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ORIGINAL PAPER

Warm spells in Northern Europe in relation to atmospheric circulation

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Abstract This study describes warm spells in Northern Europe and determines the synoptic situations that cause their occurrence. In this article, a relatively warm day was defined as a day when the maximum temperature exceeded the 95th annual percentile, and a warm spell (WS) was considered to be a sequence of at least five relatively warm days. In the analysed multiannual period and within the investigated area, 24 (Kallax) to 53 (Oslo) WSs were observed. The occurrence of WSs was mainly connected with positive anomalies of sea level pressure and a 500-hPa isobaric surface, displaying the presence of high-pressure systems. This occurrence was also accompanied by positive T850 anomalies.

1 Introduction

The observed present warming in the climate system is unequivocal and evident because of the observations of increases in the global average air and ocean temperatures, the widespread melting of snow and ice and the rising global average sea level (IPCC 2007, 2013). The analyses of the thermal conditions in different regions of Europe confirmed an increase in air temperature, which was notably visible in the last decade of the twentieth century (Brázdil et al. 1996; Wibig and Głowicki 2002; Klein Tank and Können 2003; Kürbis et al. 2009; Nordli et al. 2014). According to the authors of the Fifth IPCC Assessment Report (2013), the increase in the global average temperature between 1880 and 2012 was 0.85 °C, and the first decade of the twenty-first century is considered to be the warmest since instrumental measurements became available and were applied. The magnitude of warming was not globally uniform. According to The BACC Author Team (Assessment of Climate Change… 2008; Wójcik and Miętus 2014), the warming within the Baltic Sea region is progressing faster than on the global scale. As Tietäväinen et al. (2010) displayed that between 1909 and 2008 in Finland, the increase in the mean annual air temperature was 0.093 ± 0.072 °C/decade, whereas between 1961 and 2011, the increase was 0.4 ± 0.2 °C/decade (Irannezhad et al. 2014). A similar trend in air temperature changes was also confirmed in Norway. Between 1875 and 2004, the recorded increase fluctuated by approximately 0.5–1.5 °C (Hanssen–Bauer 2005). However, in northern Sweden, the increase in the mean annual air temperature between 1802 and 2000 was 0.099 °C/decade, and the highest warming trends were observed in winter and spring (Klingbjer and Moberg 2003). Similar trends and magnitudes of changes in the mean air temperature were also recorded in Denmark (Cappelen and Christensen 2005), Estonia (Jaagus 2006; Kont et al. 2007), Latvia (Klavins and Rodinov 2010) and Poland (Michalska 2011; Skowera et al. 2014).

Despite numerous scientific articles and media releases concerning the extreme weather phenomena including long periods of abnormally high temperature, the scientific investigations based on long and uniform data series concerning particular regions of Europe, and notably Northern Europe, are limited. Previous studies have been mainly limited to the analysis of single heat waves from 2003 to 2006 that inflicted damage in Southern and Western Europe (Beniston 2004; Vandentorren et al. 2004) and of the 2010 heat wave in

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Eastern Europe (Dole et al. 2011; Grumm 2011; Otto et al. 2012). Because of the substantial influence of warm spells on human health, the results of this study are likely interesting to a wide and diverse audience. Therefore, the following research objectives were adopted:

1. Describe the spatial variability and multi-year changes in warm spells occurrences in Northern Europe
2. Determine the synoptic conditions (mainly pressure patterns and air circulation) that cause warm spells in Northern Europe

2 Data and methods

This study was based on the daily values for the maximum (Tmax), minimum (Tmin) and mean daily air temperatures (T) obtained at 22 World Meteorological Organisation (WMO) stations located in Northern Europe for the period between 1973 and 2010 (Fig. 1). The data were obtained from the freely accessible databases maintained by NOAA (for stations in Sweden and Finland) and the Norwegian Meteorological Institute (for stations in Norway).

No universal methods or criteria can be used to classify extreme events globally or locally (Ustrnul and Czekierda 2009). Heat waves or warm spells can be defined as the following: (1) several-day periods with the maximum temperature exceeding a particular threshold value (e.g. 30.0 °C; Huynen et al. 2001; Kyselý 2002; Kosowska–Cezak 2010), (2) a period with an apparent temperature (AT) above the 95 percentile that starts with a temperature increase of a minimum 2.0 °C in relation to the previous day (Kuchcik and Degórski 2009) or (3) a period of >5 consecutive days with Tmax >5 °C above the 1961–1990 daily Tmax normal (Frich et al. 2002; Unkašević and Tošić 2009).

A weather phenomenon which is so rare within the particular area and in the particular season that lies within the 10th or 90th percentile of an observed probability density function is defined as an extreme weather event (IPCC 2007). Therefore, in this article, a relatively warm day was defined as a day with a maximum temperature above the 95 annual percentile, which value ranges from 19.2 °C in Lindesnes to 24.7 °C in Oslo (Fig. 2a). A warm spell (WS) was considered to be a sequence of at least five relatively warm days. The similar method for distinguishing heat waves was applied earlier in the analysis for the occurrence of heat waves in Central Europe (Tomczyk and Bednorz 2015) and for the variable climatic conditions of the Arctic (Tomczyk and Bednorz 2014b).

Basic climatological characteristics were calculated on the basis of source material, namely, the mean air temperature of the summer seasons and the number of relatively warm days. From among the selected days, the warm spells were identified, their variability in the multiannual period was investigated and the linear trends were computed.

Relating the occurrence of the mean daily temperature extremes to synoptic conditions, the ‘environment to circulation’ approach was applied. In this method, the circulation

