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THE ATTEMPT TO VALIDATE THE APPLICABILITY OF TWO CLIMATE MODELS FOR THE EVALUATION OF HEAT WAVE RELATED MORTALITY IN WARSAW IN THE 21ST CENTURY

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Abstract:

In the analysis of the potential of applying models to estimate threat of heat waves in Poland up to the end of the 21st century, two discrepant climate change models: the MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE have been used. In this regard, the maximum air temperature was analysed. The accepted definition of a heat wave was 3 and 5 consecutive days of temperatures ≥30°C. According to the more realistic ARPEGE model, after 2040, the number of 3-day heat waves will rise by 370% and after 2070 – 460%. In Warsaw, the extent of possible mortality rates due to cardiovascular disease in heat waves amounted to +134% in the period after 2070 according to the ARPEGE model.

Key words

climate models • heat waves • modelled air temperature • mortality • Poland

Introduction

Climate change is a significant and emerging threat to public health all over the world (WHO/WMO 2012). This is why climate projections have become an important topic of scientific and public interest and why the Intergovernmental Panel on Climate Change (IPCC) was established. The successive full reports (IPCC 2001, 2007) and special reports (e.g. IPCC 2000, 2012) present the possible scenario variants of climate change and its effects. For climate estimations, the IPCC prepared many alternative scenarios regarding the world's development, which are joined into 4 groups. The A1B scenario, used in this estimation, is characterised by rapid economic growth, a global population that reaches 9 billion in 2050 and then gradually declines, a quick spread of new and efficient technologies, a convergent world – income and way of life converge between regions, extensive social and cultural interactions worldwide and technological balanced emphasis on all energy sources.

The projected future changes of climate in Europe under the A1B scenario include a temperature increase of 2.3-5.3°C in northern Europe and 2.2-5.1°C in southern Europe by the end of the 21st century (IPCC 2007).

Each projection is a combination of the model of general atmosphere circulation and the ocean (e.g. ARPEGE, ECHAM5) and the regional model (e.g. DMI-HIRHAM, COSMO-CLM, MPI-REMO). The global model supplies coastal and initial conditions for the regional model, which, in turn, has a significantly better space resolution for country-sized or regional estimations. For instance, the fourth Intergovernmental Panel on Climate Change (IPCC) assessment report summarizes data from 21 different coupled atmosphere–ocean global climate models – GCMs (Meehl et al. 2007). Similarly, regional projections are increasingly based on ensembles of high-resolution regional climate model (RCM) simulations. Over Europe, this approach has been pioneered in the PRUDENCE and ENSEMBLES projects (Christensen & Christensen 2007; Déqué 2009).

One of the most possible impacts of climate change due to well documented changes in extreme weather and climate events (IPCC 2012) is a very likely (90-100% probability) increase in the length, frequency, and/or intensity of warm spells or heat waves over most land areas (in Europe the projection of those phenomena is – likely: 66-100% probability). Also there will be a virtually certain (99-100% probability) increase in the frequency and magnitude of warm days and nights on a global scale (in Europe accordingly – very likely).

Heat waves are several day or longer periods of exceptionally hot weather, where there is often a sudden rise in mortality rate, particularly among those with cardiovascular disease. Above all, it is caused by excessive stress on the thermoregulatory and cardiovascular systems caused by the body's adaptation processes to high air temperature. Dilation of the blood vessels in a hot environment leads to a rise in the velocity of blood flow and pulse rate, a drop in blood pressure, a rise in blood volume and thus an overall weakening of the body. Heat waves which last for a few days lead to a decrease in haemoglobin, which carries oxygen, an increase in respiratory rate, ie pulmonary ventilation, which leads to aggravation of respiratory diseases (Klonowicz & Kozłowski 1970; Jankowiak 1976). If high air temperature is accompanied by a large inflow of direct sunlight and high vapour pressure then a dangerous increase in systolic and diastolic blood pressure can take place (Biernacki et al. 1965; Zawiślak 1997; Błażejczyk 1998).

The first scientific reports on heat waves and an accompanying rise in mortality rate of over 100% came from the USA in the 1930s and 1950s regarding inhabitants of large cities (Ellis & Nelson 1978). Starting in the 1990s fatal heat waves were increasingly commonly noted in Europe and the problem became an object for many scientific research studies (Robinson 2001). At the end of July and beginning of August 1994, intense heat waves affected Central Europe and the Benelux countries (Sartor et al. 1995; Huynen et al. 2001). It was one of the most intense heat waves in Poland to date, during which the mortality rate rose, depending on the city, by as much as 64% (Kuchcik 2001; Kozłowska-Szczęsna et al. 2004; Kyselý & Huth 2004; Błażejczyk & McGregor 2007).

In 1995, during heat waves in England, the average mortality rate increase was 23% in London in a period of 5 days, mostly among people over 85 years old, but particularly among women living alone (3 times as many deaths among women than men). The main cause of death (39%) was cerebrovascular disease (Rooney et al. 1998). Whilst among the victims of the heat wave in Chicago (in the same year), dehydration, exhaustion and sunstroke dominated. Those with a greater risk of death during heat waves were, respectively: the seriously ill, people who didn't leave their homes (triple the risk), those living alone (double the risk), the poorly educated and those with low incomes (Semenza et al. 1996). This information does not only document disease groups which a heat wave could be expected to aggravate, but also points towards social groups where life is at risk in a hot thermal environment – mostly people living alone and elderly inhabitants of cities.

The selection of high risk groups and the necessity of ensuring care in weather conditions which impose a heavy burden on the body is confirmed by the most fatal heat wave in 2003, which encompassed Western and Southern Europe. In France, it was the hottest summer since 1947, with a maximum temperature of over 40°C and 15-20 thousand people died (Kosatsky 2005). In Italy, despite similarly high temperatures, the number of fatalities reached just over 1000, of whom 57% were over 84 years old, 72% of these were women (Michelozzi et al. 2004). The difference in the number of fatalities resulted from the significantly closer family ties and cultural patterns in Italy, which mean that the elderly are not left without care. In total, according to a range of sources, the number of victims of the 2003 heat wave reached 20-35 thousand people (Garssen et al. 2005; Robine et al. 2007).

The EuroHEAT project (D'Ippoliti et al. 2010) which analysed mortality rates during summer heat waves in 9 European cities from 1990 to 2004 showed a large rise corresponding to an increase in the intensity and length of heat waves.

In cities in the Mediterranean Basin, heat waves led to a growth of 21.8% in the noted number of all deaths, and in cities located in Central Europe of 12.4%. Mortality rates grew with the age of the patients, and were also higher among women, especially in the 75-84 age group.

