Theoretical and Applied Climatology (2019) 136:1259–1273
https://doi.org/10.1007/s00704-018-2554-x

ORIGINAL PAPER

Heat-related mortality during hot summers in Polish cities

Dariusz Graczyk[1] · Zbigniew W. Kundzewicz[1] · Adam Choryński[1] · Eirik J. Førland[2] · Iwona Pińskwar[1] · Małgorzata Szwed[1]

Received: 22 May 2017 / Accepted: 27 June 2018 / Published online: 11 July 2018

Abstract

The aim of this study was to estimate a likely number of additional fatalities in ten largest cities in Poland, recorded during heat waves in particularly hot summer seasons. In the period of 1989–2012, for which data on mortality were available, the most intense, long-lasting, summer heat waves occurred in 1992, 1994, 2006, and 2010. The numbers of fatalities in these years were compared to the numbers of fatalities in reference periods. These calculations were undertaken for days during heat waves and also for a longer interval including next 30 days after the end of the last sub-wave. An increase of mortality risk for people over 65 years of age and for those affected with cardiovascular diseases was noted. The total number of additional fatalities in ten largest cities in Poland could have exceeded 1070 in 1994. During the hottest days in the analyzed period, in some cities, the number of fatalities was more than three times higher than the mean value for the reference period. The results indicate that the increase of mortality during heat waves is a serious threat in Poland already in the present climate and will be even more severe in a warming climate.

1 Introduction

Numerous studies, carried out in different parts of Europe on the basis of observational data, confirm that hot extremes of air temperature increase in frequency (Della-Marta et al. 2007; Fioravanti et al. 2016; Klein Tank and Konnen 2003). At the same time, length and intensity of heat waves have been increasing. In Western Europe, length of heat waves has doubled since the end of the nineteenth century (Della-Marta et al. 2007). This implies not only serious economic consequences, but also considerable health impact. In the twenty-first century, two devastating heat waves have occurred in Europe. The first one, in 2003, may have caused 70,000 deaths in 12 countries in Western Europe (Robine et al. 2008). The second one, in 2010, covered the eastern part of the continent and could have caused 56,000 deaths (Munich Re 2011). Since the second half of the twentieth century, no single natural disaster in Europe, including the earthquakes, has caused such a high number of fatalities. So, one can say that heat waves are currently the most deadly natural disasters in the European continent.

Similarly to other parts of Europe, heat waves occur also in Poland, generating health risk. Increasing frequency of high air temperature, including hot days and very hot days (Graczyk and Kundzewicz 2014; Graczyk et al. 2017; Wibig 2012) has been observed. Also unfavorable demographic changes (aging population) take place in Poland. Advanced age is considered to be one of the most serious health risk factors during heat waves. In 1990, the population aged 65+ accounted for 10.2% of the total population in Poland, while in 2012, it was already 14.2%. Predictions indicate that by 2025 it can reach the level of 21.5%, i.e., more than twice as much, in relative terms, as in 1990 (GUS 2014).

The most intense pan-European heat wave, recorded in 2003, did not affect Poland. Although the heat wave of 2010 was felt almost everywhere in Poland, it did not produce such catastrophic consequences as farther east and in the Russian Federation, in particular. In addition to the aforementioned heat wave 2010, other intense heat waves (1992, 1994, 2006, 2014, 2015) occurred in Poland in last three decades, leading to serious consequences, also in the health sector.

So far, the problem of increased mortality during heat waves was most frequently mentioned in literature in relation to the Mediterranean and Western Europe in the context of the heat wave of 2003. Significantly, fewer references examine health impact of heat waves in Central and Eastern Europe,

✉ Dariusz Graczyk
darekgraczyk@wp.pl

[1] Institute for Agricultural and Forest Environment, Polish Academy of Sciences, Bukowska 19, 60-809 Poznań, Poland

[2] Norwegian Meteorological Institute, Oslo, Norway

including Poland. Authors generally restrict their attempts to establishing correlation between the threshold values of temperature or more complex indicators of thermal discomfort and heat stress and the number of deaths. Existing studies for the Polish territory (Kuchcik and Błażejczyk 2001, 2005; Kuchcik and Degórski 2009) examined earlier records, covering the hot summers of 1992 and 1994, but could not include the more recent cases of heat waves of 2006 and 2010.

The aim of this study is to investigate the influence of thermal conditions prevailing during four exceptionally hot summers: in 1992, 1994, 2006, and 2010 on the number of deaths and the risk of death in large cities in Poland. The total number of deaths that could have been caused by adverse weather conditions occurring during heat waves in 10 most populous cities in Poland was estimated. Additionally, the mortality rates for two risk groups: (i) elderly people of 65+ years of age and (ii) people with cardiovascular deficiencies were also examined.

2 Data and methodology

2.1 Meteorological data

Meteorological data used in the analysis are daily values of minimum, maximum, and average daily air temperature, as well as the daily average value of the relative humidity during the four summer periods subject to analysis (1992, 1994, 2006, and 2010). These indices were based on daily meteorological data, and average values of the daily heat discomfort index, humidex, were calculated, linking together air temperature and humidity. This index, introduced in Canada, has also used in works on similar themes in Europe (for example: Bisanti et al. 2004; Conti et al. 2005). The values of the humidex were calculated using the formula:

$$\mathrm{H} = \mathrm{T} + 5/9(e{-}10) \qquad (1)$$

as in Masterton and Richardson (1979) and Conti et al. (2005), where:

T is the air temperature in °C,

e is the vapor pressure index, calculated after Bisanti et al. (2004), using the empirical formula:

$$e = 6.112 \cdot 10^{[(7.5\mathrm{T})/(237{,}7+\mathrm{T})]} \cdot \mathrm{RH}/100 \qquad (2)$$

where

RH is the mean daily relative humidity in %.

2.2 Mortality data

The research material is a database containing information about the deaths in Poland for every day in the period 1989–2012, acquired from the Central Statistical Office of Poland (GUS). It includes information on age of the deceased persons and on the cause of death, according to the International Classification of Diseases (ICD). Data for 1989–2000 were organized according to the ninth revision of the international classification (ICD9) and data after 2000 were coded according to the tenth revision (ICD10). All deaths due to natural causes: ICD-9 from 1 to 799; ICD-10 groups from A to D, as well as deaths of cardiovascular and cerebrovascular diseases (CVD), ICD-9 from 390 to 459, ICD-10 group I, were subject to analysis. Also the age of the deceased persons was taken into account as a risk factor. Specifically, the age category 65+ was distinguished.

Socioeconomic changes, which took place in Poland and other countries in the region of Central and Eastern Europe, have rendered it more difficult to estimate the expected number of deaths (and further, to calculate the increase of risk of death and the number of additional deaths during heat waves). Generally, a downward trend in the number of deaths has been observed in such countries of the region as the Czech Republic (Kysely and Huth 2004), accompanying improvements in health care. In ten large Polish cities subject to analysis, considerable changes in the number of inhabitants have been noted (Table 1). Therefore, the expected number of deaths as an average for all the years for which data are available would not be representative. In addition, a protest action of physicians took place in Poland in 1997 and 1998. During this time interval, doctors did not write down the cause of death in official death certificates and this disturbed the homogeneity of records.

For each of the analyzed heat waves, an individual reference period was assumed, possibly embracing 3 years (without a heat wave and without data gaps due to doctors' protests) before and after the examined year with a heat wave. The year 2010 constituted an exception, because the available data end in 2012, so that only the years 2007–2009 and 2011, 2012 were considered (i.e., 2 years after the summer with heat wave). In published literature, reference periods are often of similar or even shorter length, e.g., 5 years in Robine et al. (2007), 4 years in Vandentorren et al. (2004), and 1 year in Conti et al. (2005).

For particular summers with occurrence of heat waves in Poland, the following reference periods were examined:

– For the summer of 1992: 1989–1991 and 1993, 1995, 1996
– For the summer of 1994: 1990, 1991, 1993, 1995, 1996, 1999
– For the summer of 2006: 2003–2005 and 2007–2009
– For the summer of 2010: 2007–2009 and 2011–2012

Table 1 Information on Polish cities, subject to analysis, ordered after recent (2012 census) population

City	Population in 1990	Population in 2012	Population change in 1992–2012	Area [sq. km]	Population density in 2012 (per sq. km)	WMO code of the nearest meteorological station
Warszawa	1,655,700	1,715,517	3.61%	517.24	3317	12,375
Kraków	750,500	758,463	1.10%	326.85	2321	12,566
Łódź	843,200	718,960	− 14.73%	293.25	2452	12,465
Wrocław	643,200	631,188	− 1.87%	292.82	2156	12,424
Poznań	590,100	550,742	− 6.67%	261.91	2103	12,330
Gdańsk	465,100	460,427	− 0.01%	261.96	1758	12,150
Szczecin	413,400	408,913	− 1.09%	300.55	1361	12,205
Bydgoszcz	381,500	361,254	− 5.31%	175.98	2053	12,240
Lublin	351,400	347,678	− 1.06%	147.47	2358	12,495
Katowice	366,800	307,233	− 16.25%	164.64	1866	12,555

2.3 Explanation of analytical process

Despite the use of a 6-year reference period, there is a considerable variability of the expected number of deaths between adjacent days. This is due to the presence of shorter hot periods or single days with high temperature that distort regularity. According to Huynen et al. (2001) and Kyselý (2004), even hot spells of moderate length often result in a significant excess mortality. Therefore, comparisons also used 7-day moving average calculated for each reference period. The increase of risk of death during a heat wave is defined as the percentage difference between the observed number of deaths in the analyzed period and the expected number of deaths calculated for corresponding days of the reference years. Also, the number of additional deaths was estimated that might have been caused by the studied heat wave. The analyzed heat waves did not have a similar course. Only in one case (Summer 2006), an uninterrupted period of occurrence of high temperatures was observed in Poland. In other summers subject to analysis (in 1992, 1994, and 2010), hot days were clearly separated by cooler days.

