IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 120, No. 4, October – December, 2016, pp. 395–414

Impact of atmospheric circulation on the occurrence of heat waves in southeastern Europe

Arkadiusz M. Tomczyk

Department of Climatology, Adam Mickiewicz University in Poznań,
Dzięlgielowa 27, 61-680 Poznań, Poland
E-mail: atomczyk@amu.edu.pl

(Manuscript received in final form May 31, 2016)

Abstract—The main objective of this article is to identify the pressure conditions conducive to the occurrence of heat waves in southeastern Europe. Before this objective could be achieved, the spatial and temporal variability of the occurrence of heat waves in the region were determined. This article defines a hot day as a day of maximum temperature (Tmax) above the 95th annual percentile, and a heat wave is considered to be a sequence of at least 5 such days. The study is based on the data of 21 stations from the period 1973–2010. In the discussed period, at all stations, a statistically significant increase in Tmax and the number of hot days were observed. The total number of heat waves fluctuated from 25 in Burgas to 48 in Drobeta-Turnu Severin, Skopje, and Split, while the sum durations of heat waves ranged between 173 days in Botosani and 414 in Split. Heat waves in southeastern Europe occurred most often when a ridge of high pressure lay over Europe. This system caused the inflow of continental air masses from the northeast or east. An alternative source of air masses causing heat waves was advection from the south.
Key-words: heat waves, atmospheric circulation, climate change, southeastern Europe

1. Introduction

One of the most important factors determining weather and climate conditions is atmospheric circulation (*Chromow,* 1952; *Niedźwiedź,* 1981; *Yarnal,* 1993). In particular, high pressure systems and blocking situations, which determine the meteorological conditions of a particular region by breaking zonal circulation, are of great importance (*Bielec-Bąkowska,* 2014). The consequence of such patterns is the occurrence of heat waves in summer and frost waves in winter

(*Porębska* and *Zdunek,* 2013; *Bielec-Bąkowska,* 2014). The impact of atmospheric circulation on thermal conditions and the occurrence of thermal extremes has been the subject of many studies (*Founda* and *Giannakopoulos,* 2009; *Avotniece et al.,* 2010; *Ustrnul et al.,* 2010; *Kažys et al.,* 2011; *Porębska* and *Zdunek,* 2013; *Tomczyk* and *Bednorz,* 2014; *Unkašević* and *Tošić,* 2015; *Tomczyk* and *Bednorz,* 2016). Further and more detailed research is required into the importance of circulation, and above all its changes, both global and local, as well as from both a holistic perspective and a perspective taking its particular elements into consideration (*Bielec-Bąkowska,* 2014).

According to the authors of the Fifth IPCC Assessment Report (2013), in each of the last three decades, at the Earth's surface temperature was higher than in the preceding decade and, simultaneously, higher than in any previous decade since 1850; in the Northern Hemisphere, the period of 1983–2012 was probably the warmest 30-year period in the last 1400 years. One manifestation of the observed warming is the increasing frequency of extremely hot days and heat waves (*Avotniece et al.,* 2010; *Kyselý,* 2010; *Shevchenko et al.,* 2014; *Keggenhoff et al.,* 2015; *Unkašević* and *Tošić,* 2015; *Tomczyk* and *Bednorz,* 2016; *Tomczyk et al.,* 2016), with the simultaneous decrease in frost days and frost waves (*Kejna et al.,* 2009; *Avotniece et al.,* 2010; *Bednorz,* 2011; *Mužíková et al.* 2011; *Niedźwiedź et al.,* 2012; *Krzyżewska,* 2014; *Migała et al.,* 2016). The heat waves from 2003 to 2010, defined as "mega heat waves," caused more than 500-year records for seasonal air temperatures across approximately 50% of the area of Europe (*Barriopedro et al.,* 2011).

In recent years, there has been an increase in the number of publications concerning extreme weather phenomena, including heat waves. These publications have largely focused on determining the influence of heat waves on the number of deaths caused by biometeorological conditions affecting human body systems (*Johnson et al.,* 2005; *Poumadere et al.,* 2005; *Paldy* and *Bobvos,* 2009; *Shaposhnikov et al.,* 2014; *Bobvos et al.,* 2015; *Revich et al.,* 2015). Despite these numerous scientific works, there is still a noticeable deficiency of scientific papers analyzing the occurrence of heat waves on the basis of long and uniform data series for the different regions of Europe. Therefore, the objective of this article was to determine the spatial and temporal variability of the occurrence of heat waves in southeastern Europe. However, the main emphasis of this article was to identify the atmospheric conditions conducive to the occurrence of heat waves in this part of Europe. The undertaking of this subject is especially relevant in light of forecasts which show that heat waves in the 21st century are going to be not only more frequent, but also longer and more intensive (*Meehl* and *Tebaldi,* 2004; *Beniston et al.,* 2007; *Koffi* and *Koffi,* 2008; *Kürbis et. al.,* 2009; *Kyselý,* 2010; *Pongracz et al.,* 2013; *Zacharias et al.,* 2015).

2. *Methods and data*

This article used daily values of the maximum (Tmax), minimum (Tmin), and mean air temperature (T) for 21 stations located in eight countries: Bulgaria, Croatia, Greece, Macedonia, Romania, Serbia, Slovenia, and Hungary (*Fig. 1*). The article defined this area simply as southeastern Europe. The data were obtained for the period of 1973–2010 from the freely accessible databases of the National Oceanic and Atmospheric Administration (NOAA).

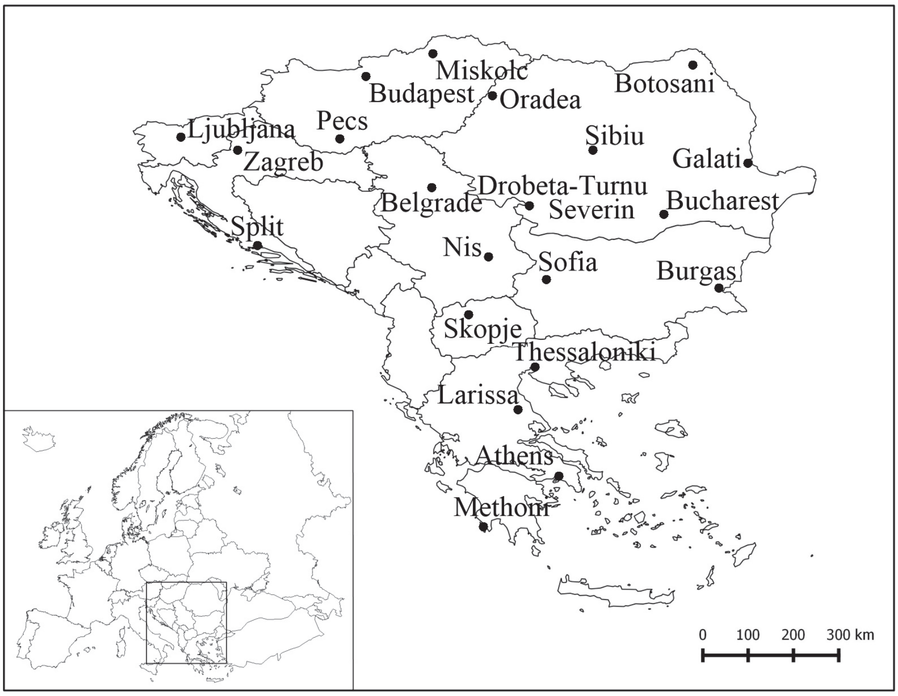

Fig. 1. Locations of the meteorological stations.

This article defines a hot day as a day with Tmax above the 95th annual percentile (*Fig. 2a*), and a heat wave (HW) is considered to be a sequence of at least 5 hot days. This assumption is based on the definition of an extreme weather event included in the IPCC reports (2007), according to which, a weather phenomenon is defined as an extreme weather event if it is so rare within a particular area and in a particular season that it lies within the range of the 10th or 90th percentile of an observed probability density function, or rarer. This definition of a HW has been used in articles concerning, among others, the occurrence of HWs in central Europe (*Tomczyk* and *Bednorz,* 2016) and northern Europe (*Tomczyk et al.,* 2016).

