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The Summers 2003 and 2015 in South-West Germany: Heat Waves and Heat-Related Mortality in the Context of Climate Change

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Abstract: After 2003, another hot summer took place in Western and Central Europe in 2015. In this study, we compare the characteristics of the two major heat waves of these two summers and their effect on the heat related mortality. The analysis is performed with focus on South-West Germany (Baden–Württemberg). With an additional mean summer mortality of +7.9% (2003) and +5.8% (2015) both years mark the top-two records of the summer mortality in the period 1968–2015. In each summer, one major heat wave contributed strongly to the excess summer mortality: In August 2003, daily mortality reached anomalies of +70% and in July 2015 maximum deviations of +56% were observed. The August 2003 heat wave was very long-lasting and characterized by exceptional high maximum and minimum temperatures. In July 2015, temperatures were slightly lower than in 2003, however, the high air humidity during the day and night, lead to comparable heat loads. Furthermore, the heat wave occurred earlier during the summer, when the population was less acclimated to heat stress. Using regional climate models we project an increasing probability for future 2003- and 2015-like heat waves already in the near future (2021–2050), with a 2015-like event occurring about every second summer. In the far future (2070–2099) pronounced increases with more than two 2015-like heat waves per summer are possible.

Keywords: heat-waves; heat-related mortality; 2003; 2015; climate change; Germany

1. Introduction

High temperatures are an established risk factor for human health [1]. Heat waves, usually understood as periods of persistent hot conditions, have been found to be associated with sharp increases in mortality all over the globe [2]. Similar effects are found using morbidity data [3]. Understanding how heat waves affect human health is an important key for the preparation and adaptation to the projected increase in heat wave durations and frequencies [4].

The risk of suffering from adverse health effects due to heat stress is related to different physiological or socioeconomic factors. In particular, older, frail people are highly vulnerable to heat stress [5] and patients with chronic deseases, e.g., cardiovascular or respiratory diseases [6]. The physiological mechanisms of the adverse health effects are well known and documented, e.g., dehydration and reduced blood viscocity, which increases the risk for thrombosis [7]. The general stress for the cardiovascular system associated with the work required to maintain thermoregulation induces another risk factor [8]. Moreover, socioeconomic ascpects like living alone [9] or living in dense urban areas [10] can increase the risk of dying during a heat wave.

In Europe, the record breaking summer of 2003 has received particular attention due to the pronounced health impacts. In particular, the August 2003 heat wave lead to large increases in the mortality rates from

Spain [11] over France [12], Italy [13], and Germany [14,15] to Austria [16]. Overall, the heat waves of the summer 2003 caused more than 80,000 additional deaths in 12 European countries [17].

As a consequence of the summer 2003, several European countries installed heat health warning systems (HHWS) to inform the health system and the public of possible threads due to upcoming heat waves [18]. In Germany, for instance, a HHWS is operational since 2005 and raises heat warnings based on the human-biometeorological index Perceived Temperature and a building simulation model [19].

In 2015, another very warm summer took place in Europe. Across Europe several temperature records were set from London over Paris and Berlin to Dobřichovice in the Czech Republic [20,21]. For Germany, the nationwide highest temperature was observed in Kitzingen (central Germany) with 40.3 °C on 5 July. and again on 7 August. While the 2003 heat waves were centered over Western and Central Europe, the heat waves of the summer 2015 were more pronounced over Central and Eastern Europe (Figure 1) [20,22].