The first aim of this work is an evaluation of the legitimacy of using 2 different regional climate models in forecasting heat waves. The next aim is to present the risk to the population which heat waves bring in Poland, in particular Warsaw, and also to attempt to estimate the threat of heat waves to the end of the 21st century.

Material and methods

In the analysis, the MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE climate change models were used, on the basis of which the maximum air temperature was forecasted until the year 2100. These are two commonly used and precisely analysed regional models: DMI-HIRHAM5 (Christensen et al. 2007) and MPI-M-REMO (Jacob et al. 2001) with the coastal conditions of the global models ARPEGE developed and used mainly by Météo-France CNRS and ECHAM5 developed at the Max Planck Institute for Meteorology. The ECHAM5 model reduces the maximum temperatures, therefore heat waves will be lowered, ARPEGE, however, tends to slightly raise the levels (ARPEGE-Climat V5.1 2008).

The reference period was the 30 years from 1971-2000, while the spatial resolution was 25×25 km. Simulations used boundary conditions proposed the A1B SRES (IPCC 2000) which considers a relatively mild increase of Greenhouse Gases in this century and is frequently used in climate change predictions. The data was extracted for the Warsaw Agglomeration which covers four E-OBS European Climate Assessment and Dataset (ECA&D) grids (Haylock et al. 2008). The data was prepared in the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM) of the University of Warsaw by Liszewska as part of the KLIMADA project, using simulations carried out in the EU ENSAMBLES project (ENSEMBLES 2009; Liszewska 2013).

It is well known that, in spite of improved parameterization of physical and chemical processes, the climate models provide much differentiated data. For example, air temperature predictions taken from various model for the A1B emission scenario differ significantly (IPCC 2007). Such uncertainty is caused by a difference in the parameterisation of particular components of climate models, both global and regional. However, the temperature data used in present research, taken from MPI-M-REMO-ECHAM5, fits very well with the reference data taken from ERA40 reanalysis (the correlation coefficient is 0.98). In case of daily values, concordance of modelled and reference data is only slightly weaker and the correlation coefficient is 0.95 (Liszewska et al. 2012).

Atmosphere physicists and statisticians in multi-model projections exploit an ensemble approach (Buser et al. 2010), and present results as for the changes in mean and variability between the control and scenario periods. This is why 2 models were consciously chosen, which supply extreme and discrepant information, knowing that the future actual picture of the frequency and intensity of heat waves will be between the two extreme forecasts (Fraga et al. 2013).

Using the models developed for the ENSAMBLES project and those commonly used for many years allows for the referencing of the results to other works.

The forecast for the maximum air temperature for Warsaw was analysed in 10 year periods. Heat waves were defined on 2 ways: as a period of minimum 3 and also 5 consecutive hot days, of maximum air temperature ≥30°C. In order to estimate the risk of heat waves in the future, the real maximum air temperature values, noted in the period 1981-2010 at the Warsaw Okęcie synoptic station, were compared with the modeled values. Although comparison of the grid and measured values is not methodologically correct – the comparison has been consciously presented in order to better portray the scale of the problem of modelling heat waves.

Despite the fact that the forecast temperature to the end of the 21st century concerns Warsaw, taking into account more exact determination of the values of threshold mortality rates in heat waves, the characteristics of this risk are presented, not only for Warsaw, but also for other large cities in Poland. The risk of mortality during heat waves was analysed on the basis of daily meteorological data and mortality characteristics (general and cardiovascular mortality among people aged 65) among the inhabitants of the 16 biggest Polish cities over a 10-year period 1993-2002: Białystok, Gdańsk, Katowice, Koszalin, Cracow, Lublin, Łódź, Olsztyn, Płock, Poznań, Rzeszów, Szczecin, Toruń, Warsaw, Wrocław and Zielona Góra.

Heat waves were delimited as below. It is a period lasting a minimum of 6 days (5 days where the start is in May or June) with an *Apparent temperature* calculated for 12 UTC above the 95th annual percentile and an increase of 2°C compared to the previous day. In the permissible 1-day breaks, the *Apparent temperature* cannot drop below the 90th percentile (Kuchcik 2006a).

The formula of the *Apparent temperature* is a simplified algorithm compared to the first one evaluated by Steadman (1984). It uses only two commonly measured inputs of air temperature and dew point temperature (Kalkstein & Valimont 1986; Michelozzi et al. 2004). It is (assuming no wind or a light wind):

$$AT = -2.653 + 0.994T + 0.0153(Td)^2$$

where: T – dry bulb temperature (°C), Td – dew point temperature (°C).

Therefore, in research on the estimation of mortality rates in heat waves, the maximum air temperature was not taken into account, but rather the biometeorological indicator, *Apparent temperature*, which better illustrates the perceptible conditions in which humans live. As the thermal burden threshold, the *Apparent temperature* value was accepted, cutting off the highest and lowest 5% of the values noted in a given month. This thermal threshold was different, therefore, in different towns, just as the levels of perceived thermal comfort are, resulting from the adaptation of inhabitants to the climate of a particular place.

The impact of heat waves on mortality

A heat wave was defined as a minimum of 6 consecutive days when *Apparent temperature* was higher than the accepted threshold, which, for example, was 26.2°C in Białystok, 27.3°C in Warsaw, or as much as 27.7°C in Rzeszów (Kozłowska-Szczęsna et al. 2004; Kuchcik & Degórski 2009). The value of 27.3°C, which was defined as a heat wave in Warsaw, corresponds to the maximum air temperature in the range 26.7-29.4°C with the differences resulted from the varying levels of vapour in the air.

Heat waves, so defined, occurred, on average, once every 16 months, normally in July in the period 1993-2002. The fewest were recorded in Gdańsk (2) and the most in Olsztyn (9). They mostly lasted 6 days and only 17% were longer than 10 days. Heat waves rarely occurred in Spring during this period and were mostly seen in the south of Poland (none were recorded in Gdańsk, Lublin or Warsaw), and they didn't reach the intensity of the summer heat waves, but led to a significant rise in mortality rates among those not adapted to the hot conditions in those cities. On average in Poland, they caused a general mortality rate rise of 15%, and a rise in deaths due to cardiovascular disease of 18% (Kuchcik & Błażejczyk 2005; Kuchcik 2006b) (Tab. 1).

Table 1. Mean rise or fall of the death risk [%] from all causes and cardiovascular mortality among people aged >65 in chosen Polish cities, 1993-2000.

