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HEAT WAVES ANALYSIS OF 2023 SUMMER IN EASTERN PART OF ROMANIA AND ATMOSPHERIC INSTABILITY EVENTS WHICH SUCCEEDED BETWEEN THEM

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Abstract. The purpose of this paper is a general climatic characterization of the 2023 summer in the region of Moldavia, in eastern part of Romania, but with focus on the analysis of the context in which the most intense tropical air advections occurred in this region. The most significant and lasting tropical air waves were in July and August. From a thermal point of view, June had only one interval in which the maximum temperatures exceeded, for 3 consecutive days, the threshold of 30ºC (between 22nd and 24th of June). Instead, in July there were three intervals in which the maximum temperature exceeded this threshold, for more than 3 days in a row (between 01st - 06th, 15th - 22nd, 24th - 26th of July), and August had the longest such intervals (between 03rd – 06th, 13th – 29th of August). Also, in August, there were four consecutive days with maximum temperatures that exceeded the heat wave threshold (26th -29th of August). Without achieving new absolute temperature records (the highest maximum temperature in this interval being 39˚C at the Iași meteorological station, on August 28th), the last heat wave was notable in terms of duration of manifestation. Considering the definition given by the World Meteorological Organization (WMO) in 2020, according to which heat waves are considered those periods of time that are unusually warm in relation to multi-year averages and that last more than 2 consecutive days, we can frame the tropical air advection of July and August in the category of heat waves.

Keywords: heat wave, atmospheric instability, thermal discomfort.

1. Introduction

The summer of 2023 has been characterized by the Copernicus Climate Change Service (CCCS) as a "season of contrasts" in Europe, with a cooler-than-average June in the south but warmer and drier in the north of the continent, followed by a July and August cooler and wetter than average in northern regions, while southern and central Europe experienced intense heat waves and wildfires [1].

A generally valid definition of heat waves, which can be applied anywhere on the Globe, has not been formulated so far because it is impossible to establish numerical limits, which can be widely adopted [2]. For this reason, there are several definitions developed based on the specifics of each region globally, depending on geography, topography, but also the built-up area [3]. Considering this aspect, a comparative analysis of heat waves between different regions is difficult to achieve, as they can have a different impact even in the same location. Severity, spatiality and duration are the main characteristics of heat waves, on which comparisons can be made between different events [3], and all the heat waves fall under the category of extreme weather events. The Met Office defines heatwaves as prolonged periods of time with unusually high temperatures for a given territory at a given time [4]. The World Meteorological Organization [5] has provided several definitions of heat waves, including those periods of time in which the maximum temperature exceeds with 5˚C for at least five consecutive days, the maximum temperature considered normal for a region (referred to the reference period 1981-2010) [6].

The WMO also offered another definition of heat waves in 2020: an unusually warm period for a region manifested in the summer season, which persists for at least two consecutive days and in which air temperatures exceed a thermal threshold, established in relation with the specific local climate. The WMO [5] also makes a clear distinction between heat values and so-called "warm spells", the latter referring to a short period of time with very hot weather which record higher temperature values compared to the average, for a certain region, but which can occur at any time of the year, while heat waves can only occur in the warm season specific to a region. Tropical air advections that cause large positive temperature anomalies from a reference period (lasting 3...5 consecutive days or more) and even breaking thermal records, associated with high thermal discomfort, can constitute heat waves [7].

There is a direct link between the phases of the Arctic Oscillation (AO) and the intrusions of warm air on the continent [8], the AO being a good indicator to forecast heat waves. The AO

index fluctuates between positive and negative values. The positive phase of AO favors warm weather in Europe and the negative phase favors cooler weather [9]. The month of June started with modest temperatures for the beginning of summer. It was also the time when the Arctic Oscillation was in its negative phase. Instead, between 21st and 30th of June, AO was positive, and tropical air advection intensified in Moldova (23rd and 24th of June). In the first half of July (between 1st – 15th), AO was negative, and between 15th and 30th of July it was predominantly positive. Also then, advection of tropical air in Moldova intensified (16th – 18th of July). Between 26th and 28th of July, AO was close to 0, and in Moldova the maximum temperatures dropped significantly. In the last part of August, between 26th and 30th, AO was positive, and the heat wave in Moldova has been intensified.

2. Methods

In this analysis, daily meteorological data were used, measured at all 23 stations of Moldova, over a three-month interval, between 01st of June and 31st of August, 2023. The data were obtained from Meteomanz.com [10], which is the old meteorological data section of Mundomanz and which provides a free database measured from official meteorological stations (from 2000 to present). The data are obtained from SYNOP messages of stations with attribute code names assigned by the World Meteorological Organization. ECMWF products were used for the analysis of mean sea level pressure, geopotential between 500 - 1000 hPa, and relative topography between 500 - 1000 hPa. The frequency and distribution of electrical discharges for the two atmospheric instability events were taken from Linet data [11]. The maps with the average, maximum and minimum temperatures, as well as those with the number of tropical days/nights, for the summer season in Moldova, were made by interpolation in ArcGis, based on the measured data. The graphs and tables were made in Excel, with the data from each station.

3. Meteorological parameters analysis of 2023 summer, in Moldova

3.1. Temperature

3.1.1. Territorial distribution of monthly and (summer) seasonal average temperature

The highest average seasonal temperatures are recorded in the entire region of Moldova in the summer season [12]. Analyzing the average temperature of the summer season from 2023, an increasing trend can be observed from north to south and from west to east, in the region of Moldova. Thus, in the northwest of the region, the average temperature was between 20ºC and 22ºC (20.3ºC at the Rădăuți meteorological station and 21.8ºC at the Darabani meteorological station), in the center of the region and in the northeast, the average temperature dropped between 22 and 23ºC (22ºC at Roman and 23.2ºC at Iași meteorological station), and in the south of the region, the average temperature was between 23ºC and 25ºC: 23.2ºC at Bârlad and 24.5ºC at Galați (Table 1).

In the north of the Oriental Carpathians, the average temperature was between 10ºC and 12ºC (10.8ºC at Rețitiș Călimani and 12.1ºC at Ceahlău Toaca meteorological stations), and in the depressions of Oriental Carpathians, the average temperature was 16...17ºC: 16.7ºC at Poiana Stampei meteorological station (Table 1).

A peculiarity of the distribution of temperature values can be observed in the east of Moldova, in the Bahlui meadow, where the average air temperature was 23.2ºC, similar to the situation in the south of Moldova. The urban heat island was responsible for achieving higher air temperatures in the city area (Fig. 1).

The highest average temperatures were achieved in August, at all meteorological stations in Moldova, although July is the hottest month of the year, when the highest average temperatures are recorded in almost the entire territory of Romania [12].

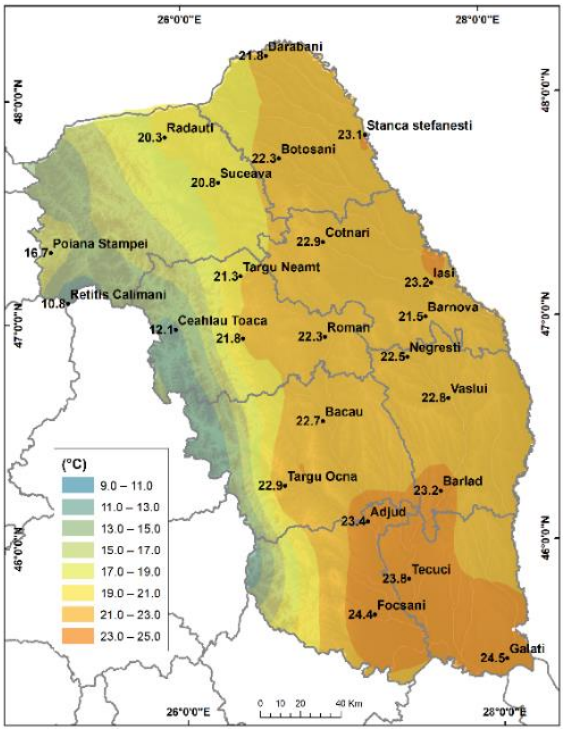


Fig. 1. Territorial distribution of the average temperature in 2023 summer months

Monthly average temperature (˚C)			
Station	**June**	**July**	**August**
Adjud	21.1	24.2	24.8
Bacău	20.4	23.6	23.8
Bârlad	20.5	24.1	25.0
Bârnova	18.9	21.9	23.7
Botoșani	19.8	23.3	23.8
Ceahlău Toaca	9.9	12.6	13.8
Cotnari	20.4	23.4	24.7
Darabani	19.4	22.3	23.6
Focșani	21.9	25.2	25.9
Galați	22.1	25.3	26.2
Iași	20.8	23.7	24.9
Negrești	19.9	23.5	24.1
Piatra Neamț	19.4	22.7	23.2
Poiana Stampei	15.0	17.3	17.8
Rădăuți	18.1	21.0	21.7
Reținș Călimani	8.5	11.3	12.4
Roman	20.1	23.0	23.8
Stânca Ștefănești	20.8	23.5	24.9
Suceava	18.6	21.6	22.1
Târgu Neamț	18.9	22.1	22.9
Târgu Ocna	20.4	23.8	24.4
Tecuci	21.1	24.7	25.5
Vaslui	20.2	23.8	24.5

Table 1. Average temperature for 2023 summer months

3.1.2. Tropical days (maximum temperatures ≥ 30°C)

The highest maximum temperatures of 2023 summer in Moldova were recorded in the east, center and south, where it was between 37ºC and 39ºC (37.2ºC at Bârlad meteorological station, 38ºC at Roman, Stânca Ștefănești, Focșani meteorological stations and 39ºC at Iași meteorological station). The highest maximum temperature in this interval was in Iași, recorded on 28th of August. In the submontane area, the maximum temperature was between 36.4ºC at Piatra Neamț and 38.5ºC at Târgu Ocna meteorological station (Table 2). On the high mountain area of the Oriental Carpathians, the highest maximum temperatures were in the range of 20ºC and 24ºC (21.9ºC at Reținș Călimani and 24.1ºC at Ceahlău Toaca meteorological station). In the Dornelor Depression region, at Poiana Stampei meteorological station, the maximum temperature in this three months was 32.7ºC (Fig. 2).

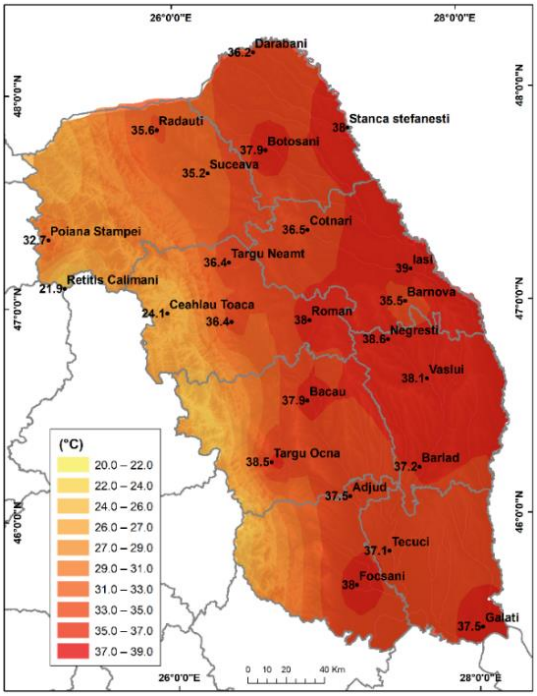


Fig. 2. Territorial distribution of the maximum temperature of 2023 summer months

Highest Maximum Temperature (˚C)			
Station	**June**	**July**	**August**
Adjud	33.4	35.5	37.5
Bacău	33.9	36.5	37.9
Bârlad	33.2	35.7	37.2
Bârnova	30.5	32.6	35.5
Botoșani	33.3	36.2	37.9
Ceahlău Toaca	22.1	22.7	24.1
Cotnari	33.1	33.4	36.5
Darabani	31.4	34	36.2
Focșani	34.7	38	37.7
Galați	34.9	37.5	36.9
Iași	34	36.7	39
Negrești	33.4	36.6	38.6
Piatra Neamț	31.7	35.3	36.4
Poiana Stampei	27.3	29.5	32.7
Rădăuți	31.5	32.9	35.6
Rețitiș Călimani	19.9	19.8	21.9
Roman	33.2	35.5	38
Stânca Ștefănești	33.2	37	38
Suceava	31.6	33.3	35.2
Târgu Neamț	31.9	34.3	36.4
Târgu Ocna	34.3	37.5	38.5
Tecuci	33.8	36.6	37.1
Vaslui	33.8	36.7	38.1

Table 2. Maximum temperature for 2023 summer months

3.1.3. Tropical nights (minimum temperatures ≥ 20°C)

The most tropical days were recorded in the south and center of Moldova, between 40...50 days in the center and 50...60 days in the south. In the northeast of the region, between 30 and 40 tropical days were achieved, in the northwest between 20 and 30 days, in the mountains and in the depressions of the north of the Oriental Carpathians, between 10 and 20 tropical days were recorded. On the high mountain area of the Oriental Carpathians, no maximum temperatures were achieved that were greater than or equal to 30˚C in the three months of 2023 summer. Iași meteorological station stands out again in the north-east of Moldova, with a higher number of tropical days than the rest of the stations, between 40 and 50, compared to Cotnari meteorological station, where the number of tropical days was between 30 and 40 days. In most of the region, the most tropical days were recorded in August, with the exception of Focșani and Galați meteorological stations, where the most tropical days occurred in July, respectively 25 tropical days, compared to 24 days in August (Fig. 3 and Table 3).

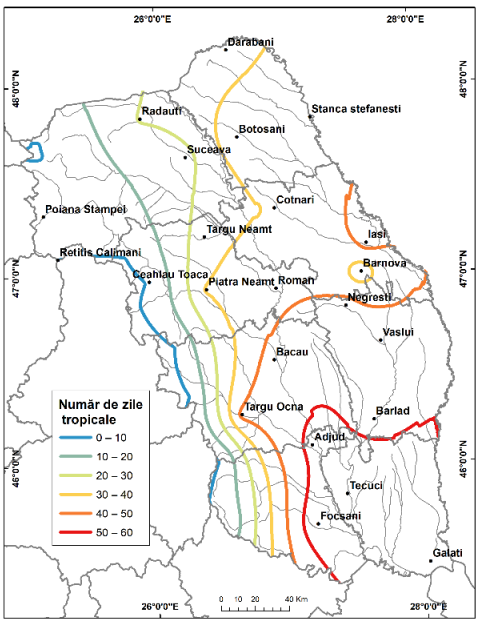


Fig. 3. Territorial distribution of the number of tropical days of 2023 summer months

Number of tropical days			
Station	**June**	**July**	**August**
Adjud	10	21	22
Bacău	4	20	20
Bârlad	4	19	22
Bârnova	1	5	16
Botoșani	3	15	20
Ceahlău Toaca	0	0	0
Cotnari	2	9	19
Darabani	1	7	17
Focșani	11	25	24
Galați	11	25	24
Iași	5	18	22
Negrești	5	19	21
Piatra Neamț	1	12	19
Poiana Stampei	0	0	4
Rădăuți	1	4	16
Reținș Călimani	0	0	0
Roman	2	15	20
Stânca Ștefănești	4	15	19
Suceava	1	5	10
Târgu Neamț	1	6	18
Târgu Ocna	4	20	20
Tecuci	10	24	25
Vaslui	5	20	21

Table 3. Number of tropical days for 2023 summer months

The highest minimum temperatures in the summer season were achieved in the southern half and the northeastern half of Moldova, with temperatures between 16ºC and 18ºC (16.3ºC at Darabani meteorological station and 17.9ºC at Cotnari meteorological station in the northeast; 16.6ºC at Adjud meteorological station and 17.6ºC at Focșani meteorological station in the south), and in the extreme southeast, at Galați meteorological station, the minimum temperature was 18.7ºC. In most of the Bârlad Plateau, the Siret Plain, but also in the east of the Suceva Plateau and the west of the Jijie Plain, the minimum temperatures were between 15ºC and 16ºC.