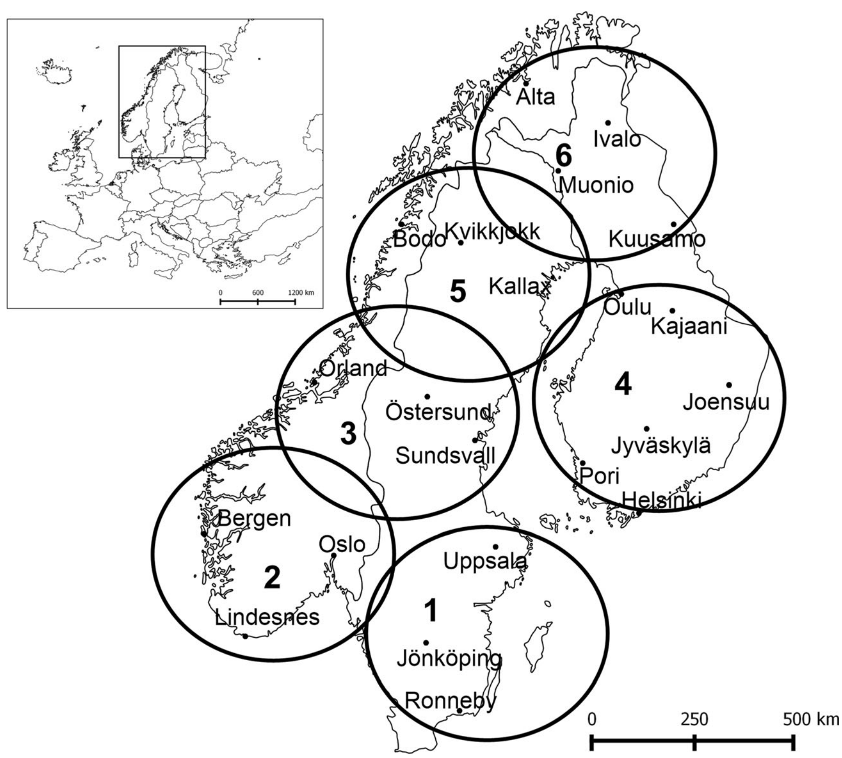

Fig. 1 Locations of the meteorological stations (the areas in which circulation types were distinguished are *circled*)

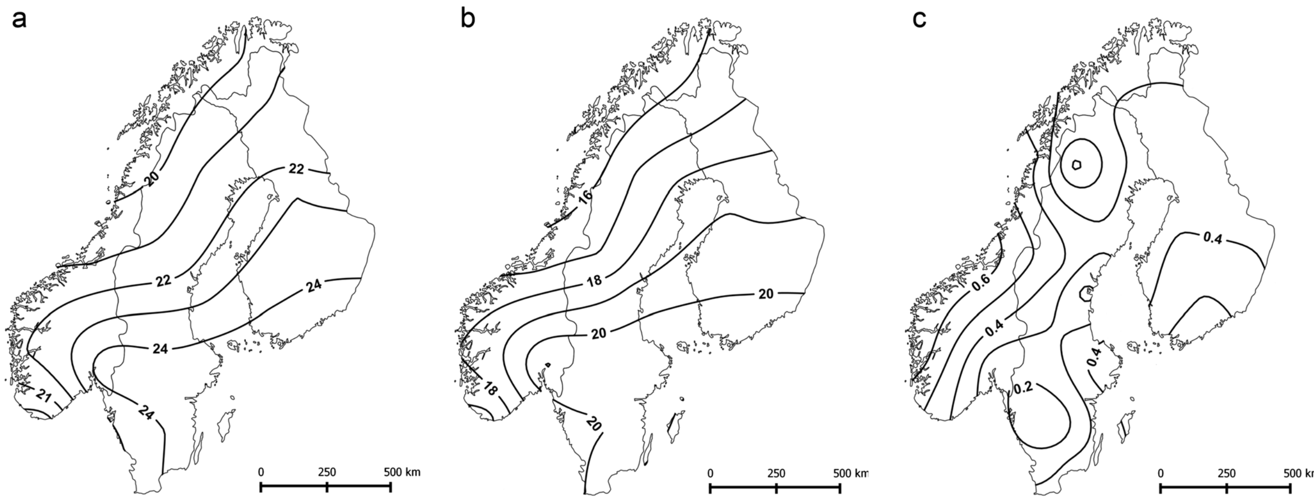

Fig. 2 The value of the 95th annual percentile of the Tmax (°C) (**a**), the mean Tmax (°C) in the summer (June–August) (**b**) and changes in the mean summer Tmax in °C/10 years during the period 1973–2010 (**c**)

classification is performed along specific environment-based criteria set for a particular environmental phenomenon, i.e. the mean daily temperature extremes in this case (Yarnal 1993; Yarnal et al. 2001; Dayan et al. 2012). To determine pressure conditions favourable to the occurrence of relatively warm days, the daily atmospheric pressure values at sea level (SLP), height of the 500-hPa isobaric surface (z500 hPa) and temperature on the 850-hPa isobaric surface (T850) were used. 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 the Climate Research Unit resources. On the basis of these data, maps of the average SLP, z500 hPa and T850 were drawn for a summer season (June–August) together with composite maps for relatively warm days forming warm spells. The composite maps included the days when the maximum temperature fulfilled the criteria of a relatively warm day in at least five stations. Distinguishing the circulation types that cause the occurrence of WSs was performed by grouping days with regard to the sea level pressure values using the minimum variance method, known as Ward's (1963) method. This method is based on Euclidean distances, which merges the pair of clusters A and B. After merging, this process provides the minimum of the sum of squares of all deviations from the newly created centre of gravity of the cluster (Ward 1963). This is a hierarchical clustering technique most frequently used in climatic classification (Kalkstein et al. 1987) to identify the atmospheric circulation patterns associated with the occurrence of specific weather phenomena (e.g. Birkeland and Mock 1996). Standardised SLP values were used for this purpose. The standardisation was made to deseasonalise the observations while maintaining the intensity of the pressure field (Esteban et al. 2005). The main reason for clustering the data objects (days in this case) is that the distance varies between them. Clusters should comprise objects that are separated by small distances relative to the distance between clusters. The commonly used distance measure in cluster analysis is the Euclidean distance in the multi-dimensional space of the data vectors. Ward's (1963) minimum variance method assumes that a pair of clusters will result in the minimum sum of the squared distances between the objects and the centroids of their respective groups summed over the resulting groups (Wilks 1995). Maps of the sea level pressure, 500-hPa heights, 850-hPa temperatures and anomalies were created for the distinctive types of circulation that are favourable for the occurrence of WSs. Additionally, the daily direction in the advection of air masses was determined for the analysed period, and the circulation defined for a daily period was also analysed using atmospheric circulation indices, namely, the direction of the geostrophic wind and the shear vorticity. For the size of the analysed area, 6 grids and 32 points were considered for the SLP data. These points were placed every 2.5° longitude and every 2.5° latitude. On the basis of these data, the calendar of circulation types for each region was determined (Fig. 1). Sixteen circulation types were distinguished (depending on the eight cardinal directions and the type of cyclonic (c) and anticyclonic circulation (a)) using Jenkinson's and Collison's (1977) method. The detailed description of the method for determining these types can be found in Piotrowski (2009).

