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Heat-related mortality in the Czech Republic examined through synoptic and 'traditional' approaches

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ABSTRACT: We compare 2 different approaches applied in the evaluation of heat-related mortality: a 'traditional' one, based on the analysis of relationships between mortality and individual meteorological variables and/or indices (such as heat index), and a synoptic one, which links mortality to objectively determined air masses, taking into account the entire weather situation rather than single elements. Various methods of cluster analysis and of final forming of air masses were tested in the air-mass classification procedure; all classifications comprise an 'offensive' air mass, which is associated with a pronounced rise in mortality of 20 to 30 deaths d^{-1} (7 to 10% relative increase). It is characterized by elevated temperatures, low cloud cover and a relatively strong flow with a southern component. Regression analysis reveals a slightly stronger correlation of mortality with heat index than temperature, enhanced response in females over males, and the strongest relationship for unlagged variables. Positive correlations hold for lags of 0 to 3 d only, while at lags of 4 to 25 d, the link is negative, which demonstrates the mortality displacement effect and its time extent. Significantly increased mortality is observed at daily maximum (average, minimum) temperatures reaching or exceeding 26°C (20°C, 14°C) and their anomalies from mean seasonal courses of 2°C or larger. The results demonstrate that the air-mass-based approach can be applied to central European conditions and is a suitable alternative to the more commonly used methods in assessing impacts of heat stress on mortality in this area.

KEY WORDS: Mortality · Heat stress · Air masses · Cluster analysis · Czech Republic

1. INTRODUCTION

Heat-related mortality, evaluated mostly in terms of numbers of excess deaths (deviations of observed daily death counts from a baseline) during hot summer periods, has been reported in many parts of the world. They include North America (e.g. Marmor 1975, Curriero et al. 2002, Davis et al. 2003), Europe (Keatinge et al. 2000), Australia (Guest et al. 1999), Japan (Bai et al. 1995, Nakai et al. 1999) and many other regions encompassing tropical (Kumar 1998), subtropical (Pan & Li 1995, Auliciems et al. 1997), mid-latitude (most studies) as well as high-latitude areas (Keatinge at al. 2000, Donaldson et al. 2003). In Europe, these studies mostly focused on the UK (Rooney et al. 1998, Hajat et al. 2002), western European countries (Kunst et al. 1993, Sartor et al. 1995, Huynen et al. 2001, Laschewski & Jendritzky 2002) and southern Europe from Portugal to Greece (Katsouyanni et al. 1993, Matzarakis & Mayer 1997, Dessai 2002, Díaz et al. 2002a,b, Zauli Sajani et al. 2002), while the impacts on central and eastern European populations have not been examined. Annual heat-related mortality was found to be similar in European countries with warm and cold summers, although it is observed at higher temperatures in countries with warmer climate (Keatinge et al. 2000).

Most of the studies have employed either the entire population or the elderly (over 65 yr of age), and focused on all-cause (total) mortality or cause-specific

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mortalities due to cardiovascular, respiratory and cerebrovascular diseases (Huynen et al. 2001, Curriero et al. 2002). The reason is that the effects of heat stress on mortality are most pronounced in people whose health is already compromised.

Physiological impacts of heat stress also depend on weather elements other than temperature, particularly on humidity, wind speed and solar radiation. Many indices have been developed to account for these effects and incorporate the entire stress due to weather, the best known of which is heat index (apparent temperature, Steadman 1979; applied, e.g. in Davis et al. 2002 and Smoyer et al. 2000b). The need for more extensive input data prevents a widespread use of complex biophysiological comfort indices and models (Höppe 1999, Laschewski & Jendritzky 2002), which could yield better results in evaluating impacts of weather on human health. Temperature is still the most frequently used variable in analyses of heat-related mortality because of its simplicity, or because it illustrates health impacts of heat similarly to the more complex methods.

The 'air-mass-based' (or 'synoptic') approach, which takes into account the entire weather situation rather than single elements and links mortality to objectively determined air masses, is an alternative to the 'individual variable' approach (termed 'traditional' here). It was developed by Kalkstein (1991) and is widely used in the US, where it describes impacts of hot weather on mortality better than or comparably to other methods (Kalkstein & Greene 1997, Smoyer et al. 2000a). The synoptic approach has also been applied in Australia (Guest et al. 1999) and southern Europe (Cegnar & Kalkstein 2000). The classification of air masses is based on common surface meteorological variables, including temperature, dew-point temperature, cloudiness, air pressure, wind speed and wind direction. Cluster analysis usually follows principal component analysis (PCA), which is applied to reduce the number of (mutually dependent) input variables. Air masses linked to increased mortality are termed 'offensive'.