In the depressions of Oriental Carpathians, the minimum temperature was between 9ºC and 11ºC (10.2ºC at Poiana Stampei meteorological station), and in the high mountain area, in the north of the Eastern Carpathians, the minimum temperatures oscillated between 7ºC and 9ºC (7.5ºC at Reținș Călimani meteorological station and 8.4ºC at Ceahlău Toaca meteorological station) (Fig. 4 and Table 4). In August, the highest minimum temperatures were achieved in the analyzed interval, in most of the region. As for the lowest minimum temperatures in the summer season of 2023, they were between 4ºC and 7ºC in central Moldova, in Bârlad Plateau, Suceva Plateau and the western Jijie Plain (Fig. 4 and Table 4).

In the extreme south of the region, the lowest minimum temperatures were between 11ºC and 13ºC (12.2ºC at Galați meteorological station) (Fig. 5 and Table 5). In the high mountain area, the lowest minimum temperatures were in the range of 0ºC and 2ºC. Responsible for these temperatures

was an advection of cold air from early June. Thus, the lowest minimum temperatures were recorded in June, as a result of the frequent advection of cold air from high altitudes in the geographical area of Moldova.

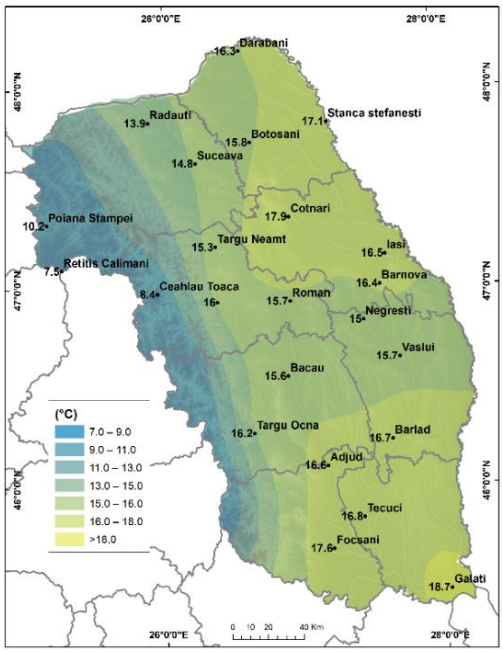


Fig. 4. Territorial distribution of minimum temperature in 2023 summer months

Minimum average temperature (°C)			
Statie	**Iunie**	**Iulie**	**August**
Adjud	14.8	17.5	17.4
Bacău	14.0	16.6	16.2
Bârlad	14.6	17.5	17.9
Bârnova	14.2	16.9	18.2
Botoșani	14.0	16.8	16.4
Ceahlău Toaca	6.4	8.8	9.9
Cotnari	15.5	18.6	19.5
Darabani	14.5	16.9	17.5
Focșani	15.7	18.3	18.8
Galați	16.3	19.4	20.2
Iași	14.7	17.3	17.3
Negrești	13.1	16.0	15.8
Piatra Neamț	14.2	16.9	16.9
Poiana Stampei	9.5	10.7	10.4
Rădăuți	12.3	14.7	14.5
Reținș Călimani	5.6	8.0	9.0
Roman	14.2	16.3	16.4
Stânca Ștefănești	15.4	17.4	18.4
Suceava	13.3	15.6	15.5
Târgu Neamț	13.5	16.3	16.0
Târgu Ocna	14.3	17.2	17.0
Tecuci	14.7	17.7	18.1
Vaslui	13.7	16.8	16.6

Table 4. Minimum temperature for 2023 summer months

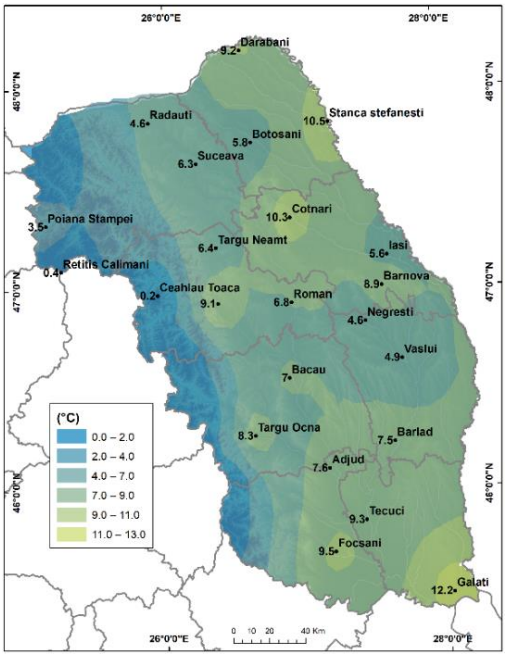


Fig. 5. Territorial distribution of the lowest minimum temperature in 2023 summer months

Lowest Minimum Temperature (°C)			
Station	**June**	**July**	**August**
Adjud	7.6	11.4	12.1
Bacău	7	9.3	10.7
Bârlad	7.5	11.4	11.3
Bârnova	8.9	10.9	12.5
Botoșani	5.8	12.5	11.9
Ceahlău Toaca	0.2	2.6	3.2
Cotnari	10.3	14.1	14.2
Darabani	9.2	11.7	12.1
Focșani	9.5	11.3	13.7
Galați	12.2	13.3	14.2
Iași	5.6	11.7	12
Negrești	4.6	9.3	10.3
Piatra Neamț	9.1	11.2	11.5
Poiana Stampei	4.2	3.5	4.4
Rădăuți	4.6	9.4	9.5
Reținș Călimani	0.4	2.1	1.9
Roman	6.8	9.3	11.3
Stânca Ștefănești	10.5	12.7	12.4
Suceava	6.3	9.4	10.3
Târgu Neamț	6.4	13.2	10.4
Târgu Ocna	8.3	11	11.5
Tecuci	9.3	11.3	12.3
Vaslui	4.9	10.9	9.8

Table 5. The lowest minimum temperature for 2023 summer months

The most tropical nights were in the south-east of Moldova, at Galați meteorological station, as a result of the greater persistence of very warm intervals, as well as the higher frequency of tropical air masses advection in this part of Moldova, compared to the north of the region which is first affected by the advection of cold air from high latitudes.

However, it can be seen in Fig. 6 and Table 6 a particularity of Cotnari meteorological station, located at an altitude of 289 meters, where there were 23 tropical nights. Not infrequently, Cotnari meteorological station stands out at regional or even national level [13], with higher temperatures compared to nearby stations. This particularity is given by the local geography, the Cotnari commune being located in Dealu Mare-Hârlău, as well as the geological substratum, where the hard horizons of limestone and sandstone are close to the surface. The high number of tropical nights can be attributed to the heat storage properties of the calcareous substratum, but it can also be the result of the manifestation of the "foehnal processes" that occur on the eastern edge of the Dealu Mare-Hârlău in situations of warm air advection. During the descent on the slope, the air is compressed and heated adiabatically [13].

The western half of Moldova is characterized by a smaller number of tropical nights compared to the eastern half of the region, between 5 and 10 tropical nights in the west and between 15 and 20 tropical nights in the northeast and southeast. The northeast of the region also had the largest positive temperature deviations in Moldova (Table 6).

The most tropical nights were in August, at most stations in the region, during the last heat wave of this month, when the tropical air mass persisted in Moldova for more than 15 consecutive days.

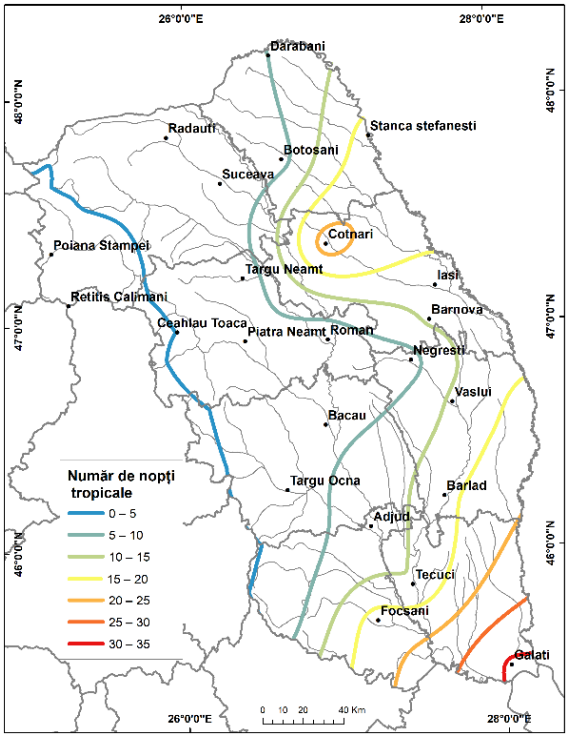


Fig. 6. Territorial distribution of the number of tropical nights in the 2023 summer months

Number of tropical nights			
Station	**June**	**July**	**August**
Adjud	1	3	3
Bacău	1	2	1
Bârlad	1	4	9
Bârnova	0	4	7
Botoșani	0	1	2
Ceahlău Toaca	0	0	0
Cotnari	0	6	17
Darabani	0	0	5
Focșani	1	8	9
Galați	1	12	18
Iași	2	4	6
Negrești	0	2	1
Piatra Neamț	1	2	1
Poiana Stampei	0	0	0
Rădăuți	0	0	1
Reținș Călimani	0	0	0
Roman	0	1	0
Stânca Ștefănești	0	4	13
Suceava	0	0	1
Târgu Neamț	0	1	1
Târgu Ocna	1	1	2
Tecuci	1	3	6
Vaslui	2	4	5

Table 6. Number of tropical nights for 2023 summer months

3.2. Atmospheric precipitation

3.2.1. Seasonal average precipitation and territorial distribution

The summer of 2023 in Moldova was characterized by negative anomalies in terms of precipitation amounts. There is an increase in the average amount from east to west, directly proportional to the increase in altitude. Thus, the lowest amounts of precipitation fell in the east and center of Moldova, between 30 and 40 l/m^2, with the lowest amount at Negresti meteorological station, in the Central Moldavian Plateau (Table 7). The highest amounts of precipitation were collected in the mountainous and submontane areas, as a result of orographic convection. Thus, on the high mountain area of the Oriental Carpathians, the amounts were between 110 and 140 l/m^2 (135.6 l/m^2 at Reținș Călimani meteorological station) (Fig. 7).

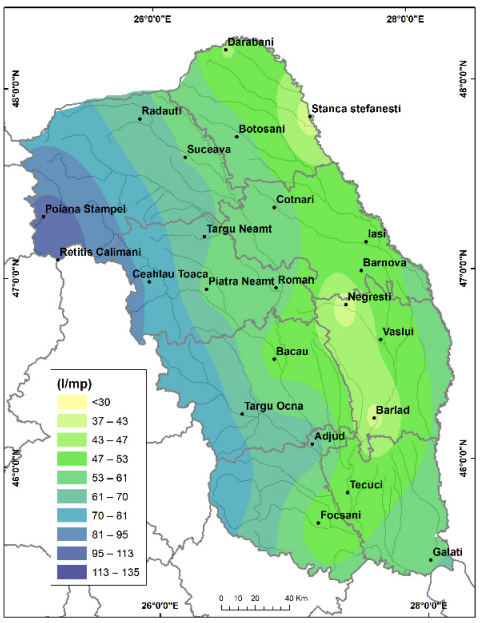


Fig. 7. Territorial distribution of the average amount of precipitation for the summer of 2023

Average amount of precipitation	
Station	**l/m^2**
Adjud	80.1
Bacău	42.6
Bârlad	33.7
Bârnova	64.7
Botoșani	56.9
Ceahlău Toaca	85.5
Cotnari	58.0
Darabani	41.1
Focșani	41.0
Galați	62.0
Iași	42.4
Negrești	30.0
Piatra Neamț	50.7
Poiana Stampei	115.8
Rădăuți	60.5
Rețitiș Călimani	135.6
Roman	61.0
Stânca Ștefănești	31.8
Suceava	59.5
Târgu Neamț	61.5
Târgu Ocna	64.6
Tecuci	46.4
Vaslui	49.2

Table 7. Average amount of precipitation for the summer of 2023

The highest amounts of precipitation, on almost the entire national territory, fall in June. They come mainly from showers, and their spatial distribution shows a high degree of non-uniformity [12]. However, in the region of Moldova, in the summer of 2023, the most total amounts of water fell in July, as a result of more frequent cold advection in this month in the east of the country. Thus, the largest amounts of precipitation fell at the Adjud (136.2 l/m^2) and Bârnova meteorological stations (118.2 l/m^2) in July, and in the high mountain area, at Rețitiș Călimani meteorological station, the cumulative water quantities in July exceeded 200 l/m^2 (216.5 l/m^2). At Ceahlău Toaca meteorological station, over 110 l/m^2 (114.7 l/m^2) were collected in total in July, and at Poiana Stampei meteorological station, 158.6 l/m^2.

In August, in the geographical area of Romania, the anticyclonic regime prevails, which contributes to the notable decrease in the amount of precipitation [12]. In August 2023 in Moldova, intervals with cyclonic and anticyclonic regime alternated and the lowest amounts of precipitation were recorded. In the center and east of Moldova, the amounts of precipitation throughout the summer season ranged between 100 and 130 l/m^2, just below 100 l/m^2 at Stânca Ștefănești, in the north-east of Moldova (Table 8). This aspect can also be attributed to a positive feed-back mechanism: drier regions received small amounts of precipitation, and regions where there was a greater reserve of moisture in the soil, received larger amounts of precipitation. In other words,

"dryness attracts more dryness". Consequently, in the mountainous and submontane areas, the cumulative amounts of precipitation fluctuated between 280 and 340 l/m^2, and in the high mountain area, between 340 and 410 l/m^2 (406 l/m^2- Reţitiş Călimani meteorological station) (Fig. 8).