3 Results

3.1 The maximum temperature in the summer

Between 1973 and 2010, the mean maximum daily air temperature in the summer (June–August) in Northern Europe was 18.4 °C, and it decreased from the south-east to north-west (Fig. 2b). Within the investigated area, the warmest summer on average was recorded in 1997, and the Tmax fluctuated from 16.9 °C (Alta) to 23.9 °C (Oslo). Equally warm summer seasons were recorded in 2002 and 2006. However, the coldest summer season was observed in 1987, with the mean Tmax fluctuating from 12.8 °C (Alta) to 18.2 °C (Oslo). Cold summer seasons were also noted in 1993 and 1981. The course of the mean Tmax showed considerable year-to-year fluctuations; however, the variability was similar within the investigated area, which was noted by the standard deviation values residing between 1 and 1.6 °C. Within the majority of the investigated area, a statistically significant increase was noted in the maximum daily air temperature, fluctuating from 0.07 °C/10 years (Kvikkjokk) to 0.69 °C/10 years (Bergen) (Figs. 2c, 3). This increase was considerably influenced by the Tmax changes in the first decade of the twenty-first century, when Tmax generally exceeded the norm from the 1973–2010 multiannual period. In the analysed period, the range of deviation fluctuated from −3.8 °C (Uppsala, 1987) to 4.3 °C (Orland, 2002). The highest maximum temperature was recorded on 8 August 1975 in Uppsala at 35.0 °C.

3.2 Relatively warm days

In Northern Europe, the observed increase in Tmax translated into an increased number of relatively warm days and, consequently, into the frequency of the occurrence of warm spells. At each station, the correlation coefficient between the mean Tmax in the summer and the number of relatively warm days in summer fluctuated from approximately 0.8 to 0.9. In the analysed region, 18 relatively warm days were annually recorded on average. In the particular years, the mean number of relatively warm days for the analysed region fluctuated from six (1987) to 37 (1997). In 1987, the number of relatively warm days fluctuated from 2 (Jönköping, Ronneby) to 10 (Ivalo, Muonio). A comparatively rare occurrence of relatively warm days was observed in 1998 (8 days on average) and in 1993 (9 days on average). However, in 1997, the number of relatively warm days fluctuated from 22 (Alta) to 55 (Lindesnes). An equally high number of relatively warm days was observed in 2002 (35 days on average) and in 2006 (34 days on average). In Northern Europe during the analysed period, a mean increase in the number of relatively warm days to 1.7 per 10 years was noted. This increase was not statistically significant. Additionally, this increase was not evenly distributed in the analysed area. The highest increase in the number of relatively warm days was recorded in south-western Norway, namely in Orland (4.4 days/10 years) and Bergen (4.2 days/10 years) (Fig. 4). Additional statistically significant changes were also found in Helsinki, Lindesnes and Muonio. A decrease (−0.3 days/10 years) was noted only in Jönköping. The course of the annual number of relatively warm days showed considerable year-to-year fluctuations. The variability was similar within the investigated area; the standard deviation values fluctuated from 6 to 12 days.

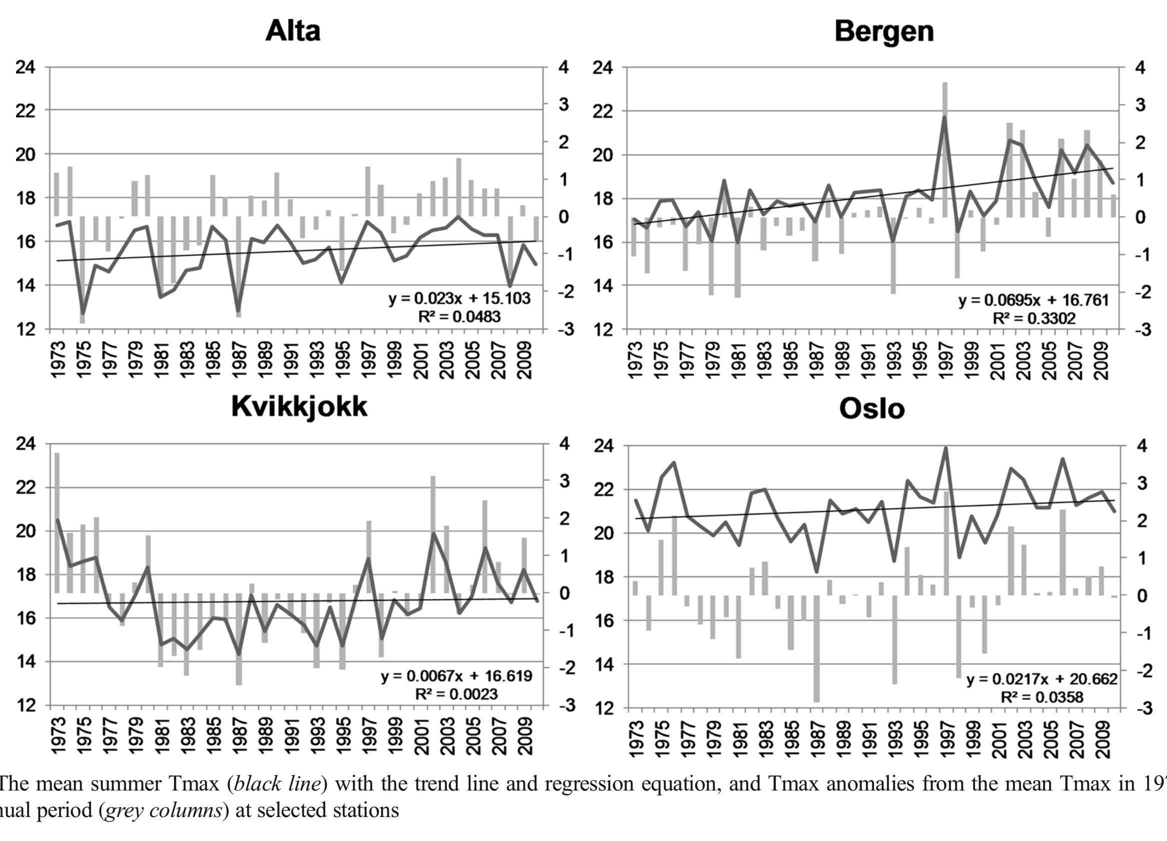

Fig. 3 The mean summer Tmax (*black line*) with the trend line and regression equation, and Tmax anomalies from the mean Tmax in 1973–2010 multiannual period (*grey columns*) at selected stations

