7,2	8,5	0,2	0,3	2,1

As can be seen from the table 1, the range of values of the average daily air temperature has wide limits, but *in December* from the first (1991-2000) to the following periods under consideration, the temperature background is smoothed out, that is, the difference between its smallest and largest values decreases: from 17,5°C (I period) to 15,4°C (II period) and further up to 13,1°C (III period). For *January* and *February*, a similar trend (namely, a decrease in amplitude) is characteristic only for the period 2001-2023: *in January* – from 18,3 to 16,6°C and *in February* – from 14,1 to 13,8°C; from 1991-2000 by 2001-2010, on the contrary, the amplitudes increase – from 13,5 to 18,3°C *in January* and from 13,9 to 14,1°C *in February*.

Thus, it can be stated that the end of the 20th century was characterized by greater differences in the average daily air temperature in the study area than the beginning of the 21st. We also observe large differences between the given values and the average monthly air temperature.

At the next stage, the ***dynamics of the number of days with average daily air temperature in different gradations*** in the period 1991-2023 were analyzed. First, the total number of days for certain gradations of air temperature in the period 1991-2023 was determined. For this purpose, the following periods were analyzed: 903 (1991-2000), 935 (2001-2010) and 952 (2013-2023). The results of this stage are shown in table 2.

Analysis of the table 2 indicates that in the last decade of the 20th century and at the beginning of the 21st, *for all months of the winter season*, the average daily air temperature in the range of 0,1...5,0°C prevailed. *In December*, the number of days with an average daily air temperature of 0°C and below (from the previous to the following periods) decreased by 14,9%, *in January* – by 5,1%, and *in February* – almost twice (from 43,5% in the period 1991-2000 to 22,0% in 2013-2023). And, on the contrary, the number of days with an average air temperature above 0°C increases with each considered decade.

Thus, on St. Odesa, in the period 1991-2023, during which 2790 winter calendar days were analyzed, positive average daily air temperature was observed in 1673 of them and this is 60%. The most intensive growth of the indicator *was registered in February*, and *the smallest – in January*.

Table 2

The total number of days with average daily air temperature in different gradations at St. Odesa in three periods (I – 1991-2000; II – 2001-2010; III – 2013-2023)

i	Temperature, °C		*December*			*January*			*February*		
	from	to	I	II	III	I	II	III	I	II	III
1	-24,9	-20,0									
2	-19,9	-15,0				-	5	1			
3	-14,9	-10,0	8	4	-	10	9	12	5	11	1
4	-9,9	-5,0	40	29	8	44	47	45	25	32	21
5	-4,9	0,0	77	87	70	107	100	101	93	73	45
6	0,1	5,0	123	107	151	133	128	136	130	123	151
7	5,1	10,0	60	76	66	16	45	44	28	43	86
8	10,1	15,0	2	7	12				2	-	1
0°C and below			125	120	78	161	168	159	123	116	67
Above 0°C			185	190	229	149	173	181	160	168	238
Indicator in percentage											
0°C and below			40,3	38,7	25,4	51,9	49,3	46,8	43,5	40,8	22,0
Above 0°C			59,7	61,3	**74,6**	48,1	50,7	**53,2**	56,5	59,2	**78,0**

To study the dynamics of the average absolute frequency in the period 1961-2023, in the table 3 are determined for three time periods of the recurrence of the average daily air temperature according to the data of meteorological observations: the period of the last decade of the 20th century, two periods of the 21st century. They include data from the Climatic Cadastre of Ukraine for the period 1961-1990 [30].

In January in the period 1991-2023 temperature in the range from -24,9 to -20,0°C was not observed, although in the period 1895-1975 such a value (according to the well-known monograph [31]) was recorded on average once every 10 years. The daily temperature ranged from -19,9 to -15,0°C in the period

Table 3

The average number of days with average daily air temperature in different gradations at St. Odesa in four periods (I – 1961-1990; II – 1991-2000; III – 2001-2010; IV – 2013-2023)

i	Temperature, °C		Month											
			December				*January*				*February*			
	from	to	I	II	III	IV	I	II	III	IV	I	II	III	IV
1	-24,9	-20,0												
2	-19,9	-15,0	0,02				0,4	-	0,5	0,09	0,1			
3	-14,9	-10,0	0,3	0,8	0,4		2,1	1,0	0,9	1,1	0,9	0,5	1,1	0,09
4	-9,9	-5,0	2,3	4,0	2,9	0,8	**5,1**	**4,4**	**4,7**	**4,1**	**3,7**	2,5	3,2	1,9
5	-4,9	0,0	**8,5**	**7,7**	**8,7**	**7,0**	**9,4**	**10,7**	**10,0**	**9,2**	**10,9**	**9,3**	**7,3**	**4,1**
6	0,1	5,0	**13,6**	**12,3**	**10,7**	**15,1**	**12,0**	**13,1**	**12,8**	**12,4**	**10,5**	**13,0**	**12,3**	**13,7**
7	5,1	10,0	**6,0**	**6,0**	**7,6**	**6,6**	2,0	1,6	4,5	4,0	1,7	**2,8**	**4,3**	**7,8**
8	10,1	15,0	0,3	0,2	0,7	1,2				0,09	0,2	0,2	0,1	0,09

1991-2000 not registered, but already in 2001-2010 was observed 5 times in 10 years or 1 time in 2 years, which coincides with the period 1895-1975 [31]. In the years 2013-2023, the daily *January* temperature in this gradation was observed on average only 9 times in 100 years. *In the central month of winter,* the daily air temperature ranging from -14,9 to -10,0°C has been observed at the station since 1961, Odesa already almost every year with a decrease in the number of days on average by two times, compared to the norm. The dynamics of the number of days with a daily air temperature in the range from -9,9 to -5,0°C tends to decrease: from 5,1 days of the period 1961-1990 to 4,1 for the period 2013-2023.