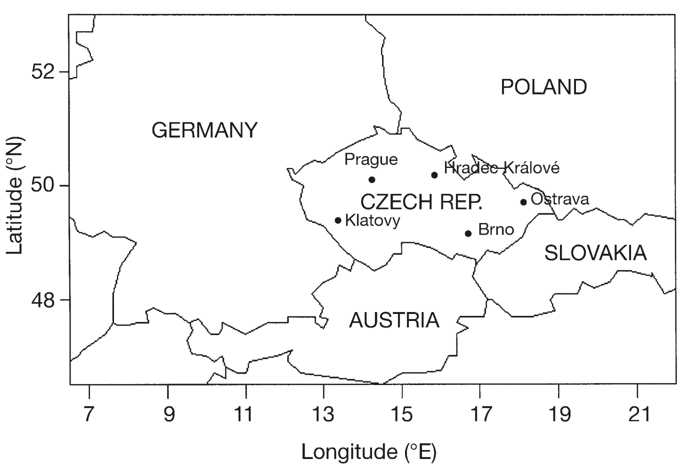

Fig. 1. Location of meteorological stations used in the analysis

The objectives of this study are to evaluate the applicability of the synoptic approach based on the objective air-mass classification in the analysis of impacts of hot weather on summer mortality in central European conditions, and to compare it with the 'traditional' approach, which links mortality to individual weather elements and indices.

2. MATERIALS AND METHODS

2.1. Mortality data

Daily data on total mortality (all causes) and mortality due to cardiovascular diseases (CVD; ICD-9 codes 390–459) in the Czech Republic (population of about 10 million), stratified by gender, over the 9 yr period 1992–2000 were employed. Excess daily mortality was established separately for total and CVD mortality and for males and females, by calculating deviations of the observed number of deaths from the expected number of deaths for each day. The expected number of deaths was computed so that it takes into account effects of the long-term trend in mortality (decline during the period examined, mainly due to socio-economic and life-style changes which followed the 1989 'Velvet Revolution'), the annual cycle (lower mortality in late than early summer, cf. Lerchl 1998) and the weekly cycle (slightly lower mortality on weekends than weekdays); see Kyselý (unpubl.) and Kyselý & Kříž (2003) for more details on the standardization procedure. A similar method was applied, e.g. by Guest et al. (1999), Smoyer et al. (2000a) and Whitman et al. (1997).

2.2. Meteorological data

Weather data on temperature, relative humidity, cloudiness, air pressure and wind speed and direction, measured 3 times daily (07:00, 14:00 and 21:00 h local time [LT]), were available at 5 stations representative for the area of the Czech Republic (Klatovy, Prague-Ruzyně, Hradec Králové, Brno and Ostrava; Fig. 1). The mean series for the Czech Republic was calculated by averaging data from individual stations. In addition to the above-mentioned variables, daily maximum, minimum and average temperatures were used in the analysis. Heat index (apparent temperature) was calculated according to Smoyer et al. (2000b).

2.3. Air-mass classification

Temperature, dew-point deficit, zonal wind, meridional wind, cloudiness and air pressure at 07:00, 14:00 and 21:00 h LT over 1992–2000 were used as input variables in the classification of air masses. This suite of weather elements is similar to other studies (e.g. Kalkstein et al. 1996, Smoyer et al. 2000a). The classification was carried out for June to August, when most heat waves and most days with increased heat-related mortality occur (Kyselý & Kříž 2003).

Three air-mass classifications that differed in the set of stations involved were performed: the input variables originated from (a) the mean series for the Czech Republic; (b) the series at all 5 stations considered together; and (c) the series for a single station (Prague). However, there were no considerable and systematic differences between the resulting classifications and their relationships to mortality, particularly because of the small area of the Czech Republic. Results presented hereafter concern the classification based on the mean series of weather elements (point a).

Since the input variables used are mutually dependent whereas cluster analysis methods frequently assume their independence, unrotated principal component analysis (PCA) was performed first to reduce their number and to form a set of new orthogonal variables (components). Time series of 4 leading components then entered the cluster analysis (Gong & Richman 1995).

Two basic approaches to the cluster analysis, hierarchical ('between group average linkage') and non-hierarchical ('*k*-means'), were employed and compared. The average linkage method (used, e.g. in Kalkstein et al. 1996 and Smoyer et al. 2000a) suffers from a 'snowball effect' (Kalkstein et al. 1987, Huth et al. 1993): one big cluster is produced, to which smaller clusters, more and more dissimilar from the mean, are stuck. To remove this effect, we utilized the approach of terminating the clustering procedure at different dissimilarity levels in different parts of the dendrogram—see, e.g. Huth et al. (1993) and Serrano et al. (1999). Individual 'reasonable' classifications (yielding 12 and 18 air masses for the average series for the Czech Republic) are formed by merging clusters from the 'basic' classification, defined by termination at a single dissimilarity level in the whole dataset.

Unlike average linkage, the *k*-means method yields clusters of similar size; its disadvantage is that they are less compact (i.e. their within-cluster variability is relatively high; e.g. Huth 1996). The number of clusters was set *a priori* to 6, 10 and 15 so that the number of examined air masses spans a range around values appearing in the literature (e.g. 7 synoptic categories in Kalkstein & Greene 1997, 10 in Smoyer et al. 2000a and 11 in Kalkstein et al. 1996).

