The heat waves, severe weather events, are generally associated with high pressure synoptic systems and tropical air mass advection. The study of the main causes and effects of these particular situations and their subsequent impacts focuses on the analysis of connections between heat waves and large-scale circulation. Daily maximum temperatures from 105 meteorological stations were used to identify the heat waves. The heat waves are identified by using thresholds imposed to the maximum temperature and to the duration of heat waves. After identification, heat waves were associated to circulation types established with GWT and WLK Catalogues developed within the COST733 Action. The most prolonged heat wave episode (18 days) was registered in 1994 at the Oradea synoptic station. The results reveal the persistence over the southeastern Europe of high pressure synoptic systems, having a northeastern circulation component at sea level and a northwestern or southwestern circulation component in altitude. These circulation types are generally responsible for extreme temperatures episodes over most parts of Romania.

Key words: heat waves, circulation patterns, GWT, WLK.

1. INTRODUCTION

On July 24, 2007 in Calafat, a city in southwestern Romania, an air temperature of 44.3°C has been measured, this value being a new national absolute record for July, replacing the old record (also reached in the first decade of the 21st Century) of 43.5°C in Giurgiu (a southern city), on July 5, 2000. The 2007 record is only 0.2°C apart from the highest value of air temperature ever measured in Romania (44.5°C on August 10, 1951 in the town of Ion Sion, in the south-east of the country). The mean air temperature in July 2007 has had the second highest value since 1961 (23.0°C), it being surpassed by that of July 2012 only (23.7°C). In July 2012 there have been 25 days during at least one temperature of 37°C or higher was recorded, and on August 7, 2012 there have been 13 synoptic stations
that have recorded the reaching or overtaking the absolute records for the maximum temperature. Every heat wave is a challenge for the forecasters, who issue warning messages that further presume reactions from agencies with specific responsibilities in dangerous meteorological situations. With the aim of helping the forecasters out, in our study we have paid special attention to the relationship between large scale circulation patterns and the occurrence of heat waves.

Heat waves can be defined in various ways, generally by quantifying the duration and intensity of daytime maximum and night-time minimum [1, 2, 3]. One way to define heat waves is based on the concept of establishing specific thresholds by analyzing the persistence and frequency of heat waves [4]. Another definition, of World Meteorological Organisation (WMO) and cited by the MetOffice is "when the daily maximum temperature in more than five consecutive days exceeds the average maximum temperature by 5°C, the normal period being 1961-1990". Starting from this, in 2002 [5] the so-called heat wave duration index was defined, which is the maximum number of consecutive days (larger than 5) during which the maximum temperature surpasses the average over 1961–1990 with at least 5 degrees. In 2001, Robinson [6] has carried out a study on the way to define a heat wave and he has defined this event as “a period of at least 36 h during which the daytime high exceeds the high threshold for a heat wave by more than 10ºF, the overnight low exceeding the low threshold for a heat wave”.

The socio-economic impact of heat waves has maintained the interest of scientists in this subject, who have tackled it in various ways. Some studies focus on the impacts and response to heat waves. For instance, in 1996 Changnon et al. [7] highlight the fact that, in the United States, the deaths caused by heat wave are visibly higher than those caused by any other weather condition, even if noting that a statistics on heat-related deaths is difficult to assess. The authors have found that during the severe 5-day heat wave in mid-July 1995 over the central United States, the urban heat island of Chicago has exacerbated the heat problem, and considered that the heat wave warnings ought to be designed for a particular place and time. A similar result has been found in 2013 by Li and Bou-Zeid [8] who, in a recent study show that because of the interaction between urban heat islands and heat waves, the urban population suffers a higher heat-related impact than the rural one. Studies regarding the increased mortality during heat waves have also been carried out by Sartor et al. [9], Rooney et al. [10] and Schär et al. [11] – the latter referring the heat wave in the summer of 2003, which was an event with a powerful socio-economic impact in a number of European countries.