Therefore, all calculations were carried out for two time intervals:

– Days with increase in mortality during, or shortly after, the occurrence of high values of air temperature and/or humidex.
– Days between the beginning of the first period of increased mortality accompanied by high values of air temperatures and/or humidex, and the 30th day after the last day of increased mortality period. Longer interval covering monthly period after the end of the heat wave will be used to estimate the number of deaths that is not associated with the "harvesting effect".

Figure 1 illustrates the process of determination of time intervals with elevated number of deaths, related to the occurrence of high values of air temperature and/or humidex, for the 1994 heat wave in Warszawa. A band of 90% confidence interval was also calculated.

3 Results

3.1 Mortality in summer months, compared to other seasons

Despite the marked increase in the number of deaths in Poland, during intense heat waves, in an average year, climatic summer is not the season with the highest number of deaths in the country. In fact, in the years 1989–2012, the greatest number of deaths occurred in Poland during the cool part of the year, culminating in the winter months and attaining a minimum value in June, August, or September, depending on the city (Fig. 2). A similar distribution of deaths holds also for the age group 65+, as well as for the category of persons with cardiovascular deficiencies. Typical annual distribution of deaths, as presented in Fig. 2 largely differs from a distribution in a year with a strong summer heat wave. There is a considerable increase in mortality during heat waves, so that the numbers of deaths can be similar to those in winter months and even higher, for some cities. This applies both to the entire population and to the 65+ age group (see Fig. 3 for Poznań and Warszawa).

3.2 Characteristics of the weather conditions and the number of deaths during summers with heat waves

3.2.1 The summer of 1992

During the summer of 1992, temperatures considerably exceeded the long-term mean (for 1961–1990) over a large area of Poland. The highest 7-day anomaly of maximum daily

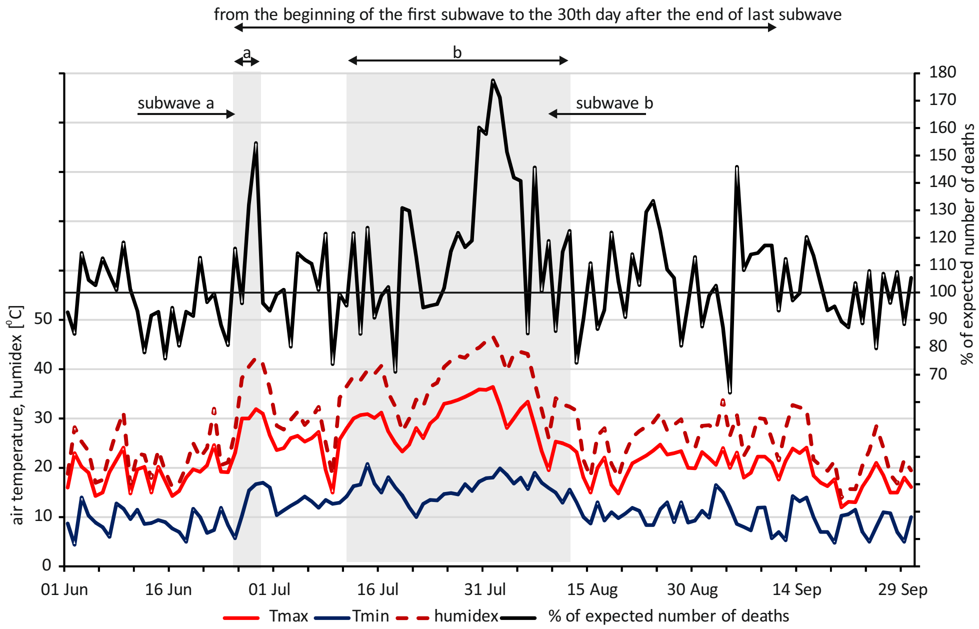

Fig. 1 Illustration of the process of determination of time intervals with elevated number of deaths, related to the occurrence of high values of the air temperature and/or the humidex (Warszawa 1994)

air temperature (Fig. 4a) occurred in the south of Poland, exceeding the long-term mean by more than 10 °C over a large area. In central Poland, the anomaly mostly exceeded the value of 7 °C and only on the coast it was less than 5 °C. A similar geographical distribution at slightly lower values (4–9 °C) was also observed for the 14-day anomaly (Fig. 4b).

The first interval of rising temperatures that lasted longer than 10 days and the accompanying increase in the number of deaths were recorded in the western part of the country in the last 10 days of June and in early July. During this period, the maximum daily temperature approached or exceeded 30 °C, while the value of the humidex exceeded 35°. In comparison with the reference period, the mortality was higher even by more than 40%. The number of deaths of people with cardiovascular deficiencies and in the age group of 65+ years increased by 80% and up to 95%, respectively. The main heat wave commenced in all the studied cities around 20th of July and lasted, interrupted by short periods of temperature drop below 30 °C, for approximately 3 weeks. During the hottest days, depending on the town, temperature reached 34–37 °C and the value of the humidex exceeded 45 °C. Only in Gdansk, located on the Baltic Sea coast, temperature in those days (except for the 10th of August) was below 30 °C. The highest increase in mortality during this heat wave was recorded for most cities in its final phase, which coincided with the occurrence of the highest temperature. The increase in mortality in the total population (all causes, not age restricted) ranged from 41% in Warszawa and Łódź up to 102% in Katowice. The last episode of this hot summer was quite unusual for late August, lasting from 2 days in the north and west to 6 days in the south, with temperatures considerably exceeding 30 °C and the humidex exceeding 45°. A clear mortality increase

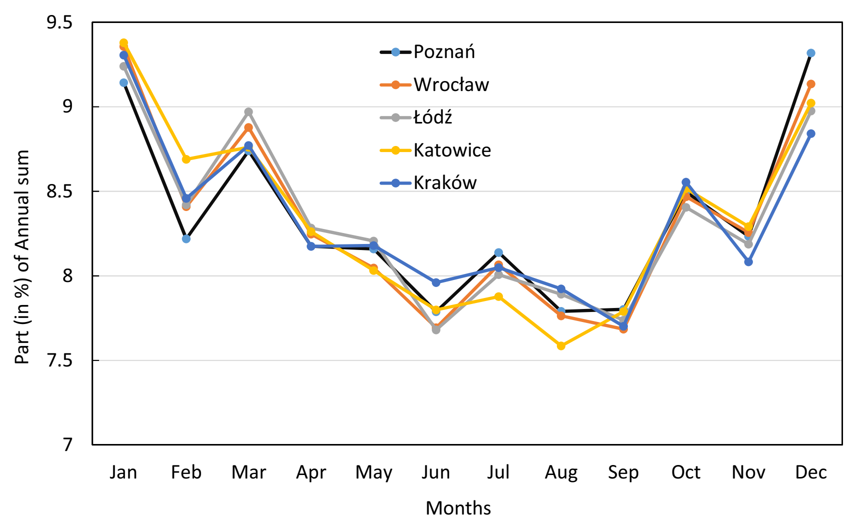

Fig. 2 A percentage of the monthly contribution to the annual sum of deaths in a year in five Polish cities (average for 1989–2012)

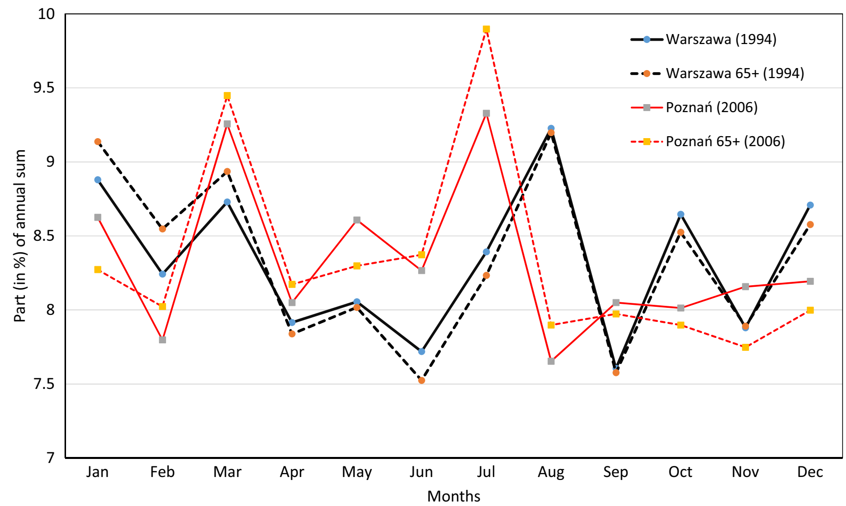

Fig. 3 Intra-annual distribution of the number of deaths, for all cases and people aged 65+ in Poznan 2006 and Warszawa 1994

was observed, which in some cities still remained for about 2 weeks after the end of the heat wave. The number of deaths (all causes and age classes) during this heat wave exceeded 150% of the expected number of deaths for the last days of August and the first half of September. Among people with cardiovascular diseases and circulatory system deficiencies, the increase was up to 200%. The course of temperature (daily maximum and minimum), humidex, and the number of deaths in Warszawa is shown in Fig. 5.