In February at the beginning of the 21st century, the probability of a daily air temperature ranging from -9,9 to -5,0°C decreases on average, since in the second half of the 20th century it was 3-4 times annually, and now it is 2-3. *A similar trend in December* (table 3).

In winter at St. Odesa was dominated by daily air temperature from 0,1 to 5,0°C in almost all periods under consideration, with a slight difference *in February* in the period 1961-1990, in which the maximum falls on the limit of -4,9-0,0°C – 10,9 days. *In the first and last months of the winter season* in the period 2013-2023 (compared to the previous decade) the number of days with a daily temperature ranging from 0,1 to 5,0°C increased significantly – by 1,4 days *in February* and by 4,4 days *in December*.

In addition, the analysis of table 3 allows us to state that on Art. Odesa *in December* from 1961 to the present (26-29 days) and *in February* in the period 1991-2023 (24-26 days) annual daily air temperatures in the range from -4,9°C to 10,0°C were observed; *in January* 1961-2023 and in February (1961-1990), the number of days with a daily air temperature ranging from -9,9°C to 5,0°C prevailed – 26-28 and 25-26 days, respectively, in the above periods.

In general, the repeatability of average daily air temperature in higher temperature ranges, which indicates warmer winters, compared to the first half of the 20th century, has increased in the study region.

Average inter-day variability of air temperature. As stated in the fundamental monograph [1], an important indicator of the thermal regime of a certain territory (point) is the inter-day variability of air temperature. It reflects air temperature fluctuations caused by advection of heat or cold. Due to the fact that in the cold period of the year circulation processes play a significant role, the inter-day variability in winter in Ukraine is characterized by the largest values [1]. For the south of Ukraine, using data of 2790 days about the average daily air temperature at St. Odesa for three periods: one of the 20th (1991-2000) and two periods of the 21st (2001-2010 and 2013-2023) centuries, calculated multi-year average daily air temperatures for each day of a specific month of the winter season.

For clarity, on the basis of the obtained indicators, graphs of inter-day variability of air temperature and marked climatic norms (1961-1990) of average monthly air temperatures were constructed (fig. 1-3).

As can be seen from fig. 1, *in December* of the period 2013-2023 an excess of the daily air temperature in accordance with the climatic norm is clearly visible. In the period 1991-2010 inter-day variability has a more unstable thermal regime – in the first decade of the month (2001-2010), the temperature exceeds the climatic norm by 0,2-3,8°C (the norm is 1,4°C); the second and almost the entire third decades are characterized by temperatures that are already lo-

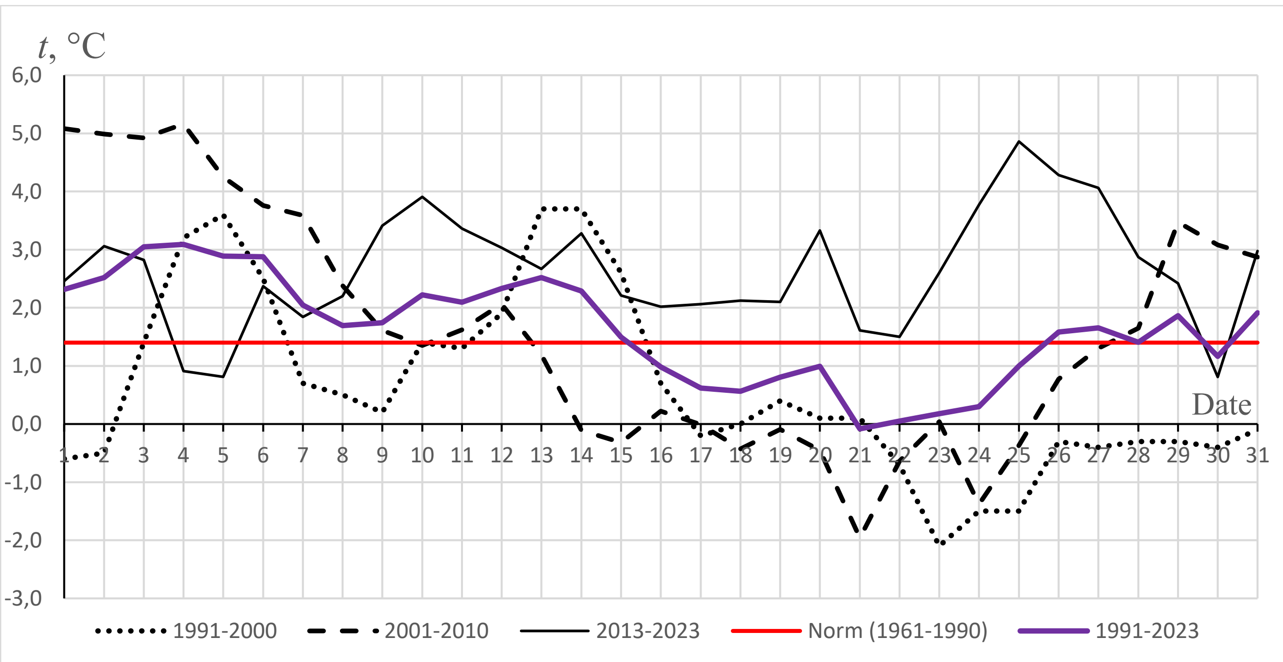

Fig. 1. Inter-day variability of air temperature (Odesa station, December)