Other studies focus on the link between types of circulation and the occurrence of heat waves. Kysely in 2002 [12] uses the Grosswetterlagen (GWL) classification for establishing the conditions favourable for the onset of heat waves in Prague (Czech Republic). He concludes that a central European high, a Fenno-scandian or Norwegian Sea/Fenno-scandian high and circulation with the inflow of warm air from south-west to south-east into central Europe are such elements, and
in another study stresses that the effects of future climate change on the occurrence and severity of temperature extremes may be exacerbated by a more persistent circulation related to a decreased cyclone activity over mid-latitudes and a northward shift of storm tracks [13]. Studies on heat waves in the Balkans have been carried out by Theoharatos et al. [14] with a focus on the synoptic conditions that influenced the occurrence of heat wave in Athens, Greece in 2007. In June that year, the air masses of North-African origin moved over the Balkans, being enriched in water vapor from the Mediterranean, and at the time they arrived over the Athens they were trapped below the pressure level of 700 hPa.

In Romania, the results of certain studies indicated changes in the extremes air temperature, pointing out their correlation with changes of large-scale circulation patterns. Thus, Bojariu and Paliu [15] reveal the connection between North Atlantic Oscillation (NAO) phase and temperature variability in winter. Certain studies focused on summer temperature patterns and variability in 2007 [16, 17]. The connection between heat waves and large-scale circulation in southeastern Europe was investigated by Georgescu et al. [18].

The current study aims to investigate which is the most appropriate definition of the heat wave for Romania and to analyze the connections between large scale circulation patterns and the occurrence of heat waves in Romania. Data and methods are being presented in Section 2, while the results and their interpretation are in Section 3. Conclusions are in the last part of this paper.

2. DATA AND METHODS

2.1. DATA SETS

To perform the analysis, observational and reanalysis data sets have been used, as follows.

The observational data consist of the daily maximum air temperature values at 2 m, measured by 105 synoptic stations spread over the entire area of Romania, their altitude being between 3 and 747 m.a.s.l. This data set covers continuous measurements over two periods of 30 years: between 1961 and 1990 and between 1983 and 2012, and they have been obtained from the database of the National Meteorological Administration of Romania.

The reanalysis data sets have been extracted from the NCEP/NCAR [19] reanalysis files, where the spatial resolution is 2.5° X 2.5° latitude/longitude and then used to build up the circulation types. These data sets consist of: the daily mean of sea level pressure (SLP), geopotential height at 925 (HGT925) and 500 (HGT500) hPa, \( u \) and \( v \) components of the wind vector at 700 hPa level, and the precipitable water content for the entire atmospheric column.
2.2. DEFINING THE HEAT WAVES

Assuming the climatic influences of the Carpathian Mountains and the Black Sea, we have divided the territory of Romania in four regions (Figure 1), to wit: 1 – the Eastern part, with climatic influences from the Black Sea and the Russian Plains; 2 – the Southern part, with a climate influenced by the Mediterranean and the Black seas; 3 – the Intra-Carpathian area, whose climate is both modeled by the shelter of the Carpathians, and influenced by northern and northwestern circulations; 4 – the Western part, whose climate is equally influenced by conditions in central Europe and the Mediterranean Sea.

![Fig. 1 – Regions in Romania subjected to particular climate and weather patterns.](image)

To establish an adequate definition for the heat wave in Romania, the maximum temperatures during the summer (June, July and August) recorded between 1961 and 1990 have been analysed, in two steps. The reference period was chosen as per the recommendation of the WMO. First, the average over the period 1961–1990 of the maximum daily temperatures was computed for each of the 105 stations with continuous observations and for each month; then, one average over the period 1961–1990 (Tmax_med) for each of the 105 stations, was computed for each month in this interval, resulting 30 values for each month. The second step was to select the highest maximum temperature at each station in each month of the 30 years, during 1961–1990, and averaging these values over this period (Med_Tmax_month).
The statistic distributions of $T_{\text{max\_med}}$ and $T_{\text{med\_Tmax\_month}}$ for June, July and August and for each of the four regions are being presented in Figure 2. The absolute values of the 90-percentile, after analysing them comparatively for each region show that, for Region 2 (South) the largest values of maximum temperatures (represented by $T_{\text{med\_Tmax\_month}}$) are spread close to 35°C, which