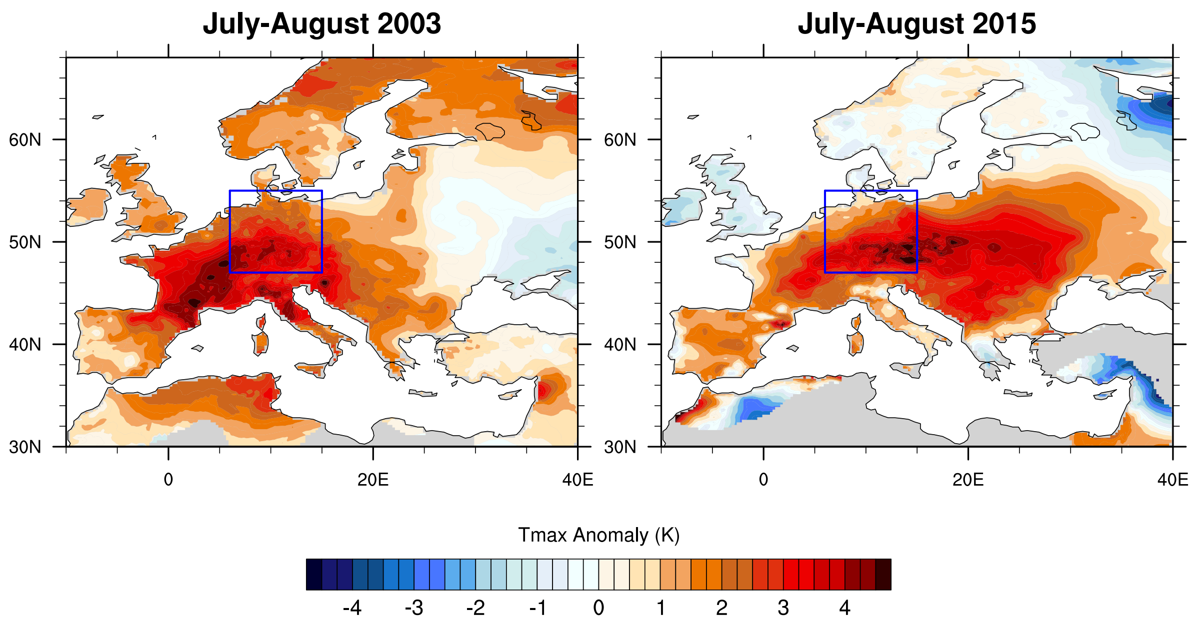

Figure 1. July–August 2003 (**left**) and July–August 2015 (**right**) daily maximum temperature (Tmax) anomalies with respect to 1981–2010 based on the E-OBS dataset (version 16.0) [23]. Within the bounding box of Germany, which is shown by the blue box, a mean July–August daily Tmax anomaly of 2.8 °C is found for both summers.

For Germany, daily maximum temperature July–August anomalies of 2.8 °C with respect to 1981–2010 are found for both summers, when using the E-OBS data set and averaging over an area in Central Europe covering Germany (Figure 1).

In general, an increasing frequency of record breaking heat waves has been observed in the recent decades: from the 2003 heat wave in Western Europe, to the 2010 heat wave in Eastern Europe and Russia, to the heat waves of the summer 2015 [24–26]. For several of these events, an anthropogenic fingerprint could be found: Stott et al. [27], for instance, estimated that the human influence on the climate system has doubled the probability for temperatures extremes as found in 2003. Similar findings apply for the summer heat waves of 2015 [28]. With the ongoing anthropogenic climate change, a further increase in the number of heat waves in the upcoming decades is very likely [4]. Given the pronounced negative health effects of heat waves, improving the adaptation of the population to heat waves is therefore crucial.

The 2003 and 2015 heat waves have been ranked as the second and sixth most severe European events with respect to their intensity and spatial extend [26]. Germany was affected by both heat waves. Here, we present a comparison of the two summers 2003 and 2015 focusing on similarities and differences with respect to the meteorological conditions and the health impact with a focus on South-West Germany. In the context of climate change, we furthermore assess the likelihood of similar heat waves in the near and far future, using regional climate model (RCM) simulations.

2. Data and Methods

2.1. Health Data

Daily mortality data for the federal state Baden–Württemberg (South-West Germany, population 10.9 Mio in 2015) for the period 1968 to 2015 were provided by the Statistisches Landesamt Baden–Württemberg. This absolute all-cause mortality was transformed to mortality rates (deaths per 100.000 inhabitants) to reduce possible biases due to changes in the population size. Therefore, daily population data were linearly interpolated from the annual values. To estimate the additional mortality associated with extreme weather conditions, we calculated the baseline mortality following an approach of Koppe and Jendritzky [29]. Therefore, a 365-day Gaussian smoothing was fitted to the mortality rates in a first step. The smoothing removed any long-term trends from the data, but is only weakly influenced by single influenza episodes or heat waves. The beginning/end of the time series were padded with artificial data, resembling the average annual cycle of the first/last five years, to allow for the computation of the Gaussian filter for the full data period. Since the Gaussian smoothing with a one-year window resulted in an underestimation of the annual cycle, the smoothed time series was adjusted with a correction factor in a second step. The correction factor was chosen in the way, which minimizes the differences between the original values and the smoothed curve. In the following, the baseline mortality is represented by the adjusted 365-day smoothed mortality rates and mortality anomalies were calculated by deviations of the absolute mortality rates from this baseline.