3. RESULTS

3.1. Relationships of mortality with temperature and heat index

In all-year data, periods with the highest deviations of the daily number of deaths from the baseline are influenza epidemics in winter and early spring, and heat waves in summer; the distribution of days with the highest excess mortality in a year is clearly bimodal, showing a main peak in late winter and a secondary one in summer. On virtually all summer days with considerably elevated mortality, the temperature deviations from normal (calculated as the mean seasonal course smoothed by 15 d running means) are positive. Out of 100 d with the highest excess mortality in April to September, only 11 possess a deviation of daily maximum temperature from normal lower than +1°C, while on 48 d it exceeds +6°C (Kyselý & Kříž 2003).

Deviations of mortality from the baseline exceed +100 deaths d^{-1} (more than 30% relative increase) in heat wave peaks and reach several hundred deaths over long-lasting hot periods, such as the 2 severe 1994 heat waves (Kyselý 2002), with +456 excess deaths (+10.3% relative increase) from June 17 to 30 and +598 deaths (+12.3%) from July 24 to August 8. However, a large portion of the mortality increase is associated with the harvesting effect, which consists in short-term shifts in mortality and leads to a decline in the number of deaths after hot periods (e.g. Rooney et al. 1998, Braga et al. 2002, Laschewski & Jendritzky 2002, Kyselý unpubl.). This effect was clearly observed after the 1994 heat waves; mortality was well below the expected values in most days following the first (altogether –238 'excess' deaths over July 1–15) and second (–290 deaths over August 9–24) heat waves. The mortality displacement effect in the severe 1994 heat waves can be estimated to account for about 50% of the total number of victims. In other words, people who would have died in the short term even in the absence of oppressive weather conditions made up about half of the total number of deaths.

Elevated mortality is observed for daily maximum (average, minimum) temperatures reaching or exceeding 26°C (20°C, 14°C) and for the temperature anomalies from the mean seasonal courses larger than +2°C (Fig. 2). (Each threshold was determined as a centre of the first 3°C wide interval in which the mortality increase is statistically significant at $p = 0.05$). The same values hold for both males and females, and for total and CVD mortality. Despite the same threshold temperatures for males and females, the mortality response at high temperatures is more pronounced in females (Fig. 3); however, the difference is mostly statistically insignificant when evaluated over 3°C wide

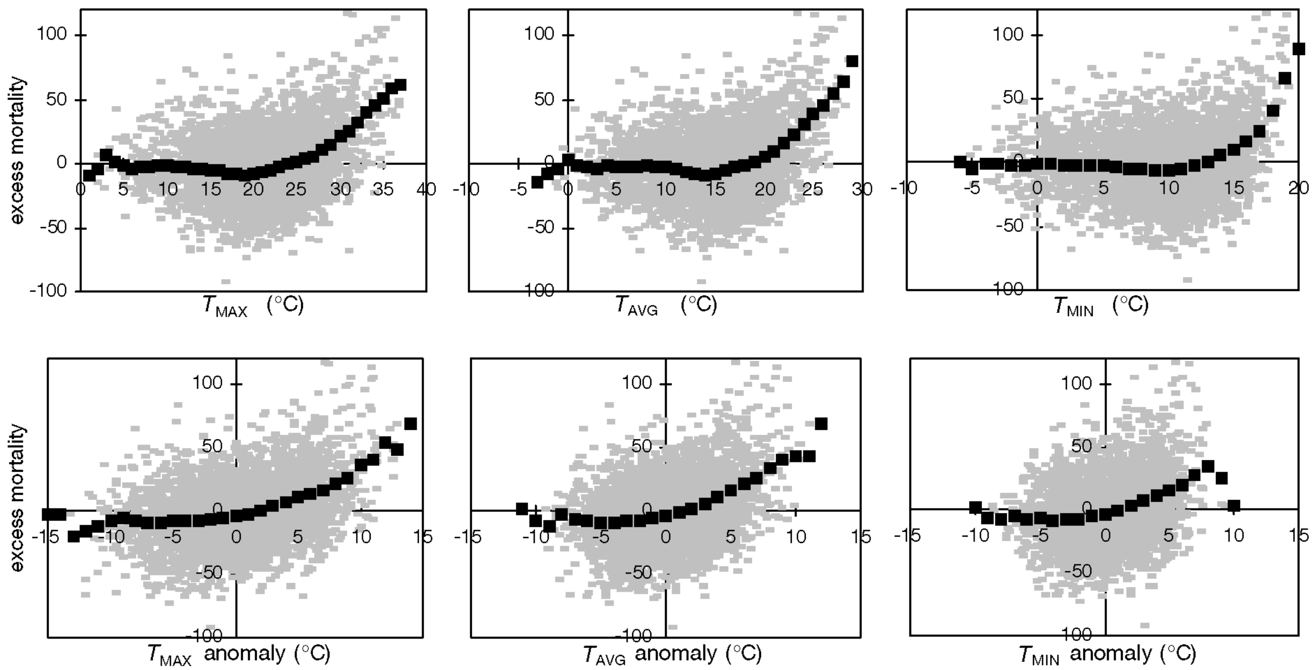

Fig. 2. Scatterplot of excess total mortality against daily maximum (T_{max}), mean (T_{avg}) and minimum (T_{min}) temperature (top) and deviations of T_{max}, T_{avg} and T_{min} from the seasonal course (bottom) for April–September. Black squares correspond to mean values set for 3°C wide intervals