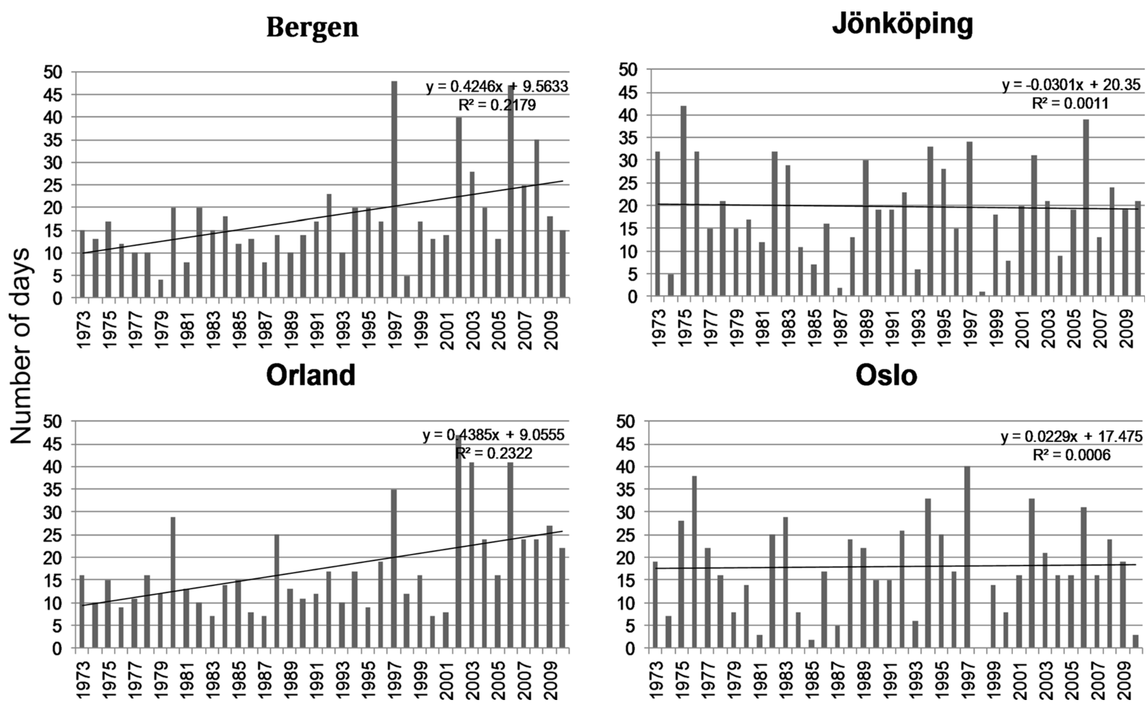

Fig. 4 Multi-year series of the annual number of relatively warm days with the trend line and regression equation at selected stations

Relatively warm days occurred from April to October. The maximum of their occurrence was recorded in July (approximately 43 % of all relatively warm days). In October, only two relatively warm days were recorded (1 day in Bergen and 1 day in Jönköping). In September, relatively warm days were most numerous at seaside stations (e.g. Bergen, Bodo, Orland), which is specific to a marine climate. The earliest and the latest relatively warm days in the discussed multiannual period occurred in Jönköping and occurred on 22 April 1996 and 24 October 1977, respectively.

3.3 Warm spells

Between 1973 and 2010, the total number of WSs in Northern Europe oscillated between 24 (Kallax) and 53 (Oslo) (Fig. 5a). The total number of WS days during the entire studied period ranged from 183 days in Orland to 404 days in Oslo (Fig. 5b). At approximately 70 % of the stations, the lowest number of WSs was recorded between 1981 and 1990, and their number oscillated between 3 (Kallax) and 10 (Ivalo) (Fig. 6). In 86 % of the stations of the analysed area, the highest number of WS occurred in the first decade of the twenty-first century—their number fluctuated from 9 (Alta, Ivalo, Kajaani, Oulu) to 18 (Bergen, Oslo, Pori). In the analysed multiannual period, the average duration of WSs oscillated from 6.5 days in Orland to 9.7 days in Lindesnes. The most frequent were 5- and 6-day WSs, constituting on average 27 and 20 % of all spells, respectively, whereas WSs lasting more than 10 days constituted 15 %. Only at four stations (Kvikkjokk, Lindesnes, Ronneby, Sundsvall) did WSs lasting more than 10 days occur more frequently than 5-day spells. Within the discussed period, only Alta noted no WSs lasting more than 10 days. The longest WS lasted as many as 32 days and was recorded in Lindesnes from 29 July to 29 August 2002. A similarly long WS occurred in Kvikkjokk and lasted 27 days, from 19 June to 15 July 1973. However, at seven stations (mainly in the western part of the region) on average, the longest WS occurred in 2003 and occurred from 16 July to 2 August 2003 (18 days).

In the analysed multiannual period, the WSs occurred from May to September. However, they were most frequently recorded in July (approximately 47 % of all WSs). Only Lindesnes recorded the highest number of WSs in August (48.8 % of all warm spells). In most of the stations, the first WS was most frequently recorded at the end of May and the beginning of June. The earliest and the latest WSs in the analysed multiannual period were recorded in Bergen, and they occurred from 5 to 9 May 2006 and from 8 to 12 September 2002, respectively. In Northern Europe, the potential period for WSs in the analysed multiannual period was 131 days, occurring from 5 May to 12 September.

The mean Tmax during the analysed WSs was 25.3 °C, whereas the Tmin was 12.9 °C. The highest mean Tmax was observed during WSs in Jönköping (3–11 August 1975) at 31.4 °C, whereas the highest mean Tmin occurred in Lindesnes (1–8 August 1982) at 19.1 °C. During the longest WS, that is, the one that occurred from 29 July to 29 August 2002 (Lindesnes), the mean Tmax was 21.7 °C, whereas the mean Tmin was 17.8 °C. In the analysed multiannual period, at three stations (Joensuu, Kuusamo, Pori) statistically significant changes of Tmin during WSs were observed.

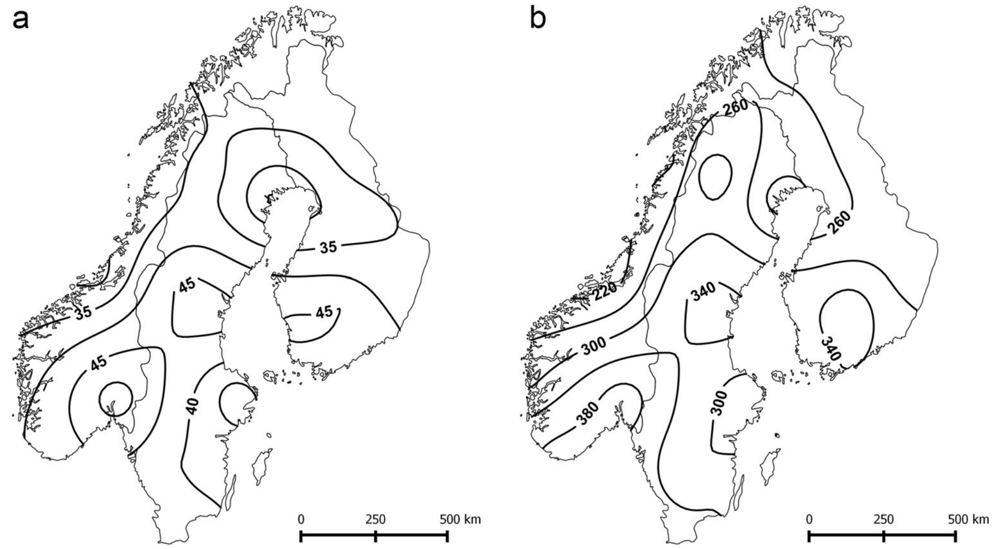

Fig. 5 Spatial pattern of the total number of WSs (**a**) and the total duration of WSs (**b**) in 1973–2010