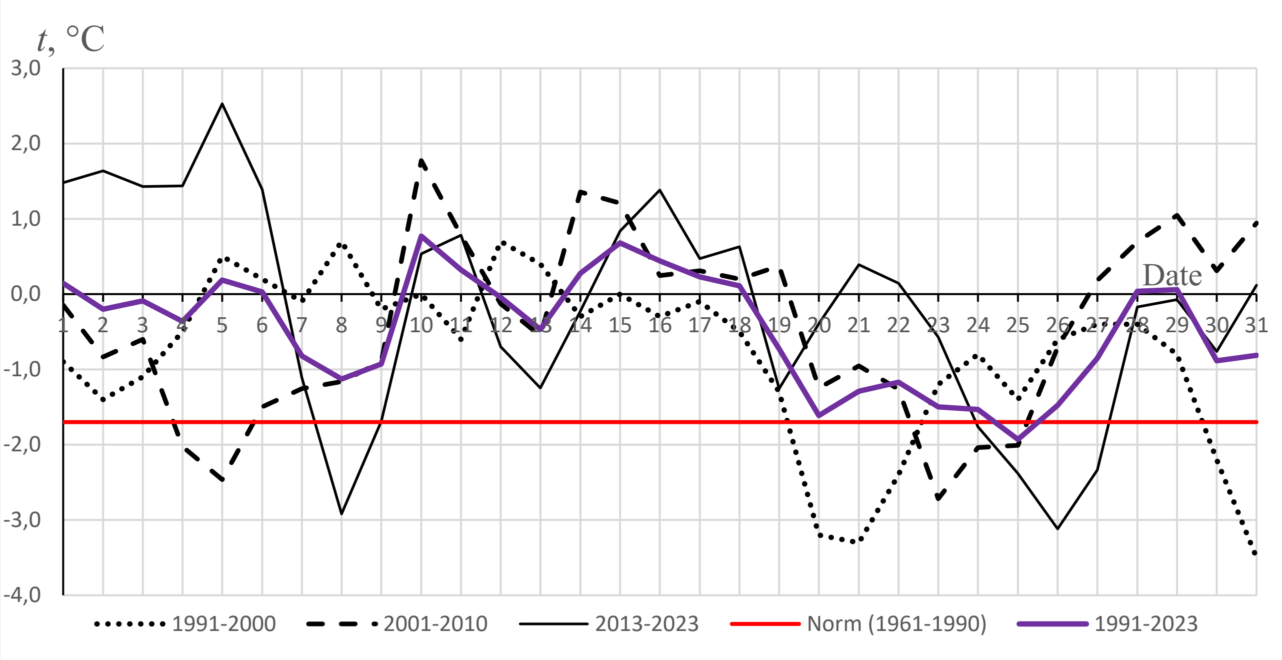

Fig. 2. Inter-day variability of air temperature (Odesa station, January)

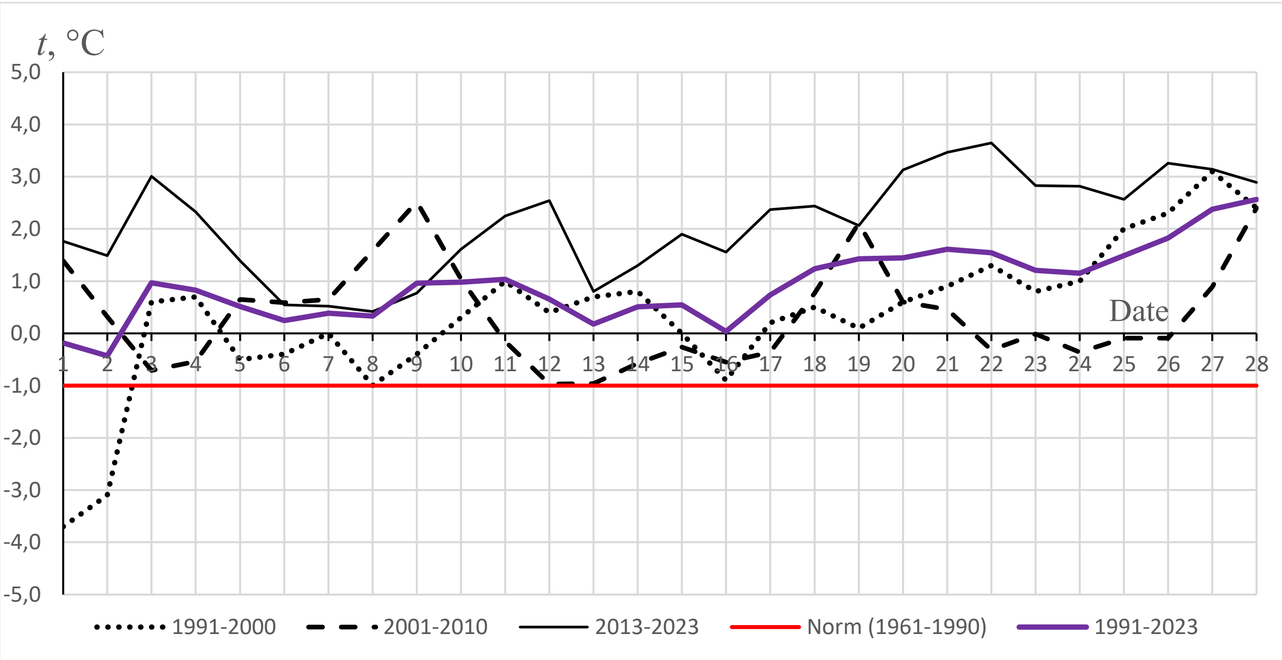

Fig. 3. Inter-day variability of air temperature (Odesa station, February)

wer than the norm by 0,1-3,4°C.