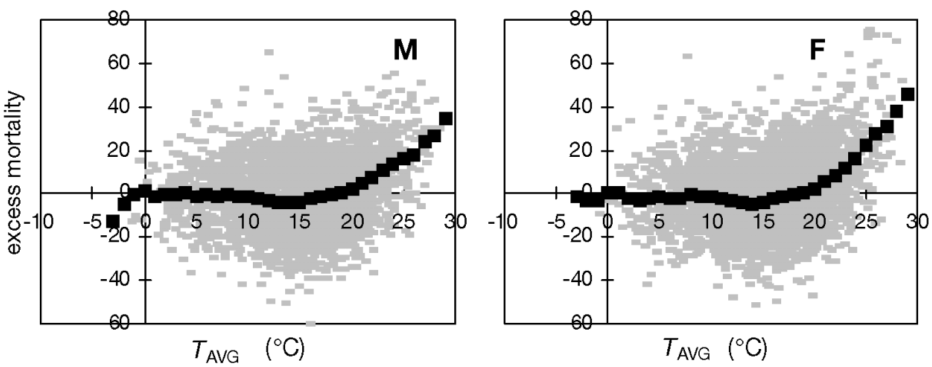

Fig. 3. Scatterplot of excess total mortality against daily mean temperature in males (left) and females (right) for April–September. Black squares correspond to mean values set for 3°C wide intervals

intervals. The thresholds are 2 to 3°C lower in April-May and September, while in July and August they are slightly higher than the values derived from the half-year data (Table 1). This shift during a season demonstrates an increasing adaptability to high temperatures towards mid-summer; on the other hand, an enhanced susceptibility to heat stress in late spring compared to early autumn is not observed.

Correlations of excess mortality with temperature and heat index (Table 2) are positive and statistically significant ($p = 0.01$), stronger for raw values of meteorological variables than for their deviations from mean seasonal courses, and stronger in females than males. Slightly higher correlation coefficients for heat index than for temperature indicate the adverse effect of high humidity on health. The unlagged correlations are stronger than correlations with lags of 1 to 3 d (Fig. 4); positive values of correlation coefficients hold for lags of 0 to 3 d only, while at lags of 4 to 25 d, the link is negative (mostly statistically significant), demonstrating the mortality displacement effect. Similar relationships were also derived for CVD mortality.

3.2. Relationships between mortality and air masses

Air masses with relative frequencies of occurrence less than 2.5% were omitted from the analysis; none of them was associated with significantly elevated mortality in any of the classifications. After this reduction,

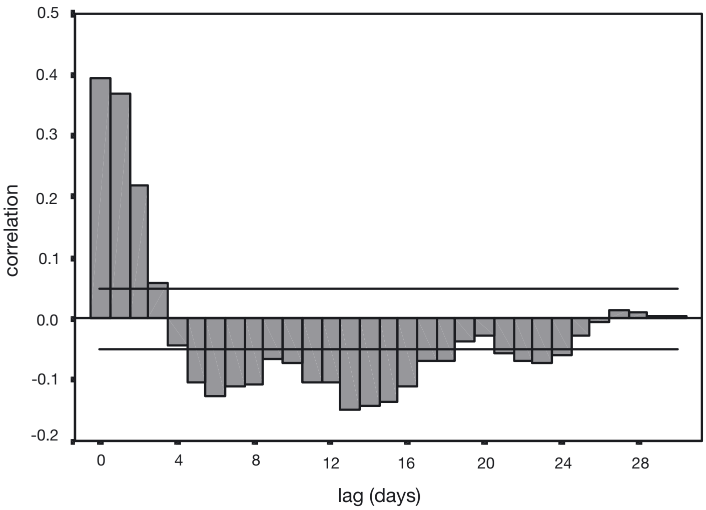

Fig. 4. Lagged correlations between excess total mortality and deviations of daily mean temperature from the seasonal course for lags of 0 to 30 d for April–September. Horizontal lines show the statistical significance limits

the numbers of air mass types in the 5 classifications considered here were 9, 12 (hierarchical cluster analysis), 6, 10 and 14 (non-hierarchical cluster analysis). The classifications are denoted H9, H12 for hierarchical cluster analysis, and N6, N10 and N14 for non-hierarchical cluster analysis hereafter.

At least 1 offensive air mass associated with conspicuously increased mortality appears in each classification (Table 3); mean daily excess total mortality under the offensive air mass with the highest mortality increase (termed 'main' offensive air mass hereafter) lies between 20 and 30 deaths, which corresponds approximately to a 7 to 10% relative increase. The rise in mortality under the main offensive air mass is statistically significant in all classifications and is observed regardless of whether total or CVD mortality is examined.