3.4 Impact of the circulation on the occurrence of warm spells

The mean sea level pressure in the Euro-Atlantic sector between 1973 and 2010 in the summer (June–August) reached the highest value in the area of the Azores Islands (>1024 hPa) (Fig. 7a). The pressure drop occurred in the northerly direction, and the centre of the low pressure was located in the southern west of Iceland (<1009 hPa). Between these pressure centres over the ocean, the considerable horizontal gradient of pressure was observed and a lower gradient was found over the continent. In the summer season, the averaged 500-hPa isobaric surface was inclined towards the north-west. The maximum height for the z500 hPa was recorded over the Mediterranean Sea (>5880 m), and the minimum was found over the northern Atlantic (<5500 m). The air temperature on the 850-hPa isobaric surface decreased from the south (>20 °C) to the north-west (<0 °C) (Fig. 7b). The pressure system caused the westerly circulation typical of Europe both in the middle and bottom troposphere.

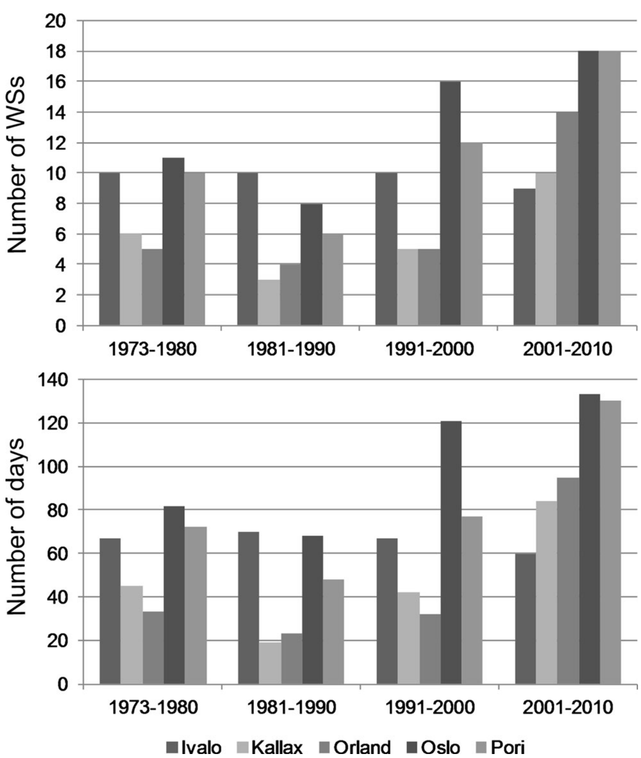

Fig. 6 The number of WSs and the duration of WSs in 1973–2010 at selected stations

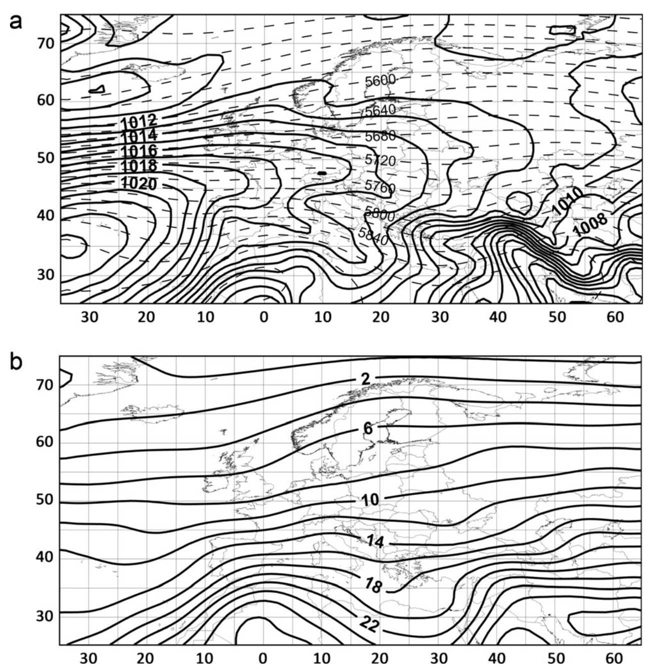

Fig. 7 Mean summer (June–August) **a** SLP in hPa (*solid lines*) and z500 hPa in m (*dashed lines*) and **b** T850 in °C

The occurrence of WSs in Northern Europe in the analysed multiannual period, on average, was connected with a ridge of high pressure lying across Europe. Within this ridge, a high-pressure area was formed with a centre over southern Finland and north-western Russia (>1018 hPa) (Fig. 8a). The contour lines of the 500-hPa isobaric surface over the majority of the continent bent northward, creating a clear elevation over Northern Europe and confirming the presence of warm air masses. Warm air masses are characterised by a lower density than cool masses, thus dropping the pressure faster than the height. During the occurrence of WSs, the pressure over the analysed area was higher than in the average summer season pressure, confirmed in the sketches of maps of SLP anomalies which oscillated between 2 and >6 hPa over the analysed area (Fig. 8b). The z500-hPa isobaric surface settled at a higher elevation over the analysed area than usually during the summer season, and the positive anomalies in the centre exceeded 120 m. The occurrence of WSs was also connected with T850 positive anomalies (in the centre, these were >4 °C) (Fig. 8c). The system described above caused an inflow of warm and dry continental air masses from the north-east in the bottom troposphere. However, tropical air masses advection from the south-west occurred in higher troposphere layers.