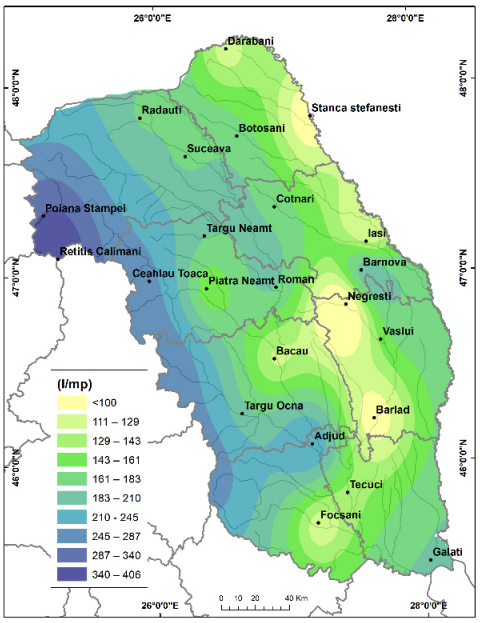


Fig. 8. Territorial distribution of the total amount of precipitation for the summer of 2023

Total amount of precipitation			
Station	**June**	**July**	**August**
Adjud	39.3	136.2	64.9
Bacău	22.8	63.5	41.4
Bârlad	19.4	55.4	26.2
Bârnova	42.5	118.2	33.3
Botoșani	72	61.6	37.2
Ceahlău Toaca	107.6	114.7	34.1
Cotnari	22.8	103.8	47.4
Darabani	42.1	52.1	29.1
Focșani	39.2	37.2	46.6
Galați	37.2	114.3	34.6
Iași	25.9	80.1	21.3
Negrești	25.4	28.4	36.1
Piatra Neamț	74.1	46.1	31.9
Poiana Stampei	158.6	136.1	52.8
Rădăuți	75	71.7	34.7
Reţitiş Călimani	118	216.5	72.3
Roman	46.3	53.5	83.2
Stânca Ștefănești	21	61.6	12.8
Suceava	62.9	54.1	61.4
Târgu Neamț	86.8	70.2	27.4
Târgu Ocna	90.2	48.6	55
Tecuci	72.8	37.8	28.6
Vaslui	26	74.9	46.8

Table 8. Total monthly precipitation for the summer of 2023

3.2.2. Maximum amounts of precipitation in 24, 48 hours (or more)

For the extra-Carpathian stations, the highest amount of precipitation that fallen in 24 hours was 81.1 l/m^2 at Bârnova meteorological station, followed by 65.8 l/m^2 at Adjud and 59.9 l/m^2 at Roman meteorological station. At Iași, Galați, Cotnari and Vaslui meteorological stations the maximum quantities in 24 hours slightly exceeded 40 l/m^2, and at Bacău, Focșani, Piatra Neamț, Târgu Neamț meteorological stations, the maximum quantities exceeded 30 l/m^2.

The lowest amounts in 24 hours fell in the Jijia Plain, 14.6 l/m^2 at Darabani meteorological station and in the Bârlad Plateau 17.4 l/m^2, at Negrești meteorological station. In 48 hours, Bârnova maintains the highest amount of precipitation (84.6 l/m^2), and Darabani records the lowest amount (19.4 l/m^2). In 72 hours, the highest amount of precipitation was at Cotnari, with 77.2 l/m^2, followed by Adjud with 71.8 l/m^2.

The lowest cumulative amounts in 24 hours were recorded at the Bârlad (7.7 l/m^2), Focșani (23.4 l/m^2), and Stânca Ștefănești meteorological stations (25.0 l/m^2). At the mountain meteorological stations, the highest amounts were recorded in the 48- and 72-hour intervals: 73.6 l/m^2 at Poiana Stampei meteorological station, 63.8 l/m^2 at Retiș Călimani and 42.8 l/m^2 at Ceahlău Toaca (in 72 hours) (Table 9).

Maximum amounts of precipitation (hours)			
Statie	**24**	**48**	**72**
Adjud	65.8	67.5	71.8
Bacău	34.4	37.9	27.5
Bârlad	22.0	30.2	7.7
Bârnova	81.1	84.6	48.8
Botoșani	26.2	29.1	29.3
Ceahlău Toaca	25.4	32.9	42.8
Cotnari	40.6	59.0	77.2
Darabani	18.5	19.4	26.1
Focșani	35.0	43.1	23.4
Galați	41.9	42.3	46.9
Iași	46.3	47.9	49.3
Negrești	17.4	30.0	30.8
Piatra Neamț	30.4	43.7	47.5
Poiana Stampei	52.9	68.8	73.6
Rădăuți	24.3	32.9	39.4
Retițiș Călimani	43.9	60.2	63.8
Roman	59.9	27.0	29.2
Stânca Ștefănești	14.6	24.4	25.0
Suceava	26.9	28.1	28.3
Târgu Neamț	34.0	37.4	45.8
Târgu Ocna	39.6	55.0	58.8
Tecuci	20.6	39.8	40.4
Vaslui	42.1	45.6	47.3

Table 9. Maximum amounts of precipitation for the summer of 2023

4. The succession of heat waves in 2023 summer

For Romania, the manifestation of heat waves is associated with advections of tropical warm air of continental origin, either from the north of Africa as a result of the extension of North African Ridge to the latitude of Romania, or from Arabia in the context of the extension of Arab Depression to the center and Eastern Europe [7]. The advection of tropical maritime air facilitated by the extension of the ridge of Azorean High to the region of Romania, represents another favorable scenario for heat waves [7].

The weak pressure gradient associated with low wind speeds, the descending movements specific to anticyclones, which do not favor the formation of clouds and which compress the air particles that heat up adiabatically, facilitate a greater amount of solar radiation that reaches the soil surface and therefore contributes positively to the increase in air temperature [6].

Among the other main types of circulation specific to the region of Romania (western circulation - 45%, polar circulation - 30%, blocking circulation - 10%), the tropical circulation, with its two variants: tropical maritime circulation and tropical continental circulation, has a frequency of 15%. Within the tropical circulation, the tropical maritime variant dominates with a frequency of 75%, and the tropical continental variant has a frequency of 25% [14].

4.1. Heat waves in June (22nd and 24th of June 2023)

The first advection of tropical air in June 2023 begins towards the end of the month, when in three consecutive days the maximum air temperature exceeded 30ºC in most of Moldova. It was the interval between 22nd and 24th of June, when a warm ridge extended to the latitude of Romania (Fig. 9).

At the continental level, the north and northwest of Europe was under the influence of a low-pressure field, while an area of high pressure dominated in the east and southwest of the continent. In the southeast, the Arabian Depression was present, carrying warm air to the south of the Balkan Peninsula.

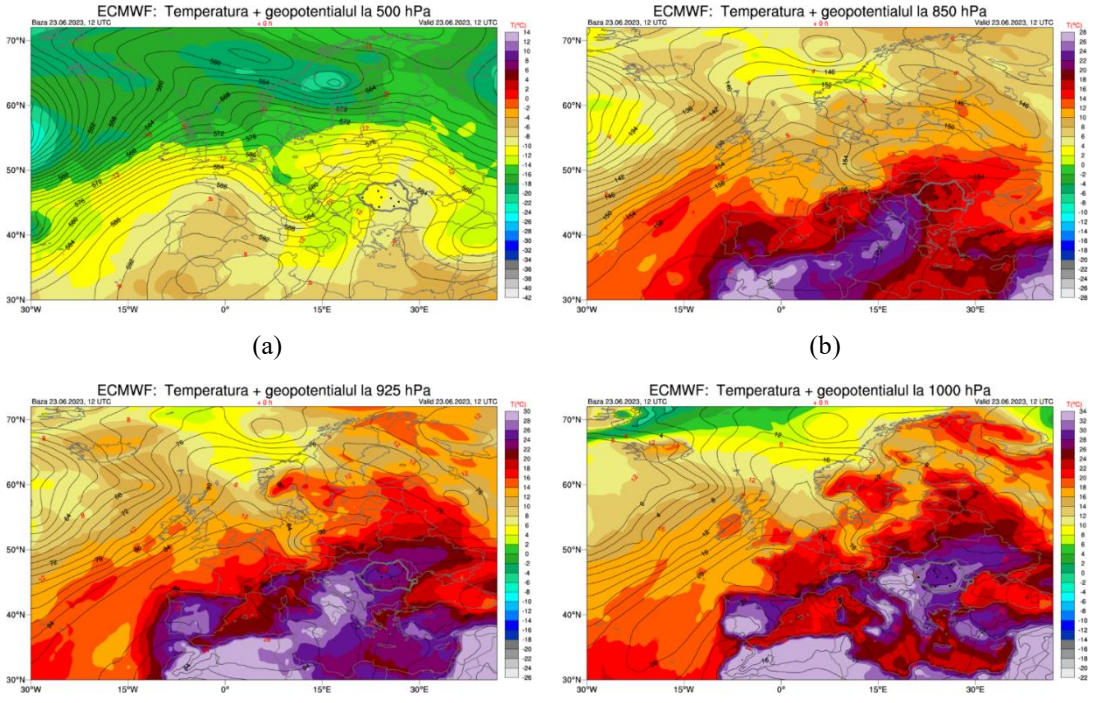


Fig. 9. Temperature and geopotential at 500 hPa (a), 850 hPa (b), 925 hPa (c), 1000 hPa (d) on 23rd of June 2023, h 12 UTC [15]

The ridge of the Azorean High was directed towards central and southern Europe by the Icelandic Low, deepened in the north-west of the continent. In this context, air masses of North African origin were drawn towards Moldova, loaded with moisture, crossing the Mediterranean Sea. Thus, in most of Moldova, on 23rd of June, the temperature-humidity index reached and exceeded the critical threshold of 80 units (in Botoșani, Iași, Vaslui, Galați, Bacău, Vrancea counties), and on 24th of June, in the southern half of the region, the thermal discomfort was accentuated (in Bacău, Vrancea, Vaslui, Galați counties), according to the National Meteorological Administration. This interval with thermal discomfort and with maximum temperatures that exceeded 30ºC (Table 10) did not persist in the Moldova region, as a result of the formation of a geopotential nucleus at the level of 500 hPa, deepened west of the Balkan Peninsula, and the atmospheric pressure at the ground level was relatively low. Thus, this short warm interval was interrupted, the hot air being replaced by a colder one.

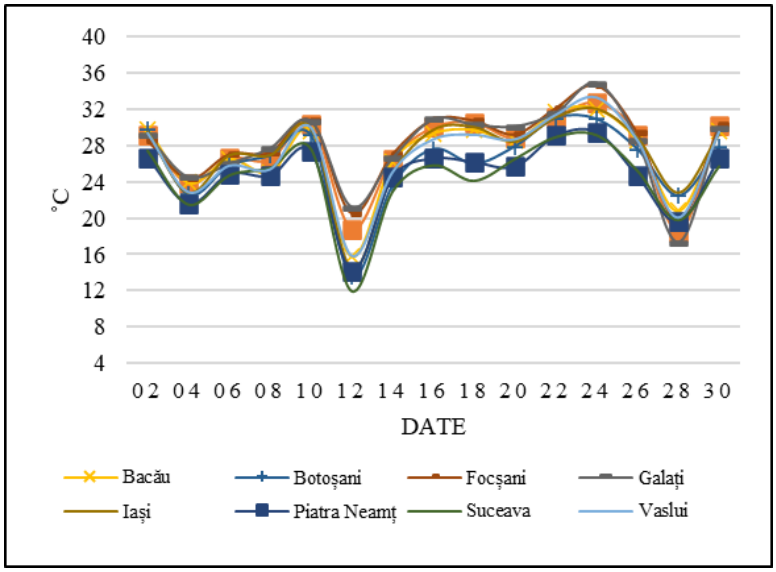


Fig. 10. Maximum temperature at the county weather stations for June 2023

Maximum temperature (˚C) June 22 - 24			
Station	**22**	**23**	**24**
Adjud	31.1	33.4	32.7
Bacău	31.7	33.9	32
Bârlad	31	32.6	33.2
Bârnova	28	30.5	29.8
Botoșani	31	33.3	30.9
Ceahlău Toaca	17.5	22.1	19.2
Cotnari	29.4	33.1	30
Darabani	29.9	31.4	29
Focșani	32.2	34.3	34.7
Galați	31.6	32.8	34.9
Iași	31.1	34	32
Negrești	31.1	33.4	32.4
Piatra Neamț	29.1	31.7	29.5
Poiana Stampei	25.4	27.3	26
Rădăuți	29.5	31.5	28.3
Reținș Călimani	15.6	19.9	18.9
Roman	30.2	33.2	29.9
Stânca Ștefănești	30.3	33.2	31.6
Suceava	28.9	31.6	29.1
Târgu Neamț	29.6	31.9	28.5
Târgu Ocna	34.3	33.3	32.7
Tecuci	31.4	33.4	33.8
Vaslui	31.4	33.8	33.3

Table 10

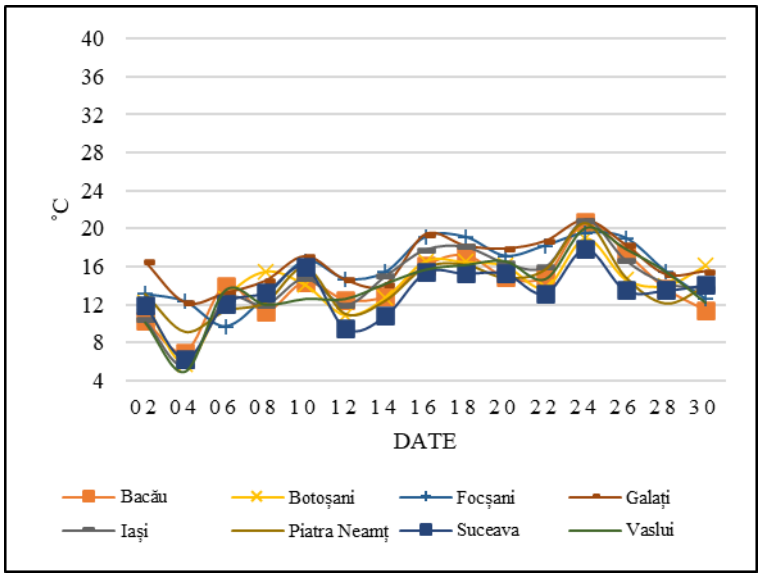


Fig. 11. Minimum temperature at the county weather stations in Moldova for June 2023

Minimum temperature (°C) June 22 - 24			
Station	**22**	**23**	**24**
Adjud	16.2	16	20.2
Bacău	15	16.4	20.7
Bârlad	15.5	18.5	20.1
Bârnova	16.2	19	18.7
Botoșani	13.8	17.2	19
Ceahlău Toaca	9.5	11.1	11.4
Cotnari	19.8	18.7	19.4
Darabani	16.8	18.2	18
Focșani	18.2	16.9	19.5
Galați	18.7	19.3	20.9
Iași	16	16.7	20.9
Negrești	13.5	14.5	19.1
Piatra Neamț	15.7	17.6	20.6
Poiana Stampei	9.5	13.3	15.1
Rădăuți	12.6	15.6	17.4
Reținiș Călimani	9.4	10.5	11
Roman	15.1	17	19.2
Stânca Ștefănești	18.3	18.1	19.9
Suceava	13.2	15.9	17.9
Târgu Neamț	14.3	17.4	18.4
Târgu Ocna	15.9	17.5	20.1
Tecuci	16.3	17.1	19.3
Vaslui	14.7	16.7	20.1

Table 11

The maximum temperature of this warm air advection episode was 34.9ºC, on 24th of June, at the Galați meteorological station, followed by 34.7ºC at Focșani (Table 10), also in the same day (Fig. 10). On the other hand, the 23rd of June was characterized by warm weather in most parts of Moldova, when at all extra-Carpathian stations, the maximum temperature exceeded the threshold of 30ºC. For the low relief areas, a summer day is characterized by maximum temperatures greater or equal with 25ºC. In the case of the analyzed event, Poiana Stampei mountain meteorological station (alt. 973 m) had in all three days maximum diurnal values that included this episode in the category of summer days (25.4ºC, 27.3ºC and 26ºC). At altitudes higher than 1800 m, the maximum temperature exceeded 20ºC (only on 23rd of June), at Ceahlău Toaca meteorological station.