Table 1. Mean temperatures (°C) and thresholds at which mortality increase appears. The temperature thresholds were set as centres of the first 3°C wide interval for which the rise in total mortality was statistically significant at p = 0.05. T_{max} (T_{min}, T_{avg}): daily maximum (minimum, mean) temperature

Period	Mean temperature			Temperature threshold		
	T_{max}	T_{min}	T_{avg}	T_{max}	T_{min}	T_{avg}
Apr	14.2	3.4	8.7	24	–	–
May	19.7	7.9	13.9	23	14	17
Jun	22.1	10.8	16.5	26	13	19
Jul	24.6	12.6	18.7	28	15	21
Aug	24.7	12.5	18.4	28	14	20
Sep	19.5	9.1	13.9	23	13	18
Apr–Sep	20.8	9.4	15.0	26	14	20

Table 2. Correlation coefficients between meteorological variables and excess total mortality. Days with (a) $T_{avg} \geq 18.0$°C (530 d) and (b) the deviation of T_{avg} from the mean seasonal course ≥ 2.0°C (457 d) in April–September only are considered. T_{max} (T_{min}, T_{avg}): daily maximum (minimum, mean) temperature; HI_{avg}: daily mean heat index

Excess total mortality	T_{max}	T_{min}	T_{avg}	HI_{avg}
(a) Raw values				
Overall	0.472	0.420	0.490	0.539
Males	0.360	0.251	0.361	0.390
Females	0.421	0.432	0.446	0.498
(b) Deviations				
Overall	0.367	0.298	0.371	0.443
Males	0.293	0.164	0.275	0.319
Females	0.320	0.321	0.340	0.413

In all classifications, the main offensive air mass is characterized by

- high temperatures — average daily maximum (mean) temperature exceeds 30°C (23°C) in all classifications;
- low cloud cover — between 20 and 40%; usually the lowest among air masses;
- relatively strong wind (in the H12 classification strongest among all air masses, over 5 m s^{-1}), with a dominant southern component (2.6 to 3.7 m s^{-1} on average).

Rather surprisingly, high humidity (measured by dew-point temperature) is not typical of the main offensive air mass. Also in this analysis, the mean mortality increase (both absolute and relative) under the main offensive air mass is higher in females than males.

Within the main offensive air mass, excess mortality is strongly correlated with temperature and heat index; the correlation coefficient between daily mean heat index (temperature) and excess total mortality is 0.68 (0.62) for the main offensive air mass of the N10 classification (Fig. 5).

In addition to the main offensive air mass, 'secondary' offensive air masses appear in classifications which recognize at least 10 types (H12, N10 and N14). They are characterized by a lower, but still statistically significant increase of 18 (in H12), 12 (in N10) and 22 and 14 (in N14) deaths d^{-1} on average. Slightly lower temperatures (daily maximum temperature 28°C, daily mean temperature 21°C), higher cloud cover, and particularly enhanced dew-point temperature are typical of the secondary offensive air masses, making them distinct from the main offensive air mass.

Frequencies of the main offensive air masses in classifications H9, H12, N6, N10 and N14 are in turn 5, 5, 16, 12 and 9%. These values demonstrate the inherent difference between the 2 methods of cluster analysis, namely the tendency towards forming clusters of similar size for the *k*-means non-hierarchical method (the frequency of most types is close to the ratio of 100% to the total number of clusters). Lower frequencies of the offensive air mass yielded by the average linkage hierarchical method also correspond to higher mortality increases observed under them (cf. Tables 3 & 4); hot days with oppressive weather are better separated from the rest of the sample here. On the other hand, it cannot be unambiguously concluded that this method is more appropriate, since the mean characteristics of the main offensive air mass are similar in all classifications, and some disadvantages of the average linkage method will be mentioned in Section 4.

To evaluate the contribution of air masses to enhanced mortality, a coefficient was calculated similarly to Kalkstein & Greene (1997) and Smoyer et al. (2000a) as a ratio of the relative occurrence of each air mass among the 50 d with the highest excess mortality over the period analyzed to its mean (climatological) frequency (Table 4). A ratio >1.0 means that the air mass is conducive to elevated mortality. For the main offen-

Table 3. Mean characteristics of air masses in 3 selected classifications (H12, N10 and N14). T_{max} (T_{min}, T_{avg}): daily maximum (minimum, mean) temperature (°C); T_d (CLOUD, WIND, $WIND_{mer}$): dew-point temperature (°C) (cloudiness (%), wind speed (m s^{-1}), meridional wind speed (m s^{-1}) at 14:00 h LT. $WIND_{mer}$ is positive (negative) for southern (northern) flow. Air masses are ordered according to their frequency; offensive air masses are given in **bold**