Analysis of fig. 1-3 allows us to state that only *in January*, from the first to the following decades, a similar trend in changes in the average inter-day variability of air temperature is observed. Multi-year daily amplitude *in December* of the period 1991-2000 is 5,8°C; period 2001-2010 – 7,2°C and 2013-2023 – 4,1°C. *In January*, from the 1st to the 3rd period, the indicator increases from 4,2°C to 5,6°C; *in February*, the inter-day variability of air temperature from 1991 to 2023 stabilizes, as the long-term average daily amplitude decreases – in the period 1991-2000 it is equal to 6,8°C; in the next decade – 4,2°C and in the period 2013-2023 is already 3,2°C. As the authors of the monograph [1] emphasize, this indicator is 2,2-2,6°C on average in winter in Ukraine.

In addition, as can be seen from Figures 1-3, *in January* and *February* for the last multi-year period (1991-2023), daily air temperatures significantly exceed the climatic norm. And only *in December* (on average) does the temperature correspond to the climatic norm of 1961-1990.

Thus, *in winter*, the inter-day variability in the study area, which reflects air temperature fluctuations caused by advection of heat or cold, and which, in turn, is related to atmospheric circulation, indicates a large spread of indicator values and depends on the month of the season. In our opinion, this is related to changes in circulation processes in the Northern Hemisphere, which were recorded at the end of the 20th and the beginning of the 21st centuries [21, 32], which is a response in the North-Western Black Sea region.

In addition to the considered indicators, important characteristics of the temperature regime of a certain territory (point) are the maximum, average maximum, absolute maximum and minimum, average minimum, absolute minimum air temperature. Below are the results of the study of the maximum and minimum air temperature, which were analyzed for the period 2013-2023 at St. Odesa.

In order to determine the dynamics of the extreme temperature indicators of the modern period, they were subsequently compared with the climatic norm (1961-1990).

Indicators of the maximum air temperature at St. Odesa in the period 1961-2023. The average maximum air temperature characterizes the warmest part of the day.

In the table 4 shows the average, the average of the absolute maxima of air temperature determined for the period 2013-2023. The listed indicators of the standard period (1961-1990) and the average monthly air temperature are given. The average maximum air temperature of each month was calculated as the arithmetic mean of the maximum thermometer. The average of the absolute maxima of air temperature was defined as the arithmetic mean of the maximum values recorded in each month of the analyzed period. The absolute maximum air temperature is not given, as it requires an increase in the volume of empirical data for analysis. But *in December and January*, it exceeded the value of the period 1961-1990, and *in February*, on the contrary, its decrease was recorded.

As can be seen from the table 4, the average and the average of the absolute maxima of the air temperature in the last period under consideration exceeded the climatic norm in all months of the winter season, but the most *in February*: the average by 3,8°C and the average of the absolute by 5,2°C.

Analysis of data on the maximum air temperature at St. Odesa showed that the maximum air temperature was above 0°C *in December* on 276 days out of 307, which is 89,9%; *in January* – 256 days out of 340, which is the least number of days among the winter months – 75,3%; *in February*, this indicator is 269 days out of 305 (88,2%).

In general, for the *winter season* of the period 2013-2023 out of 952 days, 801 days recorded the maximum air temperature above 0°C, which is 84,1%.

In the table 5 shows the average and largest number of days with a maximum air temperature above 0°C for two periods.

As can be seen from the table 5, in the period 2013-2023, compared to the standard climatic period (1961-1990), the average number of days with a max-

Table 4

Maximum air temperature (°C) at St. Odesa for two periods: I – 2013-2023; II – 1961-1990

Characteristic	*December*		*January*		*February*	
	I	II	I	II	I	II
Average	5,9	4,0	3,0	1,1	5,6	1,8
The average of the absolute	12,9	11,3	11,5	9,4	15,0	9,8
Average monthly	2,9	1,4	-0,2	-1,7	2,1	-1,0

Table 5

Number of days with maximum air temperature above 0°C on St. Odesa in two periods: I – 2013-2023; II – 1961-1990

Period, years	*December*		*January*		*February*	
	average	most	average	most	average	most
2013-2023	27,6	31 2017, 2019, 2023	23,3	30 2020	24,5	29 2016, 28 2013
1961-1990	26,0	31 1974	19,3	29 1975, 1989	18,1	28 1989,1990

imum air temperature above 0°C increased in all winter months: *in December* – by 1,6 days, *in January* – by 4,0 days and *in February* – by 6,4 days.

At the next stage of the research, using a series of observations of the minimum air temperature at St. Odesa in the period 2013-2023, received and analyzed ***indicators of the minimum air temperature,*** which characterizes the coldest part of the day.

In the table 6 shows the average minimum and the average of the absolute minimum air temperatures. The listed indicators of the standard climatic period (1961-1990) and the average monthly air temperature are given. The average minimum air temperature of each month was calculated as the arithmetic mean of the minimum thermometer. The average of the absolute minimum air temperatures was defined as the arithmetic average of the minimum values recorded in each month of the analyzed period. The absolute minimum air temperature is not given, as it requires an increase in the volume of empirical data for analysis.

As can be seen from the table 6, average minimum air temperature in the period 2013-2023 increased (compared to the climatic period) in all months of the winter calendar season: *in January* – by 0,4°C, *in December* – by 0,7°C, and most *in February* – by 1,8°C.