3.2.2 The summer of 1994

The highest values for both 7- and 14-day mean maximum temperature anomalies were observed in the summer of 1994. At some places, the maximum temperature during the hottest week of the summer (Fig. 6a) was higher by more than 12 °C than the 1961–1990 average and by more than 10 °C almost everywhere. The mean 14-day anomaly of maximum daily air temperature was only slightly lower (Fig. 6b), exceeding 9 °C for almost 60% area of Poland and being in the range of 8–9 °C in the rest of the country.

The first-time interval during the summer of 1994 with temperatures near or above 30 °C, during which an increase in mortality was noted, took place in the last week of June. For most cities, it began around June 26 and lasted for 3 or 4 days in Warszawa and Bydgoszcz and 8 days in Wroclaw and Katowice. Only in Gdansk, the first heat wave and an accompanying increase in the number of deaths began on July 11, when in other major cities the heat wave already ended. Despite the short duration of the heat wave and a moderate value of the maximum temperature and the humidex, increase in the number of deaths compared to the reference period ranged from 25% in Łódź to 80% in Lublin. The increase in the number of deaths associated with cardiovascular deficiencies was even higher, at around 60% in Poznan and Wroclaw and up to 100% in Lublin. This summer, the main heat wave occurred about 10 days after the end of the first one and lasted more than 3 weeks. On a large area, values of maximum daily air temperature were extremely high for the Polish climate. Lublin was the only city analyzed, where the highest maximum daily air temperature did not exceed 35 °C (reaching 34.2 °C). The highest temperature occurred in Szczecin and Łódź, respectively, 37.8 and 37.6 °C, breaking the previous record-high temperatures in these cities. During the hottest days, the number of deaths doubled in most cities as compared to the reference period. The intra-seasonal distribution of the

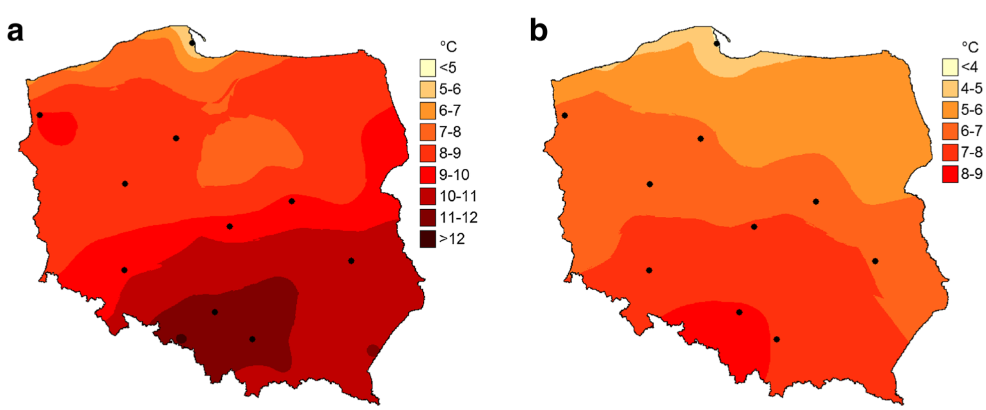

Fig. 4 The highest anomalies of maximum daily air temperature in the summer of 1992: **a** 7-day anomaly; **b** 14-day anomaly

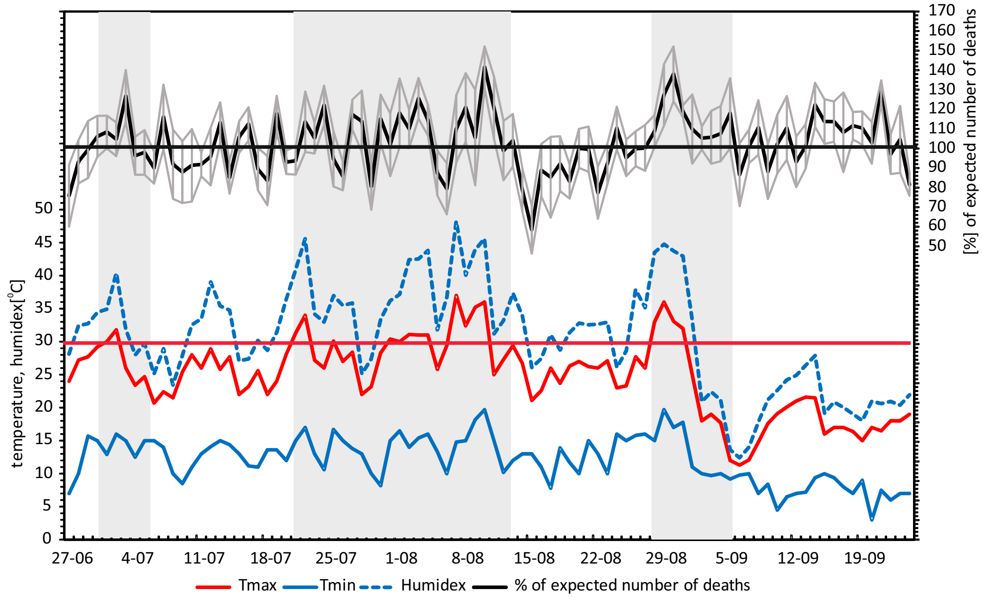

Fig. 5 The course of temperature, humidex and the number of deaths in Warszawa in the summer of 1992 (gray thin lines represent 90% confidence interval)

air temperature, the humidex, and the number of deaths in Łódź in the summer of 1994 is shown in Fig. 7. The increase in the number of deaths ranged from 63% in Krakow to 168% in Bydgoszcz. Even higher values were recorded for deaths of people with cardiovascular problems. In seven out of ten cities, the number of deaths at least doubled, ranging from 205% increase of the expected number of deaths in Katowice to 323% in Bydgoszcz. Even higher numbers were obtained for the age group "65+ years." For the combined risk groups, the risk of death more than doubled during the hottest days in all cities, reaching 330 and 431% in Łódź and Bydgoszcz.

3.2.3 The summer of 2006

The 7-day anomaly of the maximum temperature in the summer of 2006 (Fig. 8a) did not reach as extreme values as in 1994, exceeding 10 °C only locally, but relatively high values in the range of 8–10 °C occurred for most of Poland. The 14-day maximum temperature anomaly (Fig. 8b) exceeded mostly 6–7 °C, while in some places in the south-west, it reached 9 °C.

In the summer of 2006, many days were recorded with maximum temperature exceeding or close to 30 °C, on a large area. In the western and central parts of Poland, days with such high temperatures created a heat wave lasting almost 6 weeks, during which there were 2–3-day intervals with slightly lower temperatures. In contrast to the year of 1994, the level of 35 °C was exceeded only during 1 day and in two cities. The vast majority of days during this period had the maximum temperature in the range of 28–32 °C. The beginning of a heat wave in western and central parts of Poland, and the accompanying increase in number of deaths occurred as early as mid-June. Except for a single day in Wroclaw and Poznan, maximum temperature did not exceed 30 °C, but there were many days with temperatures from 27 to 29 °C. In the end of June, temperatures above 30 °C appeared frequently in all the analyzed cities except for the coastal city Gdansk. The last days of June marked a considerable 2–3-day cooling, when the maximum

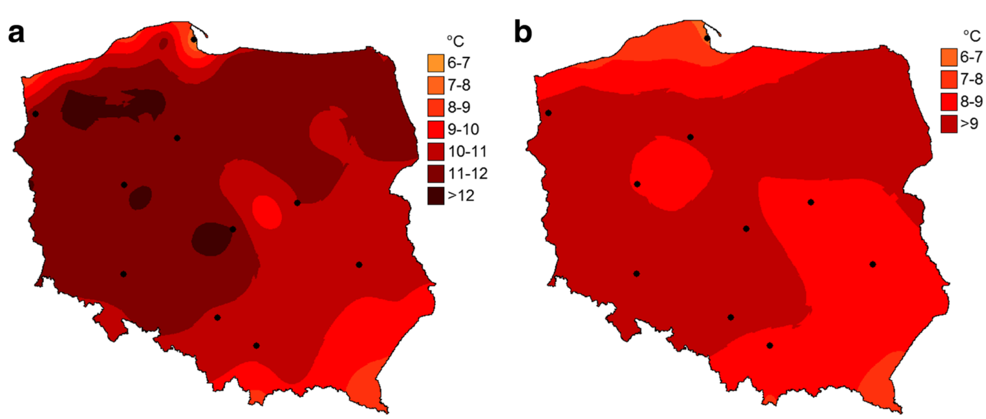

Fig. 6 The highest anomalies of maximum daily air temperature in the summer of 1994: **a** 7-day anomaly; **b** 14-day anomaly