The literature offers equal definitions of HWs which differ in methodological assumptions. According to *Krzyżewska* (2010), this results from the fact that distinguishing HWs is most of all dependent on local climatic conditions, which change with latitude, height above sea level, and direction of air mass inflow. HWs are defined as, among others: (1) a several-day period with the maximum or mean daily temperature above a specific threshold value (*Kyselý,* 2002; *Kosowska-Cezak,* 2010; *Bobvos et al.,* 2015); (2) a period with apparent temperature (AT) above the 95th percentile which starts with a minimum 2.0°C increase in relation to the preceding day (*Kuchcik* and *Degórski,* 2009); (3) a period >5 consecutive days with Tmax >5 °C above the 1961–1990 daily Tmax norm (*Frich et al.,* 2002; *Unkašević* and *Tošić,* 2009).

On the basis of the data, the mean Tmax of the particular months and summer seasons (June–August) was calculated, and hot days were selected to distinguish HWs. Additionally, Pearson's correlation coefficient was calculated between the mean Tmax in summer and the number of hot days. Subsequently, variability within the multiannual period and statistical significance ($p \leq 0.05$) were determined for the distinguished climatological characteristics.

In order to define pressure conditions conducive to the occurrence of HWs, daily values of atmospheric pressure at sea level (SLP), the height of the isobaric surface 500 hPa (z500 hPa), and the temperature on the isobaric surface 850 hPa (T850) were used. The data were obtained from the records of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (*Kalnay et al.,* 1996), which are available in Climate Research Unit resources. In the study, values of SLP and z500 hPa in 120 geographical grid points 2.5°×2.5° for the area of 25°–75°N latitude, 35°W–65°E longitude were used. On the basis of the above-mentioned data, the SLP, z500 hPa, and T850 maps for the summer season (June–August), as well as a collective map for hot days forming HWs were drawn up. The description was supplemented with the drawing up of maps of anomalies. Anomalies were calculated as differences between the mean SLP, z500 hPa, and T850 values for HWs and the mean summer values of these characteristics in the analyzed multiannual period. Only days on which the temperature met the criterion of a hot day in at least five stations were selected for analysis. The circulation types which cause the occurrence of HWs were distinguished by clustering days according to their values of sea-level pressure, using the minimum variance method known as Ward's method (1963). This method is based on Euclidean distances, and in essence involves merging the pair of clusters A and B which, after merging, provide the minimum sum of squares of all objects' deviations from the newly-created cluster's centre of gravity (*Ward,* 1963; *Wilks,* 1995). In order to achieve that, standardized SLP values were used. The standardization was made to deseasonalize the observations, while keeping the intensity of pressure field (*Esteban et al.,* 2005). Clustering methods (among others, Ward's method) are often applied in climatology, e.g., in distinguishing seasons and climatic regions, and identifying weather types (*Bednorz,* 2008; *Tomczyk* and *Bednorz,* 2016). The maps of SLP, z500 hPa, and T850, as well as maps of anomalies were drawn up for the identified circulation types. Additionally, for the selected days in the distinguished circulation types, there were 48-hour back trajectories of air particles traced by means of the NOAA HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php). Back trajectory analysis enables one to determine the area of origin of air masses on selected days, which constitutes a supplement to the information displayed by weather maps.

3. Results

3.1. Maximum temperature in the summer

In southeastern Europe, between 1973 and 2010, the mean Tmax in summer was 27.8 °C and ranged from 25.0 °C in Ljubljana to 32.4 °C in Larissa (*Fig. 2b*). In the analyzed period, at all stations the lowest mean Tmax was recorded for the years 1973–1980, and varied then from 23.6 °C in Sibiu to 31.8 °C in Larissa. Meanwhile, in 90% of the stations the highest mean Tmax was observed for the years 2001–2010, and ranged from 25.7 °C in Ljubljana to 33.0 °C in Larissa. Analysing the particular summer seasons, at 67% of the stations, the coldest summer season occurred in 1976, and at 24% of the stations it was in 1978. On the other hand, the warmest season at 52% of the stations was recorded in 2007, and at 43% of them in 2003. Deviation of the mean Tmax in the particular seasons from the mean for the analyzed multiannual period ranged from –4.1 °C in 1976 (Sofia, Skopje) to 4.5 °C in 2007 (Galati). The course of the mean Tmax in the analyzed years shows considerable year-to-year fluctuations. Within the majority of the area, the variability of the mean Tmax was similar, which is proven by its barely-diversified standard deviation values, falling within a range of 0.9–1.5 at 86% of stations. In the analyzed period, at all stations, a statistically significant increase in Tmax in summer was observed. These changes ranged from 0.4 °C/10 years in Thessaloniki to 1.2 °C/10 years in Sofia and Niš (*Fig. 2c*). The aforementioned changes were considerably influenced by an increase in Tmax in the first decade of the 21st century, when Tmax generally exceeded the norm for the 1973–2010 multiannual period. In summer, the highest increase in Tmax was observed in August and, on average, it was 0.9°C/10 years for the analyzed area. In that month, the highest increase was recorded in Sofia, and it was 1.5 °C/10 years.

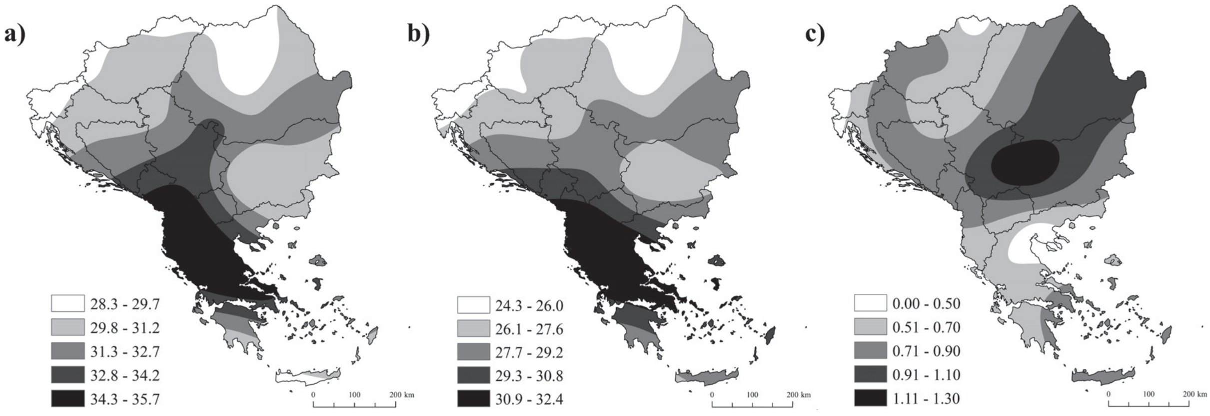

Fig. 2. The value of the 95th annual percentile of the Tmax (°C) (a); the mean Tmax (°C) in the summer (June–August) (b); and changes in the mean summer Tmax in °C/10 years during the period 1973-2010 (c).

3.2. Hot days

In southeastern Europe, the observed increase in Tmax translated into an increase in the number of hot days and, consequently, into an increase in the frequency of occurrence of HWs. At all stations, the coefficient of correlation between the mean Tmax in summer and the number of hot days fluctuated around 0.84–0.93. The average number of hot days in the summer season in the analyzed area was 18. At 95% of the stations, the lowest number of days of the aforementioned category was recorded in the 1973–1980 multiannual period, and their average number ranged from 4 days in Niš to 14 days in Thessaloniki. On the other hand, at 90% of the stations the highest number of hot days occurred in the first decade of the 21st century—then, the average number of hot days varied from 18 days in Oradea to 30 days in Bucharest and Split. When analyzing the particular summer seasons, it was found that at 80% of the stations, the lowest number of hot days—or even zero hot days—were recorded in 1976 or 1978. On the other hand, the highest number of days of the analyzed category was specific for 2003 and 2007, at 33% and 29% of the stations, respectively. In the analyzed period, the maximum number of the days recorded in one year was 57, and it was observed in 2003 in Zagreb and Methoni (*Fig. 3*). In the analyzed period, in southeastern Europe, there was an average increase in observed hot days, which was 6.2 days per 10 years, and it was statistically significant. This increase was not uniform across the analyzed area; changes ranged from 3.5 days/10 years in Miskolc and Larissa, to 8.4 days/10 years in Bucharest, and were statistically significant in all stations (*Fig. 3*). Hot days were recorded from April to November; still, the highest number of those days occurred in July and August, with 38.6% and 38.2% of all hot days, respectively. At 57% of the stations, the highest number of the above-mentioned days was found in July, while at the rest of the stations it was August. The earliest occurrence of a hot day was as early as 6 April (1998, Bucharest, Galati), and the latest one was November 5 (1980, Methoni); therefore, for the whole analyzed area, the potential period of the occurrence of hot days was 214 days.