The minimum temperatures fluctuated in this interval between 12.6ºC at Rădăuți and 18.7ºC at Galați on 22nd of June, between 14.5ºC at Negrești and 19.3ºC at Galați on 23rd of June and culminating with values between 17.4ºC at Rădăuți and 20.9ºC at Galați, Iași meteorological stations on 24th of June, when thermal values specific to tropical nights were recorded at eight land stations (Table 11 and Fig. 11).

Analyzing the satellite products, on the first day of the analyzed interval, in some places, the soil surface temperature reached 30ºC, in the context of higher cloudiness. On 23rd of June, (Fig. 12) the temperature of the soil surface exceeded 40ºC, locally in the south and northeast of Moldova, under conditions of predominantly clear skies and strong insolation. On 24th of June, the

satellite-estimated ground surface temperature reached 40ºC in the south and east of the region, considering that the cloudiness was higher in the western half of the region.

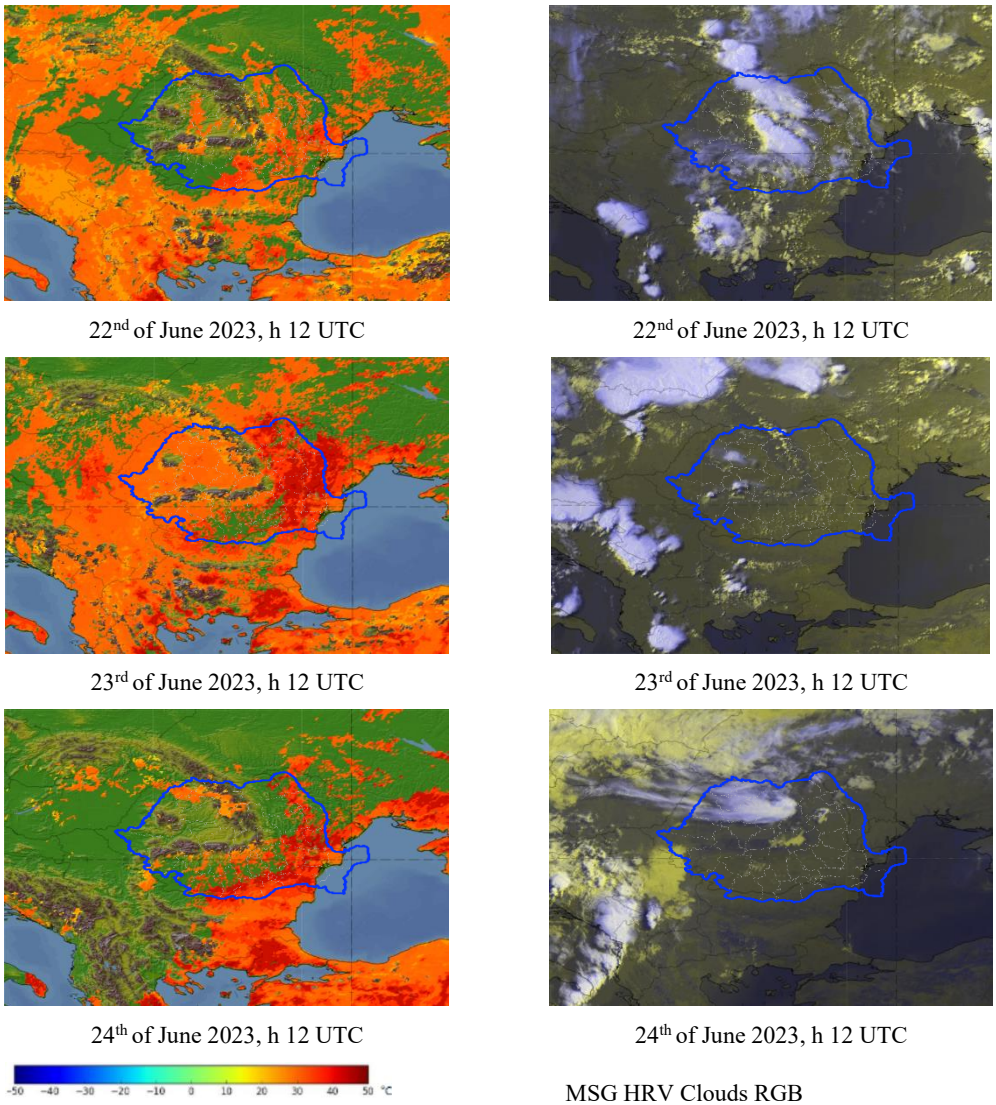


Fig. 12. Satellite imagery- ground surface temperature (left), SEVIRI HRV cloud RGB (right) for June 22nd-24th 2023 [16]

4.2. Heat waves in July (16 – 18 and 24 – 26 July 2023)

In July, the first significant advection of tropical air in the Moldova region was in the middle of the month and lasted for three days (between 16th and 18th July). During the three days, the maximum air temperature exceeded 30ºC, at most of the stations in the low relief area of the

region, and on 17th of July, the heat wave threshold temperature was reached and exceeded at 11 meteorological stations (Table 12).

These temperature values were achieved in the context of warm air advection from the north of Africa. At the level of 500 hPa a warm ridge extends to Central Europe, extending beyond the Podolic Plateau to the Baltic States region. At the ground level, a depression of North-Atlantic origin (with central values up to 990 mb), which gradually moved from the British Archipelago, west of the Scandinavian Peninsula, and reached northern Europe on 17th of July, in the region of the northwest coast of Norway, forced the maintenance of an anticyclonic regime in the west and center of Europe, which was blocked in this region during the analyzed interval.

The ridge of the Azorean High thus extended to the latitude of Romania and beyond the Dnieper Plain. In the southeast of the continent was the Arabian Low, extended to the south of Greece, with pressure values up to 1010 mb in the center, and in the south of the Iberian Peninsula a depression of Mediterranean origin was manifested, with atmospheric pressure values up to 1015 mb. This warm air advection was found throughout the tropospheric column at the 300, 500, 850, and 925 hPa levels, as shown in Fig. 13.

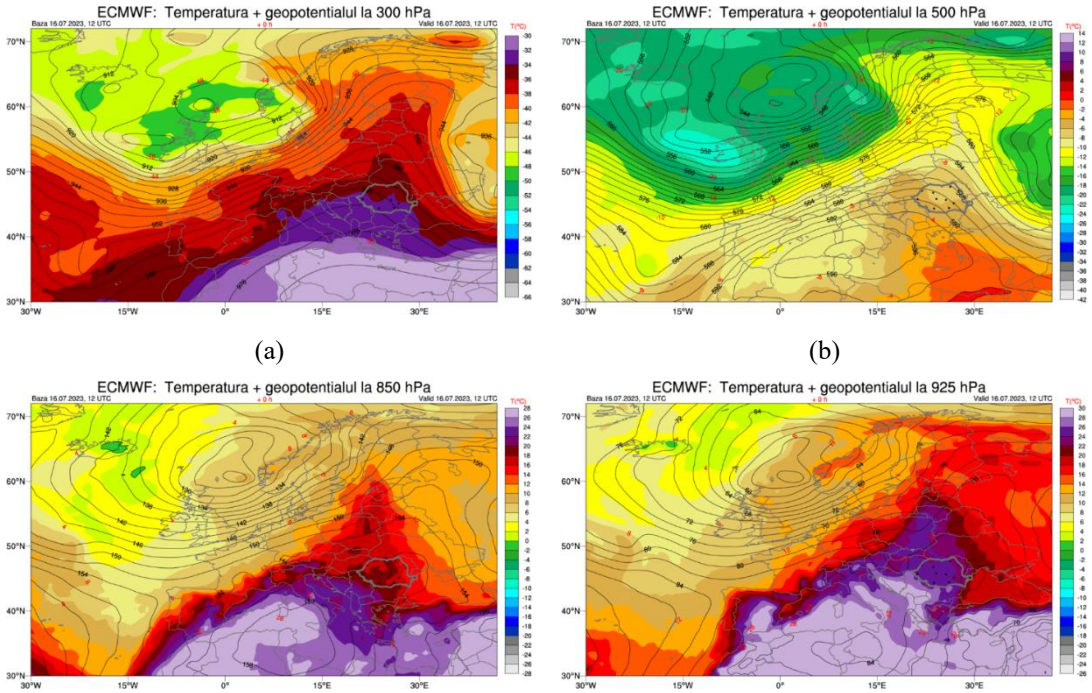


Fig. 13. Temperature and geopotential at 300 hPa (a), 500 hPa (b), 850 hPa (c), 925 hPa (d) from 16th of July 2023, h 12 UTC [15]

On July 17th, the highest maximum temperature in this episode was reached: 36.6ºC in the south of Moldova, at the Tecuci meteorological station. On this day, at ten other extra-Carpathian weather stations, values that exceeded the heatwave temperature threshold were recorded: Focșani- 35.9ºC, Vaslui- 35.9ºC, Galați- 35.6ºC, Bârlad- 35.6ºC, Târgu Ocna- 35.4ºC, Negrești- 35.4ºC, Botoșani- 35.3ºC, Adjud- 35.2ºC, Roman- 35.1ºC, Stânca Ștefănești- 35.0ºC, and at three stations the maximum temperature approached this threshold: Bacău- 34.5ºC, Iasi- 34.5ºC, Darabani- 34.0ºC (Fig. 14 and Table 12). At Ceahlău-Toaca, on all three days, the maximum temperature exceeded 20ºC, at Poiana Stampei meteorological station the maximum temperature exceeded 25ºC during this interval, and at Retiș-Călimani, the maximum temperature did not reach 20ºC in any of the three days. The thermal discomfort was high during this interval, so the temperature-humidity index reached and exceeded the critical threshold of 80 units, in the southern half of the region on the first day, locally in the counties of Bacău, Vaslui, Vrancea, Galati, then spread over on July 17th , when the temperature-moisture index exceeded the critical threshold of 80 units on large surfaces in most of the plateau areas, and on the last day of the analyzed interval, the temperature-moisture index exceeded the critical threshold in the counties of the south of the region (Vaslui, Galati, Bacău, Vrancea).

Minimum temperatures ranged between 14.1ºC at Rădăuți and 20.9ºC at Galați on July 16th, between 15.4ºC at Rădăuți and 22.2ºC at Galați on July 17th and between 19ºC and 22.8ºC at Piatra Neamț on July 18th (Fig. 15). Also, at most of the stations in the low relief area, minimum temperatures specific to tropical nights were achieved, and three other stations approached this threshold: Darabani- 19.9ºC, Focșani- 19.9ºC, Rădăuți- 19.0ºC. As for the minimum temperature at the mountain meteorological stations, it oscillated between 10.9ºC and 14.7ºC at Ceahlău Toaca, between 10.3ºC and 12.8ºC at Rețitiș Călimani, and Poiana Stampei meteorological station, the minimum temperatures were between 8ºC and 13.5ºC, in the analyzed range (Table 13).

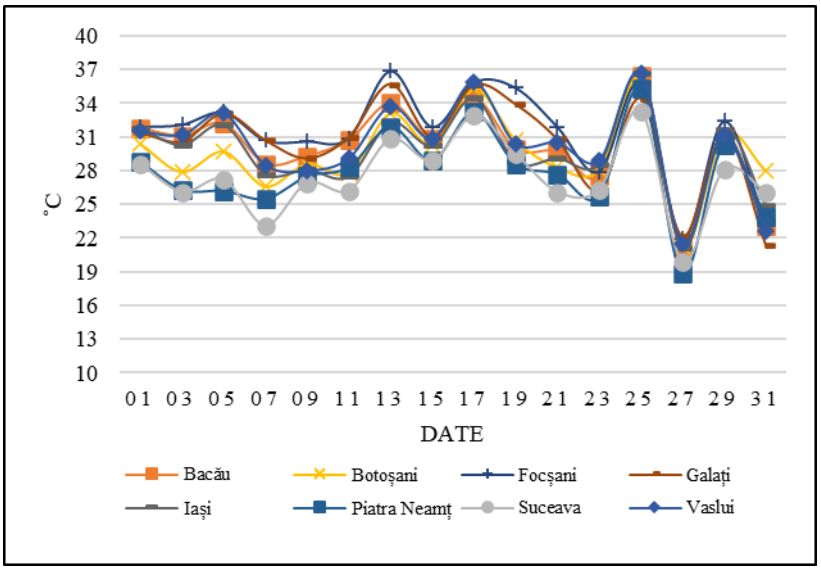


Fig. 14. Maximum temperature at the county weather stations in Moldova for July 2023

Maximum temperature (°C) July 16 - 18			
Station	**16**	**17**	**18**
Adjud	33.6	35.2	33
Bacău	33.6	34.5	32.7
Bârlad	33.3	35.6	33.5
Bârnova	29.5	31.5	27.7
Botoșani	33.2	35.3	31.4
Ceahlău Toaca	22.7	20.6	20.5
Cotnari	31.6	33	29.5
Darabani	31.7	34	28.9
Focșani	35.1	35.9	34.8
Galați	33.2	35.6	34.4
Iași	33.5	34.5	31.9
Negrești	34.6	35.4	32.9
Piatra Neamț	31.7	33.2	30.6
Poiana Stampei	27.8	29.5	25.6
Rădăuți	31.3	32.7	29
Rețitiș Călimani	19.8	19.8	17.5
Roman	33.1	35.1	30.4
Stânca Ștefănești	32.4	35	30.8
Suceava	30.8	32.9	29.4
Târgu Neamț	30.9	33	29.3
Târgu Ocna	33.9	35.4	32.4
Tecuci	34.1	36.6	35
Vaslui	34.2	35.9	32.5