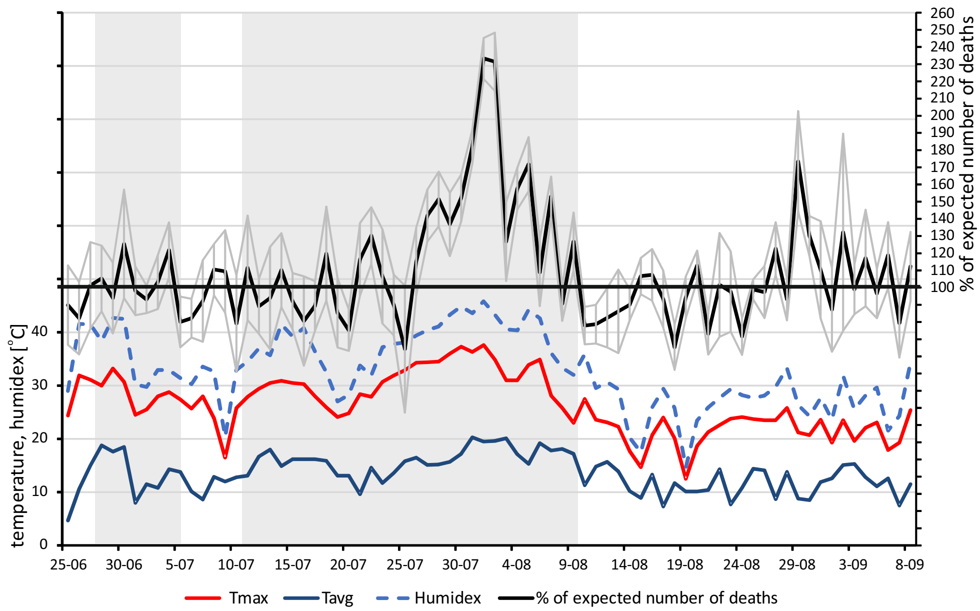

Fig. 7 The course of temperature, humidex, and the number of deaths in Łódź in the summer of 1994 (gray thin lines represent 90% confidence interval)

temperature fell below 25 °C, while in Szczecin, Gdansk, and Bydgoszcz even below 20 °C. In the beginning of July, maximum temperature increased in all analyzed cities, and on the 5th of July, it exceeded 30 °C again in seven out of ten cities. Except for a short and slight cooling around 15th of July, high temperatures lasted until the end of the month. In some cities, temperatures above 30 °C continued for more than 10 days. The highest daily increase in the number of deaths occurred for half the cities already in June when temperatures were not the highest. For the rest of the cities, the largest increase in the number of deaths was recorded during the highest temperatures, and at least a few days after the time interval with temperatures above 30 °C. The highest daily increase in the number of deaths ranged from 33% in Warszawa to 115% in Katowice (for all causes of death). An even greater increase, from 55% in Warszawa to 220% in Bydgoszcz, occurred for deaths of people with cardiovascular diseases. Similarly, a strong risk factor was the age (65+), as the highest daily increase in the number of deaths ranged from 41% in Warszawa to 134% in Bydgoszcz. The course of the air temperature, the humidex, and the number of deaths in Poznan in the summer of 2006 is presented in Fig. 9.

3.2.4 The summer of 2010

During the summer of 2010, the highest values (> 10 °C) of 7-day maximum air temperature anomalies (Fig. 10a) were recorded on a small area of north-western and central Poland. The anomaly gradually decreased towards the south-east; however, for more than 65% of the country, the anomaly reached 8–10 °C. The 14-day anomaly (Fig. 10b) also reached a value above 8 °C on a large area of northern and central Poland. Apart from the southern parts, across the whole country, the 14-day maximum temperature anomaly exceeded 7 °C.

In the summer of 2010, abnormally high temperatures occurred in most of Eastern Europe. Poland was outside of the occurrence of the highest temperature anomaly, but in

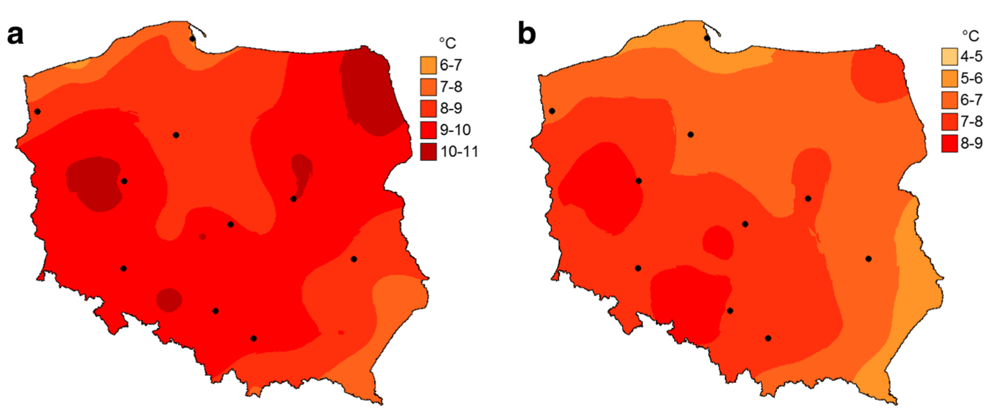

Fig. 8 The highest anomalies of maximum daily air temperature in the summer of 2006: **a** 7-day anomaly; **b** 14-day anomaly

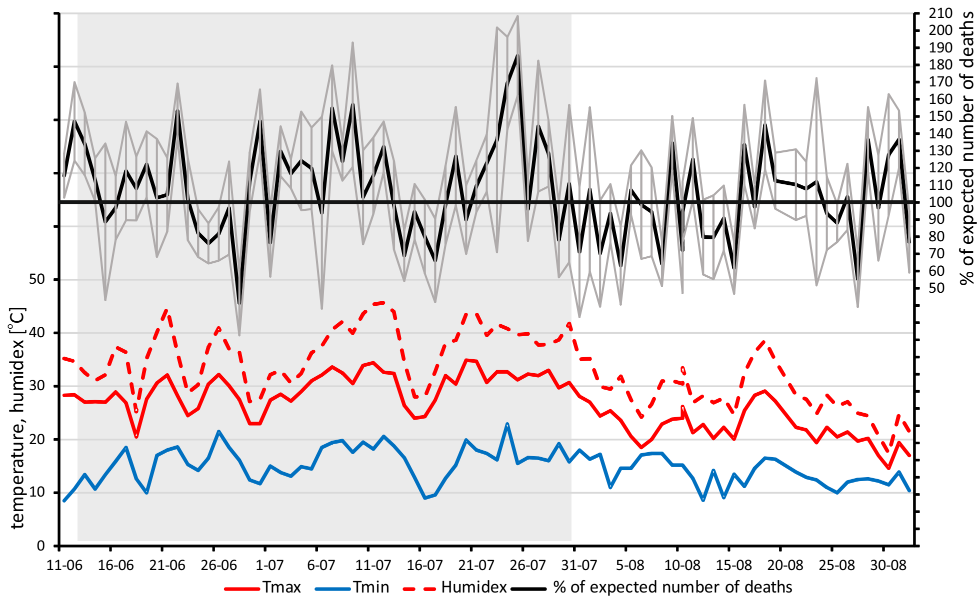

Fig. 9 The course of temperature, humidex, and the number of deaths in Poznan in the summer of 2006 (gray thin lines represent 90% confidence interval)

the eastern and northern Poland, temperatures clearly exceeded the long-term average. Also in the west of Poland, a series of days occurred, with maximum temperatures clearly exceeding 30 °C and reaching 35 °C for a few days. The first episode of high temperatures and the accompanying increase in the number of deaths occurred about 10th of June. Despite the short duration (3–5 days) of this heat wave, a marked increase in the number of deaths was recorded. The smallest increase occurred in the cities located in the north of the country (28% in Gdansk and 37% in Bydgoszcz, for all causes). In the south of Poland, days with a doubling of the number of deaths occurred in that interval. The number of deaths increased by 111% in Wroclaw and by 137% Kraków. The longest and the most intense heat wave began in early July and lasted for about 3 weeks. During many days, the maximum temperature remained at around or above 30 °C. In all the cities analyzed, a marked increase in the number of deaths was observed. During the hottest days, growth in the number of deaths in the four largest cities exceeded 50% and in other cities almost doubled. The highest increases in the number of deaths were in Lublin and Bydgoszcz (by 122 and 128%, respectively). High values were observed for mortality associated with cardiovascular deficiencies (up to 156% in Szczecin) and for the age group 65+ (157% in Lublin). In the four cities located in the eastern half of the country, one more (third) sub wave occurred, lasting approximately for 2 weeks. For many days, the maximum daily air temperature fluctuated around 30 °C but did not significantly exceed this threshold even during the hottest hours. The maximum daily increase in the number of deaths during this heat wave ranged from 26% in Warszawa to 142% in Lublin. Deficiencies are 40% in Warszawa and 105% in Lublin. In the age group 65+, daily maximum value of the increase in the risk of death was 162% in Gdansk and the lowest one again in Warszawa (24%). The course of the air temperature, humidex, and the number of deaths in Warszawa in the summer of 2010 is presented in Fig. 11.