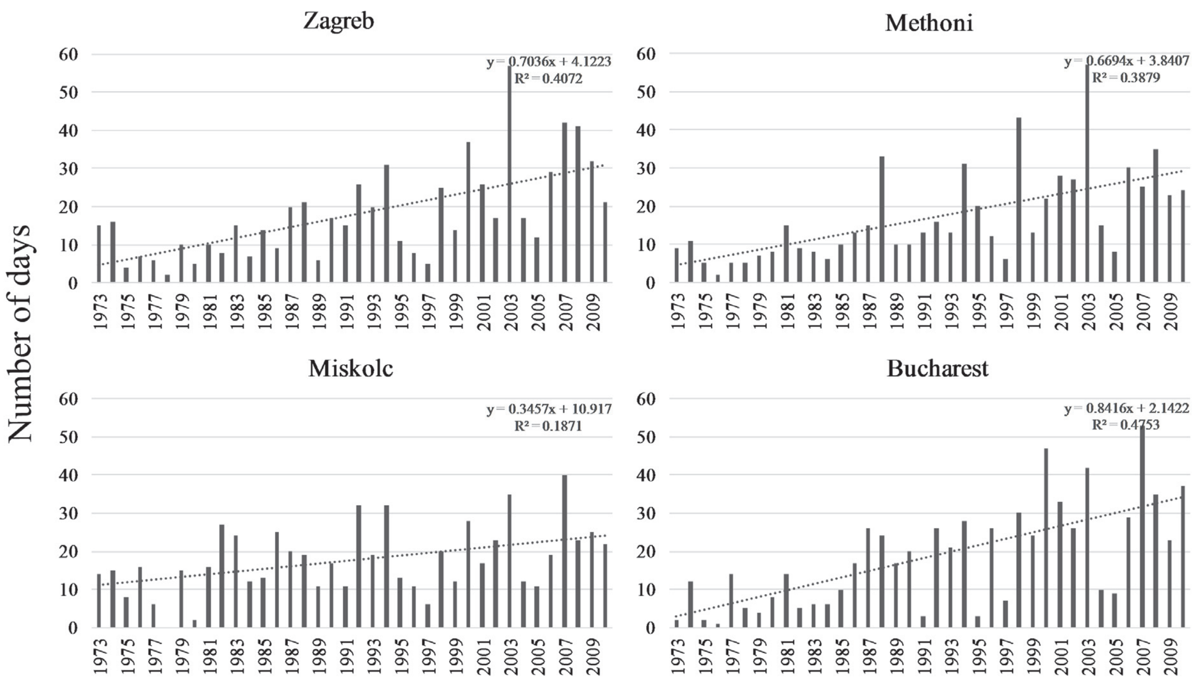

Fig. 3. Multi–year series of the annual number of hot days with the trend line and regression equation at selected stations.

3.3. Heat waves

In southeastern Europe, in the analyzed multiannual period, the total number of HWs ranged from 25 in Burgas to 48 in Drobeta-Turnu Severin, Skopje, and Split. On the other hand, the total duration of HWs ranged from 173 days in Botosani to 414 in Split. In 90% of stations, the fewest—or even zero—HWs were recorded between 1973 and 1980. Within this period, there were no HWs observed in four stations (that is, Botosani, Burgas, Galati, and Methoni), whereas the most waves were observed in Thessaloniki (seven waves), and their total duration was 39 days (*Fig. 4*). On the other hand, at 62% of the stations, the highest number of HWs was recorded between 2001 and 2010. At that multiannual period, the number varied between 7 (Oradea) and 23 (Split). In

14% of stations, the same number of waves was found both in the 1991–2000 period and the 2001–2010 period; still, in the first decade of the 21st century the waves were longer.

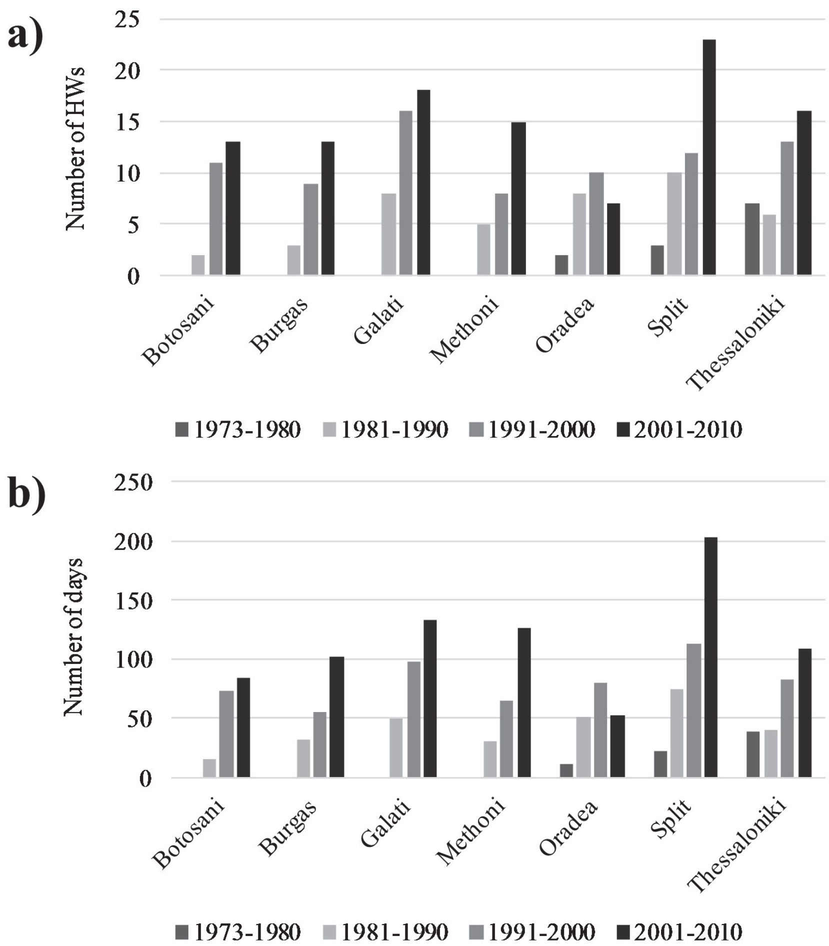

Fig. 4. The number of HWs (a) and the duration of HWs (b) in 1973–2010 at selected stations.

In the analyzed multiannual period in southeastern Europe, HWs occurred from May to September. At 62% of the stations, the highest number of HWs was recorded in August; in the case of two stations, the same number of waves was found in July and August. May HWs (four cases) only occurred in the last decade of the analyzed multiannual period. The earliest HW was recorded in Sibiu on May 7–13, 2003, while the latest, in Sofia and Skopje, were recorded on September 7–15, 1994 and September 9–15, 1994, respectively. The above-mentioned data show that the potential period of the occurrence of HWs within the particular area was 133 days, from May 7 to September 15. In the particular stations, the duration of this period ranged from 64 days in Burgas (from June 22 to August 24) to 125 days in Sibiu (from May 7 to September 8).

At 81% of the stations, the most HWs were 5-day-long, while at 9% of the stations, there were 6-day waves. 7-day waves were most numerous only in Botosani. Meanwhile, in Sofia, 5- and 6-day waves had a similar frequency. Apart from three stations (Botosani, Burgas, Split), 5- and 6-day waves constituted over 50% of all the recorded waves, and at three stations (Belgrade, Miskolc, Niš), they even constituted over 70%. The longest HW was observed in Methoni, and lasted as long as 38 days, from July 28 to September 3, 2003.