![Box plot of the average over the climatologic interval 1961 – 1990 for June, July and August of the maximum temperature (a) and the largest monthly maximum temperature (b). Upper and lower whiskers represent the 90th, respectively the 10th percentiles.](image-url)
is approximately 5 degrees more than the average of maximum daily temperatures (represented by Tmax_med). So, for this region we presume that the recommendation of WMO can be applied in order to define the heat wave threshold as the value which is 5 degrees larger than the climatologic mean (over 1961–1990) – a threshold that, in the following, for this region will be assumed to 35°C. The discussion of results for the other regions is similar to this, where a threshold of 33°C marks the onset of a heat wave. A study of the number of consecutive days in which the air temperature at each station in each region has surpassed the 35°C or the 33°C thresholds shows that the average duration of a heat wave in Romania is between 3 and 6 days. One notes the longest (18 days) heat wave, specifically that of 1994, between July, 25th and August, 11th at the Oradea synoptic station.

As such, having defining the threshold for each region we can define the heat wave as a period of at least 3 consecutive days in which the maximum temperature is larger than 33°C for Regions 1, 3 and 4 and 35°C for Region 2.

2.3. ATMOSPHERIC CIRCULATION CLASSIFICATION

To identify the connections between large scale circulation patterns and the onset of heat waves in Romania, we have used two circulation Catalogues developed by the Project “COST733Action”. The two Catalogues used in the study are GrossWetter-Typen (GWT) and Objektive WetterLagenKlassifikation (WLK), which both are automated and using specific thresholds. According to these Catalogues, each day is being attributed a particular type of circulation.

The GWT Catalogue, developed by Beck [20] was inspired by the subjective “Central European Grosswettertypes” classification scheme of Hess and Brezowsk [21]. This Catalogue is based on the idea that the air circulation can be characterised by coefficients of zonality (Z), meridianality (M) and vorticity (V) of the sea level pressure [20, 22]. In this study the GWT Catalogue was used with 18 circulation types.

The WLK Catalogue is based on the “Objektive Wetterlagenklassifikation-OWLK” classification of the weather types developed by Dittmann et al. [23]. This catalog uses information from three tropospheric levels: 925, 700 and 500 hPa, and information on the precipitable water content over the entire tropospheric column. Geopotential fields at 925 hPa and 500 hPa are used for establishing the cyclonicity or anticyclonicity, while the wind at 700 hPa for establishing the dominant direction of flow. The alphanumeric output consists of five letters: the first two indicate the dominant wind sector (01=NE, 02=SE, 03=SW, 04=NW, 00=undefined); the third and fourth denote Anticyclonicity or Cyclonicity at 925 and 500 hPa respectively; and the fifth letter denotes Dry or Wet conditions. In this study the WLK catalogue was used with 40 circulation types.
The geographic domain being used herein (Figure 3) for establishing the circulation types is centered over Romania and represents an atmospheric window between $5^\circ$ – $45^\circ$ East and $35^\circ$ – $55^\circ$ North.

![Fig. 3 – Location of Romania (the study area) and the domain used to establish circulation types.](image)

### 3. RESULTS

#### 3.1. HEAT WAVES CHARACTERISTICS

Time data sets of the maximum temperature at 105 synoptic stations were used, over the summers of 30 years between 1983 and 2012. During this time, 2144 heat waves of various lengths at all stations were found; the largest such interval was recorded at the Oradea synoptic station (located in Region 4 – western part of Romania) between July 25th and August 11th when the average maximum temperature was 34.4°C (Figure 4).

The maximum temperature measured at this station during this interval was 36.8°C, on August 11th, 1994.

The distribution of heat waves by duration and grouped by region, between 1983 and 2012 is being shown in Figure 5.
Fig. 4 – Maximum temperature during the longest heat wave in Romania between 1983 and 2012 (in 1994, between July 25th and August 11th) at the Oradea synoptic station located in Region 4. Please note that the threshold for the heat waves in this is 33°C.