City	Rise / fall of death risk [%] during heat waves					
	May–June		July		August	
	all	cardiovascular	all	cardiovascular	all	ccardiovascular
Białystok	+4	+1	+5	+10	+13	+36
Gdańsk	–	–	+3	+4	–	–
Cracow	**+30**	**+32**	**+10**	+5	**+15**	+13
Lublin	–	–	**+15**	**+28**	-4	+3
Poznań	-3	-16	**+40**	**+33**	–	–
Warsaw	–	–	**+15**	**+21**	+3	-1
Wrocław	+16	+29	**+26**	**+39**	+3	+1
Mean of 16 cities	**+15**	**+18**	**+19**	**+22**	+3	+1

bold values – statistically significant on p=0.05.

The rise of mortality rates during heat waves is visible almost immediately after the rise in air temperature. It usually appears as soon as the second day and lasts for a few days after the hot period, after which a fall in deaths is noted. To a great degree, heat waves only accelerate the death of the sick, as they would have died in a short time anyway, despite the weather conditions. This effect is called the 'harvesting effect'. Over a longer period, the final number of deaths resulting from a heat wave is, therefore, lower than that noted during a time of high air temperature (Kyselý 2004).

Deaths due to road accidents and drowning should also be added to the number of deaths connected with the stress of the heat. The number of accidents rises as a result of the extension of the simple reaction time of humans, which, in turn, goes up with the rise of air temperature. The number of drownings grows during heat waves, as people want to cool down in the many unsupervised lakes, rivers and reservoirs.

Although the average rise in risk of mortality in heat waves in July is 19% in overall deaths and 22% in relation to cardiovascular disease (Tab. 1), the growth in mortality rates during particular heat waves is often much higher.

The longest heat wave, which covered all of Poland for 15-20 days occurred at the end of July, beginning of August in 1994. The maximum air temperature reached 35.5°C in Białystok, 36.1°C in Olsztyn and 36.4°C in Warsaw. In some researched towns, the heat wave lasted unbroken, whilst in others it was split by a short period of lower air temperature. The rise in risk of mortality during this heat wave fluctuated between 23% in Szczecin up to 63% in Łódź, and due to cardiovascular disease from 37% in Warsaw to 64% in Łódź (Tab. 2). In the described heat wave, 12-15 days of high temperature (T_{max}≥30°C) were noted, depending on the location. Altogether, in all series of hot days lasting longer than 3 days, the risk of mortality was statistically significant regarding both deaths all told, and also those due to cardiovascular disease (Tab. 2).

During the heat wave in 1994, in Warsaw 132 more deaths were noted than were expected for that period (including 77 due to cardiovascular disease) among people aged over 65. However, asa 'harvesting effect', in the 30 days after the heat wave there was a natural fall in mortality. In total, the number of victims of over 65 years of age of that heat wave can be estimated at 47 (34 from cardiovascular disease). However, after including the 'harvesting effect', the number of deaths was 35.6% of the value noted just after the heat wave and 44.2% in the cardiovascular group. Therefore, the probable overall rise in mortality in Warsaw due to the heat wave in 1994 was 11.8% and due to cardiovascular disease 16.3% (Fig. 1).

Table 2. The list of all heat waves in chosen Polish cities, during which the rise of the risk of mortality among people aged >65 was statistically significant, 1993-2002.

City	Date	Number of days with T_{max}≥30°C during given heat wave	The rise of deaths risk [%]	
			all causes	cardiovascular
Warsaw	July 1994	13	**33**	**37**
	July 2002	1	7	**24**
Cracow	June 1996	4	**42**	**55**
	August 2000	4	**41**	**48**
	June 2002	2	**26**	27
Łódź	July 1994	15	**63**	**64**
	July 1995	3	**20**	17
	June 1996	3	**25**	**23**
Poznań	July 1994	12	**49**	**42**
Szczecin	July 1994	15	**23**	**38**
Wrocław	July 1994	15	**43**	**62**

bold values – statistically significant on p=0.05

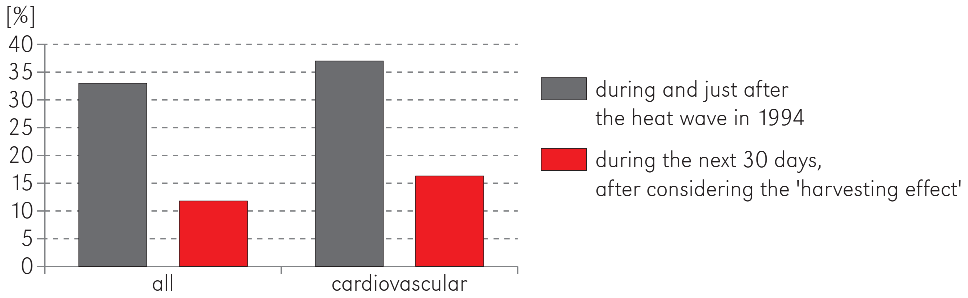

Figure 1. The rise of the death risk [%] from all and cardiovascular mortality in Warsaw among people aged >65 during the heat wave in 1994 and during the next 30 days, after considering the ‘harvesting effect’.

Predicted against observed air temperature

Comparing the maximum air temperature observed at the Warsaw Okęcie station with the modelled values shows slightly higher coefficients of determination for the applied MPI-M-REMO-ECHAM5 model (abbreviated to ECHAM5). The linear regression in the consecutive decades reaches an R^2 value of 0.59 to 0.63. The lowest is for the period 1991-2000, which is when the 1994 heat wave occurred. Introducing a polynomial to the 6th degree only insignificantly raises R^2, reaching 0.67. In the case of the ARPEGE model, the coefficients of determination are slightly lower (0.57-0.60), which bears witness to the model lower suitability. Similarly, for the whole 30 year period of 1981-2010, the ECHAM5 model hardly explains the changeability of maximum air temperature in Okęcie much better (Fig. 2).

Table 3 presents the frequency of maximum air temperature in intervals of 5°C in consecutive decades. In the context of maximum temperature the models significantly differ from each other. In the DMI-HIRHAM5-ARPEGE (abbreviated to ARPEGE) model, in comparison to the ECHAM5 model, there is a clear shift in the forecast air temperature towards higher values. The scope of the modelled temperature in ECHAM5 is close to that presently recorded at the Warsaw Okęcie

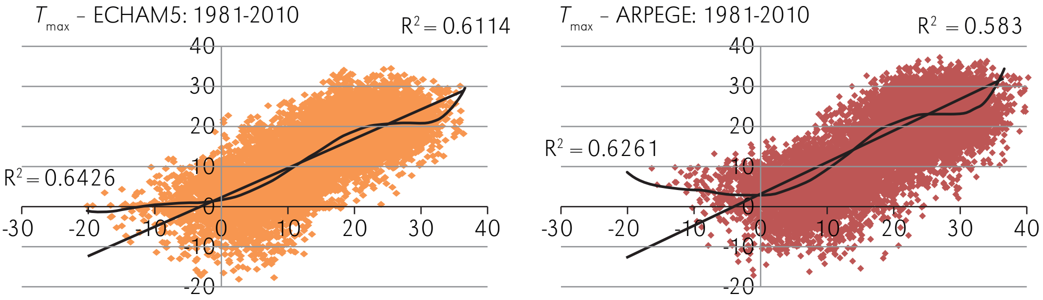

Figure 2. Maximum air temperatures observed at the Warsaw Okęcie station versus predicted (models MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE) over the years 1981-2010. Coefficients of determination R^2 for linear regression – right top corner and for polynomial of degree 6 – left side.