The mean Tmax during the analyzed HWs was 34 °C, while Tmin was 18.8 °C. The highest average Tmax was observed during HWs in Larissa (July 3–9, 2000) and was 40.6 °C. Moreover, at that station, there were four HWs found with a mean Tmax above 40 °C; namely, in 1982, 1987, 1998, and 2007 (*Table 1*). HWs with a mean Tmax above 40 °C were also observed in Niš and Skopje. On the other hand, the highest mean Tmin was found in Athens (July 5–10, 1988), and was 27.1 °C, while the lowest was in Ljubljana (13–17 August 1993) with an average of only 10.7 °C. In the analyzed multiannual period, a statistically significant increase in Tmax during HWs was found at only two stations, while in the case of Tmin, these changes were recorded at seven stations.

Table 1. Occurrence of heat waves with a mean Tmax above 40 °C (their duration and average Tmax) in southeastern Europe between 1973 and 2010

Station	**Date**	**Tmax**
Larissa	July 3–9, 2000	40.6 °C
	June 24–28, 1982	40.4 °C
	July 18–27, 1987	40.3 °C
	June 30–July 4, 1998	40.1 °C
	June 19–28, 2007	40.1 °C
Niš	July 15–24, 2007	40.2 °C
Skopje	July 18–26, 1987	40.1 °C

3.4. Impact of circulation on the occurrence of heat waves

The occurrence of HWs (424 days) in southeastern Europe in the analyzed period was connected, on average, with an extensive ridge of high pressure lying across the continent and reaching as far as eastern Europe. Over the analyzed area, SLP ranged from approximately 1008 to 1016 hPa (*Fig. 5a*). Apart from the northwestern and southern part of the analyzed area, positive anomalies up to > 1 hPa were recorded in the east (*Fig. 5b*). The described system caused an inflow of air masses from the northeast and east. Contour lines of the isobaric surface 500 hPa over southeastern Europe bent northeastward, creating its elevation over the analyzed area, which confirms the settling of warm air masses over this part of the continent. The pattern of z500 hPa contour lines shows western and southwestern air flow in the middle troposphere layer. The described conditions were accompanied by T850 positive anomalies, which fluctuated from 2 to >4 °C over the analyzed area (*Fig. 5c*).

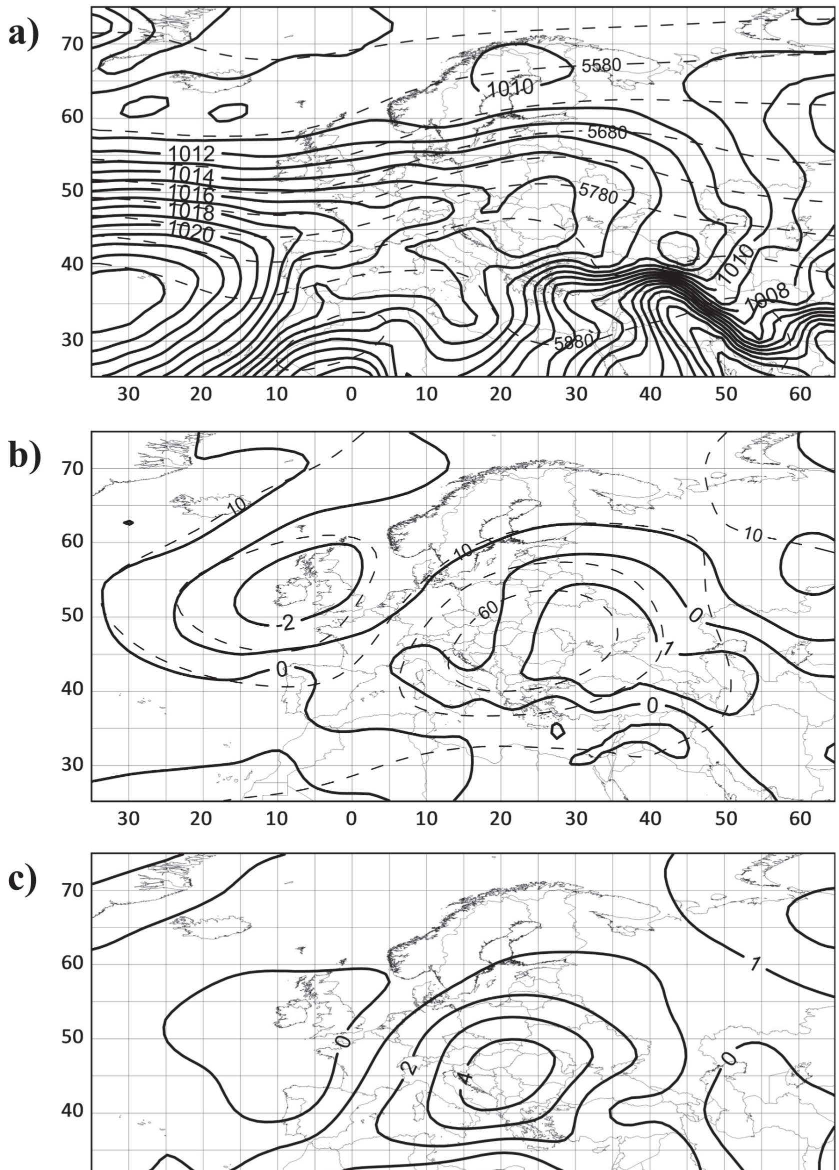

Fig. 5. SLP and z500 hPa (a), SLP and z500 hPa anomalies (b), and anomalies of T850 (c) for the HWs days.

The above-mentioned maps only display pressure conditions which cause the occurrence of HWs in southeastern Europe. However, individual HWs might be caused by different synoptic situations; therefore, the next step consisted in clustering HWs days by SLP, in order to distinguish circulation types. On this basis, two circulation types conducive to the occurrence of HWs within the analyzed area were distinguished. 324 hot days were classified as type 1. On those days, there was a ridge of high pressure settled over Europe, within which, there was a local high-pressure area (>1017 hPa) over the eastern part of the analyzed area (*Fig. 6a*). SLP positive anomalies occurred over the majority of the continent. Over the analyzed area, SLP was higher than the summer average, from approximately 0 to over 2 hPa in the east (*Fig. 6b*). The centre of anomalies was located over central Ukraine, and these exceeded 3 hPa. The described conditions were accompanied by z500 hPa positive anomalies, which fluctuated from 20 to over 90 gpm over southeastern Europe. The presence of warm air masses is also confirmed by T850 positive anomalies, which were from 1 to >4 °C over this part of the continent (*Fig. 6c*). The described system caused an inflow of dry, continental air masses from the northeast and east. This direction of air inflow was also shown by the traced 48-hour back trajectories of air particles for the selected days of this type (*Fig. 7*). All the trajectories showed settlement of air masses, which is typical of high pressure systems.

There were 100 days classified as type 2. The composite maps drawn up for these days show two main pressure systems over Europe, that is, a well-developed Azores High and a low with its centre over southern Scandinavia and Denmark (*Fig. 8a*). A weak pressure gradient occurred over the analyzed area. SLP negative anomalies were recorded over the continent, which ranged between –5 and –2 hPa over the analyzed area (*Fig 8b*). The presence of warm air masses was confirmed by z500 hPa positive anomalies. The settling air masses were warmer than in type 1, which is shown by T850 anomalies. The temperature on the isobaric surface 850 hPa was higher than the summer average by 1 to >6 °C (*Fig. 8c*). The described system caused an inflow of air masses from the southwest, from over northern Africa. This direction of air mass advection was confirmed by the traced back trajectories of air particles (*Fig. 9*). Most of the trajectories show rising air masses, which is typical for low-pressure systems.