Table 6

Minimum air temperature (°C) at St. Odesa for two periods: I - 2013-2023; II - 1961-1990

Characteristic	*December*		*January*		*February*	
	I	II	I	II	I	II
Average	-0,4	-1,1	-3,8	-4,2	-1,4	-3,2
The average of the absolute	-7,5	-9,8	-14,6	-13,2	-9,8	-11,1
Average monthly	2,9	1,4	-0,2	-1,7	2,1	-1,0

A similar trend is observed with the average of the absolute minimum air temperatures, but only *in December* and *February*. *In January*, on the contrary, the average of the absolute minimums decreased (compared to the climatic norm of 1961-1990) from -13,2°C to -14,6°C.

Absolute minima of air temperature, which were determined for the entire period of instrumental observations, in the period 2013-2023 were not surpassed: *in December,* -23,1°C (1902), *in January*, -28,3°C (1940) and *in February*, -29,0°C (1929) opinion, the absolute minimum air temperature of the 20th century is unlikely to be changed, taking into account the global warming of the climate, which began in the 70s of the last century.

Analysis of empirical data showed that the minimum air temperature was 0°C and below *in December* on 184 days out of 307, which is 59,9%; *in January* – 258 days out of 340, which is the largest number of days among the winter months – 75,9%; *in February*, this indicator is 195 days out of 305 (63,9%). In general, for the *winter season* of the period 2013-2023 out of 952 days, 637 recorded the minimum air temperature of 0°C and below, which is 66,9%.

The average and maximum number of days with a minimum air temperature of 0°C and below in the period 2013-2023 was also calculated; average: *in December* it was 18,4, *in January* – 23,5, and *in February* – 17,7 days; the largest number of days: *in December* – 27,0 (2013*), in January* – 29,0 (2017) and *in February* – 24,0 (2017).

Thus, on St. Odesa and in the period 2013-2023, as well as in previous periods (according to research by Ukrainian scientists [1, 13]), *January remains the coldest winter month*, with an average of 23,5 days with a minimum air temperature of 0°C and lower.

During the winter season in Ukraine, conditions are often created for the formation of ***low air temperatures (-10,0°C and below)***. Such a decrease in air temperature is considered a dangerous weather phenomenon [1, 32]. As emphasized in the fundamental monograph [1], the low air temperature is caused by the intrusion of continental arctic air, which spreads in anticyclones from the northeast, north, or northwest behind diving cyclones. Cold anticyclonic weather is established, during which the Arctic air undergoes additional radiation cooling, which leads to a significant decrease in air temperature (-35... -30°C). For southern regions up to -25°C.

A strong cooling of the air also occurs during the spread from the east of the spur of the Siberian anticyclone, which is intensified by anticyclones from the northwest or northeast. If the spur is oriented from the northeast, cold air can spread over the entire country. A decrease in air temperature also occurs in those cases when a high multicenter depression forms over the southeast of Eastern Europe and Western Siberia, behind which there is a significant advection of cold in the western and southern regions. Long-term maintenance of air temperature -10,0°C and below in combination with atmospheric phenomena negatively affects the activity of many branches of the economy and, first of all, agricultural production. Such a decrease in air temperature causes the death of winter crops, fruit trees, and forest plantations. At an air temperature of -25,0°C and below, the parts of machines and mechanisms are destroyed, the operation of railway transport deteriorates [1].

An important characteristic thermal regime is ***the duration of the period with low air temperature***, which can vary widely from month to month: from several hours to several days. The analysis of empirical data made it possible to analyze this indicator in the period 2013-2023. It turned out that at Art. Odesa *in December*, the longest duration of low air temperature was recorded for 3 days (21, 22, 23) and was observed in 2021 (-10,0°C); in general, 9 days out of 307 days were registered, that were considered; *in December* 2015, 2017, 2019, 2020 and 2023, a temperature of -10,0°C and below was not registered at the station. *In January*, the years 2016 and 2021 were marked by particularly long periods with low temperatures (up to 7 days) (-10,0... -19,0°C). Of the 340 days of the 11-year period for the central month of the winter season, air temperatures of -10,0°C and below were recorded in 54 days; *January* 2020 and 2023 were the warmest – no such temperatures were recorded.

Low temperatures *in February* 2013-2023 were observed on 18 days out of 305. Long periods with temperatures of -10,0°C and below were recorded in 2014 (6 days: 1.02-6.02); 3 days *of January* (29.01-31.01) are added to them. In 2018, 4 days (25.02-28.02) have been determined, followed by an extension in March, two more days (1.03-2.03). *In February* 2016, 2020, 2022 and 2023 low temperatures at Odesa is not recorded.

The authors V.M. Babichenko, S.F. Rudishina, N.V. Nikolaeva, L.M. Gushchyna [1] the emphasizes the significant interest of data on the repeatability of low air temperatures of -20, -25, -30°C and below. Such a temperature, although it does not last long, often causes significant damage to agriculture. Therefore, it was interesting to analyze the presence (absence) of such temperatures at St. Odesa in the period 2013-2023. In eleven years, only one case with a minimum temperature of -20°C and below -21°C was recorded (January 8, 2015).

Table 7 contains the average number of days with minimum air temperature in different gradations from 2013 to 2023. To determine the dynamics of this indicator in months of the winter calendar season, information of the standard climatic period is provided.