Air mass	Frequency (%)	Excess total mortality Overall	Males	Females	Excess CVD mortality	T_{max}	T_{min}	T_{avg}	T_d	CLOUD	WIND	$WIND_{mer}$
H12 classification (average linkage method; 12 types with frequency >2.5%)												
1	20.1	8.2	3.3	5.0	4.3	27.8	12.9	20.9	12.2	40	3.4	2.1
2	17.2	−1.4	−2.1	0.7	−0.4	23.3	13.2	17.5	13.3	74	3.6	2.3
3	15.5	−8.3	−4.7	−3.6	−4.5	20.3	11.7	15.3	10.6	79	4.6	1.1
4	7.3	0.0	−0.5	0.5	0.1	24.5	12.0	18.3	12.2	60	2.9	0.7
5	7.0	−1.8	0.3	−2.0	−0.6	27.7	11.7	20.5	10.2	33	3.2	0.2
6	5.4	0.3	2.6	−2.3	0.1	23.6	12.4	17.9	13.5	77	3.6	1.9
7	**4.6**	**30.2**	**10.6**	**19.5**	**15.1**	**30.8**	**15.4**	**23.3**	**12.9**	**36**	**5.2**	**3.7**
8	4.5	−16.7	−6.3	−10.4	−6.2	19.8	9.9	14.5	7.1	67	5.0	−1.3
9	4.0	−11.8	−6.0	−5.8	−4.4	21.6	10.5	16.0	8.3	58	3.6	0.7
10	2.9	−11.0	−5.9	−5.0	−6.5	24.9	9.3	18.1	8.5	30	3.2	−0.3
11	**2.7**	**17.9**	**10.5**	**7.3**	**8.2**	**28.5**	**13.5**	**21.4**	**13.3**	**48**	**3.6**	**2.3**
12	2.5	−13.8	−3.2	−10.6	−7.9	18.5	11.4	14.6	11.7	89	3.4	0.9
N10 classification (*k*-means method; 10 types with frequency >2.5%)												
1	14.5	−3.8	−4.0	0.2	−2.4	22.4	12.6	16.9	12.4	75	3.7	1.9
2	**11.8**	**25.3**	**11.1**	**14.2**	**12.3**	**31.1**	**14.2**	**23.5**	**13.1**	**26**	**3.9**	**2.9**
3	11.5	−0.9	−1.2	0.3	−0.4	25.9	11.5	19.2	10.6	41	2.9	1.4
4	**10.9**	**12.4**	**6.4**	**6.0**	**7.9**	**26.9**	**14.0**	**20.3**	**14.2**	**60**	**3.6**	**2.6**
5	10.6	−4.6	−1.1	−3.5	−3.5	22.2	12.0	16.8	12.6	76	3.0	1.1
6	10.4	−5.2	−4.7	−0.4	−3.3	22.3	12.9	16.9	11.9	75	5.1	2.0
7	10.0	−3.8	−2.4	−1.4	−1.4	27.1	11.5	20.1	10.1	33	3.4	−0.4
8	9.9	−13.1	−4.8	−8.3	−6.4	18.9	10.2	14.0	8.4	75	4.6	−1.2
9	5.6	−12.2	−5.5	−6.8	−5.8	22.2	10.9	16.5	8.0	56	4.6	0.6
10	4.8	−5.9	−2.6	−3.4	−2.2	22.0	12.3	16.6	13.0	81	3.2	1.5
N14 classification (*k*-means method; 14 types with frequency >2.5%)												
1	10.1	−10.4	−5.9	−4.6	−5.8	20.8	11.9	15.6	11.7	79	4.0	1.9
2	**9.4**	**26.0**	**11.3**	**14.7**	**13.7**	**31.6**	**14.2**	**24.0**	**12.6**	**24**	**3.8**	**2.6**
3	**9.1**	**13.5**	**4.5**	**9.0**	**7.0**	**27.9**	**14.1**	**21.1**	**13.9**	**49**	**3.7**	**2.8**
4	8.8	−4.2	−3.0	−1.2	−2.6	26.1	11.1	19.3	10.2	36	2.9	0.9
5	8.6	2.7	1.1	1.6	2.6	25.1	12.4	18.7	12.3	58	3.0	1.4
6	8.1	−13.0	−5.1	−7.9	−5.9	19.5	10.1	14.4	7.4	70	4.8	−0.8
7	7.5	−4.4	−2.3	−2.1	−3.8	21.2	11.9	16.2	12.3	79	3.0	1.4
8	6.5	−4.5	−2.6	−1.9	−1.8	27.8	11.6	20.2	9.9	31	3.6	−0.7
9	6.4	−9.3	−4.7	−4.6	−5.8	20.2	12.3	15.4	11.4	82	4.9	1.0
10	6.2	−0.1	1.5	−1.5	0.5	23.6	13.7	17.9	14.7	81	3.4	2.6
11	5.0	−8.9	−4.7	−4.2	−4.2	23.1	10.9	17.2	8.8	54	3.9	0.9
12	4.7	4.8	−0.2	5.0	1.9	25.5	13.7	19.2	12.6	63	5.7	3.1
13	3.7	−11.1	−4.3	−6.8	−9.4	22.3	11.3	16.9	12.0	68	3.3	0.2
14	**3.6**	**21.7**	**8.8**	**12.9**	**13.2**	**28.4**	**13.9**	**21.3**	**14.0**	**53**	**4.0**	**2.6**