The coefficients of determination R^2 for individual 10-year periods:

Period	R^2 – linear regression		R^2 – polynomial of degreee 6	
	ECHAM5	ARPEGE	ECHAM5	ARPEGE
1981-1990	0.63	0.57	0.67	0.63
1991-2000	0.60	0.58	0.63	0.62
2001-2010	0.62	0.60	0.64	0.63

Table 3. The frequency [%] of predicted maximum air temperatures in its chosen intervals [°C] and succeeding 10-years periods according the MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models over the years 1981-2100 and the values observed in Warsaw Okęcie in the period 1981-2010.

	<-25;-20)	<-20;-15)	<-15;-10)	<-10;-5)	<-5;0)	<0;5)	<5;10)	<10;15)	<15;20)	<20;25)	<25;30)	<30;35)	<35;40)	<40;45)
MPI-M-REMO-ECHAM5														
1981-1990	–	0.11	0.47	2.35	6.98	19.52	14.24	14.46	20.07	16.16	4.76	0.88	–	–
1991-2000	–	–	0.41	1.20	5.58	19.90	14.29	15.60	20.01	17.03	5.37	0.60	–	–
2001-2010	–	0.22	0.90	2.38	6.93	19.58	13.09	16.35	19.88	15.31	4.65	0.71	–	–
2011-2020	–	0.08	0.36	2.03	6.82	19.71	12.46	13.82	18.07	18.15	7.34	1.18	–	–
2021-2030	–	0.08	0.38	1.37	6.30	21.22	13.91	14.43	19.63	16.59	5.23	0.82	0.03	–
2031-2040	–	–	0.05	1.01	4.19	16.32	17.41	14.70	19.13	19.68	6.60	0.88	0.03	–
2041-2050	0.03	0.05	0.22	0.85	4.79	17.47	16.95	15.03	19.11	18.54	5.89	1.01	0.05	–
2051-2060	–	0.05	0.16	0.52	2.66	16.51	18.40	15.90	18.29	18.12	7.97	1.37	0.05	–
2061-2070	–	–	0.25	0.99	3.67	14.16	17.63	16.24	17.61	18.98	8.27	2.16	0.05	–
2071-2080	–	–	–	0.33	2.00	13.77	19.11	16.01	18.92	18.78	8.84	1.89	0.36	–
2081-2090	–	–	0.11	0.52	1.92	13.28	19.63	14.24	17.50	19.99	9.97	2.55	0.30	–
2091-2100	–	–	0.19	0.71	1.89	12.54	20.02	16.02	16.02	20.18	10.05	2.05	0.33	–
DMI-HIRHAM5-ARPEGE														
1981-1990	–	0.03	0.52	1.56	6.57	16.62	18.35	12.60	13.94	14.84	11.83	3.01	0.14	–
1991-2000	–	0.08	0.47	2.41	7.66	15.08	16.37	13.03	14.48	15.47	10.43	4.38	0.14	–
2001-2010	–	–	0.27	1.62	6.08	14.68	18.37	15.01	14.76	14.57	10.73	3.70	0.22	–
2011-2020	–	–	0.71	2.11	6.38	17.11	17.14	12.67	13.50	14.92	10.65	4.38	0.44	–
2021-2030	–	0.05	0.30	1.92	5.86	15.47	18.67	14.18	13.25	13.88	11.25	4.71	0.44	–
2031-2040	–	0.08	0.22	1.18	5.23	14.18	21.16	13.66	13.52	14.59	10.29	5.37	0.47	0.05
2041-2050	–	–	0.66	1.53	5.48	13.58	17.77	14.62	14.16	14.81	10.93	5.86	0.60	–
2051-2060	–	0.08	0.33	1.59	5.12	13.28	17.60	13.96	13.55	14.67	11.91	6.60	1.29	0.03
2061-2070	–	0.05	0.25	1.48	4.57	12.02	18.26	16.02	13.91	14.98	11.09	6.11	1.15	0.11
2071-2080	–	–	0.08	1.31	5.86	13.74	18.59	13.99	12.24	15.25	11.69	5.72	1.53	–
2081-2090	–	–	–	1.23	3.53	12.90	21.36	15.80	12.24	13.69	12.05	6.54	0.66	–
2091-2100	–	–	0.27	0.82	2.88	12.73	21.71	14.76	12.13	12.92	11.69	8.00	2.03	0.05
Okęcie (observed)														
1981-1990	0.03	0.14	0.49	2.22	6.90	17.03	14.27	14.76	17.33	17.47	8.24	1.12	–	–
1991-2000	–	–	0.49	2.05	7.23	16.75	15.93	13.55	15.82	16.86	9.28	1.81	0.22	–
2001-2010	–	0.08	0.44	2.41	7.48	15.69	12.65	14.90	15.94	17.03	10.79	2.55	0.05	–

station, although the value is lowered. According to this model, we shouldn't expect perceivable maximum temperatures of above 35°C to occur until after 2021, whilst 10 examples were recorded between 1991 and 2010. According to the ARPEGE model the frequency of temperatures in the range 15-25°C, which in the summer means comfortable conditions for the human body or low heat stress, will be significantly lower, whilst the frequency of extreme high temperatures will rise. It seems that this is the climate change trend that will be observed in the 21st century. In the ECHAM5 model, the maximum temperature values achieve a smaller range, are lower and are often within the boundaries of thermally comfortable conditions (Figs. 3, 4).