Relatively warm days forming WSs at least five stations were grouped by the sea level pressure, and on this basis, two circulation types conducive to the occurrence of WSs in Northern Europe were determined. For type 1, 272 relatively warm days were recorded. On these days, Northern Europe was under the influence of a centre of high pressure (with its centre >1021 hPa) (Fig. 9a). SLP anomalies of this type were much more frequent than those of type 1. Over the analysed area, the SLP anomalies oscillated between 3 and >10 hPa (Fig. 9b). The distribution of z500 hPa anomalies was similar. The entire system shifted to the west. Over the analysed area, the z500 hPa settled at a higher elevation than usual during the summer season, from 75 to >150 m. The described pressure conditions were also accompanied by T850 positive anomalies, which varied from 2.5 to >5.0 °C over the analysed area (Fig. 9c). This barometric situation caused an inflow of warm and dry continental air masses from the east. Using the

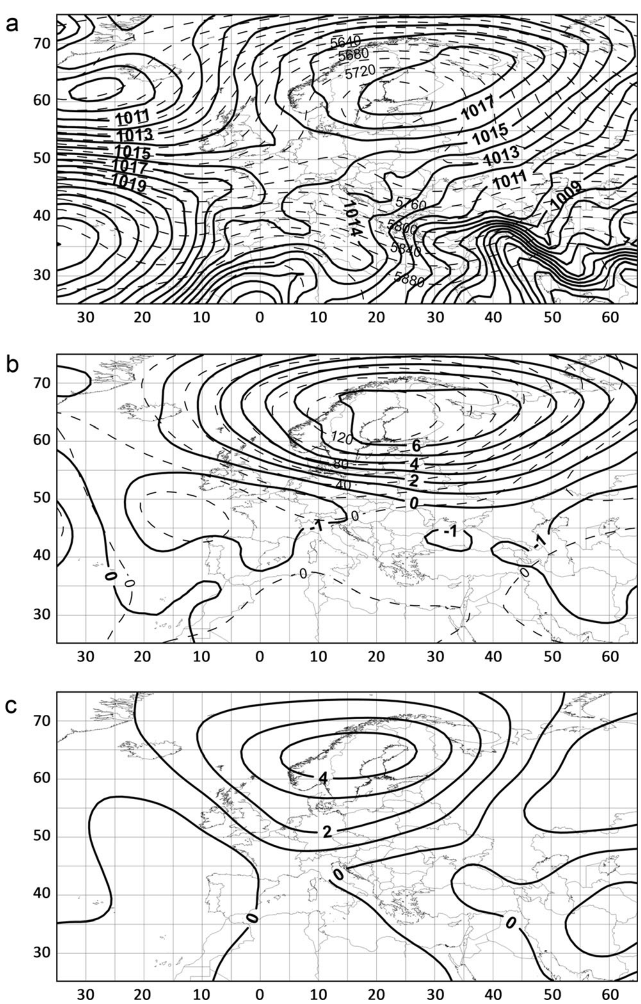

Fig. 8 SLP and z500 hPa (a), SLP and z500 hPa anomalies (b) and anomalies of T850 (c) for the WS days

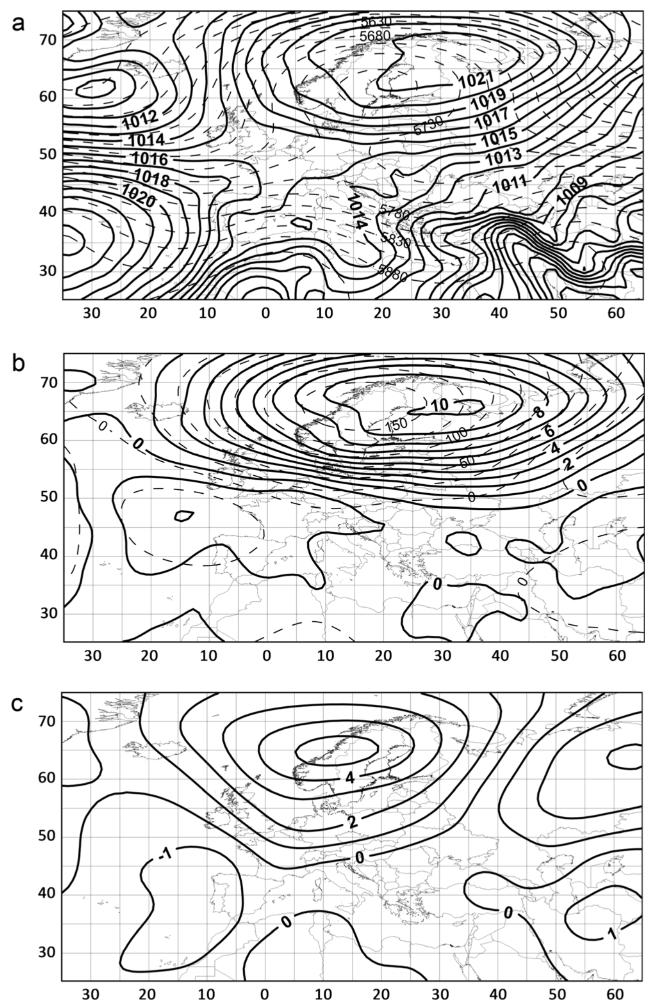

Fig. 9 Mean SLP and z500 hPa (a), SLP and z500 hPa anomalies (b) and anomalies of T850 (c) for the synoptic type 1 causing WSs

developed calendar of circulation types, the probability of occurrence of WSs was noted to be higher with anticyclonic circulations (13 % on average) than with cyclonic circulations (2.9 % on average) (Table 1). The occurrence of anticyclonic circulations from the east and the south-east is connected with the highest probability of WS occurrence within the analysed area. The probability of the occurrence of WSs in region 1 with an eastern anticyclonic circulation is 48.5 %, whereas in region 6 with a southeastern anticyclonic circulation, the probability is 47.1 %.

For type 2, 213 relatively warm days were classified. On average, their occurrence was connected with a ridge of high pressure covering the European continent, within which a local high-pressure area was formed (>1015 hPa), with its centre over Latvia (Fig. 10a). Over the analysed area, the SLP in this type was higher than usual during the summer season, and anomalies oscillated between 0 and >3 hPa (Fig. 10b). A similar course concerned z500 hPa anomalies, which exceeded 100 m in the centre. The described conditions were accompanied by T850 positive anomalies, which oscillated between 3.0 and >4.0 °C over the analysed area (Fig. 10c). This barometric situation caused an inflow of warm and dry continental air masses from the south and south-west. For this type, a higher probability of WS occurrence with anticyclonic circulation (8.2 % on average) than with cyclonic circulation (4.2 %) was also recorded (Table 2). The predominance of anticyclonic circulation over cyclonic is less considerable when compared to type 1. The greatest probability of WS occurrence was connected with the occurrence of anticyclonic circulations from the south-west and the west in summer. In region 1, as opposed to the rest of the area, the highest probability of WS occurrence was connected with the inflow of air masses from the south.

3.5 Case studies of the 1975 and 2002 warm spells

Detailed analyses were performed for two selected WSs, namely, for the warmest WS during which the Tmax in Jönköping (3–11 August 1975) was 31.4 °C and for the longest WS lasting 32 days in Lindesnes (29 July–29 August 2002).