Fig. 5 – The absolute frequency of heat waves grouped by the region, between 1983 and 2012.

In Figure 5 one can note the significant difference between the four regions; thus, Region 2 was the region which was the most affected by heat waves. The number of heat waves in it (1111) is larger than the sum of heat waves’ numbers
over the other regions (Region 1, 3 and 4). Region 2 is being followed by Region 4 (428 heat waves), Region 1 (359 heat waves) and Region 3 (246 heat waves).

Figure 6 presents the relative frequency of heat waves in Romania by their duration.

![Figure 6 – Relative frequency of heat waves period in Romania, between 1983 and 2012.](image.png)

With regard to the duration of heat waves, the most frequent are those between three and six days (Figure 6). Those longer than three days are the most frequent, as expected and have had a relative frequency of 37.4%. They are followed by the heat waves 4-days long (26.6%), 5-days long (14.6%) and 6-days long (7.6), with the total of the other durations' frequencies being 13.9%.

3.2. LARGE-SCALE MECHANISMS RESPONSIBLE FOR HEAT WAVES OCCURRENCE

Due to the orography of Romania, where the altitudes range between 0 and 2544 m.a.s.l. the analysis is useful of circulation types both in the lower and middle troposphere. For this, the Catalogues GWT (for surface analysis) and WLK (for the middle troposphere) were used simultaneously.

3.2.1. Surface analysis – GWT circulation types

In Figure 7, the relative frequencies of every circulation type during each heat wave in each region are being presented - as established by the GWT Catalogue with 18 types.
Fig. 7 – Relative frequency of GWT18 circulation types determined for days with heat waves for Region 1 (black columns), Region 2 (red), Region 3 (blue) and Region 4 (green).

In Figure 7 one can see that the dominant circulation during the heat waves was northeastern in an anticyclonic pattern – NE(A), with a frequency of about 30% for Region 1, 25% for Region 2, 35% for Region 3 and 33% for Region 4. This can be explained by the fact that the Carpathian Mountains act like a barrier against air masses coming from central Europe (western circulation), and modify their trajectory to one with a northern component. From the analysis of the composite SLP maps for dominant circulation one can conclude that the heat waves are favoured when the ridge of the Azores Anticyclone extends over central Europe, reaching the West of the Black Sea (Figure 8, upper panel). NE(A) type of circulation is followed by the Undefined Anticyclonic type – Undef(A), which means an anticyclone centered on the study area (implicitly, over Romania, Figure 8 – lower panel) isolated from the ridge of the Azores or North African Anticyclone. As expected, the heat waves in Romania are associated with high pressure systems (over 70% of all cases), one explanation being that inside an anticyclone the air moves downward, and wind speed is low – these conditions forcing the air mass to linger over an area and get warmer.
3.2.2. Lower and middle troposphere analysis – WLK circulation types

In Figure 9, the relative frequency of each circulation type, as established by WLK Catalogue with 40 types, during the heat waves for Region 1 (a), Region 2 (b), Region 3 (c) and Region 4 (d) for the entire period of the study (1983–2012).
Fig. 9 – Relative frequency of WLK40 circulation types determined for days with heat waves for Region 1 (a), Region 2 (b), Region 3 (c) and Region 4 (d).
As for the circulation in the lower and middle troposphere, the dominant circulations are the southwestern and northwestern ones in anticyclonic regime. This dominance can be explained by the fact that the mean circulation in the middle troposphere is zonal, and considering that the WLK Catalogue establishes the dominant direction of flow by using the wind at 700 hPa one can see how the maximum height of the Carpathians (2544 m) does not allow them to act as a barrier like in the case of surface circulations. In this case too, like with surface circulations, the flow is taking place in anticyclonic regime. Regarding the humid or dry character of the air mass - for Region 3 there is a dry air mass, while for the other regions it is humid. The explanation for this could be that the humidity of the atmosphere is concentrated in the lower levels of the troposphere, and that Region 3 is sheltered by the Carpathians which block the intrusion of humid air coming from the Mediterranean Sea. It is known that humidity together with high temperatures are responsible for the rising in thermal discomfort for human beings.