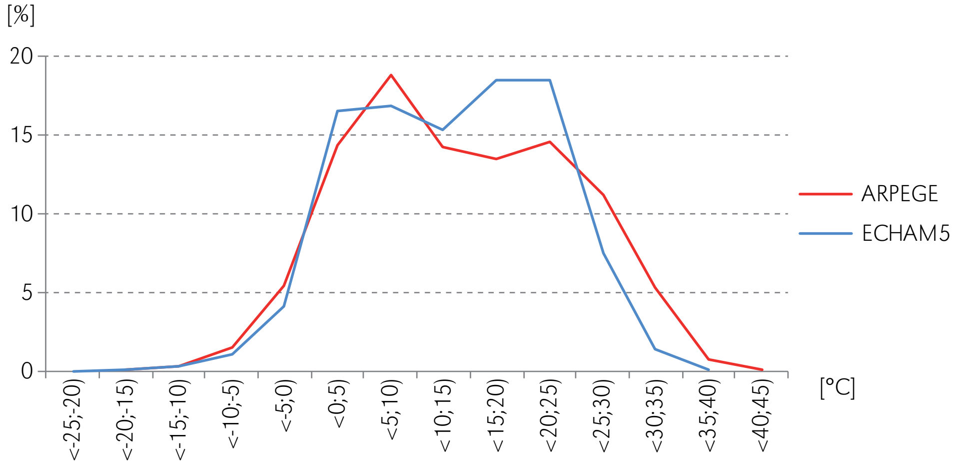

Figure 3. Mean frequency [%] of predicted maximum air temperatures in its chosen intervals [°C] according the MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE over the years 1981-2100.

When the analysis includes the highest values and actual and modelled maximum air temperature in Warsaw, the difference between the two models become even clearer. The forecasted absolute maximum air temperatures according to ECHAM5 are lower than 36.4°C, which was noted at the Warsaw Okęcie station. Whilst according to the ARPEGE model, the maximum air temperature could reach as much as 43.4°C (Fig. 5).

An analysis of the modelled maximum temperature values above 30°C, according to ECHAM5, doesn't point towards a rise above the presently observed values until 2070. Whilst the ARPEGE model forecasted a doubling of the number of days with temperatures from 30 to 35°C, and also above 35°C, in the period 1981-2010. According to ARPEGE, after 2040, the frequency of hot days could rise by 3.5-4 times, whilst the maximum temperature of ≥35°C could be 12 or even 17 times more frequent in comparison with the years 1981-2010 (Fig. 6).

The ECHAM5 significantly lowers the possible air temperature values, while the ARPEGE model probably increases them. Therefore, the forecast from both models, analysed together, seems to give a good framework which the thermal conditions of the 21st century will not exceed.

In order to estimate the risk of heat waves it was also necessary to compare the recorded heat waves at the Warsaw Okęcie station in the period 1981-2010, with those forecasted until the end of the 21st century (Tab. 4). In the period 1981-2010, 26 3-day heat waves were noted in total, which occurred between May and August. Also there were 6 5-day heat waves which occurred in July and August. Assuming that the 3-day heat waves occurred between May and August and the 5-day heat waves in July and August, this corresponds to an average of 2.2 3-day heat waves per month and and in July and August one 6-day heat wave. The ECHAM5 model lowered the number of 3-day heat waves by 70%, whilst ARPEGE increased it by 100% (52 3-day heat waves). In the case of 5-day heat waves, ECHAM5 lowered the value by 67%, while ARPEGE increased it by 250%. According to ECHAM5, it will not be until after 2070 that the number of forecasted 5-day heat waves will equal the actual observed number in the period 1981-2010 and until then it will be significantly lower.

According to the forecasted number of heatwaves in the next 30 years of the 21st century, ECHAM5 predicts a lower or similar number to that which is observed, while ARPEGE predicts a rise of 370% of 3-day heat waves after 2040 and 460% after 2070. In accordance with ARPEGE, the number of 5-day heat waves after 2040 will be 7 times higher and after 2070 almost 8 times higher than the number observed in the period 1981-2010 (Fig. 7).

Together with the rise in the number of heat waves, a lengthening in the period of their occurrence is also forecast. Until present they have been recorded between June and August, but in

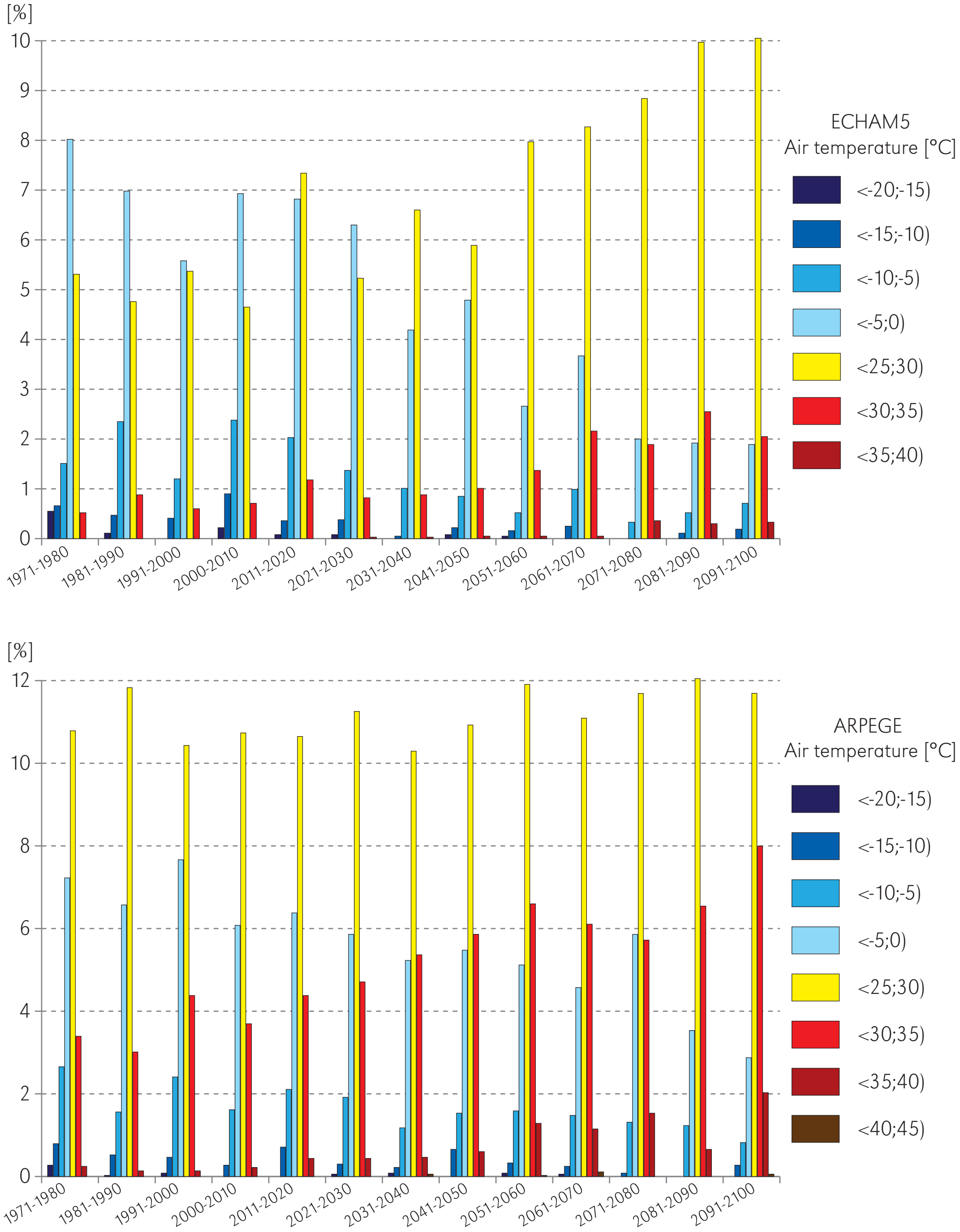

Figure 4. The frequency [%] of predicted maximum air temperature in its chosen intervals [°C] according to MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models in the succeeding 10-year periods of the 20th and 21st centuries.