Table 7

The average number of days with low air temperature in different gradations
for two periods: I – 2013-2023; II – 1961-1990

Temperature, °C	*December*		*January*		*February*	
	I	II	I	II	I	II
≤ -10,0	0,9	1,6	4,9	6,1	1,6	3,3
≤ -15,0		0,1	1,7	1,8	0,2	0,7
≤ -20,0			0,09	0,2		0,03
≤ -25,0				0,03		0,03

As can be seen from the table 7, on St. Odesa the number of days with a minimum air temperature of -10,0°C and below was reduced by half (compared to the climatic norm) *in December*. In the range of -15,0°C and below, not a single case was recorded in the eleven years of the period 2013-2023. *January* also became warmer (compared to the climatic norm). The number of days with a low air temperature of -10,0°C and below decreased from 6,1 (1961-1990) to 4,9 days (2013-2023). *In the central month of the winter season*, the minimum air temperature in the range of -15,0°C and below almost corresponds to the climatic norm, and in the range of -20,0°C and below, it has become a rare phenomenon, since the average number of days in the period 2013-2023 is 0,09 (9 times in 100 years), compared to the period 1961-1990, in which such a temperature was observed once in five years with an indicator of 0,2.

The minimum air temperature of -25,0°C and below was not observed at all in the first period, while in the years 1961-1990 it was observed three times in 100 years. *In the last month of the winter season*, the number of days with a minimum air temperature of -10,0°C and below almost halved: from 3,3 (1961-1990) to 1,6 days (2013-2023); the number of days with an air temperature in the range of -15,0°C and below almost tripled: from 7 cases in every 10 years (1961-1990) to 1 case in every 5 years. On St. Odesa in the period 2013-2023 the minimum air temperature in the range of -20,0°C and below was not recorded *in February*.

Thus, the beginning of the 21st century is characterized by warmer winter conditions (compared to the period 1961-1990), which caused a decrease in the number of days with a low air temperature of -10,0°C and below.

Daily amplitude of air temperature in the winter season. The authors of the well-known monograph [1] emphasize that the amplitude of temperature fluctuation is one of the important indicators of air temperature. Amplitude information is important for many industries, especially construction, as a large amount of work is done outdoors. It is also necessary for agricultural production. Amplitude data is used in weather forecasting. For the territory of Ukraine, this issue has hardly been studied, despite its importance and relevance. Daily changes in air temperature depend on the nature of the weather. In winter, the largest daily amplitude is due to the movement of atmospheric fronts and a sharp change in air masses. The periodic daily amplitude is the difference between the warmest and coldest times.

In this article, aperiodic amplitudes are defined and analyzed. By definition [1]: 'It is the difference between the average maximum and average minimum temperature, which gives an idea of the average daily amplitude and characterizes the instability of the weather of a given month'.

In the table 8 shows the average daily air temperature amplitude calculated for the period 2013-2023 and the amplitude of the standard climatic period, taken from the climatic Cadastre of Ukraine. As can be seen from the table 8, at the beginning of the 21st century on St. Odesa, during the winter calendar season, the daily amplitude decreases compared to the standard climatic period: *in December* and *January* – by 1,5-1,6°C, which is almost 30%, and the largest *in February* – by 2,0°C and the growth of this daily air temperature index exceeds 40%.

In the table 9 shows the values of the absolute amplitude of the air temperature, calculated for each month of the winter season based on the values of daily maximums (according to the maximum thermometer) and daily minimums (according to the minimum thermometer) of the air temperature.

As can be seen from the table 9, *in the winter season* of the period 2013-2023 absolute monthly amplitude of air temperature at St. Odesa fluctuated between 22-26°C. *The highest* temperature was recorded *in January* (26,2 °C), and *the lowest in December* (21,5 °C).

Table 8

Average daily aperiodic amplitude of air temperature

Month	Daily temperature, °C		Amplitude, °C		Difference, °C (I – II)
	maximum	minimal	I 2013-2023	II 1961-1990	
December	5,9	-0,7	6,6	5,1	1,5
January	3,1	-3,8	6,9	5,3	1,6
February	5,6	-1,4	7,0	5,0	2,0

Table 9

Daily extremes (t_{max}, t_{min}) and absolute monthly amplitude (*A*) of air temperature, °C

Year	*December*			*January*			*February*		
	t_{max}	t_{min}	*A*	t_{max}	t_{min}	*A*	t_{max}	t_{min}	*A*
2013	9,3	-9,0	18,3	13,0	-16,0	29,0	10,6	-5,0	15,6
2014	14,8	-11,0	25,8	13,4	-17,0	30,4	11,0	-14,0	25,0
2015	17,0	-8,0	25,0	9,0	-21,0	30,9	12,0	-10,0	22,0
2016	12,1	-11,0	23,1	9,8	-19,0	28,8	22,0	-5,0	27,0
2017	14,0	-5,0	19,0	5,6	-16,0	21,5	16,1	-11,0	27,1
2018	9,0	-14,0	23,0	11,7	-12,0	**23,7**	12,0	-17,0	29,0
2019	15,0	-8,0	23,0	9,8	-13,0	22,8	15,2	-10,0	25,2
2020	12,0	-4,0	16,0	12,0	-7,0	19,0	18,0	-8,0	26,0
2021	13,0	-10,0	23,0	13,0	-19,0	32,0	18,1	-14,0	32,1
2022	-	-	-	14,0	-18,0	32,0	14,0	-6,0	20,0
2023	15,9	-3,0	18,9	15,7	-3,0	18,7	15,6	-7,5	23,1
Average			21,5			26,2			24,7

The amplitude of the air temperature does not remain constant from year to year and undergoes fluctuations. The absolute amplitude of air temperature fluctuations (the difference between the absolute maximum and the absolute minimum) gives the greatest changes in air temperature in any part of Ukraine [1].

Thaw. A characteristic feature of the winter season in Southern Ukraine is frequent thaws. A day with a thaw is considered a day when the maximum air temperature above 0°C is observed against the background of constant negative air temperature [1].