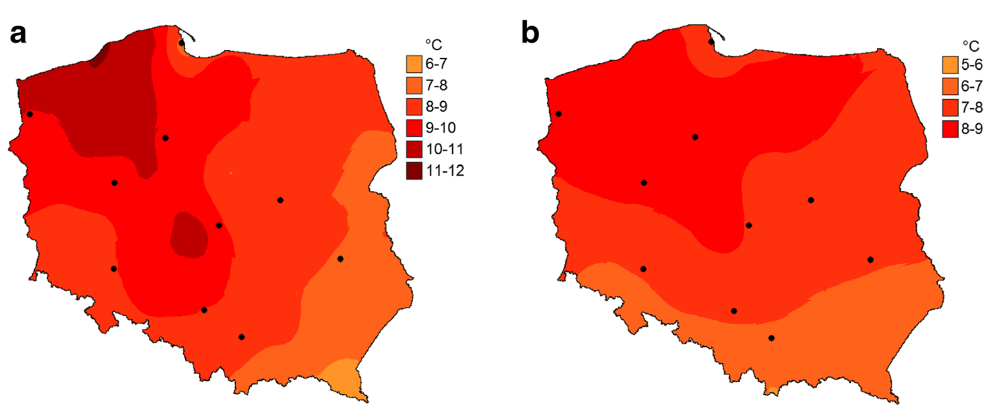

Fig. 10 The highest anomalies of maximum daily air temperature in the summer of 2010: **a** 7-day anomaly; **b** 14-day anomaly

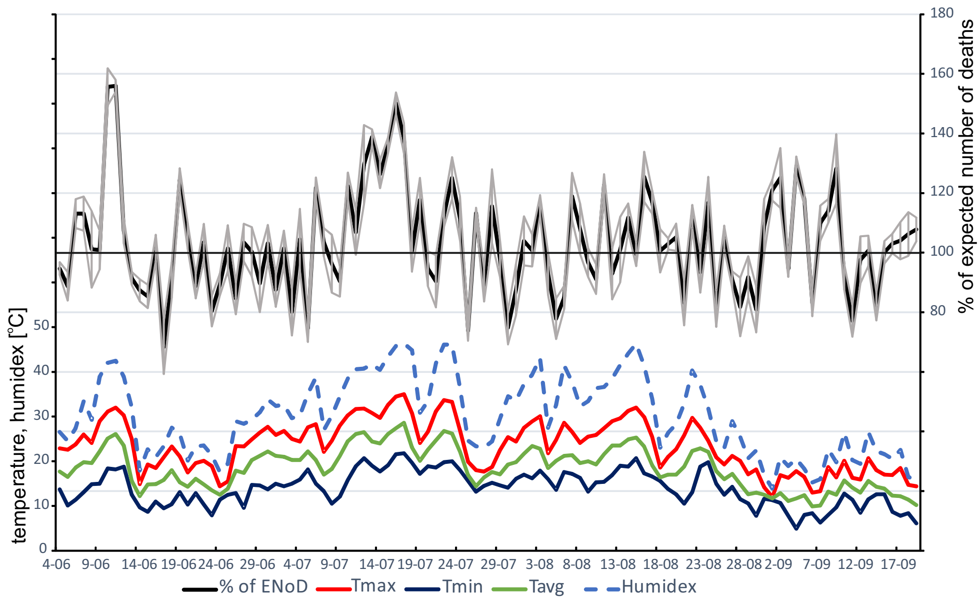

Fig. 11 The course of temperature, humidex and the number of deaths in Warszawa in the summer of 2010 (gray thin lines represent 90% confidence interval)

3.3 Cardiovascular diseases and age as risk factors

Simultaneous occurrence of cardiovascular diseases (CVD) and senior age (65+) were factors responsible for the strongest increase in mortality in comparison to the control, for all surveyed summer seasons with heat waves. This was particularly evident during the most sweltering summer of 1994. Only in one city (Katowice) values for this risk factor were lower than those calculated for all causes and age groups. However, even for Katowice, the highest calculated value can be associated with this risk factor. In the summer of 1994, the increase in the number of deaths for risk factors counted separately was generally higher than for all causes and age groups. For six cities, higher values were found for both factors and for the next three cities—for one factor.

For summers, in which the temperature did not reach such extreme values or heat waves were less permanent, results were not so evident. In 2006, the highest daily increase in the number of deaths for all cities except for Krakow appeared for the combined risk groups (CVD and 65+). For other summers with heat waves, it happened that the essential factor was either related to the age or to the cardiovascular diseases (separately).

Mortality factors during the two summer periods when heat waves differed in duration and amplitudes of air temperature are summarized in Table 2.

Figure 12 illustrates that, in general, changes of the number of additional deaths during heat waves, both in their milder stages and when temperature attains its peak, are of similar shape for specific risk groups and for all deaths. There are only differences in values. Local maxima are usually highest for the combined risk groups (CVD and 65+), but at the same time one can observe the deepest lows for this risk group. Small differences are apparent during periods of lower air temperatures, separating sequences of hot days. There are, typically, 1–3-day shifts in decrease in the number of deaths and the amount of the decline for individual risk groups.

3.4 The balance of heat waves in selected summer periods

Table 3 summarizes the estimated number of additional deaths during the analyzed four summer seasons with heat waves for the ten largest cities in Poland. Nationwide, the largest increase in the number of deaths occurred in the summer of 1994, when 1076 (90% CI 615 to 1537) additional deaths were recorded during the analyzed period. The highest number of deaths, 397 (90% CI 264–500), occurred in Warszawa, although in relative terms, compared to the population, higher values were recorded during the 1994 heat wave in Poznan and Łódź. These cities are located in the vicinity of the highest maximum temperature anomalies observed. Except for Katowice and Gdansk, differences between the increase in the number of deaths during heat waves and during the longer period including days between the beginning of the first heat wave and the 30th day after the end of the heat wave are small. In other analyzed years, the number of additional deaths in days during heat waves exceeded 700 people and was the highest in cities located in the zone of highest anomalies of air temperature. The sum calculated for individual cities suggest that the most vulnerable are cities with more than 500,000 inhabitants, in which in particularly hot years, the number of additional deaths increased by more than 100 cases. The exception is Wroclaw, the 4th on the population list (Table 1), despite the fact that twice it was located in the zone of highest temperature anomalies, the increase in the number of deaths has not exceeded 100 people, for any of the hot summers.

Table 2 Age (65+) and cardiovascular deficiencies (CVD) as risk factors during heat waves (numbers in the brackets represent 90% confidence interval)

City	Time period	1994				2006			
		AC	CVD	65+	CVD 65+	AC	CVD	65+	CVD 65+
Bydgoszcz	During heat waves	131 (122 to 140)	131 (120 to 142)	135 (124 to 144)	142 (131 to 153)	114 (111 to 117)	112 (105 to 119)	116 (112 to 120)	114 (105 to 123)
	Heat waves + 30 days	109 (105 to 113)	107 (101 to 113)	113 (108 to 111)	114 (108 to 122)	107 (104 to 110)	111 (105 to 112)	109 (105 to 113)	112 (105 to 119)
	Highest daily value	278	330	359	432	186	210	234	341
Gdańsk	During heat waves	109 (106 to 112)	116 (112 to 120)	118 (115 to 121)	126 (123 to 129)	100 (95 to 105)	115 (110 to 120)	101 (95 to 107)	114 (107 to 121)
	Heat waves + 30 days	95 (92 to 98)	102 (99 to 105)	102 (99 to 105)	110 (106 to 114)	98 (93 to 103)	116 (114 to 118)	99 (96 to 102)	113 (110 to 116)
	Highest daily value	175	216	190	249	147	184	163	211
Katowice	During heat waves	121 (117 to 125)	112 (105 to 119)	120 (114 to 126)	104 (97 to 111)	106 (99 to 113)	100 (94 to 106)	108 (102 to 114)	108 (101 to 115)
	Heat waves + 30 days	100 (94 to 106)	94 (90 to 98	100 (94 to 106)	91 (87 to 95)	103 (99 to 107)	100 (95 to 105)	107 (103 to 111)	103 (97 to 109)
	Highest daily value	204	215	219	261	173	181	203	226
Kraków	During heat waves	112 (107 to 117)	113 (107 to 119)	110 (106 to 114)	113 (107 to 119)	111 (108 to 114)	113 (110 to 116)	109 (105 to 113)	114 (109 to 119)
	Heat waves + 30 days	108 (105 to 111)	109 (105 to 113)	108 (105 to 111)	109 (106 to 112)	104 (102 to 106)	104 (101 to 107)	103 (101 to 105)	104 (101 to 107)
	Highest daily value	163	199	163	220	152	236	167	234
Lublin	During heat waves	120 (116 to 124)	142 (135 to 149)	122 (118 to 126)	147 (139 to 155)	107 (104 to 111)	122 (115 to 129)	105 (102 to 108)	125 (118 to 132)
	Heat waves + 30 days	104 (102 to 106)	104 (99 to 109)	101 (97 to 105)	111 (105 to 117)	106 (103 to 109)	110 (107 to 113)	103 (100 to 106)	113 (110 to 116)
	Highest daily value	223	291	242	315	197	232	221	267
Łódź	During heat waves	122 (115 to 129)	129 (121 to 137)	129 (121 to 137)	135 (136 to 144)	114 (112 to 116)	118 (116 to 120)	113 (111 to 115)	120 (116 to 124)
	Heat waves + 30 days	110 (107 to 113)	114 (109 to 117)	113 (109 to 117)	120 (115 to 125)	110 (108 to 112)	111 (108 to 114)	107 (105 to 109)	110 (107 to 113)
	Highest daily value	233	274	277	330	154	210	162	220
Poznań	During heat waves	137 (126 to 148)	139 (127 to 151)	147 (134 to 150)	147 (134 to 150)	111 (109 to 113)	105 (101 to 109)	116 (112 to 120)	105 (102 to 108)
	Heat waves + 30 days	116 (110 to 122)	120 (112 to 128)	120 (113 to 127)	127 (119 to 135)	107 (105 to 109)	103 (98 to 108)	113 (110 to 116)	104 (100 to 108)
	Highest daily value	220	249	265	282	185	221	209	258
Szczecin	During heat waves	112 (107 to 117)	108 (101 to 115)	123 (117 to 129)	116 (109 to 123)	109 (105 to 113)	108 (102 to 114)	109 (103 to 115)	105 (98 to 112)
	Heat waves + 30 days	105 (102 to 108)	100 (96 to 104)	110 (106 to 114)	104 (99 to 109)	101 (99 to 103)	107 (103 to 111)	103 (99 to 107)	106 (102 to 110)
	Highest daily value	218	221	213	260	172	295	198	264
Warszawa	During heat waves	119 (116 to 122)	121 (114 to 128)	124 (122 to 126)	126 (119 to 133)	111 (109 to 113)	110 (106 to 114)	112 (110 to 114)	111 (106 to 116)
	Heat waves + 30 days	110 (107 to 113)	110 (106 to 114)	113 (111 to 115)	113 (105 to 121)	101 (99 to 103)	92 (88 to 96)	101 (99 to 103)	94 (91 to 97)
	Highest daily value	177	188	188	205	133	158	141	159
Wrocław	During heat waves	114 (108 to 120)	128 (118 to 138)	127 (115 to 139)	141 (126 to 156)	110 (107 to 113)	112 (108 to 116)	111 (107 to 115)	113 (109 to 117)
	Heat waves + 30 days	108 (103 to 113)	115 (109 to 121)	112 (104 to 120)	120 (111 to 129)	107 (104 to 110)	108 (104 to 112)	107 (104 to 110)	109 (105 to 113)
	Highest daily value	202	242	227	278	181	189	193	229