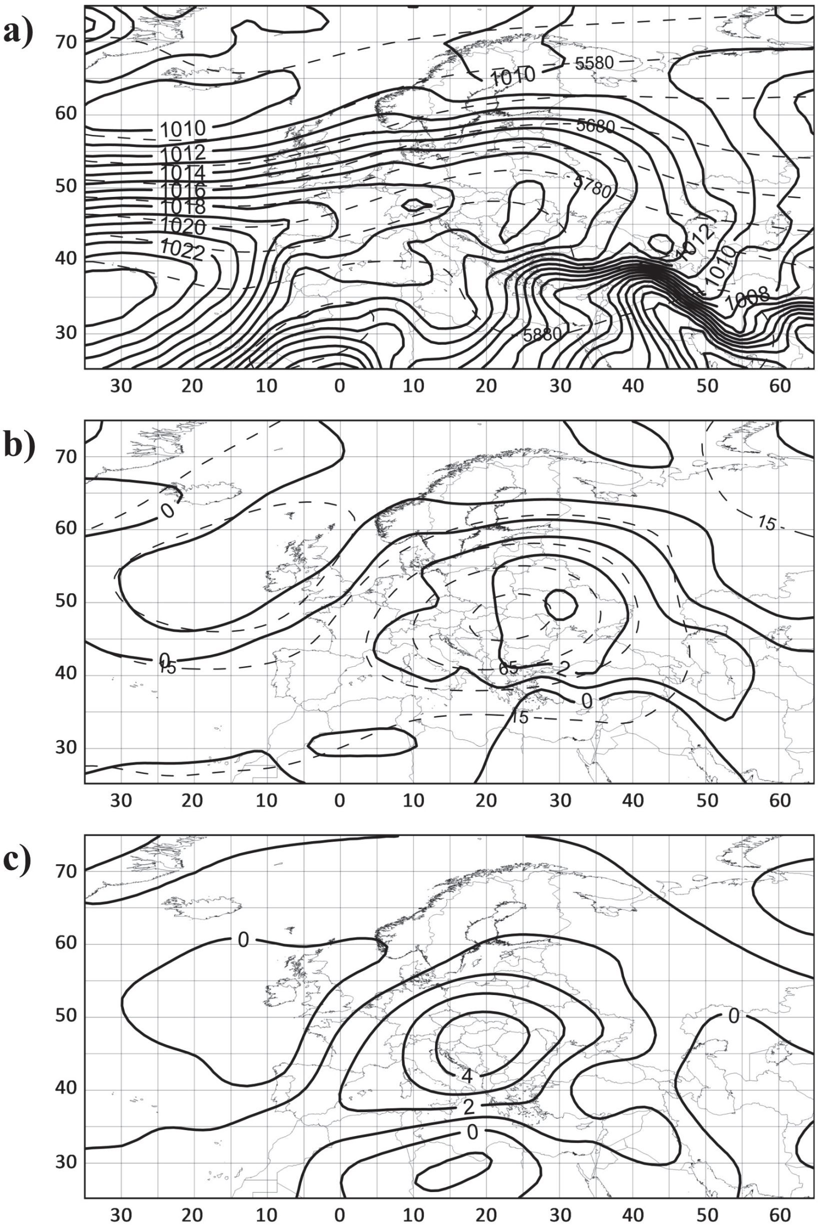

Fig. 6. Mean SLP and z500 hPa (a), SLP and z500 hPa anomalies (b), and anomalies of T850 (c) for the synoptic type 1 causing HWs.

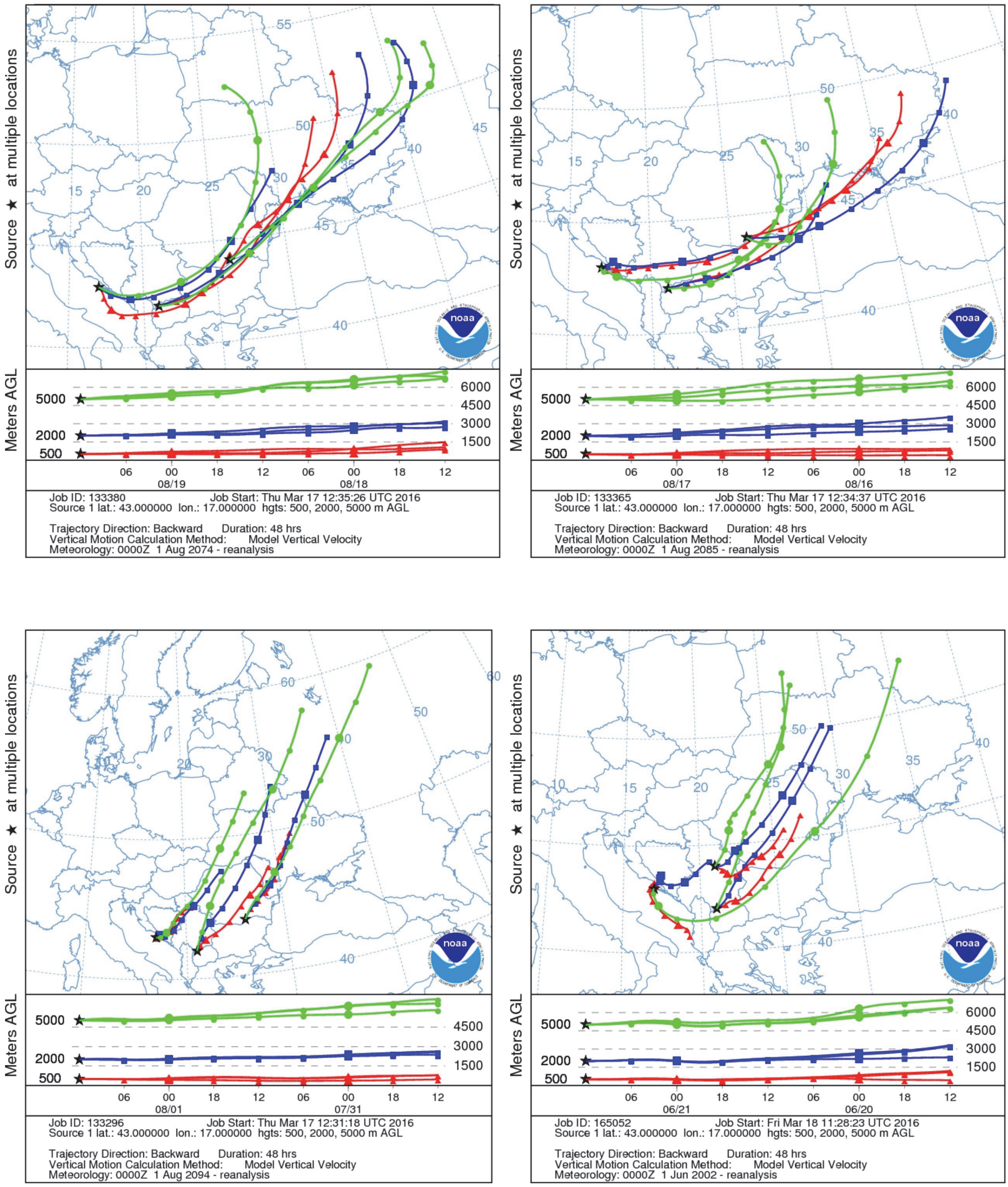

Fig. 7. 48-hour backward trajectories for the selected days in the synoptic type 1 causing HWs based on the reanalyses of the NOAA HYSPLIT model.