Intense and prolonged thaws are considered a dangerous phenomenon. After low air temperature, they negatively affect the overwintering of winter crops, reduce their hardening, sharply increase the consumption of carbohydrates, cause the formation of an ice crust, water saturation of the upper soil horizon, which during the next decrease in air temperature can lead to freezing of winter crops. Intensive melting of snow leads to wetting and washing of winter crops. Freezing and thawing of various metal structures and building structures reduces their stability and prevents construction work. During a thaw, the walls of buildings get wet, and with the subsequent cooling, an ice crust forms on them, which leads to their collapse. Thaws hinder the movement of trucks and motor vehicles. Sometimes, during the thaw, the ice on the rivers breaks in the middle of winter and floods are noted. Frequent change of periods of thaws with frosts reduces the resistance of the human body, the number of cold diseases increases. Thaws are caused by the instability of the weather in the winter season, are most often found in the south of Ukraine [1]. Considering the conditions listed above, it was important to analyze this indicator of the thermal regime for the St. Odesa, which was carried out based on the data of the maximum air temperature in the months of the winter season for the period 2013-2023.

In the first month of the winter season, no thaws were observed in 2017, 2019, 2020 and 2023. In those years, the maximum air temperature at the station during the month was positive. Unfortunately, there are no data for 2022. *In December*, 15 periods with thaws were characterized by different duration and intensity. The longest duration was recorded in 2014 and 2021 – 20 days with temperatures from 1,2 to 14,8°C against the background of constant negative temperature according to the maximum thermometer in the range of 0,0 ... -3,9°C. The thaws of 2018 (duration of 16 days with temperatures of 0,2-9,0°C against the background of negative temperatures of -1,0 … -2,9°C) and 2015, in which the duration of the thaw consisted of 18 days with temperatures of 1,7-17,0°C against the background of negative temperatures of -1.0... -3.5°C. The thaw in 2013 lasted 19 days with temperatures in the range of 2,0-9,3°C against the background of much lower negative temperatures (0,0... -1,0°C).

In January, 340 days (2013-2023) with maximum air temperature were analyzed and 32 periods with thaws were determined, which amounted to 226 days in eleven years. Thaws *in January* (as well as *in December* and *February*) were characterized by different duration and intensity. The longest duration was recorded in 2014 and 2015 – 21 and 22 days, respectively. The thaw in 2014 was characterized by maximum air temperatures of 0,2-13,4°C against a background of constant negative temperature within the range of 0,0...-8,2°C. Another thaw this year lasted only 2 days with temperatures of 1,0°C, but against the background of already lower temperatures (-5,0... -11,0°C).

The 2015 thaw, which lasted 22 days, was characterized by positive temperatures from 2,0°C to 9,0°C against the background of negative temperatures -1,0... -11,8°C.

The thaws of 2013 (three periods lasting 12, 6, and 2 days), 2016 (three periods lasting 13, 5 and 1 day), 2017 (four periods lasting 5, 4, 4 and 1 day), 2018 (three periods), 2019 (five periods – 9, 6, 4, 3 and 2 days of different intensity), 2021 (12, 12 and 2 days) and 2022 (10, 10 and 5 days), in which three periods and the year 2023 (11, 10, 2 and 2 days) are registered. And only in 2020, no negative air temperatures were registered, but only positive ones – in the range of 1,0-12,0°C.

In the last month of the winter season, 18 periods (160 days) with thaw were recorded, which accounted for 30% of the total number of days with thaw. In 2013, 2016, 2020 and 2022, only positive temperatures were observed and, thus, thaws were not recorded. Prolonged thaws were registered in 2014 (one period of 24 days with temperatures of 1,0-11,0°C against the background of negative air temperatures in the range of -2,0…-7,0°C); a similar picture was observed in 2023 (21 days), 2019 (22 days), 2018 (23 days); 2015 and 2021 turned out to be more unstable, with frequent thaws of varying duration and intensity.

It turned out that in the past eleven years, 65 thaw periods were registered, which totaled 539 days per season. *Most often* (42% of the total number of days), they were repeated *in January* – 32 cases; *in December* there were 15 (28%) of such cases, and *in February* – 18 (30%).

As stated in the monograph 'Climate of Ukraine' [1]: 'Thaws significantly affect the regime of snow cover. The greater the repeatability of thaws, the less likely it is to form a stable snow cover. Years with frequent and long thaws are characterized by a small number of days with snow cover and its low altitude, and sometimes even a complete absence of snow cover. Thaw lasting more than 10 days almost always leads to snow cover of any height. In winter, when thaws are rarely observed, the snow cover is always stable'. Therefore, information about thaws is very important for the North-Western Black Sea region, which is the leading highly developed industrial and agricultural region of Ukraine.

Conclusions:

1. An analysis of empirical data from 1991 to 2023 indicates that the late 20th century was characterized by greater fluctuations in the average daily air temperature in the study area compared to the early 21st century. During this period, 60% of the days exhibited positive temperature values, predominantly ranging from 0.1°C to 5.0°C. The most significant increase in temperature was recorded in February, while the least pronounced change was observed in January. Overall, the study region has experienced an increased frequency of average daily air temperatures within higher temperature ranges, indicating milder winters compared to the first half of the 20th century.

2. The inter-daily variability of air temperature at the St. Odesa exhibits significant fluctuations and depends on the month of the winter season. In our view, this variability is associated with changes in atmospheric circulation processes in the Northern Hemisphere, which were observed at the end of the 20th and the beginning of the 21st century, and have consequently influenced the climate dynamics in the North-western Black Sea region.