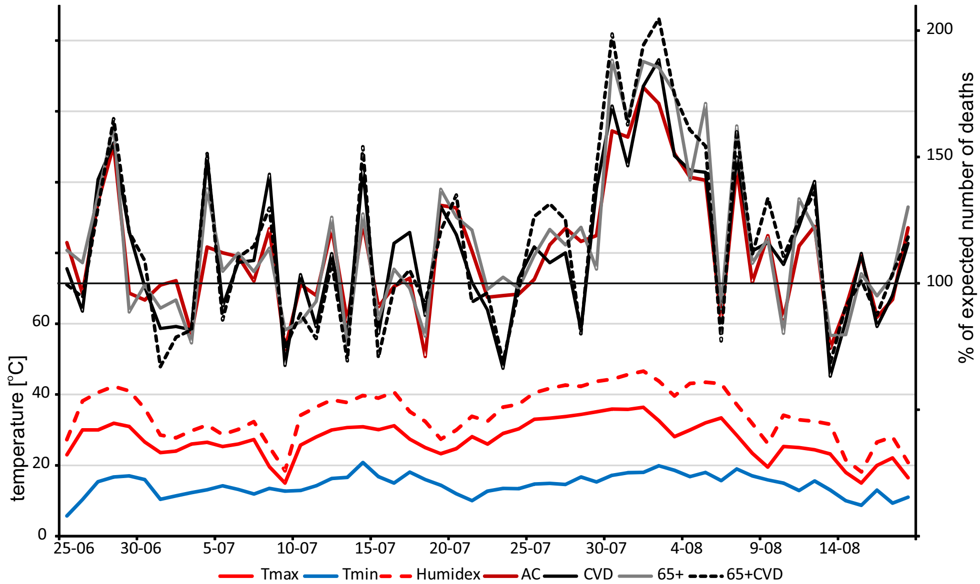

Fig. 12 The course of temperature, humidex, and the number of deaths for all cases (AC), cardiovascular diseases (CVD), age above 65 (65+), and age above 65 with cardiovascular diseases (65+ CVD) in Warszawa in the summer of 1994

4 Discussion

Many studies on the mortality increase associated with heat waves is focused on threshold values in air temperature or indicators based on a combination of temperature and humidity at which an increase in the number of deaths can be observed. Quantitative values reported in various references differ from each other, often very substantially, depending on geographical location of an analyzed city or country. For instance, Ishigami et al. (2008) examined cities with mean summer temperatures from 20.4 °C in London to 26.3 °C in Milan, while Laaidi et al. (2006) studied different

Table 3 Estimated number of additional deaths (in absolute terms) during four extremely hot summer seasons (numbers in the brackets represent 90% confidence interval)

City	Time period	1992	1994	2006	2010	Sum
Bydgoszcz	During heat waves	6 (− 17 to 29)	90 (56 to 124)	54 (27 to 81)	32 (24 to 40)	183 (90 to 274)
	Heat waves + 30 days	33 (18 to 48)	59 (28 to 90)	49 (32 to 66)	− 29 (−59 to 1)	113 (19 to 205)
Gdańsk	During heat waves	14 (− 7 to 35)	26 (17 to 35)	− 1 (− 13 to 11)	74 (51 to 97)	113 (48 to 165)
	Heat waves + 30 days	54 (23 to 85)	− 33 (− 50 to − 16)	− 14 (− 41 to 13)	46 (9 to 84)	54 (− 59 to 166)
Katowice	During heat waves	84 (59 to 109)	66 (27 to 105)	18 (4 to 32)	73 (59 to 87)	242 (149 to 335)
	Heat waves + 30 days	53 (15 to 91)	− 4 (− 29 to 21)	20 (− 6 to 46)	69 (50 to 88)	137 (30 to 244)
Kraków	During heat waves	108 (84 to 132)	98 (57 to 139	81 (57 to 105	152 (142 to 162)	439 (340 to 538)
	Heat waves + 30 days	133 (122 to 154)	109 (61 to 157)	57 (32 to 82)	120 (90 to 150)	419 (305 to 533)
Lublin	During heat waves	30 (18 to 42)	35 (26 to 44)	18 (8 to 28)	48 (41 to 55)	131 (93 to 169)
	Heat waves + 30 days	− 9 (− 26 to 11)	20 (6 to 34)	30 (19 to 41)	31 (20 to 42)	71 (19 to 123)
Łódź	During heat waves	164 (109 to 219)	226 (148 to 304)	180 (154 to 206)	107 (90 to 134)	676 (501 to 851)
	Heat waves + 30 days	150 (79 to 221)	211 (129 to 293)	210 (164 to 256)	68 (50 to 86)	639 (422 to 856)
Poznań	During heat waves	107 (63 to 151)	201 (171 to 231)	84 (60 to 108)	83 (65 to 101)	475 (359 to 591)
	Heat waves + 30 days	67 (− 10 to 144)	199 (142 to 256)	82 (59 to 105)	70 (40 to 100)	418 (231 to 605)
Szczecin	During heat waves	37 (21 to 53)	47 (31 to 63)	39 (23 to 55)	29 (14 to 44)	151 (89 to 213)
	Heat waves + 30 days	− 22 (− 52 to 8)	43 (17 to 69)	8 (− 12 to 28)	5 (− 22 to 32)	33 (− 69 to 121)
Warszawa	During heat waves	165 (107 to 214)	332 (277 to 388)	136 (114 to 158)	237 (203 to 271)	870 (701 to 1039)
	Heat waves + 30 days	172 (39 to 305)	397 (264 to 500)	26 (− 13 to 75)	155 (73 to 237)	751 (363 to 1117)
Wrocław	During heat waves	73 (33 to 113)	66 (38 to 94)	79 (52 to 106)	85 (74 to 96)	304 (197 to 411)
	Heat waves + 30 days	6 (− 33 to 45)	75 (27 to 133)	93 (53 to 133)	13 (− 27 to 53)	187 (20 to 354)
Sum	During heat waves	790 (470 to 1110)	1186 (848 to 1524)	689 (502 to 876)	919 (751 to 1087)	3584 (2571 to 4597)
	Heat waves + 30 days	637 (220 to 1054)	1076 (615 to 1537)	561 (194 to 928	548 (223 to 873)	2822 (1252 to 4392)

regions of France with mean summer temperatures from 17.8 to 23.6 °C. Ma et al. (2015) researched the issue for different regions of China, with temperature values varying significantly, from 19.5 °C in the north of the country up to 27.4 °C in the south. For England and Wales, Hajat et al. (2007) studied even lower values (17–18 °C). The differences are also seen in the work of analyzing various country-specific thresholds of the maximum daily air temperature, like about 24 °C for Estonia (Oudin Åström et al. 2016), 26 °C in the Czech Republic (Kysely and Huth 2004) and 31 °C in Italy (Zauli Sajani et al. 2002). In Poland, the number of additional deaths in largest cities increased noticeably, depending on the region, when daily maximum air temperature exceeded 26–28 °C. In areas with warmer climates, threshold temperatures at which an increased risk of death can be noticed are also generally higher than in regions with more moderate climate. One explanation may be the lifestyle (e.g., a siesta) and adaptation of housing to the warmer climate. Physiological acclimatization can also play an important role (Keatinge et al. 2000).

During summers investigated in this work, significant difference in change of mortality can be observed, between the cities, despite the relatively small differences in climatic conditions. Similarly to the results of Oudin Åström et al. (2016), the additional mortality caused by heat in the area on the coast is lower than inland. This is also in accordance with previous studies, such as Urban et al. (2017) and Medina-Ramon and Schwartz (2007). The largest number of deaths associated to the occurrence of high air temperature was recorded in cities with the highest population density (and, simultaneously, with the largest population). The urban heat island is probably most intense in these cities, which according to Tan et al. (2010) affects the intensity of heat waves and thus increases the exposure to unfavorable thermal conditions. Among the Polish cities of similar size and population density, such as Wroclaw and Poznan, there were large differences in the number of deaths during heat waves in 1994, in similar weather conditions. Hajat and Kosatsky (2010) and Hondula et al. (2015) explain such a difference in mortality rates by the age of population and economic conditions. Urban et al. (2017) draws attention to the differences in the physical environment, while Son et al. (2016) to the differences in urban vegetation.