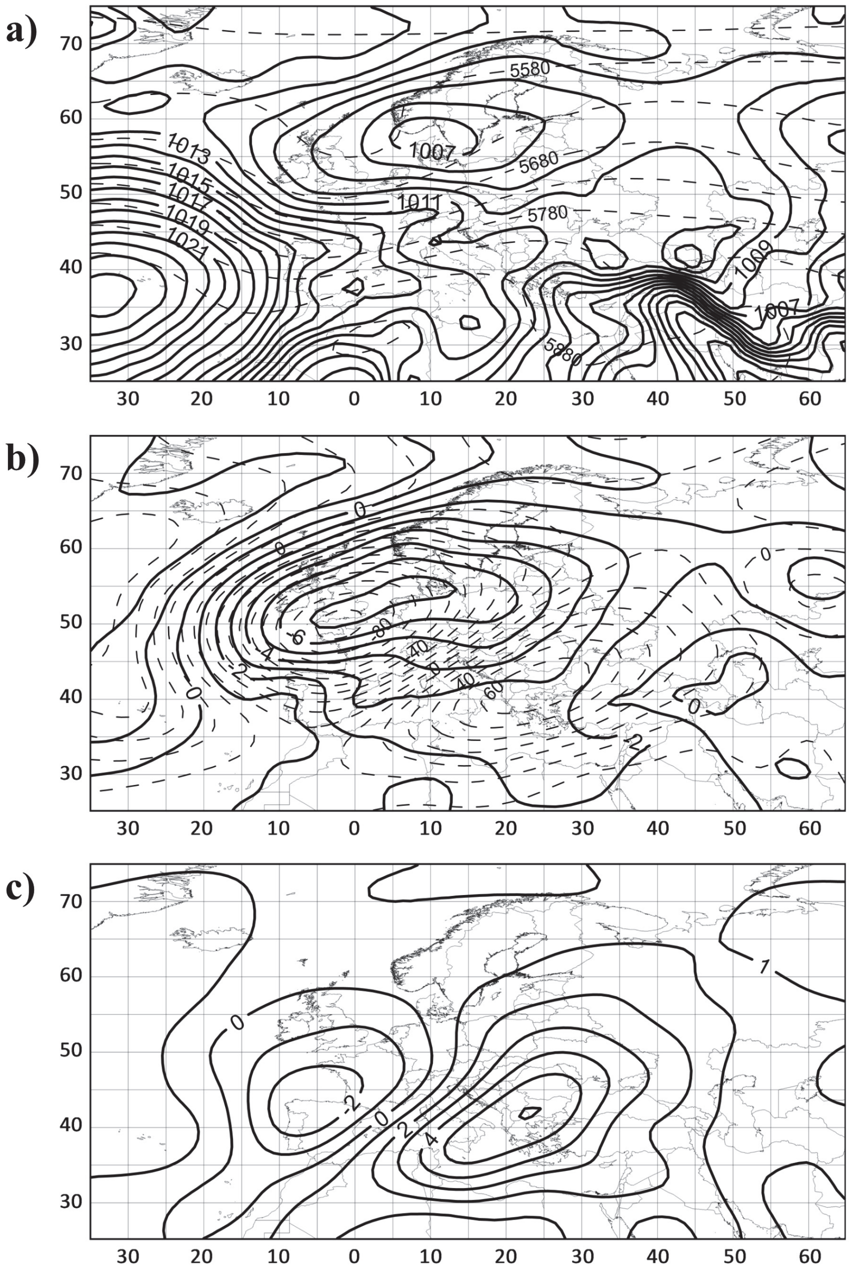

Fig. 8. Mean SLP and z500 hPa (a), SLP and z500 hPa anomalies (b), and anomalies of T850 (c) for the synoptic type 2 causing HWs.

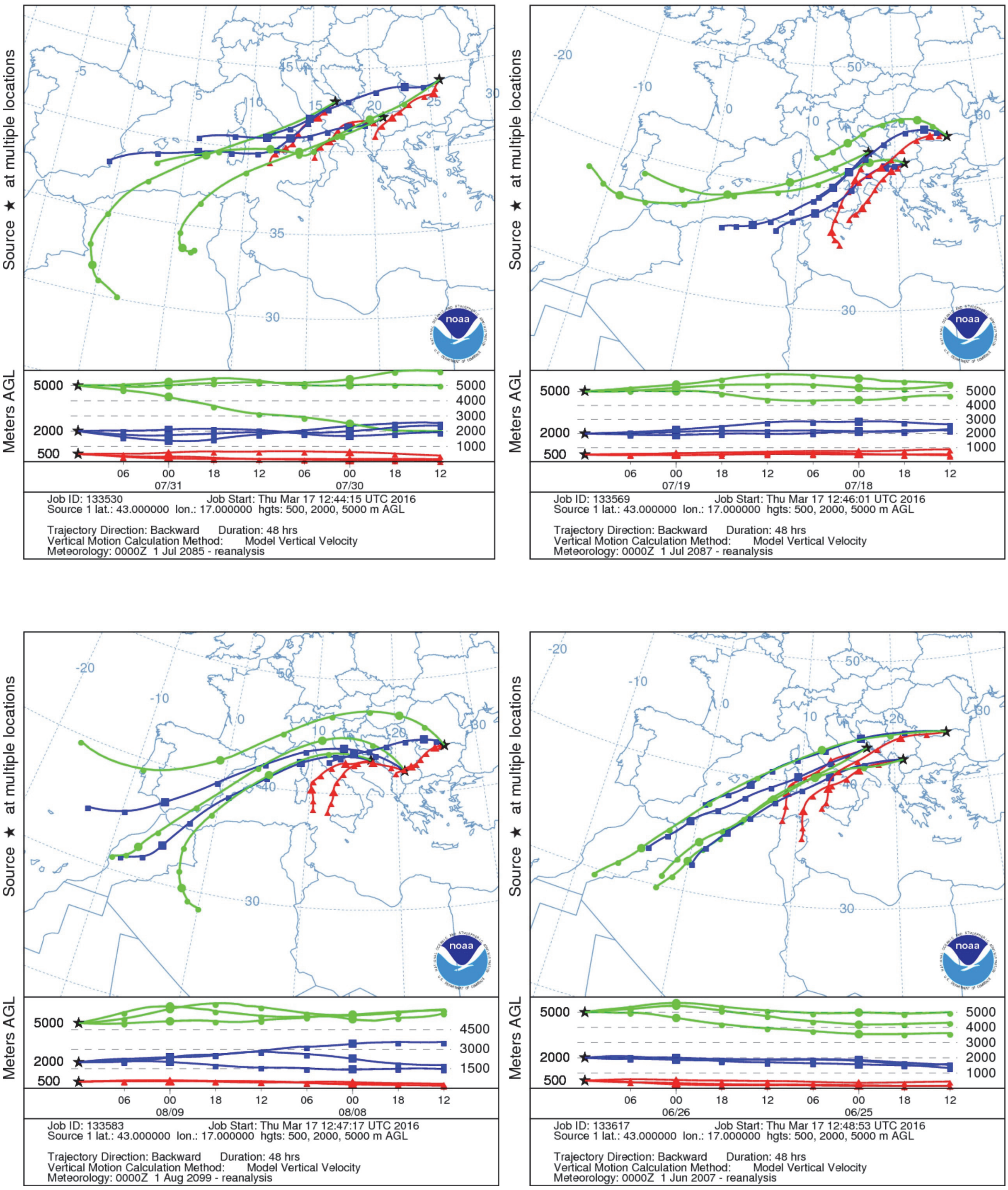

Fig. 9. 48-hour backward trajectories for the selected days in the synoptic type 2 causing HWs based on the reanalyses of the NOAA HYSPLIT model.

4. Discussion and summary

According to the research, in southeastern Europe between 1973 and 2010, there was an increase in Tmax in summer, which, averaged for the whole area, was 0.78 °C/10 years. A similar trend of changes in Tmax was also observed in central Europe (0.52 °C/10 years; *Tomczyk* and *Bednorz,* 2016) and northern Europe (0.38 °C/10 years; *Tomczyk et al.,* 2016). Within the analyzed area, similarly to other regions of Europe, the recorded increase was considerably influenced by changes in Tmax in the first decade of the 21st century, when Tmax generally exceeded the norm of the 1973–2010 multiannual period. The obtained results are consistent with previous research concerning air temperature changes in, among others, Greece (*Philandras et al.,* 2008; *Founda* and *Giannakopoulos,* 2009), Moldova (*Corobov et al.,* 2010), Romania (*Ionita et al.,* 2013), Serbia (*Bajat et al.,* 2015; *Unkašević and Tošić,* 2009), Slovenia (*de Luis et al.,* 2014; *Tošić et al.,* 2016), and the Mediterranean (*Efthymiadis et al.,* 2011).