Table 4. Ratios of relative occurrence of air masses on 50 d with the highest excess mortality to their mean (climatological) frequency. Air masses are ordered according to their frequency; offensive air masses are given in **bold**

Classification	Air mass	Excess total mortality	Ratio
Hierarchical cluster analysis			
H9	1	−1.0	0.57
	2	8.6	1.70
	3	−9.8	0.29
	4	−1.4	0.45
	5	6.1	1.73
	6	**30.2**	**5.23**
	7	−11.8	0.00
	8	−11.0	0.00
	9	−13.8	0.00
H12	1	8.2	1.50
	2	−1.4	0.70
	3	−8.3	0.13
	4	0.0	0.28
	5	−1.8	0.29
	6	0.3	1.10
	7	**30.2**	**5.23**
	8	−16.7	0.45
	9	−11.8	0.00
	10	−11.0	0.00
	11	**17.9**	**3.01**
	12	−13.8	0.00
Non-hierarchical cluster analysis			
N6	1	−1.5	0.55
	2	−2.9	0.58
	3	−5.5	0.49
	4	0.7	0.87
	5	**21.7**	**3.44**
	6	−13.7	0.15
N10	1	−3.8	0.55
	2	**25.3**	**4.06**
	3	−0.9	0.52
	4	**12.4**	**2.02**
	5	−4.6	0.19
	6	−5.2	0.58
	7	−3.8	0.20
	8	−13.1	0.00
	9	−12.2	0.72
	10	−5.9	0.41
N14	1	−10.4	0.00
	2	**26.0**	**3.61**
	3	**13.5**	**2.87**
	4	−4.2	0.23
	5	2.7	0.70
	6	−13.0	0.25
	7	−4.4	0.27
	8	−4.5	0.31
	9	−9.3	0.31
	10	−0.1	0.32
	11	−8.9	0.40
	12	4.8	1.27
	13	−11.1	0.00
	14	**21.7**	**3.86**

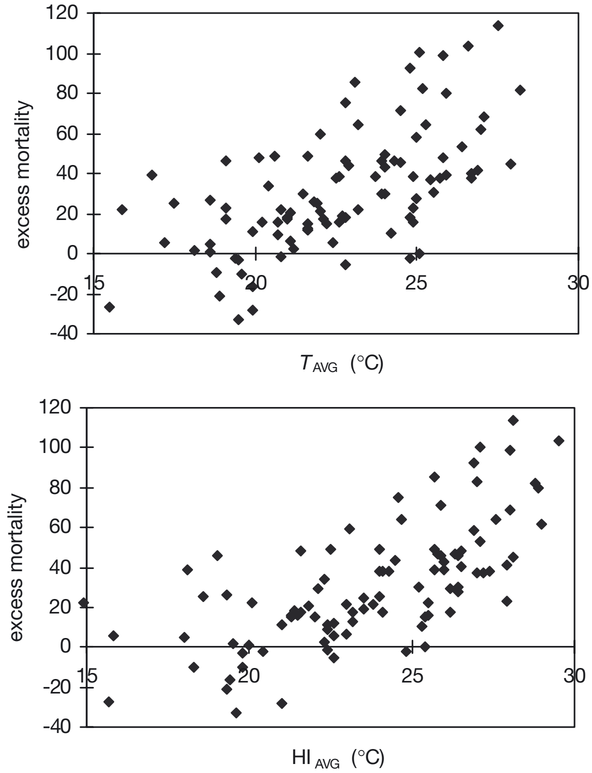

Fig. 5. Scatterplot of excess total mortality against daily mean temperature (T_{avg}) and heat index (HI_{avg}) within the main offensive air mass of the N10 classification

sive air mass, this ratio lies between 3.4 and 5.2 in all classifications, while for the secondary ones it ranges from 2.9 to 3.9; a ratio >2.0 was chosen here as a criterion for the air mass to be considered offensive, particularly in the delimitation of the secondary offensive air masses. It is also worth mentioning that the values of the coefficient for the main offensive air mass in the Czech Republic are higher than in most US cities analyzed by Kalkstein & Greene (1997) and Smoyer et al. (2000a).

4. DISCUSSION

Both the 'traditional' (examining relationships of mortality to individual meteorological variables and indices) and the synoptic (based on an objective air-mass classification) approaches applied here to evaluate links between hot summer weather and mortality show that heat stress leads to considerably elevated total mortality and mortality due to cardiovascular diseases in the Czech Republic.

Threshold temperatures at which adverse effects on human health appear differ among populations as well as within an individual population due to diverse climates, living conditions, adaptability, etc. (Keatinge et al. 2000, Curriero et al. 2002). The shape of the relationship and the threshold value of 20°C for daily mean temperature in the Czech Republic match the results of the pan-European study of Keatinge et al. (2000), where threshold temperatures of 18–19°C in northern Italy and 20–21°C in SW Germany were reported, as well as the finding of a 19°C threshold in London (Hajat et al. 2002). Within-year adaptation (Hajat et al. 2002) plays an important role, since the thresholds vary during the summer half-year. The short-term and long-term adaptability as well as the recent findings on changes towards a decreased vulnerability of populations in developed countries to heat stress (Davis et al. 2002, 2003, Weisskopf et al. 2002, Donaldson et al. 2003) must be taken into account when scenarios of future changes in heat-related mortality are constructed.