Although this analysis focuses only on the years 2003 and 2015, the full 48 yr period was used to estimate the singularity of the years 2003 and 2015. For comparison to the reference period of the meteorological data, the same period 1971–2000 was used to estimate the standard deviation (σ) of the mortality data. Any long-term trends in the mortality record were removed by the complex approach to estimate the baseline mortality, and do not affect the calculation of σ over the 30 yr period.

2.2. Meteorological Data

Since mortality data was available for South-West Germany, the analysis of the meteorological conditions also focused on this region. Hourly observational measurements of 2 m air temperature and humidity for the weather stations Freiburg, Stuttgart, and Mannheim were extracted from the database of the Deutscher Wetterdienst. For each observation time, the average over the three stations was calculated to represent the average for the federal state Baden–Württemberg. Note, this average can not resemble an area weighted average over the entire federal state, due to the large topographical differences within the federal state, reaching from the Upper-Rhine valley (about 200 m. a.s.l.) to the highest altitudes of the Black Forest and the Swabian Alb (above 1000 m a.s.l). By focusing on the three larger cities—with two of them being situated in the south and the north of the warm and densely populated Rhine valley—this approach allows to estimate the meteorological conditions perceived by the majority of the population of Baden–Württemberg. Estimates for the mean climate, the standard deviation, and percentiles were calculated over the reference period 1971–2000.

In addition to the direct meteorological observations we calculated the index HUMIDEX, which combines the thermal load due to air temperatures and water vapour pressures. HUMIDEX was calculated using hourly air temperature and dew point observations [30]. In a first step the HUMIDEX was computed for each station. In a second step the Baden–Württemberg average was derived as described above. The daily minimum and maximum values of the parameters considered were calculated based on the hourly average values of the Baden–Württemberg average.

2.3. Climate Model Data

16 RCM experiments for Europe from the World Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX) initiative [31] were used to estimate future changes in the number of extreme heat waves per summer (Table 1). All simulations were performed with a high resolution of 12.5 km for the past (historical) and the future under the Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5. For two of the 16 RCMs, the RCP4.5 simulation was not available. The boundary conditions for the RCMs were taken from different global models (compare Table 1).

Table 1. Overview of the CORDEX EUR-11 simulations used in this study [31].

RCM	Driving GCM	Modelling Center	Scenarios
CLM	CanESM2	CLM Community with contributions by BTU, DWD, ETHZ, UCD, WEGC	historical, RCP8.5
CLM	CNRM-CM5		historical, RCP4.5, RCP8.5
CLM	EC-EARTH		historical, RCP4.5, RCP8.5
CLM	MIROC5		historical, RCP8.5
CLM	HadGEM2-ES		historical, RCP4.5, RCP8.5
CLM	MPI-ESM-LR		historical, RCP4.5, RCP8.5
CNRM	CNRM-RM5	Météo France	historical, RCP4.5, RCP8.5
HIRHAM5	EC-EARTH	Danish Meteorological Institute, Copenhagen, Denmark	historical, RCP4.5, RCP8.5
WRF	IPSL-CM5A-MR	Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA/CNRS/UVSQ and Contributors INERIS Institut National de l'Environnement Industriel et des Risques, Verneuil en Halatte, France/Institut Pierre Simon Laplace, CNRS, France	historical, RCP4.5, RCP8.5
RACMO22E	EC-EARTH	Royal Netherlands Meteorological Institute, Ministry of Infrastructure and the Environment	historical, RCP4.5, RCP8.5
RACMO22E	HadGEM2-ES		historical, RCP4.5, RCP8.5
RCA4	CNRM-CM5	Rossby Centre, Swedish Meteorological and Hydrological Institute, Norrkoping Sweden	historical, RCP4.5, RCP8.5
RCA4	EC-EARTH		historical, RCP4.5, RCP8.5
RCA4	CM5A-MR		historical, RCP4.5, RCP8.5
RCA4	MPI-ESM-LR		historical, RCP4.5, RCP8.5
RCA4	HadGEM2-ES		historical, RCP4.5, RCP8.5

For each simulation, the data at the grid points of Freiburg, Stuttgart, and Mannheim was extracted and the HUMIDEX was calculated based on the modeled daily mean 2 m temperature and dew point temperature. The Baden–Württemberg average was calculated by averaging over the three stations.