During the warmest WS, a strong high pressure system settled over Northern Europe with its centre lying over the southern part of the Scandinavian Peninsula (>1023 hPa) (Fig. 11a, left column). The research area stayed within the reach of the SLP positive anomalies, with the centre >11 hPa (Fig. 11a, middle). Contour lines of the isobaric surface located over the northern part of the continent bent northward, creating a clear elevation and confirming the presence of warm air masses. Over the southern part of the Scandinavian Peninsula, z500 hPa settled at 5860 m. Therefore, this level was higher than usual in summer by >220 m. During the analysed WS, T850 positive anomalies were also recorded with a centre (>9 °C) characterised by a similar location to the centres of SLP and z500 hPa anomalies (Fig. 11a, right column).

The longest WS was connected with a high pressure system with its centre over the Gulf of Finland (1019 hPa) (Fig. 11b, left column). Similar to the warmest WS, the z500 hPa contour lines bent northward, creating a clear elevation over the

Table 1 Probability (%) of the occurrence of circulation types in the particular regions for the synoptic type 1 causing WSs

Type	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Na	5.0	9.2	13.3	5.0	13.9	6.2
NEa	19.3	10.5	7.5	14.2	20.5	18.5
Ea	48.5	9.3	14.0	30.9	35.9	33.0
SEa	34.1	16.5	20.1	38.5	26.0	47.1
Sa	14.4	16.0	21.8	24.5	10.9	22.5
SWa	3.6	19.7	19.0	9.5	6.3	3.9
Wa	0.4	15.2	9.6	4.7	5.5	1.9
NWa	1.2	12.9	8.2	4.6	7.8	2.3
Nc	3.0	1.0	1.9	1.2	1.5	0.0
NEc	11.4	1.6	1.7	3.6	1.9	7.1
Ec	20.5	0.8	3.3	5.9	8.2	13.6
SEc	13.3	2.6	2.4	5.0	6.6	16.2
Sc	3.2	2.2	4.3	4.1	0.4	7.3
SWc	1.5	3.3	2.7	1.8	1.3	3.4
Wc	0.0	2.5	1.8	1.5	0.8	0.6
NWc	1.3	6.5	1.9	0.9	0.6	1.4
Anticyclonic circulation	12.3	13.7	13.7	13.1	13.8	12.0
Cyclonic circulation	3.4	2.4	2.6	2.8	2.3	3.8

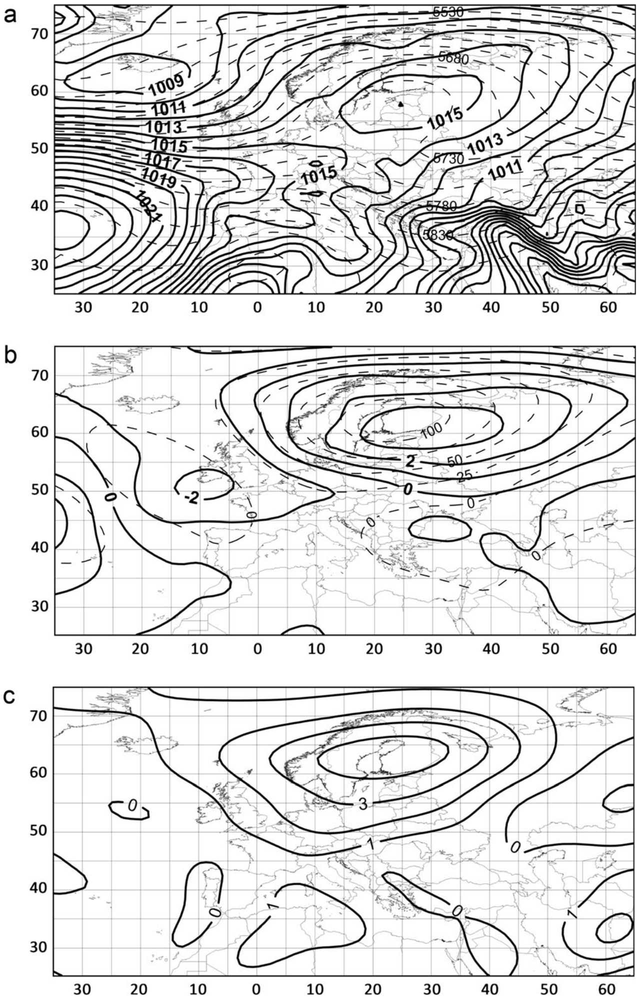

Fig. 10 Mean SLP and z500 hPa (**a**), SLP and z500 hPa anomalies (**b**) and anomalies of T850 (**c**) for the synoptic type 2 causing WSs

analysed region. The SLP anomalies over the research area oscillated between 2 and >7 hPa, whereas the z500 hPa anomalies varied from 80 to >130 m (Fig. 11b, middle). During the analysed WS, T850 positive anomalies were recorded (in the centre >5 °C) (Fig. 11a, right column). This barometric situation caused an inflow of warm air masses from the south-east.

4 Discussion and summary

This study showed an increase in the Tmax in the summer season in Northern Europe between 1973 and 2010. On average, this increase was 0.38 °C per 10 years for the analysed area, and the most significant changes occurred in the first decade of the twenty-first century. A similar trend was noted in other regions of Europe, e.g. in Greece (Founda and Giannakopoulos 2009), Serbia (Unkašević and Tošić 2009), Moldavia (Corobov et al. 2010), Spain (Martínez et al. 2010) and in Lithuania, Latvia and Estonia (Jaagus et al. 2014). Kossowska–Cezak and Twardosz (2013) analysed the occurrence of extremely cold summer months and seasons in Central and Eastern Europe and showed that the currently observed warming manifests itself mainly through the increasingly frequent occurrence of extremely hot summers and not through the disappearance of extremely cold summers. Model studies have shown that an increase in the air temperature in Europe will persist during the next few decades of the twenty-first century (IPCC 2013).

The lowest mean Tmax and number of relatively warm days were recorded in the summer of 1987, and the highest were recorded in the summer of 1997. In the analysed multiannual period, an increase in a number of relatively warm days was observed, and a mean change for the analysed area was 1.7 days per 10 years. Statistically significant changes were confirmed at five stations. Only Jönköping in the analysed multiannual period displayed a small decrease in the number of relatively warm days (−0.3 days/10 years). The increase in frequency of occurrence of hot days was confirmed in other studies conducted in the Czech Republic (Kyselý 2010), Greece (Founda and Giannakopoulos 2009), Latvia (Avotniece et al. 2010), Lithuania (Kažys et al. 2011) and Poland (Tomczyk and Bednorz 2014a). The consequences of the increasing climate warming include the changes observed in the Arctic, which are indicated by the decrease in the number of frost days (Niedźwiedź et al. 2012; Tomczyk 2014a) and the increase in the number of warm days (Bednorz and Kolendowicz 2013; Tomczyk and Bednorz 2014b).