Table 12

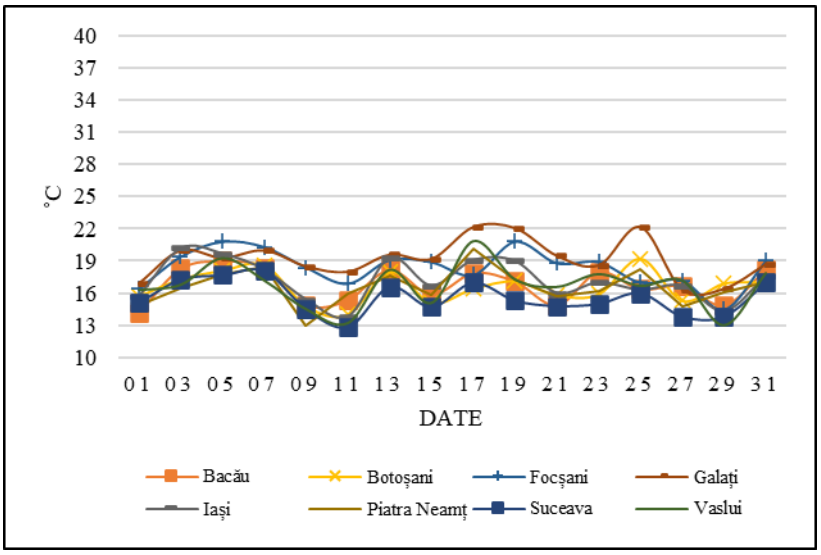


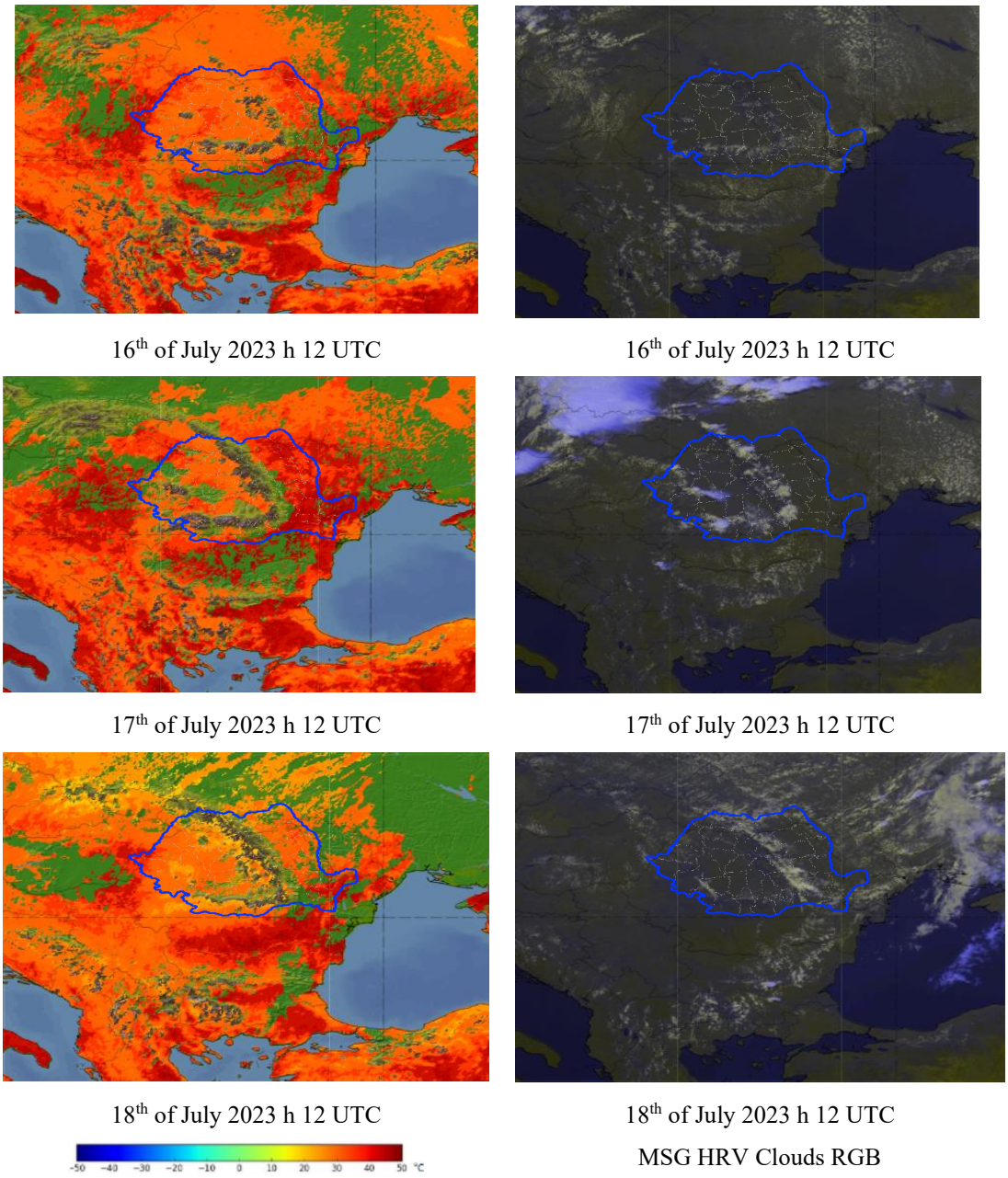
Fig. 15. Minimum temperature at the county weather stations in Moldova for July 2023

Minimum temperature (°C) July 16 - 18			
Station	**16**	**17**	**18**
Adjud	17.4	18.5	20.9
Bacău	15.3	17.9	20.9
Bârlad	17.9	19.7	21.4
Bârnova	20.8	20.3	20.7
Botoșani	15.6	16.4	20.9
Ceahlău Toaca	10.9	14.7	12.1
Cotnari	20.4	19.8	22.2
Darabani	19.5	19.2	19.9
Focșani	20.1	17.7	19.9
Galați	20.9	22.2	22.1
Iași	17.8	19.1	21.7
Negrești	15.9	16.5	22
Piatra Neamț	16.8	20.1	22.8
Poiana Stampei	8	10.5	13.5
Rădăuți	14.1	15.4	19
Rețitiș Călimani	10.3	12.8	10.8
Roman	16.1	17.8	20.5
Stânca Ștefănești	16.4	20	22.2
Suceava	14.4	17	19.5
Târgu Neamț	14.8	18.7	20.2
Târgu Ocna	17.3	19.5	21.4
Tecuci	17.9	17.6	20.5
Vaslui	16.7	20.9	22.3

Table 13

The soil surface temperature from remote sensing data estimated values above 40ºC isolated in the north-east of Moldova and in some places in the south of the region, and for the northern half, temperatures between 35...40ºC and 25...30ºC in the submontane area, for the first day of the analyzed event. On July 17th, in the southern half, in the east and north, the temperature of the soil surface exceeded 40...45ºC, and in the rest, the temperatures were between 35 and 40ºC. In the submontane area, under conditions of high cloudiness, the soil surface temperature could not be estimated. July 17th is also the day when the highest maximum temperatures were achieved,

which exceeded the heatwave threshold. On the last day, high values of the soil surface temperature are maintained in the south of Moldova, where values above 40ºC are still reached, while in the northern half, they decrease significantly compared to the previous day (Fig. 16). The highest temperatures were recorded during the afternoons, in conditions of more clear skies and strong insolation.



16th of July 2023 h 12 UTC | 16th of July 2023 h 12 UTC

17th of July 2023 h 12 UTC | 17th of July 2023 h 12 UTC

18th of July 2023 h 12 UTC | 18th of July 2023 h 12 UTC

MSG HRV Clouds RGB

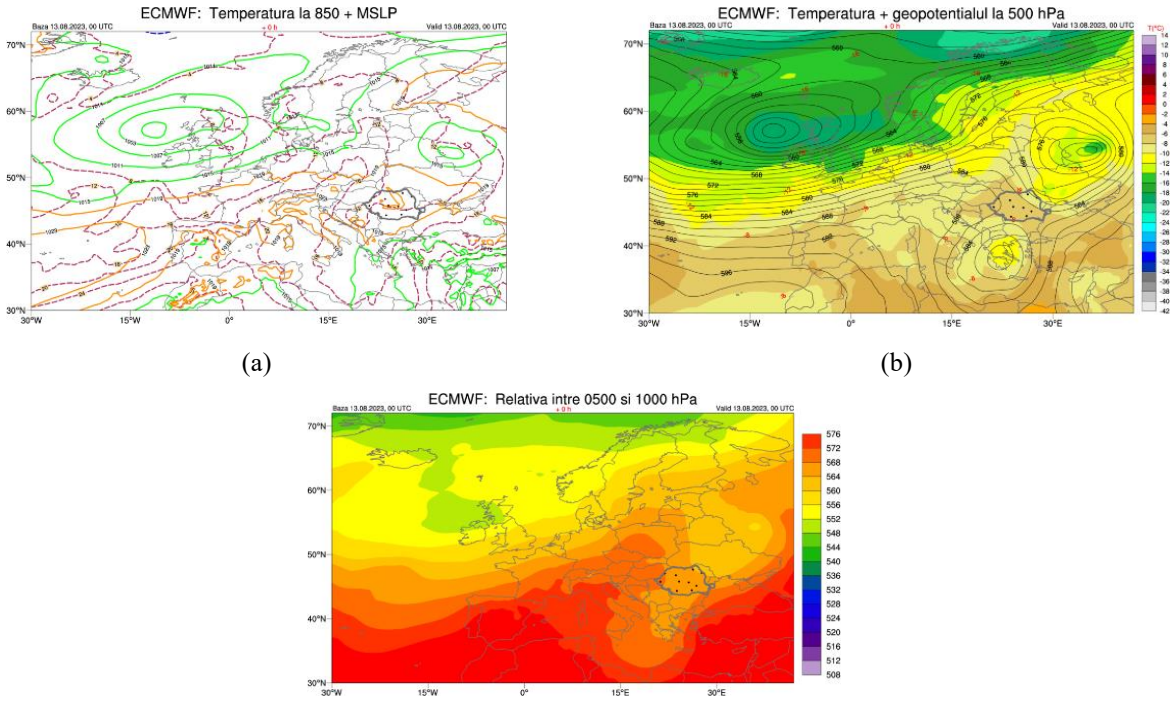
Fig. 16. Satellite imagery- ground surface temperature (left), SEVIRI HRV cloud RGB (right) for 16th-18th of July [16]

4.3. End of August Heatwave (13th and 29th of August, 2023)

In the second half of August, the most representative heat wave occurred in the region of Moldova, from the warm season of 2023. This episode can be included in the definitions of a genuine heat wave. The earliest in this episode, tropical air advection was initiated on 13th of August, when the ridge of the Azorean High extended into Central and Eastern Europe, beyond the Podolic Plateau to the east and the German-Polish Plain to the north.

The advance of the ridge in this part of the continent was forced by the presence of the active and well-defined Icelandic Low in the north-west of the continent, north-west of the British Archipelago. In the southeast of the continent was the Arabian Low, and in the northeast of Europe, in the north of the Eastern European Plain, a high-pressure field was present. Warm air advection occurred throughout the tropospheric column, so that at the level of 500 hPa, the North African warm ridge was extended over the geographical space of Romania. On August 15th, the circulation at ground level changes, as a result of the presence and extension of a high-pressure area in the east of the continent. In this way, the circulation from the southeast intensifies and masses of tropical-continental air from the Asia Minor Peninsula were transported to the latitude of Romania. This circulation is also maintained in the immediately following interval, between 16th -20th of August and intensifies, so that the advection of tropical air from the Asia Minor Peninsula was also found in the middle atmosphere, where the warm ridge was present and well-defined, which extended to in the extreme north-east of Europe, beyond the East European Plain.

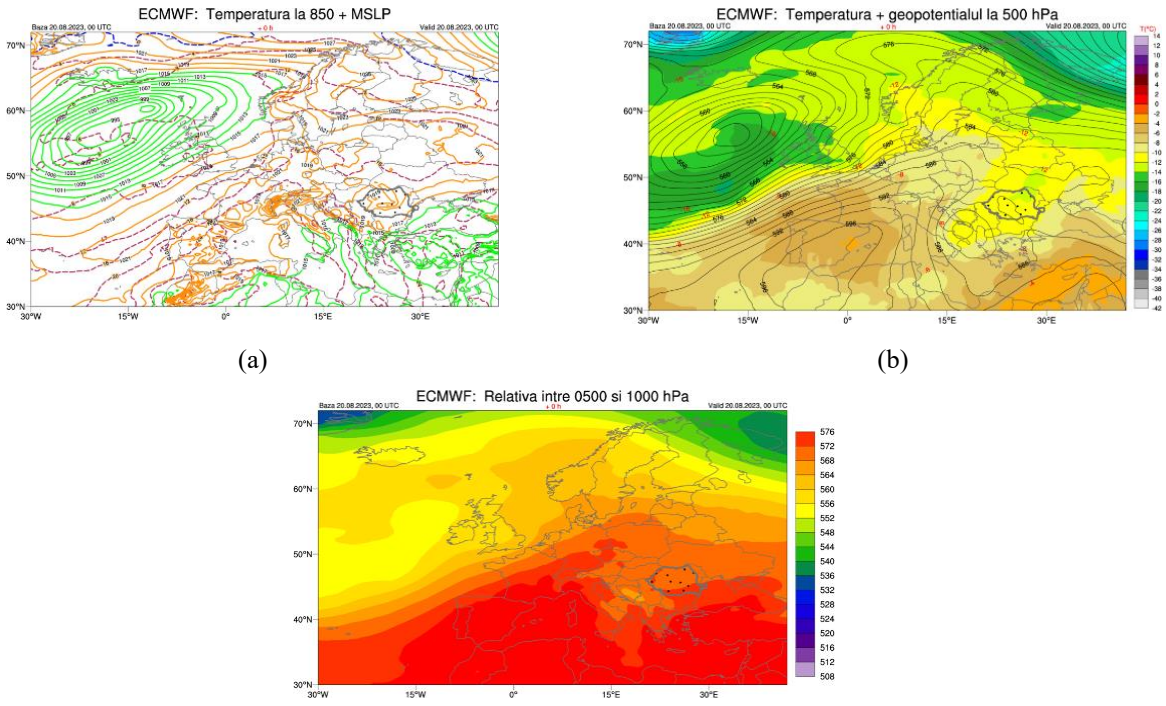
The retreat of the East-European High has again facilitated the advance of the ridge of the Azorean High to the latitude of Romania, so the circulation gradually changes between 20th - 22nd of August, and is oriented from the southwest. Again, tropical air masses from northern Africa are drawn into central and southern Europe, and in altitude, the warm North African ridge extends over most of central and eastern Europe, and the heat wave intensifies, so that two days in a row, in most of Moldova, the maximum temperatures exceed the heatwave threshold. Between 23rd and 24th of August, the Azorean High Ridge gradually remains blocked to the center of the continent, being flanked to the north and south by low pressure areas. In the last week of August, the prevailing west-south-west altitude circulations facilitated a new transport of tropical air, thus prolonging the heat wave in the region of Moldova (Fig. 17, 18, 19).