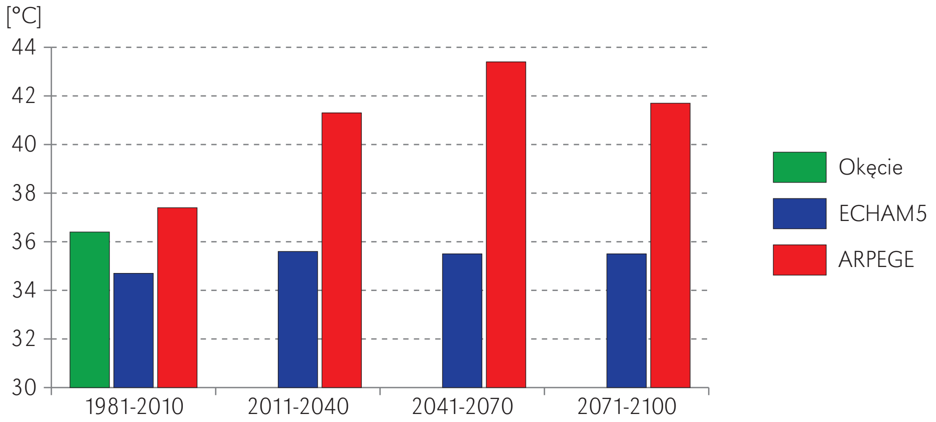

Figure 5. Observed (Warsaw Okęcie) and predicted maximum air temperatures according to MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models in the succeeding 30-years periods of 20th and 21st centuries.

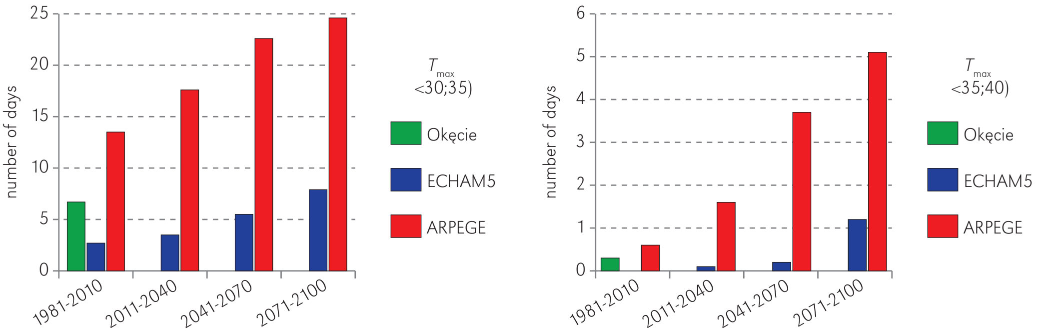

Figure 6. Observed (Warsaw Okęcie) and predicted mean number of days with given maximum air temperature intervals from 30°C to 35°C and from 35°C to 40°C according to MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models in the succeeding 30-years periods of 20th and 21st centuries.

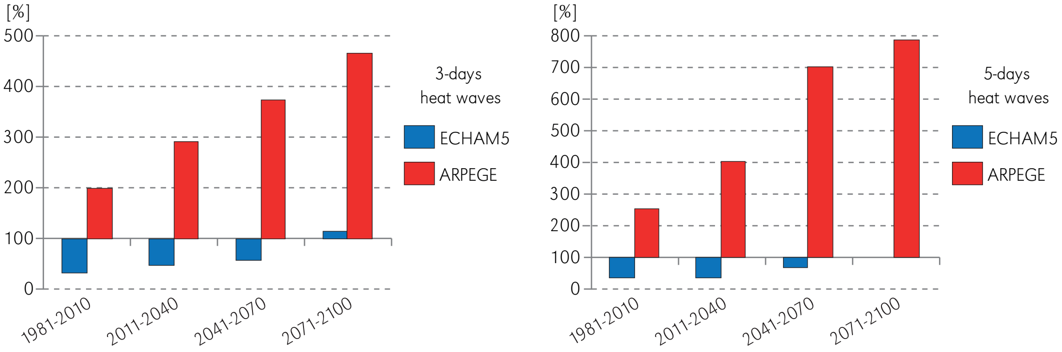

Figure 7. Predicted change of the frequency [%] of the heat waves lasting at least 3 and 5 days in the succeeding 30-years periods according to MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models comparing to the observed heat waves at Warsaw Okęcie station over the years 1981-2010.

Table 4. Number of heat waves defined as: minimum 3- and 5-day periods with maximum air temperature ≥30°C and months of their occurrence in the succeeding 10-year periods according to MPI-M-REMO-ECHAM5 and DMI-HIRHAM5-ARPEGE models.

Model	ECHAM5				ARPEGE			
period	no. of heat waves (3-day)	time of occurence	no. of heat waves (5-day)	time of occurence	no. of heat waves (3-day)	time of occurence	no. of heat waves (5-day)	time of occurence
1981-1990	3	VI-VIII	1	VIII	14	VI-IX	3	VII-IX
1991-2000	2	VI-VII	–	–	21	VI-IX	6	VI-VIII
2001-2010	3	VII	1	VII	17	VI-IX	6	VI-VIII
2011-2020	6	VI-VIII	1	VI	22	V-IX	10	VI-IX
2021-2030	2	V-VI	–	–	25	V-IX	4	VII-VIII
2031-2040	4	VI-VIII	1	VIII	29	VI-IX	10	VI-VII
2041-2050	4	VI-VII	–	–	26	VI-IX	12	VI-VIII
2051-2060	3	VI-VII	–	–	33	VI-IX	16	VI-IX
2061-2070	8	VII-IX	4	VII-IX	38	VI-IX	14	VI-IX
2071-2080	11	VI-VIII	2	VII-VIII	29	VI-IX	12	VI-IX
2081-2090	12	V-IX	1	VIII	44	VI-IX	12	VI-IX
2091-2100	7	VI-VIII	3	VII-VIII	48	V-IX	23	VI-IX

Observed data at the station Warsaw Okęcie over the years 1981-2010

period	no. of heat waves (3-day)	time of occurence	no. of heat waves (5-day)	time of occurence
1981-1990	3	VII-VIII	–	–
1991-2000	11	VI-VIII	2	VII-VIII
2001-2010	12	V-VIII	4	VII

the future they will occur between May and September, although sporadically in May, but very often in September. This is significant information, as early, spring heat waves will lead to the described significant rise in mortality. On the other hand, late heat waves, which now occur in August, but may occur in September in the future, will not cause such a rise in the number of deaths. This is due to human adaptation to conditions after the summer (Tab. 4).