The northwestern circulations in anticyclonic regime (both those for humid and dry air) total 26% of the cases with heat waves in Region 1, 41% for Region 2, 28% for Region 3 and 36% for Region 4. In the case of southwestern circulations, regardless of the humid or dry character of the air mass, these total 30% for Region 1, 26% for Region 2, 31% for Region 3 and 24% for Region 4. This analysis may be an explanation for high number of heat waves in Region 2 (see Figure 5) and supports the study algorithm of dividing Romania's territory in four distinct parts and highlights the different impact of circulations for each Region.

Like for the GWT Catalogue, the dominant circulation patterns during heat waves were presented as per the WLK Catalogue with 40 types, so Figure 10 shows the dominant patterns. Analysing this figure we see that in the case of the southwestern, anticyclonic type, both in the lower and middle troposphere a ridge extends of the Azores Anticyclone, which in turn starts the advection of warm air from the North of Africa – a typical situation for heat waves in Romania, while the circulation (as established by the dominant direction of wind at 700hPa) is mostly southwestern.

As for the northwestern circulation type in anticyclonic regime, as established by the WLK with 40 types, one can see the same ridge both in the lower and middle troposphere as in the case of the southwestern, anticyclonic type, only in this case said ridge is far more extended – over the most part of Europe. From the analysis of wind at 700hPa results the dominant northwestern direction of flow.

These two situations are responsible for more than two thirds of the occurrences of heat waves in Romania.
Fig. 10 – WLK40 southwestern anticyclonic circulation pattern (upper panel) and WLK40 northwestern anticyclonic circulation pattern (lower panel). Colors represent the geopotential height at 925hPa (in hPa), solid lines represent the geopotential height at 500hPa (in hPa) and vectors represent the wind speed at 700hPa (in m/s).
4. SUMMARY AND CONCLUSIONS

The aim of this study was to establish a link between heat waves and large-scale mechanisms which are responsible for their onset. To accomplish this, 2144 cases of heat waves were analysed, that were recorded at 105 synoptic stations in Romania over the time interval between 1983 and 2012. To define the heat wave, the territory of Romania was split in four regions, each with its own climate influenced by the Carpathian Mountains and the Black Sea; for each region the statistic distributions of the maximum temperatures' average and those of the monthly absolute maximum temperatures for the climatologically period of 30 years, during 1961-1990 were computed. By taking into account the 90-percentile, thresholds were established for a heat wave in each region. The threshold for Region 2 is 35°C and 33°C for Region 1, 3 and 4. By this rule, 2144 heat waves were identified with a duration of at least 3 days. The daily circulation types, which were established with two circulation Catalogues – GWT (with 18 types) and WLK (with 40 types), could be associated to each day within a heat wave. Then, the frequencies of the circulation types during each heat wave were computed. This way, the main synoptic patterns were spotted that were responsible for the heat waves in Romania.

The longest heat wave (18-days) within the entire of 30 years (1983 – 2012) study period was registered at the Oradea synoptic station in 1994, during July, 25th and August, 11th.

The dominant circulation types, as they were established with the GWT Catalogue are those that are northeastern and Undefined anticyclonic, while those established with the WLK Catalogue are those that are southwestern and northwestern in anticyclonic regime - both in humid and dry air.

After concluding this analysis, we can state that the main baric system responsible for the onset of heat waves in Romania is the ridge of the Azores Anticyclone, which extends over the central Europe close to Romania. The movement of this Anticyclone towards the North of Africa leads to its ridge's extension over southeastern Europe, conducive to a southwestern circulation in the middle troposphere that favours warm air advection from northern Africa. This ridge eventually envelopes the South of the continent and modifies the southwestern circulation into northwestern. Also significant are the situations in which an anticyclone is being centered over Romania and plays a major part in influencing the onset of heat waves. Our results are in agreement with those noted in previous studies [17, 18].

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