A large portion of heat-related deaths are short-term displacements that are unlikely to be avoided within a few weeks even in the absence of oppressive weather. This harvesting effect accounts for about 50% of excess deaths during the 1994 severe heat waves in the Czech Republic. A cross-correlation analysis yields an estimate of the length and the lag of the period after a heat wave, during which mortality is lower than expected; this period lasts for about 3 wk and starts a few days after the temperature peak. A similar negative link between mortality and temperature with lags of 7 to 30 d was revealed by Huynen et al. (2001) in the Netherlands.

Females appear to be more sensitive to heat stress than males, whatever approach ('traditional' or synoptic) is used. This is consistent with other studies for European populations (Mackenbach et al. 1997, Rooney et al. 1998, Díaz et al. 2002a,b) and is likely connected with age structure, the higher percentage of women living alone, and enhanced physiological and behavioural vulnerability of women to heat stress.

Relationships between temperature and mortality in summer are usually strongest with zero lag (Kunst et al. 1993, Keatinge et al. 2000, Curriero et al. 2002, Hajat et al. 2002) or lags of 1 to 2 d (Ramlow & Kuller 1990, Sartor et al. 1995, Whitman et al. 1997, Díaz et al. 2002b). Present results put the population of the Czech Republic into the former group.

An offensive air mass was identified by all the classifications applied (differing in the number of types and the cluster analysis method). The optimum number of clusters (air masses) should be close to 10: the classification with only 6 types (N6) leads to an offensive air mass which is 'too frequent' and not well separated from the rest of the sample (and hence the relative mortality increase is less pronounced); and the classification with 14 types (N14) produces 'too many' offensive air masses, by splitting the secondary offensive air mass into two air masses with nearly the same weather characteristics. The hierarchical average linkage method results in the main offensive air mass being less frequent (and thus better separated) than in the non-hierarchical k-means cluster analysis. Hence, the relative mortality increases in the main offensive air mass are higher when the average linkage method is used (about 30 deaths d^{-1} compared to 25 for k-means); on the other hand, because of the lower frequency of the main offensive air mass, it is observed on a smaller fraction of days with the highest mortality (only about 25% out of 50 d with the highest excess mortality compared to about 50% for the k-means method). To conclude, both methods should be considered for a potential future development of a heat-watch warning system which would mitigate avoidable impacts of hot weather in central-European conditions.

The classifications with at least 10 air masses yield a secondary offensive air mass in addition to the main one; this is not an undesirable result, since this air mass is characterized by weather conditions more or less different from the main offensive air mass, particularly by higher dew-point temperature (which together with lower air temperature implies increased relative humidity) and higher cloudiness (more than doubled in some classifications). These characteristics indicate that the secondary offensive air mass is rather a 'maritime' tropical one, while the main offensive air mass can be termed 'continental' tropical. The secondary air mass is better separated from the main one when the k-means clustering method is used, which again points to a slight superiority of the non-hierarchical clustering approach.

The secondary air mass in the N10 classification (which combines the optimum number of types with the optimum [k-means] method for separation of the secondary offensive air mass from the main one) is not the second but the third warmest air mass in terms of T_{max}. However, it is much more humid compared to the second warmest air mass, and it has a considerably lower diurnal temperature range and much higher cloudiness. The second warmest air mass is associated with negative excess mortality. This shows that high temperatures alone do not necessarily lead to enhanced mortality, that other weather parameters contribute to the mortality increases, and that the classification method used is capable of distinguishing the offensive air masses from the non-offensive ones that may be comparably hot.

The large relative increases in mortality during heat waves and under main offensive air masses (7 to 10%) are noteworthy also because the study, unlike many other heat-related mortality analyses, was not restricted to urban areas (Smoyer et al. 2000a,b, Braga et al. 2002, Curriero et al. 2002, Dessai 2002, Díaz et al. 2002a,b, Hajat et al. 2002) and/or the elderly sector of the population (Sartor et al. 1997, Smoyer et al. 2000b, Díaz et al. 2002a,b, Donaldson et al. 2003). The mean mortality increase under the main offensive air mass is only slightly lower than the mean mortality increase under heat-wave conditions (about 13% in the Czech Republic: Kyselý unpubl.; a similar value of 12% was reported by Huynen et al. 2001 in the Netherlands), which indicates comparable achievements of the 2 approaches (taking into account the fact that the percentage of days occurring in heat waves is similar to that under the main offensive air mass of the hierarchical classification).

The synoptic approach based on the objective classification of air masses is a useful alternative to more traditional methods used in the evaluation of heat-related mortality, and it should be considered for application in heat-watch warning systems (Kalkstein et al. 1996, Cegnar & Kalkstein 2000, Kalkstein 2000) also in central Europe.

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