(a) (b)

(c)

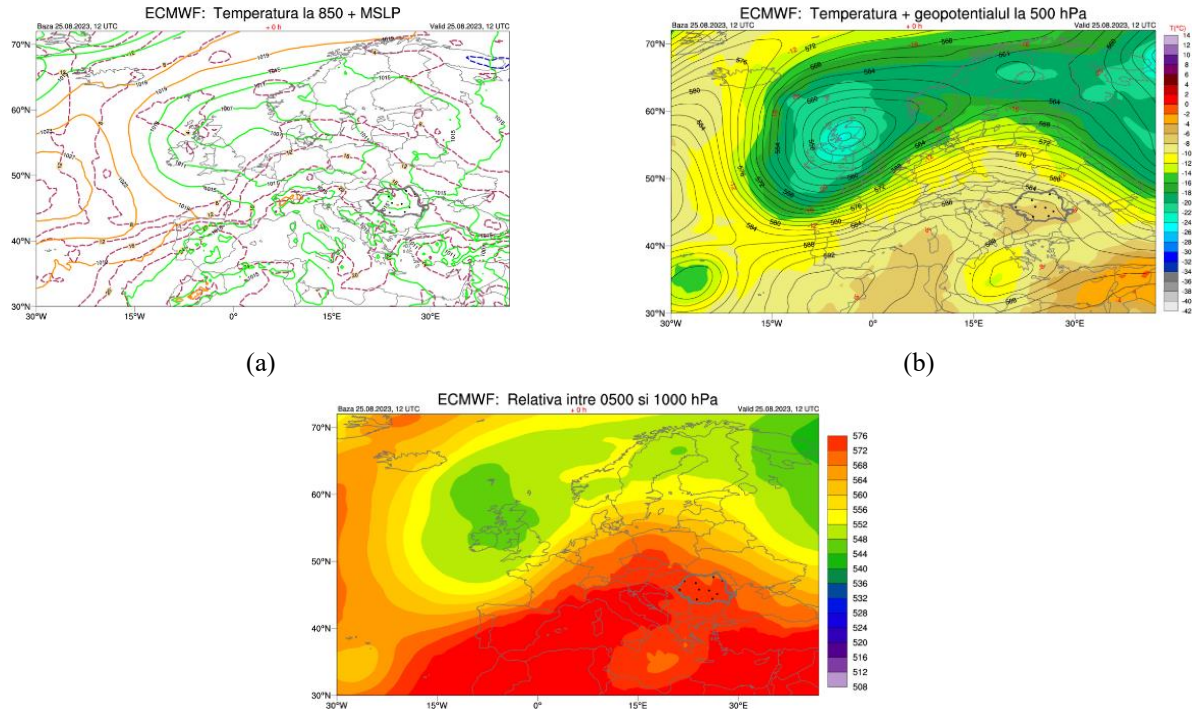
Fig. 17. Mean sea level pressure field and air temperature at 850 hPa (a), geopotential field at 500 hPa (b) and relative topography between 500 and 1000 hPa (c), for 13rd of August 2023



(a) (b)

(c)

Fig. 18. Mean sea level pressure field and air temperature at 850 hPa (a), geopotential field at 500 hPa (b) and relative topography between 500 and 1000 hPa (c), for 20th of August 2023



(a) (b)

(c)

Fig. 19. Mean sea level pressure field and air temperature at 850 hPa (a), geopotential field at 500 hPa (b) and relative topography between 500 and 1000 hPa (c), for 25th of August 2023

As a result, between 26th and 29th of August, there were four consecutive days of temperatures that reached and exceeded the heatwave threshold, on large areas in the plains and plateau areas of Moldova. The cyclonic regime on the ground intensified the advection of tropical air from the north of Africa, and in the middle troposphere, at the level of 500 hPa, the warm North African ridge was kept blocked in the south and center of Europe, up to the latitude of Romania.

Under these conditions, on August 28th, at Iași meteorological station, the highest maximum temperature at the national level was achieved, of 39.0ºC. A particular note of this episode was the realization of the highest maxima in the north of Moldova and not in the south, as a result of the position of the axis of the altitude ridge. The warm ridge extended beyond the region of the Pannonian Plain, being directed towards the north of Romania. As a result, on August 28th, the maximum temperatures oscillated between 39.0ºC, in the north-east of Moldova, at Iași and 36.9ºC at Tecuci meteorological stations (Fig. 20) and minimum temperatures oscillated between 9ºC and 24ºC (Fig. 21).

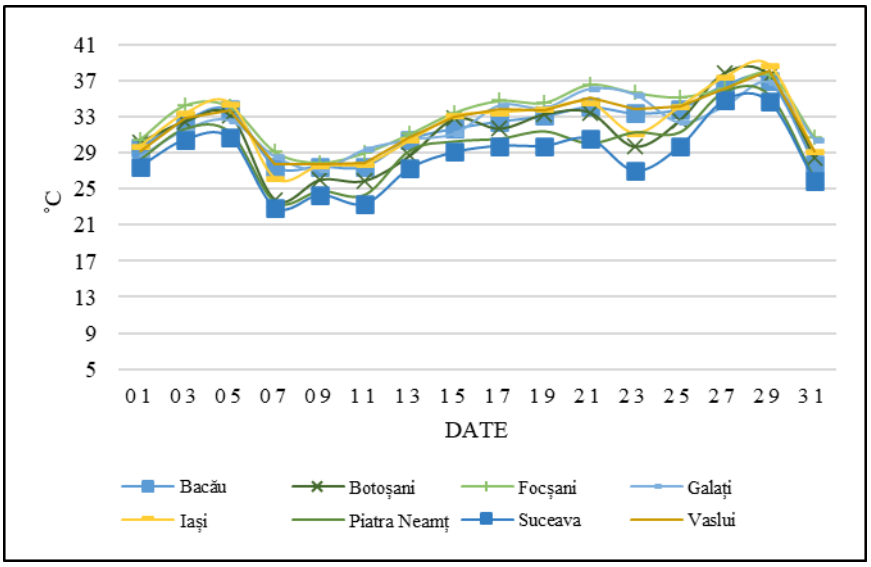


Fig. 20. Maximum temperature at the county weather stations in Moldova in August 2023

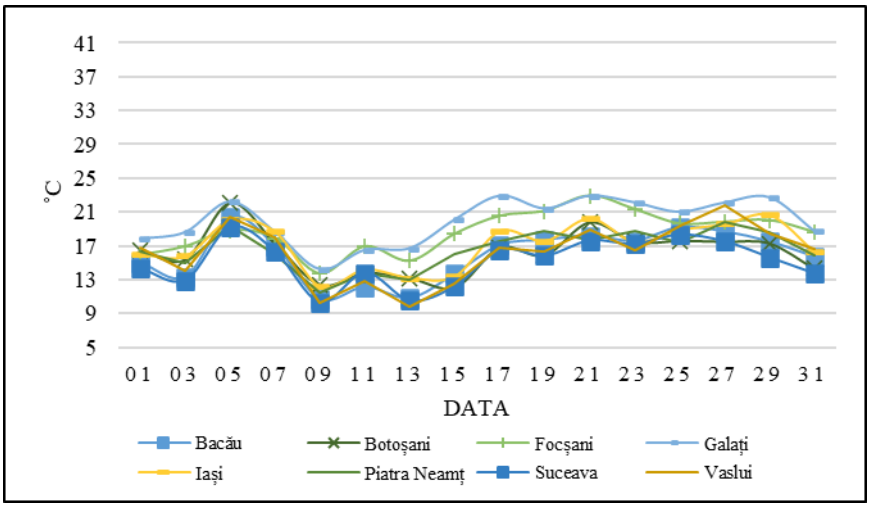


Fig. 21. Minimum temperature at the county weather stations in Moldova in August 2023

In the high mountain area, the maximum temperatures oscillated between 22.7ºC - 24.1ºC at Ceahlău Toaca and between 20.6ºC – 21.9ºC at Retiș Călimani (Table 14). The thermal discomfort was accentuated, and between August 26th and 29th the temperature-humidity index exceeded the critical threshold of 80 units, over extended areas at all stations in the low relief areas. Also in the analyzed interval, minimum temperatures characteristic of tropical nights were achieved. At some meteorological stations e.g. Cotnari, there were 15 tropical nights, similar to Galați, 11 tropical nights at Stânca Ștefănești, 8 at Focșani and Bârlad, 6 tropical nights at Bârnova, 5 at Tecuci and 4 at Darabani, 3 at Vaslui (Table 15).

Maximum temperature (°C) August 13 - 29

Station	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Adjud	30.7	32.9	32.5	30.2	33.8	33.7	33.8	36.2	35.4	34.9	33.9	33.4	34.8	35.8	35.6	37.5	36.8
Bacău	30.5	32.1	31.7	28.6	32.5	32.4	33.1	35.5	34.1	33.7	33.4	32.5	33.9	35.9	36.5	37.9	37
Bârlad	30.2	32.5	31.8	34.1	33.2	33.2	33.5	35.9	35.3	34.6	34.3	33.6	33.3	35.2	35	36.8	37.2
Bârnova	27.7	30.1	29.8	31.6	30.3	30.4	31	32.9	30.9	29.6	29.4	30.2	30.4	33.5	34.2	35.5	34.7
Botoşani	28.7	31.5	32.8	32.3	31.7	32	33.3	34.7	33.5	32.1	29.7	31	32.6	35.7	37.9	37.8	37.6
Ceahlău Toaca	17.6	18.7	17	17.1	17.5	19.2	19.3	22	19.9	20.9	19.2	18.3	18.9	22.7	24.1	23.6	23.6
Cotnari	28.1	30	30.9	31.2	30.5	30.8	31.6	33.1	32	30.7	29.3	30	31.5	34.5	36	36.5	36.2
Darabani	27.4	30.6	31.8	32.7	30.3	30.5	32.1	33.3	31.4	29.9	27.8	29.4	31.2	33.8	36	36.2	36.2
Focşani	31.1	33.1	33.5	31.1	34.8	34.5	34.6	36.9	36.6	36	35.7	33.8	35.2	36.7	36.2	37.6	37.7
Galaţi	30.5	32.4	31.2	33.2	34.3	33.7	34	36.9	36.1	34.7	35.5	33.9	32.4	34.8	34.2	35.7	36.8
Iaşi	30.4	32.9	33.1	34.7	33.5	33.8	33.9	35.8	34.6	33.3	31.2	33.1	34.1	36.6	37.4	39	38.7
Negreşti	30.8	33.1	32.2	33.7	33.4	32.9	34.3	35.4	35.3	33.7	33.3	33.2	34.1	36.7	37.1	38.6	37.5
Piatra Neamţ	29.3	30.6	30.3	25.6	30.6	31	31.4	33.7	30.1	31.7	31.3	30.4	31.3	34.4	35.8	36.4	35.4
Poiana Stampei	24.9	27.6	26.3	22	25.6	27.2	28.6	29.4	28.7	28	22.9	26.1	26.5	29	30.5	32.7	30.6
Rădăuţi	27.6	30	30.2	27.6	29.9	30.3	31.3	33.1	30.7	30.1	27.5	27.7	30.4	33	35.1	35.6	35.3
Reţitiş Călimani	16.1	18.8	17.2	15.2	17.3	17.5	18.2	18.9	18.3	18.2	18.1	17.1	17.1	20.6	21	21.9	20.2
Roman	29.4	31.6	32.7	28.5	32.1	32.5	33.1	35.3	33.1	32.4	30.1	31.9	32.9	35.6	37	38	37.5
Stânca Ştefăneşti	29.3	32.5	33.6	34.3	32.9	32.9	34	35.5	33.3	32.3	29.2	32	33.7	36	37.3	37.9	38
Suceava	27.3	28.8	29.1	28.5	29.8	28.7	29.8	31.9	30.6	29.9	27	28.3	29.7	33.4	34.9	35.2	34.7
Târgu Neamţ	28	30.7	30.6	29	30.6	30.2	31.9	33.5	31.4	31.4	29.6	30.2	31.8	34.6	36.2	36.4	35.9
Târgu Ocna	30.9	32.4	31.6	28.8	32.4	33.3	32.9	35.7	34.7	35.6	32.7	31.5	33.9	36.9	37.7	38.5	36.8
Tecuci	31.2	33.6	33	32.5	34.7	34.7	34.6	37.1	36.4	35.9	35.3	33.7	34.4	35.6	35.7	37	36.9
Vaslui	30.7	33.2	33	34.2	33.9	33.1	33.7	36.4	35.2	33.8	33.8	33.2	34.2	36.3	36.2	37.8	38.1

Table 14. Temperature ≥ 30 Celsius degrees (with red)

Minimum temperature (°C) August 13 - 29																	
Station	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Adjud	12.7	13.9	15.2	17.1	18.2	18.6	19.5	18.3	19.9	21	19.5	20.5	19.3	18.8	18.6	16.7	18.9
Bacău	10.8	12.2	13.7	17	17.1	16.7	17.7	16.8	18.2	19.3	17.6	18.6	19.2	16.6	18.7	18.8	17.5
Bârlad	12.7	14.4	15.4	19.9	19.9	20.9	18.9	18.7	20.3	21.5	19.1	20.5	19.7	20.7	20.6	20.7	20.6
Bârnova	15.5	18.5	19.6	19.7	19.1	20	21.3	20.5	19.6	19.4	19.9	18.2	17.5	20.2	20.9	22.9	23.9
Botoşani	13.2	11.9	12.1	17.9	16.8	17.2	15.9	16.2	19.8	21.7	17.5	17.4	17.6	16.4	17.5	19.2	17.3
Ceahlău Toaca	7.1	10	11.7	11.4	11.6	12	11.9	10.2	12.6	11.5	11.8	9.3	10	12.7	15.8	16.9	15.5
Cotnari	18.2	21	20.8	21.9	21.9	20.5	20.7	23.1	23.3	22.5	19	20.7	21	22.4	21.3	22.6	22.4
Darabani	13.9	16.5	17.1	20.4	18.2	19.5	20.9	19.1	19.5	19.9	16.9	17.5	18.3	19.9	18.6	21.9	21.7
Focşani	15.2	15.5	18.4	19.9	20.5	20.7	21.1	21.2	22.9	24	21.3	21.7	19.6	19.2	19.8	17.9	20
Galaţi	16.7	18.2	20.1	22.4	22.9	22.1	21.4	22	22.9	23.4	22.1	23	21	22.5	22.1	21.2	22.7
Iaşi	13.2	12	13.4	18.4	18.8	18.7	17.6	19.2	20.3	20.1	17.5	19.6	18.9	18.5	19.6	20	20.7
Negreşti	10.3	10.7	11.6	17.1	16.4	16.2	15.4	15.7	19.2	20	16.5	18.1	17.5	15.6	18.4	19	17.4
Piatra Neamţ	13	14.5	16	17.9	17.6	18.3	18.7	18.7	17.7	19	18.7	18.7	17.4	18.8	19.8	20.4	18.6
Poiana Stampei	5.2	7.9	6.9	14.4	11.2	11	12.7	11.3	12	11.3	11.5	13.9	13	9.6	12.2	10	11
Rădăuţi	9.5	10.9	11.3	16.5	15.1	15.8	15.7	15.1	17.9	17.9	17	16.9	18.2	15.4	17.1	16	14.3
Reţitiş Călimani	5.8	10.4	10.2	10.2	11.1	10.7	11.2	10.5	11.2	11.3	9.9	11.1	9.7	11.6	14.1	15.5	12.1
Roman	12.4	13.4	13.1	17.7	16.9	17.9	16.4	17.6	18.2	18.3	18.2	18.9	18.6	17.7	19	19.4	19.4
Stânca Ştefăneşti	12.9	14	14.7	20.7	21.9	21.8	22.2	21.2	21.6	21.6	18.5	20.4	21.1	18.4	19.6	21.6	21.4
Suceava	10.5	12.5	12.2	17.1	16.5	17	15.8	15.5	17.6	20.1	17.2	18.3	18.3	16.9	17.5	18.2	15.6
Târgu Neamţ	11.7	13.1	13.9	17.8	16.8	16.9	17.1	17.3	18.9	22.3	17.7	18.3	17.5	18.3	18.7	18.9	16.5
Târgu Ocna	13.2	14.6	15.7	18.5	17.9	18.4	19.4	18.1	18.4	19.9	19.2	19.7	18.1	18.4	19.5	20.1	18.7
Tecuci	13.5	13.9	16.8	19.3	19.4	20.4	20.5	19.1	21.6	22.8	19	22.4	19.9	18.2	19.8	18.6	18.5
Vaslui	9.8	10.7	12.5	17.7	16.8	16.7	16.3	16.7	18.9	20.2	16.5	18.4	19.3	16.7	21.8	21.5	18.4

Table 15. With red Temperature ≥ 20 Celsius degrees (with red)

Satellite measurements estimated temperatures of 50ºC on the ground surface, in the eastern half of Moldova and 40...50ºC in the center and south, and in the submontane area temperatures of over 30ºC, on August 27th. The following day, on August 28th, the temperature on the surface of the soil intensifies so that in larger areas they reach 50ºC, especially in the east of Moldova.