The potential rise in mortality rates in heat waves until the end of the 21st century

Therefore, assuming the previously described rise in risk of mortality during heat waves among people aged 65 or above, as well as the forecasted number of heat waves, the overall risk of mortality and that of those with cardiovascular disease in the next 30 years of the 21st century has been estimated. An average mortality risk has been assumed, calculated on the basis of mortality rates in the period 1993-2002 for 16 Polish towns, where the overall mortality rate was +19% and for cardiovascular patients was +22%. The calculation for Warsaw during the longest and most intense heat waves from the end of July and beginning of August 1994 was assumed as the maximum risk. It amounted to +33% overall deaths and +37% for cardiovascular patients.

In effect the ECHAM5 model with the minimum of 3-day heat waves until 2070 forecasts a drop in mortality rate in relation to that recorded in the period 1993-2002 (Fig. 8). The change in mortality rate was calculated under the assumption that the average mortality rate amounted to -8% for 2041-2070 due to cardiovascular disease. When assuming the maximum mortality risk in the same period and with the same causes of death, the change reaches -14% and -20% respectively. After 2070, according to the ECHAM5 model, there is a small forecasted increase in mortality reaching 5.5% in the cardiovascular group. In contrast, the ARPEGE model predicts a very large increase in mortality. Taking the average risk of death into account, the rise in mortality will be between 36% in overall deaths in the period 2011-2040 and 80% in the cardiovascular group after 2070. Assuming the maximum risk of death, causes the predicted rise in mortality in the same periods and groups of 63% and 134% respectively (Fig. 8).

Therefore, the possible change in mortality rates in 3-day heat waves ranges between -20% due to cardiovascular disease in the period 2011-2040, according to the ECHAM5 model and a fall in heat wave occurrence, to 134% in the period after 2070 according to the ARPEGE model. The forecast rise in mortality (calculated on the basis of the average for Poland and the highest recorded death rates for Warsaw) could be higher than present by 230% assuming the highest mortality risk values in heat waves confirmed in 1994 in Łódź or in Wrocław and reaching +64%.

The predicted significant fall in the number of recorded 5-day and longer heat waves, according to the ECHAM5 model, will result in a fall in overall mortality of 22%, and after 2070 it will equal the present state. However, according to ARPEGE, there will be a 6 times higher number of 5-day heat waves after 2040, which could result in a rise in mortality rates of over 225% and deaths due to cardiovascular disease of over 252% (Tab. 5). One can assume that the 2 scenarios will be the limits between which the actual (probable) rise in number of heat waves and, thus, mortality rates will occur.

Due to the unreal, lowered forecasts by the ECHAM5 model, a supplementary picture of the rise in mortality rates could be the potential rise in death risk (in the form of its numbers) noted in the heat waves forecasted only according to the ARPEGE model. In Warsaw, on every day of the

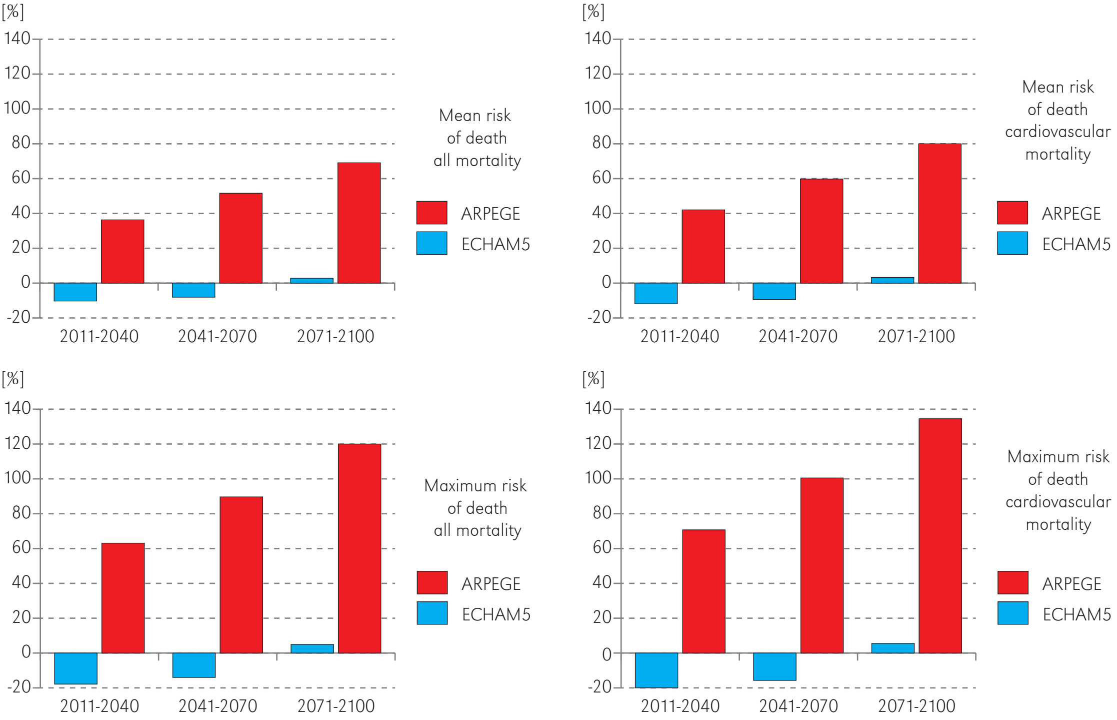

Figure 8. At least 3-day heat waves – predicted rise / fall of the death risk [%] during heat waves among people over 65 years of age in the succeeding 30-year periods of the 21st century and assumed death risk.
Mean risk of death: +19% among all mortality and +22% among cardiovascular mortality
Maximum risk of death: +33% among all mortality and +37% among cardiovascular mortality