To the knowledge of the present authors, this work is the first one that seeks to estimate the additional mortality during particularly hot summer periods in Poland. The results indicate that by far the most deadly heat waves occurred, almost throughout the entire Polish territory, in the summer of 1994. In the 10 largest cities, the additional mortality associated with extreme heat almost reached 1100 people, including almost 400 in Warszawa itself (Table 3). In other studies related to individual cities, serious health consequences of the heat wave in Athens in 1988 were recorded, when the number of additional deaths was estimated by Katsouyanni et al. (1988) at the level of about 2000 people. A heat wave in Chicago in 1995, lasting for only a few days, was found responsible for over 700 deaths (Semenza et al. 1996). There were 201 additional deaths spotted in 2012 in the capital of Moldova (Corobov et al. 2013), Chisinau, being of similar sized as the studied cities in Poland.

Nationally, the number of approximately 1100 additional deaths estimated in Poland in 1994 is significantly lower than those recorded in France, Italy, and England in 2003, being 14,700 (Fouillet et al. 2006), 3134 (Conti et al. 2005), and 2234 (Green et al. 2016), respectively. In the neighboring Czech Republic, the largest number of deaths probably also occurred in 1994 and could reach almost 2000 (Urban et al. 2017) and around 1500 in 2015. In Slovakia, the highest mortality rate (540) was recorded in 2015 (Výberči et al. 2017). The present study, however, covers only the ten largest cities inhabited by a total of ca. 16% of the Polish population. Probably, the mortality increase due to heat waves in 1994 was significantly higher although it is not possible to assess this quantitatively, without conducting more research (whereas collection of mortality data would be extremely difficult). The increase in mortality during heat waves is the highest in large and densely populated urban centers. However, there is also a problem of mortality increase in smaller cities and rural areas, where, jointly more than 83% of the Polish population reside. Results of Conti et al. (2005), for the heat wave of 2003 in Italy, show an increase in the number of deaths by 13.8% in cities with less than 100,000 inhabitants. The increase in health risk associated with heat waves in rural areas was also reported by Gabriel and Endlicher (2011) and Hajat et al. (2007). According to Sheridan and Dolney (2003), especially during extreme thermal conditions, an increase in the number of deaths in rural areas and the suburbs may be similar or even higher than in cities.

While analyzing the course of temperature and the number of additional deaths during hot summers in Poland, if can be noticed that the first even relatively mild and brief episode of temperature increase is often associated with the occurrence of a high daily increase of mortality. During the first hot days, mortality of the elderly and those suffering cardiovascular diseases is much higher (by 200% and more) compared to the days of the air temperature close to normal. This agrees with results of previous studies (Hajat et al. 2002; Kyselý 2004; Kyselý and Kim 2009). Similarly, high values of daily numbers of deaths occur later, at much higher temperature values or longer duration of heat waves. Allen and Sheridan (2015) explain reduction in the risk during the summer season by acclimatization. The heat waves studied in this work are characterized by different intensity and duration.

According to D'Ippoliti et al. (2010), heat wave duration plays a greater role than the intensity but the combination of high values of these two factors caused the greatest increase in mortality for most cities in Italy. Long heat waves resulted in the daily number of deaths being 1.5 to 3 times higher than during short heat waves. Similarly, in the case of the analyzed periods of summer in Poland, the largest number of deaths occurred in 1994, when each of the two factors attained high values, i.e., a high maximum daily air temperature during the hottest days (in excess of 35 °C) and the length of the heat wave exceeding 10 days. During the heat wave of 2006, in a part of Poland, a long heat wave was recorded that lasted continuously for about 3 weeks, with temperatures approaching or exceeding 30 °C but not reaching 35 °C. The increase in the number of deaths during this wave was lower than in 1994, which indicates that, for conditions of temperate climate of Poland, the intensity of a heat wave may be more important than its length. Both of these summer seasons have been considered as particularly hot also in the German region of Brandenburg and Berlin, neighboring with Poland. While the temperature values were similar to western Poland, also there the heat wave of 1994 resulted in higher mortality. Also experience from the heat wave in 2003 in France show that the intensity of the heat wave is crucial. From 1 to 20 August 2003, temperatures exceeded the long-term average of the maximum temperature by 11–12 °C and over a large area for nine consecutive days, the Tmax did not fall below 35 °C (Fouillet et al. 2006). A particularly dangerous combination of hot days and tropical nights ($T_{max} > 35$ °C and $T_{min} > 20$ °C) occurred in a few large cities for 9 to 15 days (Vandentorren et al., 2004). A significant increase in the risk of death in elderly people associated with the presence of high value of both the maximum and minimum daily air temperature also was observed by Heudorf and Schade (2014) in Frankfurt am Mein, Germany. Similar conditions, lasting 3–4 days, occurred in 1994 in Poland, which may explain the higher number of victims of heat compared to other years analyzed.

Estimating the number of additional deaths caused by extreme thermal conditions during hot summers is difficult, because in many studies, it is presented as a short-lived effect followed by a compensation in the form of a reduced number of deaths occurring within a few weeks after the end of a heat wave (Keatinge et al. 2000; Huynen et al. 2001; Kyselý 2004). This leads to the interpretation that most of the victims of heat are people whose health could have allowed them to survive the next few days or weeks. Baccini et al. (2013) estimate that 30-day mortality displacement reduces the number of deaths by 75%. In the summers analyzed, the effect of shifting deaths in time did not occur, or was very low in the most intense heat waves and the most vulnerable cities. In such cases, the effect of reducing the number of deaths within 30 days did not occur, while in Warszawa in 1994, there was even a 16% increase. Similarly, a lack of a shift of mortality was also confirmed by Le Tertre et al. (2006) for the heat wave of 2003 in France.

Climate-model based projections indicate a further increase in the number of hot and very hot days in Poland in the future (Błazejczyk et al. 2013; Kuchcik 2013), and the number of days with conditions threatening life and health is likely to increase significantly.

The methodology used in this work should limit the impact of demographic and socioeconomic changes as well as technical progress and health care on the obtained results. When comparing particular hot summer periods, these factors should be taken into account. Since the beginning of the 1990s, there has been a significant progress in health care, especially related to cardiac and cardiovascular diseases. According to the Polish Statistical Office (GUS 2015) data, in 1990 these diseases were responsible for 52% of all deaths and in 2013 for 46%. During the same period, the average life expectancy increased from 66.2 to 72.1 years in men and from 75.2 to 80.1 in women. In Poland, similar studies have not been conducted so far, but in countries with developed economies, regardless of geographic location, a decline in the heat-related mortality has been found in last decades (Gasparrini et al. 2015). In countries affected directly by the 2003 heat wave, this may be the result of improvement of preventive measures and warning systems (Fouillet et al. 2008).

In Poland, among both decision-makers and the broad public, this problem is underestimated and downplayed. Warning systems dedicated to such events exist for a short time only and deliver rather general messages. They are part of a broader crisis management system that was created in the country in 2008 and has so far mainly focused on phenomena related to gale wind and heavy precipitation. Perhaps this is related to the fact that Poland has not yet experienced a large-scale heat wave, similar to that in Western Europe in 2003. The lack of such a system in the Czech Republic was also reported by Urban et al. (2017).

5 Conclusions

An evident increase of mortality, especially during very hot summer periods, can also be observed in countries like Poland, where maximum air temperatures are not as extreme as in southern parts of Europe. In the analyzed interval of 23 years, for at least some cities, mortality increase during heat waves took place during four summers, which proves that the problem does not restrict only to continental-scale, record-beating heat waves.

The increase in the number of fatalities during particularly intense and long-lasting heat waves is not characterized only by a temporal shift of mortality caused by the harvesting effect. Within the most affected urban areas, it is compensated only slightly (up to 25%) or even not at all, by a later decrease of the number of fatalities. This indicates that the majority of additional victims could survive for at least 30 days after the heat wave.

There are large differences of the mortality increase during hot summer periods between analyzed municipalities. Apart from demographic factors, these differences can be explained by the population size that influences the urban heat island effect and by the population density, which implies, inter alia, the size of green areas (parks, lawns, gardens, urban forests).

Increase of mortality risk during heat waves in Poland is particularly high for people older than 65 years and suffering from cardiovascular diseases. During the hottest days, the number of fatalities in some cities was more than three times higher than the mean mortality in the reference period.

For examined cities, the highest rises of mortality risk took place during heat waves that were both intense and long-lasting, i.e., with maximum air temperature exceeding 35 °C and heat wave duration longer than 4 weeks (for all sub-waves together). For long-lasting heat waves in urban conditions in Poland, their intensity seems to be of higher importance than their duration.

Funding information The reported research has been carried out within the CHASE-PL (Climate change impact assessment for selected sectors in Poland) project of the Polish–Norwegian Research Programme, Project Contract No. Pol-Nor/200799/90/2014. Observation data used in this work were provided by the Institute of Meteorology and Water Management—State Research Institute (IMGW-PIB).