The analysis of the RCM data was performed for three different time frames: 1971–2000 was used as reference period to identify possible biases between model simulations and observations. The future projections were evaluated for the near (2021–2050) and far (2070–2099) future. The uneven period for the far future is related to the fact that not all model simulations were available until the year 2100.

The model spread is quantified by the interquantile range (IQR, resembling the box area of a boxplot), which is defined by the range which contains exactly 50% of the values of a distribution. Model results and range are given as multi-model mean, separately for each scenario and time period.

3. Results

3.1. Comparison of the 2003 and 2015 Heat Waves

Focusing first on the meteorological summer season (Figure 2), we found an JJA daily maximum temperature anomaly of 5.6 °C and 3.2 °C for 2003 and 2015, respectively, corresponding to 4.7 and 2.7 standard deviations of the interannual variability of the 30 yr period 1971–2000. With these anomalies, the two summers correspond to the two warmest summers since 1968, with respect to the average daily maximum temperature.

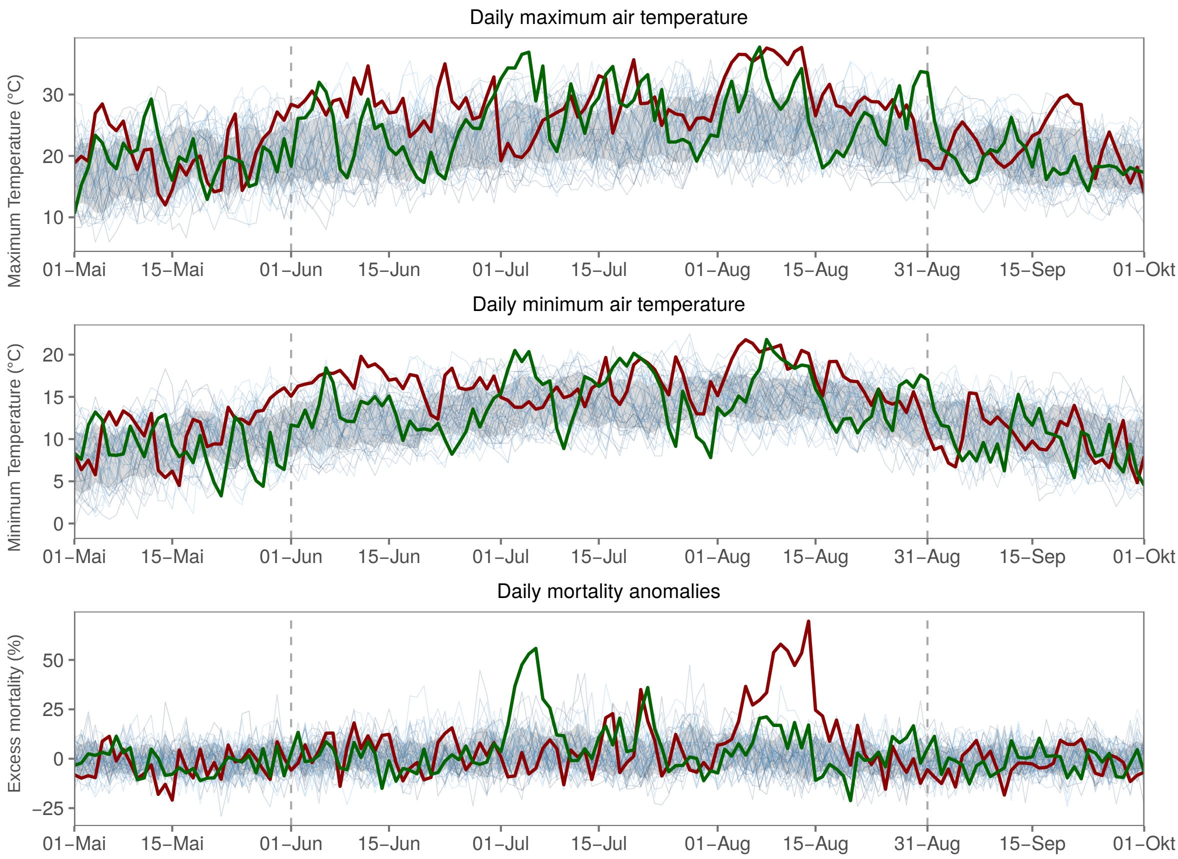

Figure 2. Daily maximum temperature (**top**), daily minimum temperature (**middle**), and daily excess mortality (**bottom**) from May to September in Baden-Württemberg. Beginning and end of the climatological summer season is highlighted by the vertical gray dashed lines. The summer 2003 is displayed in red; green lines denote the conditions of the summer 2015. Other years of the period 1968–2015 are shown by the thin gray lines in the background. The gray shading denotes the standard deviation of the corresponding parameter, estimated over the reference period 1971–2000.