The consequence of the increase in Tmax was an increasingly frequent occurrence of hot days and HWs. In the analyzed period, the rate of change in the number of hot days was 6.2 days/10 years. The observed changes are much more intensive than in central Europe (2.9 days/10 years; *Tomczyk* and *Bednorz,* 2016) and northern Europe (1.7 days/10 years; *Tomczyk et al.,* 2016). In the analyzed multiannual period, at most of the stations, both hot days and HWs were most numerous in the first decade of the 21st century. The obtained results are consistent with trends of changes found in Europe (*Gocheva et al.*, 2006; *Kyselý,* 2010; *Efthymiadis et al,* 2011; *Papanastasiou et al,* 2014; *Shevchenko et al.,* 2014; *Spinoni et al.,* 2015; *Unkašević* and *Tošić,* 2015; *Lakatos et al.,* 2016) and worldwide (*Batima et al.,* 2005; *Ding et al.,* 2010; *Pai et al.,* 2013; *Peterson et al.,* 2013; *Keggenhoff et al.,* 2015).

The occurrence of HWs in southeastern Europe was mostly connected with a well-developed ridge of high pressure settling over Europe, which caused an inflow of air masses from the northeast and east. Similar results were obtained by *Unkašević* and *Tošić* (2009) when they were analysing the occurrence of HWs in Serbia. The authors showed that HWs occurred most frequently during BM type according to the Grosswetterlagen (GWL) classification; therefore, with the presence of a ridge of high pressure over central Europe. Summer advection of continental air masses from the eastern sector also causes the occurrence of high temperatures and HWs in central Europe (*Wibig,* 2007; *Ustrnul et al.,* 2010; *Porębska* and *Zdunek,* 2013; *Tomczyk* and *Bednorz,* 2016).

The second circulation type conducive to the occurrence of HWs in southeastern Europe is connected with the occurrence of the Azores High over the continent and a low with its centre spreading from the North Sea to the Baltic Sea. Then, there was a weak pressure gradient recorded over the analyzed area. This situation was conducive to the advection of warm air masses from the south and southwest. A similar circulation type was identified by *Unkašević* and *Tošić* (2011), who investigated the HW of 2007 in Serbia. During HWs, T850 positive anomalies were also observed, which were higher in type 2, and this confirms that advection of air masses from the southern sector is related to higher temperatures within the analyzed area than to advection from the northeast and east. The obtained results are consistent with previous research studies which have proven that the occurrence of extreme temperatures in southern Europe is caused by the inflow of air masses from over North Africa (*Domonkos et al.,* 2003; *Gocheva et al.,* 2006; *Unkašević* and *Tošić,* 2009).

Acknowledgements: This work was supported by the Polish National Science Centre under grant number: UMO-2014/15/N/ST10/00717.

References

Avotniece, Z., Rodinov, V., Lizuma, L., Briede, A., and *Kļaviņš, M.,* 2010: Trends in the frequency of extreme climate events in Latvia. *Baltica 23,* 135–148.

Bajat, B., Blagojević, D., Kilibarda, M., Luković J., and *Tošić I.,* 2015: Spatial analysis of the temperature trends in Serbia during the period 1961–2010. *Theor. Appl. Climatol. 121*, 289–301.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M., and *García-Herrera R.,* 2011: The hot summer of 2010: redrawing the temperature record map of Europe. *Science 332*, 220–224.

Batima, P., Natsagdorj, L., Gomboluudev, P., and *Erdenetsetseg B.,* 2005: Observed climate change in Mongolia. *AIACC Working Paper 13*, 4–25.

Bednorz, E., 2008: Synoptic conditions of snow occurrence in Budapest. *Meteorologische Zeit. 17,* 39–45.

Bednorz, E., 2011: Occurrence of winter air temperature extremes in Central Spitsbergen. *Theor. and Appl. Climatol. 106*, 547–556.

Bielec-Bąkowska, Z., 2014: Silne wyże nad Europą (1951-2010). *Wydawnictwo Uniwersytetu Śląskiego*, Katowice, 219. (in Polish)

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylha, K., Koffi, B., Palutikof, J., Scholl, R., Semmler, T., and *Woth, K.,* 2007: Future extreme events in European Climate: An exploration of regional climate model projections. *Climatic Change 81*, 81–95.

Bobvos, J., Fazekas, B., and *Páldy, A.,* 2015: Assessment of heat-related mortality in Budapest from 2000 to 2010 by different indicators. *Időjárás 119, 2*, 143–158.

Chromow, S.P., 1952: Meteorologia i klimatologia, Warszawa, *PWN*, 488. (in Polish)

Corobov, R., Sheridan, S., Overcenco, A., and *Terinte, N.,* 2010: Air temperature trends and extremes in Chisinau (Moldova) as evidence of climate change. *Climate Res. 42*, 247–256.

Ding, T., Qian, W.H., and *Yan Z.W.,* 2010: Changes of hot days and heat waves in China during 1961–2007. *Int. J. Climatol. 30*, 1452–1462.

de Luis, M., Čufar, K., Saz, M.A., Longares, L.A., Ceglar, A., and *Kajfež-Bogataj, L.,* 2014: Trends in seasonal precipitation and temperature in Slovenia during 1951–2007. *Regional Environmental Change 14*, 1801–1810.

Domonkos, P., Kyselý J., Piotrowicz, K., Petrovic, P., and *Likso, T.,* 2003: Variability of extreme temperature events in south-central Europe during the 20th century and its relationship with large-scale circulation. *Int. J. Climatol. 23*, 987–1010.

Efthymiadis, D., Goodess, C.M., and *Jones, P.D.,* 2011: Trends in Mediterranean gridded temperature extremes and large-scale circulation influences. *Nat. Haz. Earth Sys. Sci. 11*, 2199–2214.

Esteban, P., Jones, P.D., Martin–Vide, J., and *Mases, M.,* 2005: Atmospheric circulation patterns related to heavy snowfall days in Andorra, Pyrenees. *Int. J. Climatol. 25*, 319–329.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A.M.G., and *Peterson T.,* 2002: Observed coherent changes in climatic extremes during 2nd half of the 20th century. *Climate Res. 19*, 193–212.

Founda, D., and *Giannakopoulos, C.,* 2009: The exceptionally hot summer of 2007 in Athens, Greece–a typical summer in the future climate? *Glob. Planet. Change 67,* 227–236.

Gocheva, A., Trifonova, L., Marinova, T. and *Bocheva, L.,* 2006: Extreme Hot Spells and Heat Waves on the Territory of Bulgaria. Paper presented in Water Observation and Information System for Decision Support, 23 - 26 May 2006, Ohrid, Republic of Macedonia.

Ionita, M., Rimbu, N., Chelcea, S., and *Patrut, S.,* 2013: Multidecadal variability of summer temperature over Romania and its relation with Atlantic Multidecadal Oscillation. *Theor. Appl. Climatol. 113,* 305–315.

IPCC (2007) Climate change: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel in Climate Change. Cambridge University Press, Cambridge.

IPCC (2013), Climate change: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel in Climate Change, Cambridge University Press, Cambridge.

Johnson, H., Kovats, R.S., McGregor, G., Stedman, J., Gibbs, M., and *Walton, H.,* 2005: The impact of the 2003 heat wave on daily mortality in England and Wales and the use of Rapid Weekly Mortality Estimates. *Eurosurveillance 10, 7-9*, 168–171.

Kalnay, E., Kanamistu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. and *Joseph D.,* 1996: The NMC/NCAR 40–Year Reanalysis Project. *Bull. Amer. Met. Soc. 77*, 437–471.

Kažys, J., Stankūnavičius, G., Rimkus, E., Bukantis, A., and *Valiukas D.,* 2011: Long–range alternation of extreme high day and night temperatures in Lithuania. *Baltica 24, 2,* 71–82.

Keggenhoff, I., Elizbarashvili, M., and King, L., 2015: Heat Wave Events over Georgia since 1961: Climatology, Changes and Severity. *Climate 3,* 308–328.

Kejna, M., Araźny, A., Maszewski, R., Przybylak, R., Uscka-Kowalowska, J., and *Vizi, Z.,* 2009: Daily minimum and maximum air temperature in Poland in the years 1951–2005. *Bull. Geography – Physical Geography, Ser. 2/2009*, 35–56.

Koffi, B, and *Koffi, E.,* 2008: Heat waves across Europe by the end of the 21st century: multiregional climate simulations. *Climate Research 36*, 153–168.