These values were achieved in the context of a clear sky and strong insolation. On the other hand, on August 29th, values of up to 50ºC were recorded, isolated in the northeast and south, and 40ºC in the north and west of the region. The cloudiness associated with the cyclonic regime on the ground contributed to the decrease of the temperature of the soil surface in the mountainous, sub-mountainous area and also in the southeast of Moldova (Fig. 22).

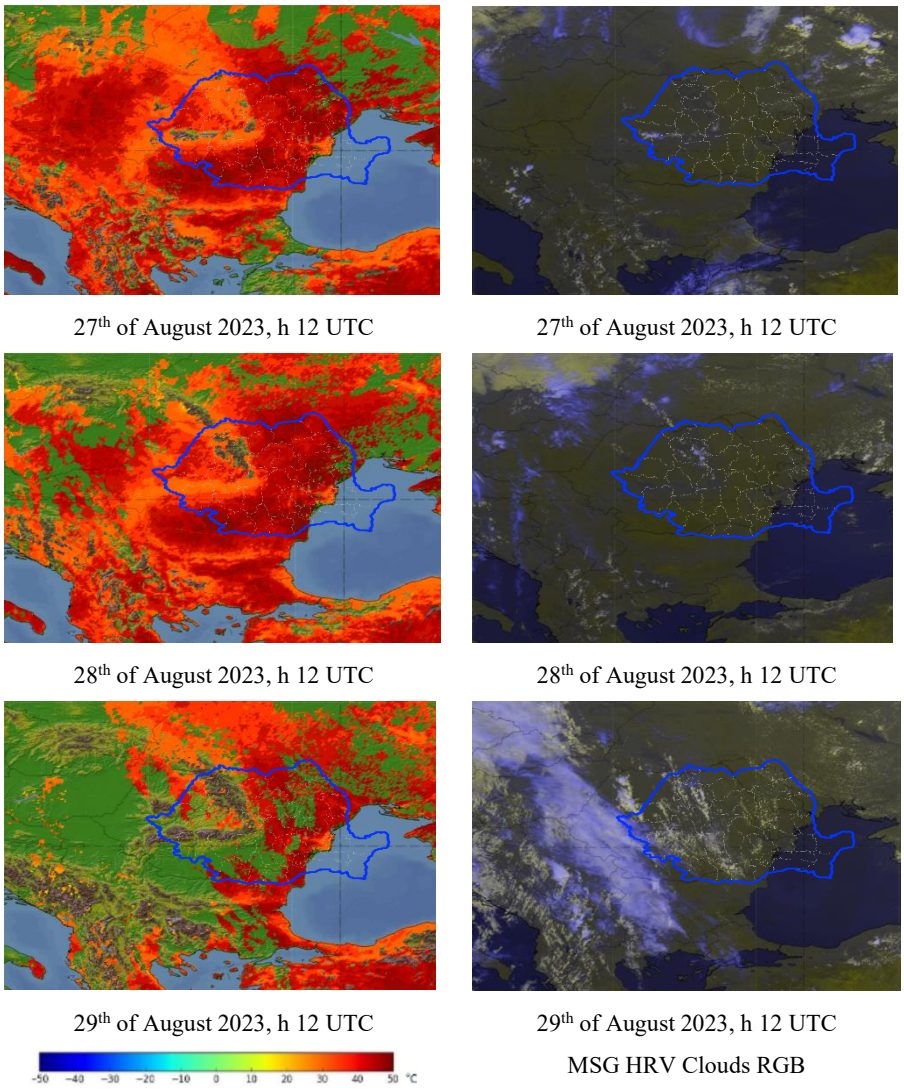


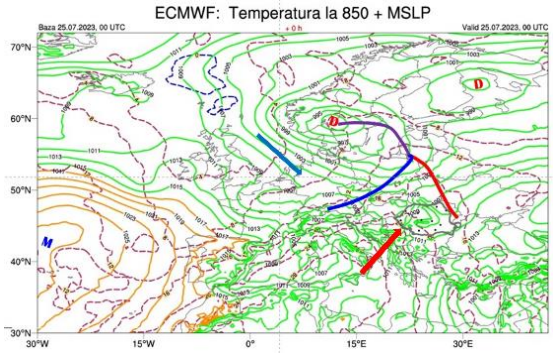
Fig. 22. Satellite imagery- ground surface temperature (left), SEVIRI HRV cloud RGB (right) for 27th-29th of August 2023 [16]

5. Episodes of atmospheric instability for the summer of 2023

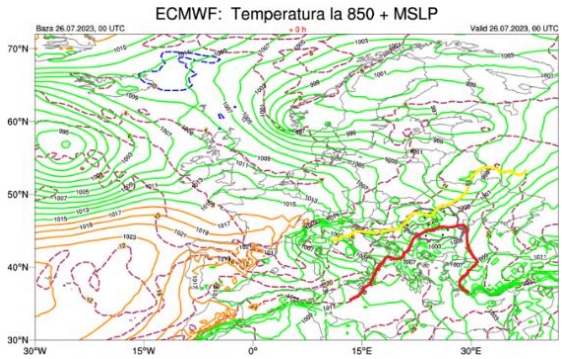
The warm and very warm intervals, interrupted by cold air advections, from polar latitudes, represented the specifics of the summer of 2023 in the region of Moldova. The transition from warm to cold, by displacing tropical air with cold air masses, was accompanied by atmospheric instability phenomena, which on the one hand brought quantitatively significant and long-awaited atmospheric precipitation in the region of Moldova, and on the other hand had violent character, bringing strong wind gust and hail.

5.1. Case study: 25th of July 2023

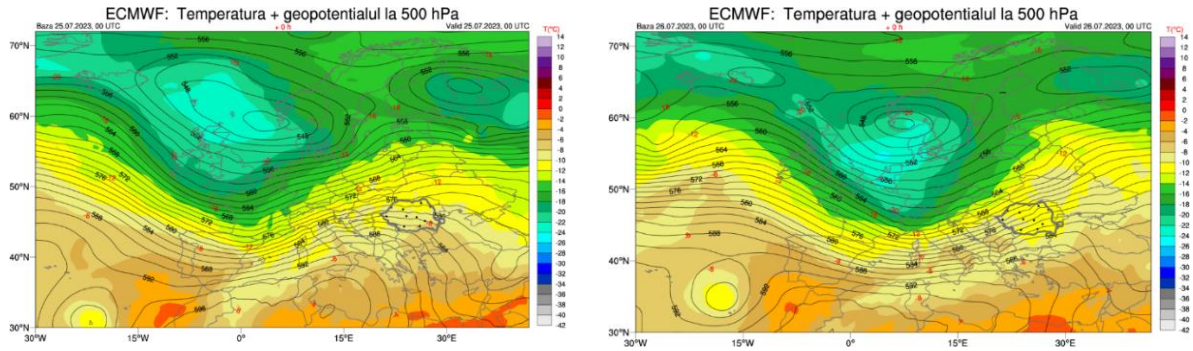
The end of July finds most of Europe under the influence of a cyclonic regime, with the lowest value of atmospheric pressure in the south of the Scandinavian Peninsula, where a well-defined depression (below 995 hPa) of Icelandic origin was deepening. At the opposite pole, the south-west of Europe was under the influence of the Azoric High Ridge, extended to the region of the Iberian Plateau. The cold front associated with the depression of Icelandic origin, extended south of the German-Polish Plain, was to descend gradually towards the south of Europe. In this way, it contributed to the triggering of convective phenomena, which also affected Romania (Fig. 23).



(a) 25th July 2023 M- anticyclone, D- cyclone, red arrow- warm air mass, blue arrow- cold air mass, purple curve- occluded front, red curve- warm front, blue curve- cold front



(a) 26th July 2023 with red – isotherm of 24 degrees, with yellow – isotherm of 16 degrees



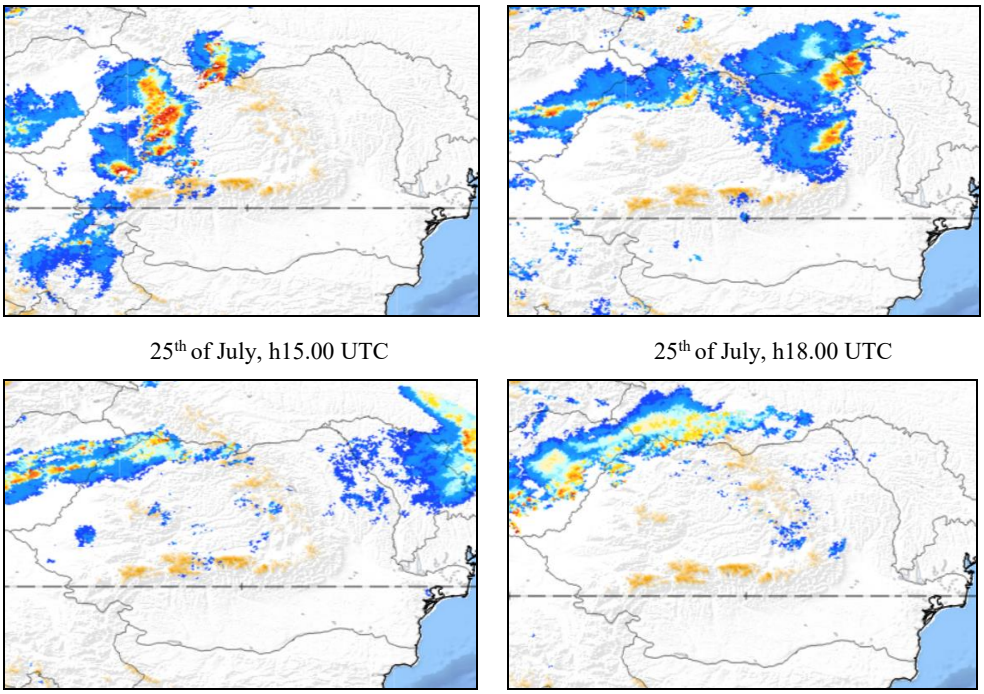
(b) 25.07.2023 (b) 26.07.2023

Fig. 23. Mean sea level pressure field and air temperature at 850 hPa (a), Geopotential field at the level of 500 hPa (b), from July 25th and 26th, 2023 [15]

A polar-maritime air mass was transported from behind the front towards Central Europe, with temperatures between 4°C and 12°C at the level of 850 hPa. In front of it, a depression of Mediterranean origin transported tropical air to the south and southeast of the continent, with thermal values between 20°C and 28°C, visible through isotherms at the level of 850 hPa. Tropical air advection intensified in the Moldova region on July 25, when maximum temperatures were achieved 2°C....5°C higher than those of the previous day (e.g: 37°C compared to 32.1°C at Stânca Ștefănești, 36.7°C compared to 32.5°C at Iași, 33.2°C compared to 31.1°C at Darabani meteorological station). The presence of the tropical air mass in the region of Moldova can be easily observed by analyzing the geopotential and temperature map from the 500 level, where the presence of the warm ridge of North African origin extending to the latitude of Romania can be distinguished. Also, at the level of 500 hPa a moderate zonal circulation was described. The geopotential cores at the level of 500 hPa, in the region of the Scandinavian Peninsula, correspond to the depression of Icelandic origin visible on the mean sea level pressure map (Fig. 23).

The presence of this nucleus denotes the vertical extension of almost the entire tropospheric column of this depression, as well as its mature stage. Also, the high density of isohypses at the level of 500 hPa indicates the presence of a very intense circulation. Gradually, the cold front associated with the depression of Icelandic origin advances towards the center of Europe, causing the displacement of the tropical air mass. In the region of Moldova, the weather destabilizes from the evening hours and especially at night (Fig. 24). The presence of dry and very warm air at the ground level (Fig. 25), high multidirectional vertical shear (the wind switched from a predominantly southerly direction to an exclusively westerly direction at the 500 hPa level), as well as the rapid and intense atmospheric circulation at altitude, primarily determined strong wind gusts

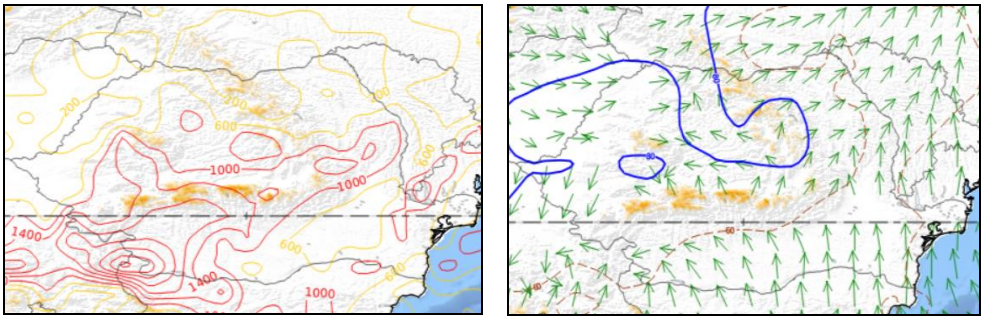
(in the area of Bacău, Vaslui, Botoșani, Suceava counties) with speeds of 20 - 30 m/s (30.7 m/s at Stânca-Ștefănești, 24 m/s at Vaslui, 22 m/s at Bacău, 22 m/s at Suceava meteorological stations).



25th of July, h15.00 UTC | 25th of July, h18.00 UTC

25th of July, h21.00 UTC | 26th of July, h00.00 UTC

Fig. 24. Radar imagery from 25th July 2023 at h15, 18, 21 UTC and from 26th July 2023 at 00 UTC [16]



(a) 25.07.h18 | (b) 25.07.h18

Fig. 25. Distribution of CAPE (Convective Available Potential Energy) values (a), relative humidity (in blue 80% and brown 60%) and ground wind vectors (b), from July 25th, 2023, h18 UTC [16]

The amounts of precipitation from the convective cells were limited due to the rapid atmospheric circulation that reduced the manifestation time of the cells in certain areas of Moldova. The less significant amounts of precipitation that fell in this interval can also be attributed to the presence of a mass of dry air in Moldova that led to the rapid evaporation of precipitation, as the

drops approached the surface of the soil, but also to the unidirectional shear, which led to the shearing of the updrafts in the convective cells and thus to their weakening. Thus, the amounts of water were between 5 and 10 l/m^2 in the low relief areas (7.0 l/m^2 at Vaslui and 9.1 l/m^2, at Bacău meteorological stations) and reaching up to 30 l/m^2 in the mountain area (31.2 l/m^2 at Poiana Stampei). The frequent electric discharges followed the alignment dictated by the atmospheric circulation (Fig. 26).