3. The average and the mean of absolute maximum air temperatures during the period 2013–2023 exceeded the climatic norm for all months of the winter season, with the most significant deviations recorded in February: the mean temperature was higher by 3.8°C, and the mean of absolute maximums exceeded the norm by 5.2°C. In 84.1% of cases, the maximum daily temperature was above 0°C. The average number of days with a maximum temperature above 0°C increased compared to the climatic norm: by 1.6 days in December, 4.0 days in January, and 6.4 days in February.

4. The average minimum air temperature during the period 2013-2023 exceeded the climatic norm, increasing by 0.4°C in January, 0.7°C in December, and reaching the highest deviation of 1.8°C in February. A similar trend was observed in the mean of absolute minimum air temperatures, but only in December and February; in January, however, this indicator fell below the climatic norm of 1961-1990 by 1.4°C, from -13.2°C to -14.6°C. During the study period, the number of days with a minimum air temperature of 0°C or lower accounted for 66.9%. At the Odesa station, January remained the coldest winter month between 1991 and 2023, with an average of 23.5 days per year registering minimum temperatures of 0°C or below.

5. The average number of days with a minimum air temperature of -10.0°C or lower has significantly decreased over the past eleven years across all winter months (compared to the climatic norm). This reduction is most pronounced in December and February, where the frequency has halved – from 1.6 to 0.8 days and from 3.3 to 1.6 days, respectively. In January, the decrease was from 6.1 to 4.9 days. For temperatures of -15.0°C or lower during 2013-2023, no occurrences were recorded in December (compared to a norm of once per decade). In January, the frequency remained close to the climatic norm, with an average of 1.7 days (compared to the norm of 1.8). In February, temperatures of -15.0°C or lower were observed twice in ten years, whereas the historical norm is seven times per decade. Minimum temperatures of -20.0°C or lower have become increasingly rare. In December, such temperatures have not been recorded for the entire observational period (1961-2023). In January, only one occurrence of -20°C or lower (-21.0°C, recorded on January 8, 2015) was documented, compared to the norm of once every five years. In February, no cases were observed, whereas the historical norm was three occurrences per century. Extremely low temperatures of -25.0°C or lower have not been recorded in the 21st century, while during 1961-1990, such temperatures occurred three times per century in January and February. These findings indicate that the early 21st century is characterized by significantly milder winter conditions compared to the 1961-1990 period, as evidenced by the reduced number of days with extremely low air temperatures.

6. At the beginning of the 21st century, the daily aperiodic amplitude of air temperature at the Odesa station during the winter season has decreased compared to the standard climatic period. In December and January, the reduction amounts to 1.5-1.6°C, which corresponds to nearly 30%, while the most significant decrease is observed in February – by 2.0°C – where the decline exceeds 40%.

7. Over the eleven years of the 21st century, 65 thaw periods have been recorded, totalling 539 days. These periods occurred most frequently in January, accounting for 32 cases (42% of the total thaw days). In December, 15 cases (28%) were documented, while in February, 18 cases (30%) were recorded.

8. The obtained results may serve as a foundation for analysing the dynamics of regional climate change in the context of global climate transformations. The rational and timely application of the climatic information presented in this study will contribute to the development of effective adaptation strategies, which, in turn, will significantly support the sustainable development of the country. Future research will focus on studying the thermal regime indicators of other southern regions of Ukraine.

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Аналіз динаміки температурного режиму північно-західного Причорномор'я в контексті глобальних кліматичних змін

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Температура повітря, як одна з основних метеорологічних величин, визначає характер та режим погоди, впливає на різнобічну життєдіяльність людини будь якої території. У статті, на прикладі станції Одеса, пропонується статистичний підхід до визначення регіональних відгуків у температурному режимі Північно-Західного Причорномор'я у зв'язку з глобальними кліматичними змінами. Проаналізована база емпіричних даних за 2790 зимових календарних днів періоду 1991-2023 рр., в яких 60% спостерігалась додатна середня добова температура повітря. Отримані показники порівнювалися зі стандартною кліматичною нормою 1961-1990 рр.. Проаналізована середня міждобова мінливість температури повітря, досліджена динаміка екстремальних температур повітря у період 1961-2023 роки. Визначено число днів і тривалість періоду з низькою температурою повітря (-10,0°С і нижче). З'ясовано, що початок XXI століття характеризується зменшенням числа днів з низькою температурою повітря -10,0°С і нижче, тобто в регіоні відмічаються більш теплі зими (порівняно з періодом 1961-1990 рр.). Наводяться значення абсолютної амплітуди температури повітря, які розраховувалися для кожного місяця зимового сезону за значеннями добових максимумів та добових мінімумів температури повітря. Визначена добова аперіодична амплітуда температури повітря. На ст. Одеса за одинадцять останніх років зареєстровано 65 періодів з відлигою, які за сезон налічували 539 днів. Найчастіше (42% загального числа днів) вони повторювалися у січні – 32 випадки; у грудні таких випадків зареєстровано 15, що складає 28% та у лютому – 30% (18 випадків). Запропонований статистичний підхід (на прикладі конкретної станції) є певним внеском у вивченні як теоретичних, так і практичних аспектів дослідження термічного режиму окремих територій з використанням емпіричних даних. Отримані результати можуть бути враховані для вирішення конкретних соціально-економічних та природно-екологічних проблем, перспективного планування та адаптації різних галузей економіки в умовах глобальних кліматичних змін.

Ключові слова: *клімат, показники термічного режиму, календарний сезон, багаторічні характеристики, температурна мінливість, відлига.*

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