Kossowska-Cezak, U., 2010: Fale upałów i okresy upalne - metody ich wyróżniania i wyniki zastosowania. *Prace Geograficzne 123*, 143–149. (in Polish)

Krzyżewska, A., 2010: Fale upałów jako zjawisko ograniczające turystykę w dużych miastach świata. *Krajobrazy rekreacyjne – kształtowanie, wykorzystanie, transformacja. Problemy Ekologii Krajobrazu XXVII,* 239–244. (in Polish)

Krzyżewska A., 2014: Warm and cold waves in South-Eastern (V) bioclimatic region in years 1981-2010. *Annales UMCS, Geographia, Geologia, Mineralogia et Petrographia 69, 2*, 143–154.

Kuchcik, M., and *Degórski, M.,* 2009: Heat– and cold–related mortality in the north–east of Poland as an example of the socio–economic effects of extreme hydrometeorological events in the Polish Lowland. *Geographia Polonica 82*, 1, 69–78.

Kürbis, K., Mudelsee, M., Tetzlaff, G., and *Brázdil R.,* 2009: Trends in extremes of temperature, dew point, and precipitation from long instrumental series from Central Europe. *Theor. Appl. Climatol. 98*, 187–195.

Kyselý, J., 2002: Temporal fluctuations in heat waves at Prague–Klementinum, the Czech Republic, from 1901–1997 and their relationships to atmospheric circulation. *Int. J. Climatol. 22*, 33–50.

Kyselý, J., 2010: Recent severe heat waves in central Europe: how to view them in a long–term prospect? *Int. J. Climatol. 30*, 89–109.

Lakatos, M., Bihari, Z., Szentimrey, T., Spinoni, J., Szalai, S., 2016: Analyses of temperature extremes in the Carpathian Region in the period 1961–2010. *Időjárás 120,* 41-51.

Meehl, G.A., and *Tebaldi C.,* 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science 305*, 994–997.

Migała, K., Urban, G., and *Tomczyński, K.,* 2016: Long-term air temperature variation in the Karkonosze mountains according to atmospheric circulation. *Theoretical and Applied Climatology125,* 337–351.
Mužíková, B., Vlček, V., and *Středa, T.,* 2011: Tendencies of climatic extremes occurrence in diff erent Moravian regions and landscape types. *ACTA Universitatis Agriculturae et Silviculturae Mendelianae Brunensis LIX, 5*, 169–178.
Niedźwiedź, T., 1981: Sytuacje synoptyczne i ich wpływ na zróżnicowanie przestrzenne wybranych elementów klimatu w dorzeczu górnej Wisły. *Rozprawy Habilitacyjne Uniwersytetu Jagiellońskiego* 58, Kraków. (in Polish)
Niedźwiedź, T., Łupikasza, E., and *Małarzewski, Ł.,* 2012 Wpływ cyrkulacji atmosfery na występowanie dni mroźnych w Hornsundzie (Spitsbergen). *Problemy Klimatologii Polarnej 22*, 17–26. (in Polish)
Pai D.S., Nair, S.A, and *Ramanathan, A.N.,* 2013: Long term climatology and trends of heat waves over India during the recent 50 years (1961–2010). *Mausam 64*, 4, 585–604.
Paldy, A. and *Bobvos, J.,* 2009: Impact of the Unusual Heatwave of 2007 on Mortality in Hungary. *Epidemiology 20, 6*, 126–127.
Papanastasious, D.K., Melas, D., and *Kambezidis, H.D.,* 2014: Heat waves characteristics and their relation to air quality in Athens. *Global Nest J. 16,* 919–928.
Peterson, T.C Heim, R.R., Hirsch, R., Kaiser, D.P., Brooks, H., Diffenbaugh, N.S., Dole, R.M., Giovannettone, J. P., Guirguis K.,. Karl, T.R., Katz, R.W., Kunkel, K., Lettenmaier, D., McCabe, G.J., Paciorek, C.J., Ryberg, K.R., Schubert, S., Silva, V.B.S., Stewart, B.C., Vecchia, A.V., Villarini, G., Vose, R.S., Walsh, J., Wehner, M., Wolock, D., Wolter, K., Woodhouse, C.A., and *Wuebbles, D.,* 2013: Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bull. Amer. Met. Soc. 94,* 821–834.
Philandras, C., Nastos, P., and *Repapis, C.,* 2008: Air temperature variability and trends over Greece. *Global Nest J. 10*, 273–285.
Pongrácz, R., Bartholy, J., and *Bartha, E.B.,* 2013: Analysis of projected changes in the occurrence of heat waves in Hungary. *Adv. Geosci. 35*, 115–122.
Porębska, M., and *Zdune M.,* 2013: Analysis of extreme temperature events in Central Europe related to high pressure blocking situations in 2001–2011. *Met. Zeit. 22,* 533–540.
Poumadere, M., Mays, C., Le Mer, S., and *Blong, R.,* 2005: The 2003 Heat Waves in France: Dongerous Climate Change Here and Now. *Risk Analysis 25,* 1483–1494.
Revich, B.A., Shaposhnikov, D.A., Podol'naya, M.A., Khor'kova, T.L., and *Kvasha E.A.,* 2015: Heat Waves in Southern Cities of European Russia as a Risk Factor for Premature Mortality. *Studies on Russian Economic Development 26, 2*, 142–150.
Shaposhnikov, D., Revich, B., Bellander, T., Bedada, G.B., Bottai, M., Kharkova, T., and *et al.,* 2014: Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. *Epidemiology 25,* 359–364.
Shevchenko, O., Lee, H., Snizhko, S., and *Mayer H.,* 2014: Long–term analysis of heat waves in Ukraine. *International J. Climatol. 34*, 1642–1650.
Spinoni, J., Lakatos, M., Szentimrey, T., Bihari, Z., Szalai, S., Vogt, J., and *Antofie T.,* 2015: Heat and cold waves trends in the Carpathian Region from 1961 to 2010. *Int. J. Climatol. 35,* 4197–4209.
Tomczyk, A.M., and *Bednorz, E.,* 2014: Heat and cold waves on the southern coast of the Baltic Sea. *Baltica 27,* 45–53.
Tomczyk, A.M., and *Bednorz, E.,* 2016: Heat waves in Central Europe and their circulation conditions. *Int. J. Climatol. 36,* 770–782.
Tomczyk, A.M., Piotrowski, P., and *Bednorz, E.,* 2016: Warm spells in Northern Europe in relation to atmospheric circulation. *Theor. Appl. Climatol.* DOI 10.1007/s00704-015-1727-0
Tošić, I., Zorn, M., Ortar, J., Unkašević, M., Gavrilov, M.B., and *Marković, S.B.,* 2016: Annual and seasonal variability of precipitation and temperatures in Slovenia from 1961 to 2011. *Atmos. Res. 168*, 220–233.
Unkašević, M., and *Tošić, I.,* 2009: An analysis of heat waves in Serbia, *Glob. Planetary Change 65*, 17–26.
Unkašević, M., and *Tošić, I.,* 2011: The maximum temperatures and heat waves in Serbia during the summer of 2007. *Climatic Change 108*, 207–223.

Unkašević, M., and *Tošić, I.,* 2015: Seasonal analysis of cold and heat waves in Serbia during the period 1949-2012. *Theor. Appl. Climatol. 120*, 29–40.
Ustrnul, Z., Czekierda, D., and *Wypych A.,* 2010: Extreme values of air temperature in Poland according to different atmospheric circulation classifications. *Physics Chemistry Earth 35*, 429–436.
Ward, J.H., 1963: Hierarchical grouping to optimize an objective function. *J. Amer. Statistical Assoc. 58*, 236–244.
Wibig, J., 2007: Fale ciepła i chłodu w środkowej Polsce na przykładzie Łodzi. *Acta Universitatis Lodziensis, Folia Geographica Physica 8*, 27–61. (in Polish)
Wilks, D.S., 1995: Statistical methods in the atmospheric sciences: an introduction. International geophysics series, vol. 59. Academic, New York, 464 pp.
Yarnal, B., 1993: Synoptic Climatology in Environmental Analysis. Belhaven Press, London.
Zacharias, S., Koppe, Ch., and *Mücke, H–G.,* 2015: Climate change effects on heat waves and future heat wave–associated IHD mortality in Germany. *Climate 3,* 100–117.