Table 5. At least 5-day heat waves – predicted rise / fall of the death risk [%] during heat waves among people over 65 years of age in the succeeding 30-year periods of the 21st century and assumed death risk.
Mean risk of death: +19% among all mortality and +22% among cardiovascular mortality
Maximum risk of death: +33% among all mortality and +37% among cardiovascular mortality

Period	MPI-M-REMO-ECHAM5				DMI-HIRHAM5-ARPEGE			
	all mortality		cardiovascular mort.		all mortality		cardiovascular mort.	
	mean risk	max risk	mean risk	max risk	mean risk	max risk	mean risk	max risk
2011-2040	-12.7	-22.0	-14.7	-24.7	57.0	99.0	66.0	111.0
2041-2070	-6.3	-11.0	-7.3	-12.3	114.0	198.0	132.0	222.0
2071-2100	0.0	0.0	0.0	0.0	129.8	225.5	150.3	252.9

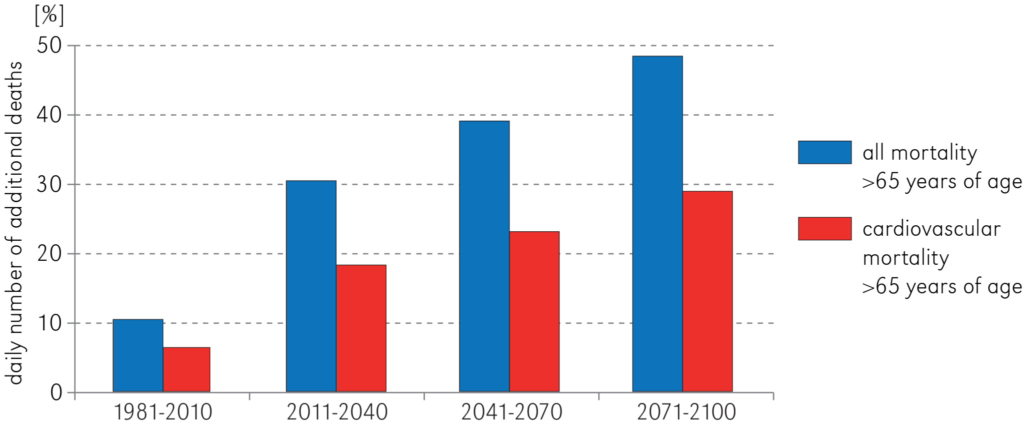

Figure 9. The potential additional daily overal number of deaths and those due to cardiovascular disease among those over 65 years of age in Warsaw during heat waves, forecasted according to the DMI-HIRHAM5-ARPEGE model.

1994 heat wave and just after its end, 10.5 additional deaths were recorded among people aged 65 and over due to cardiovascular disease. According to the extreme forecasts of the ARPEGE model after 2070, the additional number of deaths among the elderly during heat waves in Warsaw could be 49 including 29 due to cardiovascular disease (Fig. 9). The final total of deaths, taking the 'harvesting effect' into account, could be over 60% less.

Conclusions

In Warsaw, in the period 1981-2010, there were 26 heat waves lasting at least 3 days, but during just 2 of those heat waves was a significant statistical rise in mortality noted amongst those aged over 65. The average rise in mortality in heat waves calculated on the basis of data from the 16 largest cities in Poland was 15% overall and 22% among those with cardiovascular disease. This was similar to data recorded in the Czech Republic or Hungary, for example (Kozłowska-Szczęsna et al. 2004; Kyselý 2004; Idzikowska 2011).

The investigated ECHAM5 model seems to significantly lower the possible air temperature values, whilst ARPEGE probably slightly increases them. According to the first model, the number of heat waves to the end of the 21st century will be lower than present and will reach the levels recorded during the period 1981-2010. Whereas ARPEGE, in every decade, predicts an increase in heat waves. According to this model, after 2070, we will have 4.5 times as many 3-day heat waves and almost 8 times as many 5-day heat waves. It is possible to assume that the forecasts of these 2 models, analysed together, form a good parameters, which the thermal conditions in Poland will probably not exceed during the 21st century.

Such a rise in extremely hot atmospheric conditions will probably lead to a mortality rate due to heat waves which is several times higher than present. Of course, the final total of deaths, taking into account the natural drop in mortality after a period of its increase, may be over 60% lower, however, during the actual heat wave the medical services should be prepared to help a much higher number of patients than usual.

In this work calculations based on the ECHAM5 model were used, with the knowledge that the Max Planck Institute for Meteorology had developed a new version of ECHAM – ECHAM6 which represents the present climate as well as, or better than, its predecessor (Stevens et al. in print). However, the forecasted air temperature calculated on the basis of ECHAM6 was not available to the author.

For the Fifth Assessment Report of the IPCC (2013), the scientific community has defined a set of four new scenarios, denoted Representative Concentration Pathways (RCPs) instead of SRES scenarios. They are identified by their approximate total radiative forcing in the year 2100 relative to 1750: 2.6 W·m^{-2} for RCP2.6, 4.5 W·m^{-2} for RCP4.5, 6.0 W·m^{-2} for RCP6.0, and 8.5 W·m^{-2} for RCP8.5. These four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5). RCPs are based on a combination of integrated assessment models, simple climate models, atmospheric chemistry and global carbon cycle models (Meinhausen et al. 2011; IPCC 2013).

Thus, the majority of future climate projections will be based on the RCP scenario instead of the SRES. According to these, however, at the end of the 21st century (2081-2100), the projections regarding the number of sultry days and heat waves are the same – with 99-100% probability the number of hot days and tropical nights will rise, while there is 99-100% probability that the frequency and duration of heat waves will increase.

The predicted change in average surface temperature between 1986-2005 and 2081-2100 in Central Europe reaches 1-1.5°C with RCP 2.6-4.5°C assuming RCP of 8.5. In the case of RCP 8.5, when the combined CO$_2$-equivalent concentrations would reach 1313 ppm, the average surface temperature in north-east Europe rose by as much as 7-9°C (IPCC 2013).

Therefore, the calculated forecast according to the ARPEGE model is highly probable.

However, the results described above must be taken with a great degree of caution, as there are many unknowns. The adaptation process of the population to hot conditions is unknown, as is the speed of equipping private apartments in Poland with air-conditioning units. However, what is known is the constant aging tendency of the Polish population, in other words, the lengthening of its life and, inevitably, in the second half of the 21st century, the group of those aged over 65 or 75, which is most sensitive to extreme thermal conditions, will be a greater percentage of the population than it is today. On the other hand, they may be people who will take greater care of their health, in better physical condition and therefore less sensitive to heat waves than we are now. However, irrespective of the aforementioned unknowns, scientists are agreed on the direction climate change is heading and the currently observed increase in the frequency of extreme phenomena in Poland, including heat waves.

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