References

Allen MJ, Sheridan SC (2015) Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. Int J Biometeorol 62:57–67. https://doi.org/10.1007/s00484-015-1117-4

Baccini M, Kosatsky T, Biggeri A (2013) Impact of summer heat on urban population mortality in Europe during the 1990s: an evaluation of years of life lost adjusted for harvesting. PloSOne 8:e69638

Bisanti L, Cadum E, Costa G, Michelozzi P, Perucci C, Russo A (2004) 2003 heat waves and mortality in Italy. Epidemiology 15(4):97

Błażejczyk K, Idzikowska D, Błażejczyk A (2013) Forecast changes for heat and cold stress in Warszawa in the 21st century, and their possible influence on mortality risk. Papers on Global Change IGBP 20:47–62

Conti S, Meli P, Minelli G, Solimini R, Toccaceli V, Vichi M, Beltrano C, Perini L (2005) Epidemiologic study of mortality during the Summer 2003 heat wave in Italy. Environ Res 98:390–399

Corobov R, Sheridan S, Ebi K, Opopol N (2013) Heat-related mortality in Moldova: the summer of 2007. Int J Climatol 33:2551–2560

Della-Marta PM, Haylock MR, Luterbacher J, Wanner H (2007) Doubled length of western European summer heat waves since 1880. J Geophys Res 112:D15103

D'Ippoliti D, Michelozzi P, Marino C, de'Donato F, Menne B, Katsouyanni K, Kirchmayer U, Analitis A, Medina-Ramon M, Paldy A (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environ Health 9:37

Fioravanti G, Piervitali E, Desiato F (2016) Recent changes of temperature extremes over Italy: an index-based analysis. Theor Appl Climatol 123:473–486. https://doi.org/10.1007/s00704-014-1362-1

Fouillet A, Rey G, Laurent F, Pavillon G, Bellec S, Guihenneuc-Jouyaux C, Clavel J, Jougla E, Hémon D (2006) Excess mortality related to the August 2003 heat wave in France. Int Arch Occup Environ Health 80:16–24

Fouillet A, Rey G, Wagner V, Laaidi K, Empereur-Bissonnet P, Le Tertre A et al (2008) Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int J Epidemiol 37:309–317

Gabriel K, Endlicher W (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ Pollut 159:2044–2050

Gasparrini A, Guo Y, Hashizume M, Kinney PL, Petkova EP, Lavigne E (2015) Temporal variation in heat-mortality associations: a multicountry study. Environ Health Perspect 123:1200–1207

Graczyk D, Kundzewicz ZW (2014) Changes in thermal extremes in Poland. Acta Geophysica 62(6):1435–1449

Graczyk D, Pińskwar I, Kundzewicz ZW, Hov Ø, Førland EJ, Szwed M, Choryński A (2017) The heat goes on—changes in indices of hot extremes in Poland. Theor Appl Climatol 129:459

Green HK, Andrews N, Armstrong B, Bickler G, Pebody R (2016) Mortality during the 2013 heatwave in England—how did it compare to previous heatwaves? A retrospective observational study. Environ Res 147:343–349. https://doi.org/10.1016/j.envres.2016.02.028

GUS (2014) Population projection 2014—2050, series — Statistical Analyses and Studies, Warszawa

GUS (2015) Podstawowe informacje o rozwoju demograficznym Polski do 2014 roku, Notatka informacyjna Warszawa, 27.01.201

Hajat S, Kovats RS, Atkinson RW, Haines A (2002) Impact of hot temperatures on death in London: a time series approach. J Epidemiol Community Health 56:367–372

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? Occup Environ Med 64:93–100

Hajat S, Kosatsky T (2010) Heat-related mortality: a review and exploration of heterogeneity. J Epidemiol Community Health 64(9):753–760

Heudorf U, Schade M (2014) Heat waves and mortality in Frankfurt am Main, Germany, 2003–2013: what effect do heat-health action plans and the heat warning system have? Z Gerontol Geriatr 47:475–482

Hondula DM, Davis RE, Saha MV, Wegner CR, Veazey ML (2015) Geographic dimensions of heat-related mortality in seven U.S. cities. Environ Res 138:439–452

Huynen MM, Martens P, Schram D, Weijenberg MP, Kunst AE (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. Environ Health Perspect 109:463–470

Ishigami A, Hajat S, Kovats RS, Bisanti L, Rognoni M, Russo A, Paldy A (2008) An ecological time-series study of heat-related mortality in three European cities. Environ Health 7:5. https://doi.org/10.1186/1476-069X-

Katsouyanni K, Trichopoulos D, Zavitsanos X, Touloumi G (1988) The 1987 Athens heat wave. Lancet 2:573

Keatinge WR, Donaldson GC, Cordioloi E, Martinelli M, Kunst AE, Mackenbach JP, Nayha S, Vuori I (2000) Heat related mortality in warm and cold regions of Europe: observational study. Br Med J 321:670–673

Klein Tank AM, Konnen GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe 1946-99. J Clim 16:3665–3680

Kuchcik M (2013) The attempt to validate the applicability of two climate models for the evaluation of heat wave related mortality in Warszawa in the 21st century. Geogr Pol 86(4):295–311

Kuchcik M, Błażejczyk K (2001) Wpływ warunków pogodowych na zachorowalność i umieralność mieszkańców Warszawy, [In:] B.

Krawczyk, G. Węcławowicz (Ed.), Badania środowiska fizycznogeograficznego w aglomeracji warszawskiej, Prace Geograficzne, IGiPZ PAN, 180:71–87

Kuchcik M, Błażejczyk K (2005) Regional differentiation of heat waves in Poland and their impact on mortality. DWD. Ann Meteorol 41(1): 415–418

Kuchcik M, 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. Geogr Pol 82(1):69–78

Kyselý J (2004) Mortality and displaced mortality during heat waves in the Czech Republic. Int J Biometeorol 49:91–97

Kysely J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and 'traditional' approaches. Clim Res 25:265–274

Kyselý J, Kim J (2009) Mortality during heat waves in South Korea, 1991 to 2005: how exceptional was the 1994 heat wave? Clim Res 38: 105–116

Laaidi M, Laaidi K, Besancenot J-P (2006) Temperature-related mortality in France, a comparison between regions with different climates from the perspective of global warming. Int J Biometeorol 51: 145–153

Le Tertre A, Lefranc A, Eilstein D, Declercq C, Medina S, Blanchard M, Chardon B, Fabre P, Filleul L, Jusot J-F, Pascal L, Prouvost H, Cassadou S, Ledrans M (2006) Impact of the 2003 heatwave on all-cause mortality in 9 French cities. Epidemiology 17:75–79

Ma W, Wang L, Lin H, Liu T, Zhang Y, Rutheford S, Luo Y, Zeng W, Zhang Y, Wang X (2015) The temperature-mortality relationship in China: an analysis from 66 Chinese communities. Environ Res 137:72–77

Masterton JM, Richardson FA (1979) Humidex: a method of quantifying human discomfort due to excessive heat and humidity. CLI 1–79. Environment Canada, Atmospheric Environment Service, Downsview

Medina-Ramon M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 United States cities. Occup Environ Med 64:827–833. https://doi.org/10.1136/oem.2007.033175

Munich Re (2011) Natural Catastrophes 2010 Analyses, Assessments, Positions. Munich Re, Munich, Germany

Oudin Åström D, Åström C, Rekker K, Indermitte E, Orru H (2016) High summer temperatures and mortality in Estonia. PLoS One 11(5): e0155045. https://doi.org/10.1371/journal.pone.0155045

Robine JM, Cheung SL, Le Roy S, Van Oyen H, Herrmann FR (2007) Report on excess mortality in Europe during summer. 2003 G. A. EU Community Action Programme for Public Health, p. 13

Robine JM, Cheung SL, Le Roy S, Van Oyen H, Griffiths C, Michel JP, Herrmann FR (2008) Death toll exceeded 70,000 in Europe during the summer of 2003. C R Biol 331:171–178

Semenza JC, Rubin CH, Falter KH, Selanikio JD, Flanders WD, Howe HL, Wilhelm JL (1996) Heat-related deaths during the July 1995 heat wave in Chicago. N Engl J Med 335:84–90

Sheridan SC, Dolney TJ (2003) Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, US. Clim Res 24:255–266

Son J, Lane K, Lee J, Bell ML (2016) Urban vegetation and heat-related mortality in Seoul, Korea. Environ Res 151:728–733

Tan J, Zeng Y, Tang X, Guo C, Li L, Song G, Zhen X, Yuan D, Kalkstein AJ, Li F, Chen H (2010) The urban heat island and its impact on heat waves and human health in Shanghai. Int J Biometeorol 54:75–84

Urban A, Hanzlíková H, Kyselý J, Plavcová E (2017) Impacts of the 2015 heat waves on mortality in the Czech Republic—a comparison with previous heat waves. Int J Environ Res Public Health 14:1562

Vandentorren S, Suzan F, Medina S, Pascal M, Maulpoix A, Cohen JC, Ledrans M (2004) Mortality in 13 French cities during the August 2003 heat wave. Am J Public Health 94:1518–1520. https://doi.org/10.2105/AJPH.94.9.1518

Výberči D, Labudová L, Eštóková M, Faško P, Trizna M (2017) Human mortality impacts of the 2015 summer heat spells in Slovakia. Theor Appl Climatol 2017:1–12. https://doi.org/10.1007/s00704-017-2224-4

Zauli Sajani S, Garaffoni G, Goldoni CA, Ranzi A, Tibaldi S, Lauriola P (2002) Mortality and bioclimatic discomfort in Emilia-Romagna, Italy. J Epidemiol Community Health 56:536–537

Wibig J (2012) Has the frequency or intensity of hot weather events changed in Poland since 1950? Adv Sci Res 8:87–91