The northern half of Moldova was the most affected by this episode, while in the south of Moldova, the advection of tropical air continued, which seemed to intensify on July 26th . As a result, on July 26th, an asymmetric thermal picture is emerging between the north and the south of Moldova.

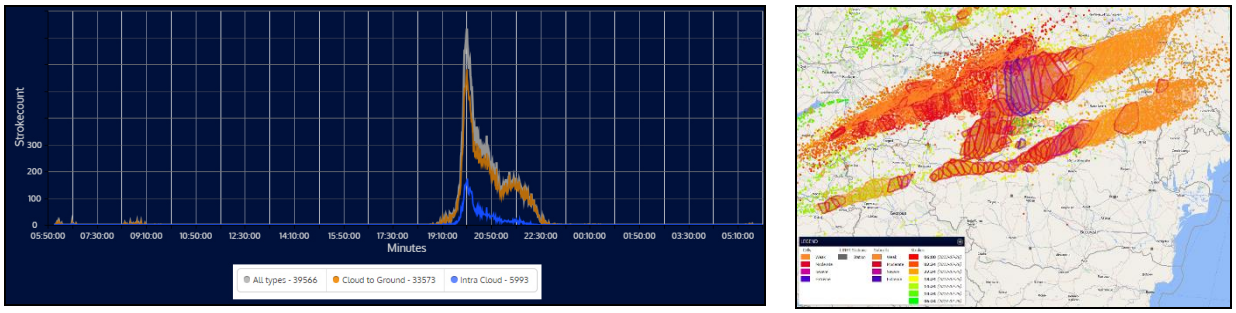
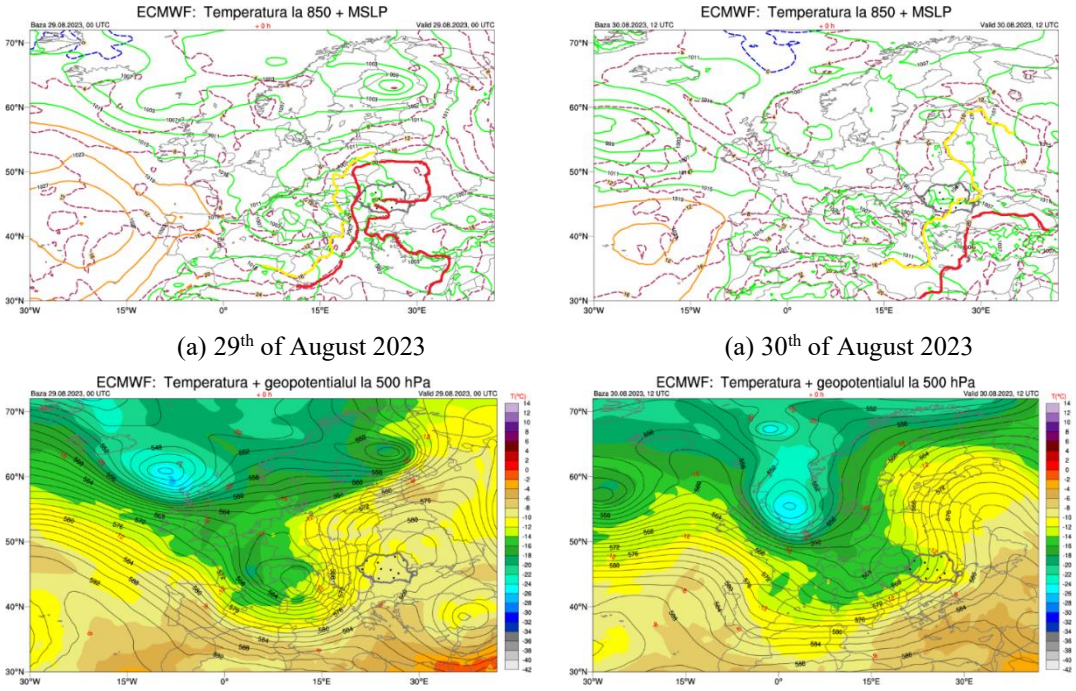


Fig. 26. Number and spatial distribution of electrical discharges on July 25th, 2023 (h17-22UTC) [11]

5.2. Case study: 30th of August 2023

On August 29th, but more pronounced the following day, a well-defined trough at 500 hPa continued to deepen in northern Europe, starting from the West European Plain and reaching the Pannonian Plain region. Romania gradually entered the ascending part of this high-altitude trough, which contributed to the initiation of convection, first in the western half of the country, and then, from the early hours of August 30th, it also started in the region of Moldova, starting with the mountain area. Also in the middle troposphere, a moderate southerly circulation, with wind speeds of 18 – 20 m/s, contributed to the development of well-organized storms in the region of Moldova. The Icelandic Low and two other well-defined depressions moving from west to east (one in the south of the Scandinavian Peninsula and another in the Baltic States region), rule the north-west of Europe and cause intrusions of cold air towards the center of the continent. The rest of Europe is also under the influence of a generalized depression area, except for the southwest, where the Azorean High Ridge is gradually retreating. In this context, a cold atmospheric front associated

with the depression of Icelandic origin, crossed Romania from west to east, pushed the 20ºC isotherm, found at the level of 850 hPa, far to the southeast of Europe and thus dislocated the mass of tropical air installed in the region of Moldova during the last heat wave, from the summer season. The storms were organized along a line of convergence, formed in eastern Romania (Fig. 27).

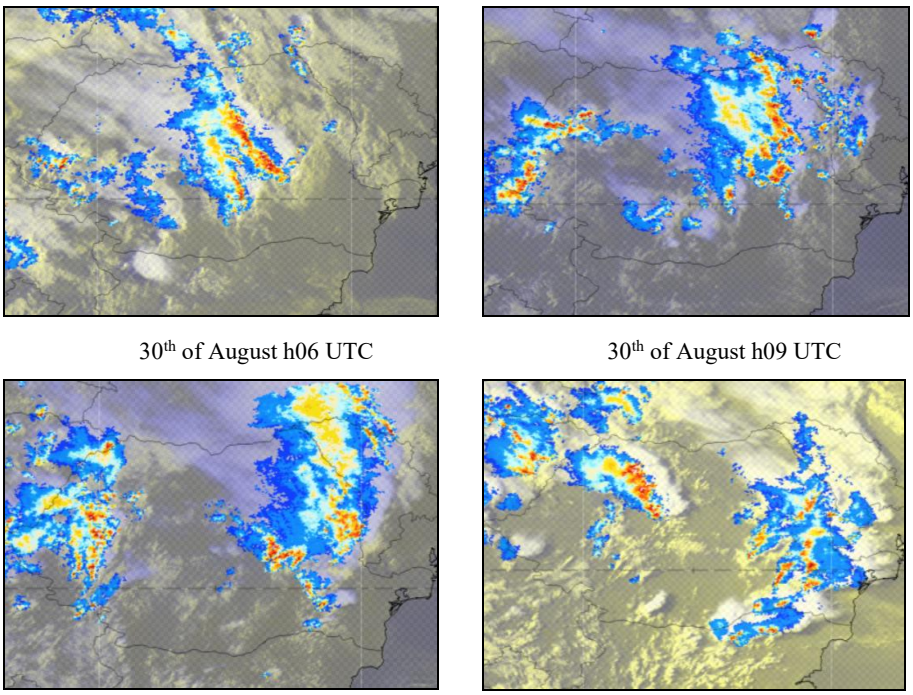


(a) 29th of August 2023 (a) 30th of August 2023

(b) 29th of August 2023 (b) 30th of August 2023

Fig. 27. Mean sea level pressure field, air temperature at 850 hPa (a) and the geopotential field at the level of 500 hPa (b), from August 29th and 30th, 2023 (RUN h00UTC). With red - isotherm of 20 degrees and with yellow - isotherm of 16 degrees [15]

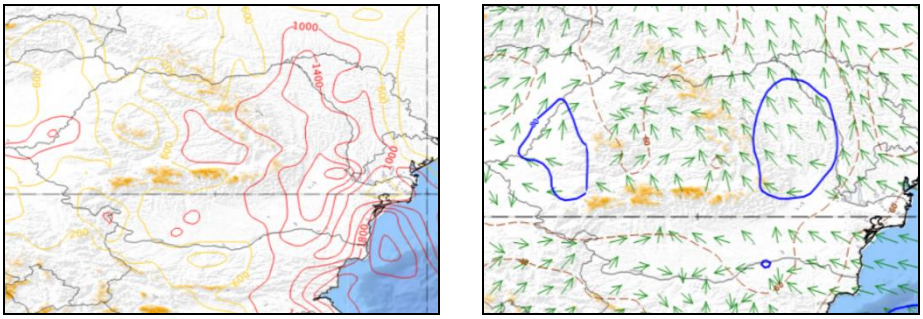
The instability was fully manifested starting at noon, when the air was sufficiently heated, and the CAPE values increased and reached values of 1000 - 1400 J/Kg (Fig. 29). Given the ground circulation, convective systems organized and succeeded one another in a dictated alignment from west and southwest to east and northeast. Under these conditions, the storms formed in the same areas, especially in the south and southeast of the region, causing the accumulation of significant amounts of precipitation in some points. These storms appeared along a line of convergence that formed in eastern Romania, when air masses from the ground were forced to rise (Fig. 28). Consequently, the amounts of water were, in general, between 20...30 l/m^2 (20.4 l/m^2 at Iași, 30.9 l/m^2 at Bârnova, 34.4 l/m^2 at Bacău, 35.0 l/m^2 at Focșani meteorological stations) and isolated of 40...50 l/m^2 (42.1 l/m^2 at Vaslui, 48.5 l/m^2 at Adjud, 59.9 l/m^2 at Roman meteorological stations).



30th of August h06 UTC | 30th of August h09 UTC

30th of August h12 UTC | 30th of August h15 UTC

Fig. 28. Radar imagery from 30th of August 2023 at h06, 09, 12 and 15 UTC [16]



(a) 30.08.h12 | (b) 30.08.h12

Fig. 29. Distribution of CAPE values (a), relative humidity (in blue 80% and brown 60%) and ground wind vectors (b), from August 30th 2023, h12 UTC [16]

Torrential showers were accompanied by frequent electrical discharges (Fig. 30) and wind gust, in general, of 13...15 m/s (13 m/s at Iași, 14 m/s at Bacău, 15 m/s at Darabani, 16 m/s at Adjud meteorological stations) and isolated over 20 m/s (23 m/s at Roman meteorological station). Also, isolated falls of hail were recorded in the area of Bacău, Iași, Vaslui counties.

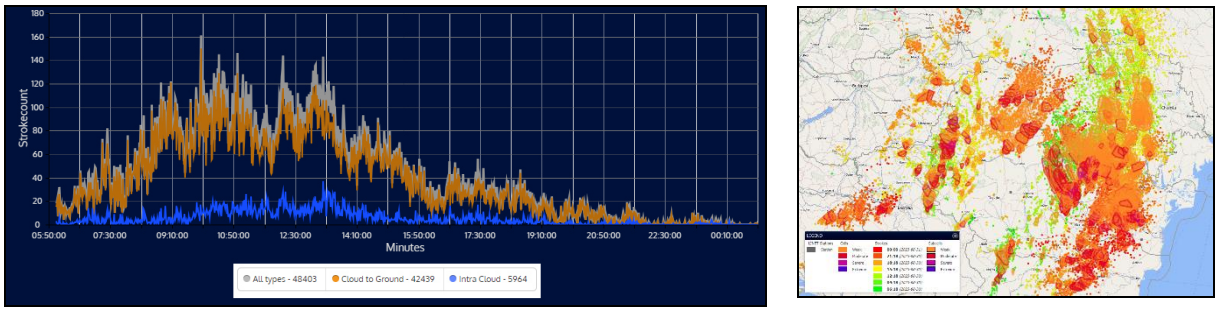


Fig. 30. Number and spatial distribution of electrical discharges between 30th of August, h05 UTC – 31st of August h01 UTC [11]

6. Conclusions

The lack of a general definition has allowed each region to set its own numerical benchmarks to classify certain events as heat waves. The summer of 2023 brought with it intense tropical air advections in Moldova, and overall, it was a summer with positive temperature anomalies on the one hand, but on the other hand with negative precipitation anomalies.

In this context, analyzing the characteristics of each summer month in Moldova, the following conclusions were reached: June had a maximum of 11 tropical days (at Focșani, Galați meteorological stations) and a minimum of 1 tropical day (at Bârnova, Darabani, Piatra Neamț, Rădăuți, Suceava, Târgu Neamț meteorological stations), and the maximum temperature in June was 34.9ºC at Galați meteorological station; July had a maximum of 25 tropical days (at Focșani, Galați meteorological stations) and a minimum of 4 tropical days (at Rădăuți meteorological station), and the maximum temperature was 38ºC at Focșani meteorological station; August had a maximum of 25 tropical days (at Tecuci meteorological station) and a minimum of 10 days (at Suceava meteorological station), and the maximum temperature of August of 39ºC at Iași meteorological station.

If in June, there were no temperatures higher than 35ºC, July had a total of 37 maximum temperatures that exceeded this threshold, of which 7 in Focșani, 5 in Tecuci, 4 in Galați , 3 in Adjud, Bârlad and Târgu Ocna, 2 in Botoșani, Negrești, Roman and Vaslui, 1 in Iași, Bacău, Piatra Neamț and Stânca Ștefănești meteorological stations, and August had 105 maximum temperatures that exceeded 35 degrees, of which 10 in Focșani, 9 in Tecuci, 8 in Negrești, 7 in Adjud, Iași, Târgu Ocna, Vaslui, 6 in Bacău, Bârlad, Roman, 5 in Botoșani, Galați, Stânca Ștefănești, 3 in Cotnari, Piatra Neamț, Rădăuți, Târgu Neamț, 1 in Bârnova, Suceava meteorological stations.

Although the episode of tropical air advection between 22nd and 24th did not meet all the conditions to be classified as a heat wave, it was treated as the result of the persistence of high temperatures in almost the entire region of Moldova for 3 consecutive days and high thermal discomfort (two days in a row, 23rd and 24th of June, the temperature humidity index exceeded the critical threshold of 80 units). The episode between 16th and 18th of July can be included in the definition of heat waves due to the persistence of high temperatures for 3 consecutive days and even exceeding the value of 35ºC at most stations in Moldova on July 17th, as well as exceeding the critical threshold of 80 of temperature-humidity index units. The last episode of tropical air advection analyzed was the most intense and fulfills all the characteristics given by the previously mentioned definitions regarding heat waves. Between 13th and 29th of August, with small variations at some meteorological stations, the maximum temperatures remained constant between 32...34ºC or even exceeded 35ºC for 4 days in a row (between 26th and 29th of August). Also, between 16th and 29th of August, the temperature-humidity index constantly reached the critical threshold of 80 units in the south and east of Moldova, so that later, between 26th and 29th of August, this threshold was exceeded in the entire low relief area of the region.

Thus, the summer of 2023 was a contrasting season for Moldova region, with alternations from warm and very warm periods to cool periods.

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