In the analysed multiannual period in Northern Europe, an increase in the frequency and duration of WSs was noted. On average, the lowest number of WSs was recorded between 1981 and 1990, and the highest in the first decade of the twenty-first century. Similar results were also obtained for Central Europe (Tomczyk and Bednorz 2015). The increase in frequency of extreme weather phenomena, including heat waves, was found in the Czech Republic (Kyselý 2010), Poland (Kossowska–Cezak 2010; Tomczyk 2014b), Serbia (Unkašević and Tošić 2009), Ukraine (Shevchenko et al. 2014) and Spitsbergen (Tomczyk and Bednorz 2014b). As Twardosz and Kossowska–Cezak (2013) showed, currently, in Central and Eastern Europe, there is an increase in a number of extremely hot months, which were most frequently recorded in the first decade of the twenty-first century. According to the predictions, heat waves in the twenty-first century are going to be more frequent and more intense (Meehl and Tebaldi 2004; Koffi and Koffi 2008; Kürbis et al. 2009; Pongracz et al. 2013; Amengual et al. 2014; Zacharias et al. 2015).

The occurrence of WSs in Northern Europe was connected with two circulation types. However, the most frequent was type 1, which was connected with a strong high pressure system providing the inflow of dry continental air masses from the east. Additionally, an important factor influencing the air temperature is the strong insolation that occurs during high pressure weather characterised by cloudlessness or a small

Table 2 Probability (%) of the occurrence of circulation types in the particular regions for the synoptic type 2 causing WSs

Type	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Na	5.0	5.6	6.4	3.9	8.5	4.8
NEa	8.7	1.6	1.7	7.1	7.0	5.2
Ea	8.3	4.9	6.5	3.2	6.2	14.2
SEa	11.2	4.5	5.0	7.4	7.1	7.4
Sa	16.8	7.3	6.1	8.8	6.3	8.1
SWa	10.9	9.4	11.2	15.6	15.4	12.0
Wa	5.9	13.2	14.6	8.1	13.9	6.3
NWa	4.0	12.1	9.8	6.9	8.2	3.2
Nc	4.2	4.3	2.2	2.4	3.7	3.6
NEc	4.8	2.6	3.1	4.0	1.9	5.5
Ec	9.0	1.7	3.6	2.2	0.0	6.8
SEc	7.2	3.7	4.2	7.2	5.5	14.1
Sc	7.7	6.0	6.2	5.9	2.0	10.1
SWc	4.6	8.4	8.6	6.5	2.6	7.5
Wc	1.3	8.2	4.4	4.4	4.7	2.5
NWc	1.5	5.8	1.9	1.4	1.7	1.9
Anticyclonic circulation	8.6	7.4	8.3	8.1	9.7	7.1
Cyclonic circulation	3.7	4.9	4.2	4.2	2.8	5.2

cloud cover. The inflow of continental air masses from the eastern sector in summer, also in Central Europe, is connected with the occurrence of extreme temperatures or heat waves (Ustrnul et al. 2010; Porębska and Zdunek 2013; Tomczyk 2014b). An alternative source of warm air masses causing the occurrence of heat waves in the analysed region was the inflow of air masses from the south and the south-west. The analyses of the circulation conditions concerning the selected heat waves in many regions of Europe showed that these occur mainly during anticyclonic weather (Black et al. 2004; Fink et al. 2004; Founda and Giannakopoulos 2009). The occurrence of the warmest WS was connected with a higher SLP and z500 hPa and more T850 anomalies than on average during all of the WSs. The most considerable differences were recorded in T850 anomalies over the southern part of the Scandinavian Peninsula. Fewer considerable differences were observed for the longest WS.

5 Conclusions

The conducted research confirmed an increase in both the mean maximum air temperature in the summer and the frequency of the occurrence of relatively warm days in Northern

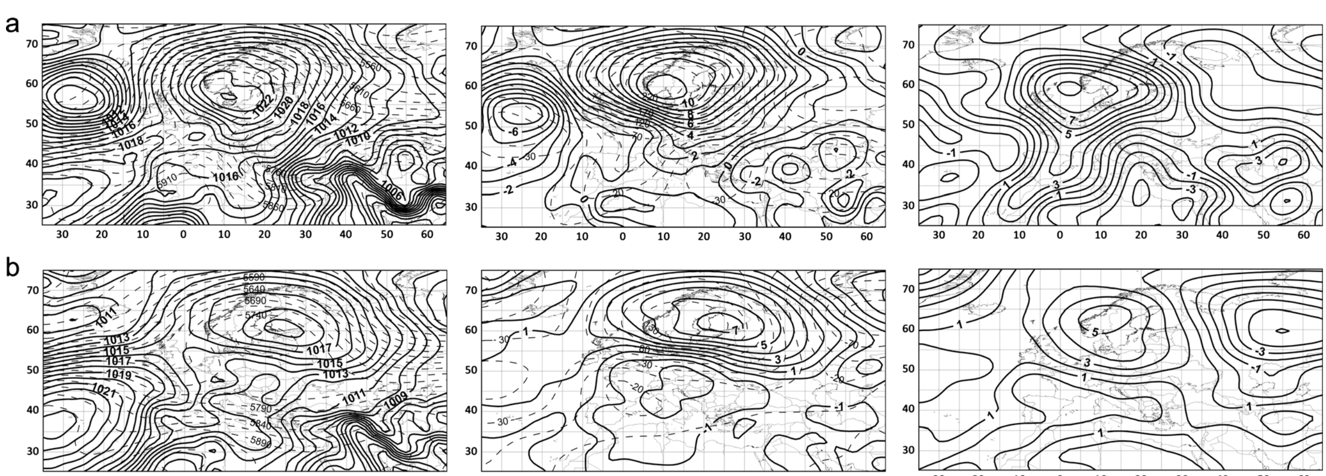

Fig. 11 SLP and z500 hPa (*left column*), the SLP and z500 hPa anomalies (*middle column*) and the T850 anomalies (*right column*) for the WSs of 1975 (**a**) and 2002 (**b**)

Europe. In the analysed period, an increase in the frequency of occurrence of WSs and their duration was noted. Notably, these changes increased in the first decade of the twenty-first century. The occurrence of WSs was mainly connected with positive anomalies of the sea level pressure and the height of the 500-hPa isobaric surface, indicating the presence of high pressure systems. This occurrence was also accompanied by positive T850 anomalies.

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