In the JJA mortality data similar anomalies occurred. Averaged over the summer season a daily excess mortality of 7.9% and 5.8% was found for 2003 and 2015, respectively (3.9 and 2.6 standard deviations), making the two summers the summers with the highest summer mortality since 1968. With respect to the average population size of the years 2003 and 2015 these anomalies correspond to about 1770 additional deaths during the summer 2003 and about 1380 additional deaths in 2015.

To identify possible anomalies in the preceding seasons or potential effects of mortality displacement in the seasons following the summer, we briefly assessed the mortality anomalies for all seasons of the years 2003 and 2015. In the winter seasons (December to February) prior to the summers 2003 and 2015, a flu epidemic took place, however, only in 2015 a pronounced increase in the mortality anomalies of the winter season was found (compare Table 2). During the spring season (March to May) of 2003 and 2015, mortality was close to normal. Similarly, the mortality anomalies during autumn (September to November) and winter are within the normal range of variability.

Table 2. Seasonal mortality anomalies (%) with respect to the baseline for the years 2003 and 2015. †: For 2015 only December was available, therefore, no DJF anomaly could be calculated.

Season	2003	2015
December–February (previous)	0.9	7.2
March–May	1.1	0.9
June–July	7.9	5.8
September–November	1.3	0.3
December–February (following)	1.1	– †

Furthermore, no pronounced periods of negative anomalies took place within the summer seasons (Figure 2). In 2015 a few days with mortality anomalies below the long term range of variability are visible around August 20, and in 2003, a tendency towards below average mortality values can be found towards the end of August. Overall, however, negative anomalies are very rare, suggesting no distinct mortality displacement.

Heat related mortality, however, is particularly sensitive to multi-day periods with enhanced heat stress, i.e., heat waves (e.g., [32]). In Figure 2 one major event with enhanced mortality values and high temperatures can be identified per summer: In 2003 a pronounced increase of the mortality rates took place in August, with strongly positive values for up two weeks. In 2015 a period of persistent positive mortality anomalies occurred in early July, lasting for about 9 days. Furthermore, a few days with positive mortality values show up in the second half of July for both summers and a weakly positive event in the first half of August 2015.

The major deviations of the mortality values, however, were found in early July 2015 and early August 2003. The development of the minimum and maximum air temperature, dew point temperature, and HUMIDEX together with the mortality anomalies are shown in Figure 3. The dates are shifted to a common relative time axis with day zero (2 August 2003 and 1 July 2015) being the first day with a daily maximum temperature exceeding the 95th percentile. Since the focus of this analysis is on the heat-related mortality during theses events, we display the time series of the variables, until the mortality anomalies reach again the level of background variables (anomalies $< \sigma$). Daily air temperature maxima (Figure 3a) and minima (Figure 3d) also exceeded the 90th, 95th, and 99th percentile for several consecutive days, e.g., 11 days in a row are above the 99th percentile of the daily maximum temperature in 2003 and 7 above the 99th percentile of the daily minimum temperature. In 2015, the air temperature values were not as extreme as in 2003, however, 5 and 4 consecutive days above the 95th percentile for the daily maximum and minimum temperature, respectively, are found as well.

Besides the high temperature, also the water vapour content of the atmosphere is of major importance for the perception of heat stress, mainly due to its impacts on the heat loss of the body by evaporation. The daily minimum and maximum dew point temperature (Figure 3b,e) reveal some differences between the two heat waves. In 2003, daily maximum dew points temperatures were almost within the normal range and reached the 90th percentile threshold only during the last two days of the heat wave. During the night, the daily minimum temperature was even below the climatological average. In June 2015, however, very high daily maximum and minimum dew points were measured, related to the transport of warm and moist air from the Mediterranean region into the Rhine valley. The 95th percentile was reached for 5 days in a row for the daily maximum dew points and for 3 (not consecutive) days for the daily minimum values.

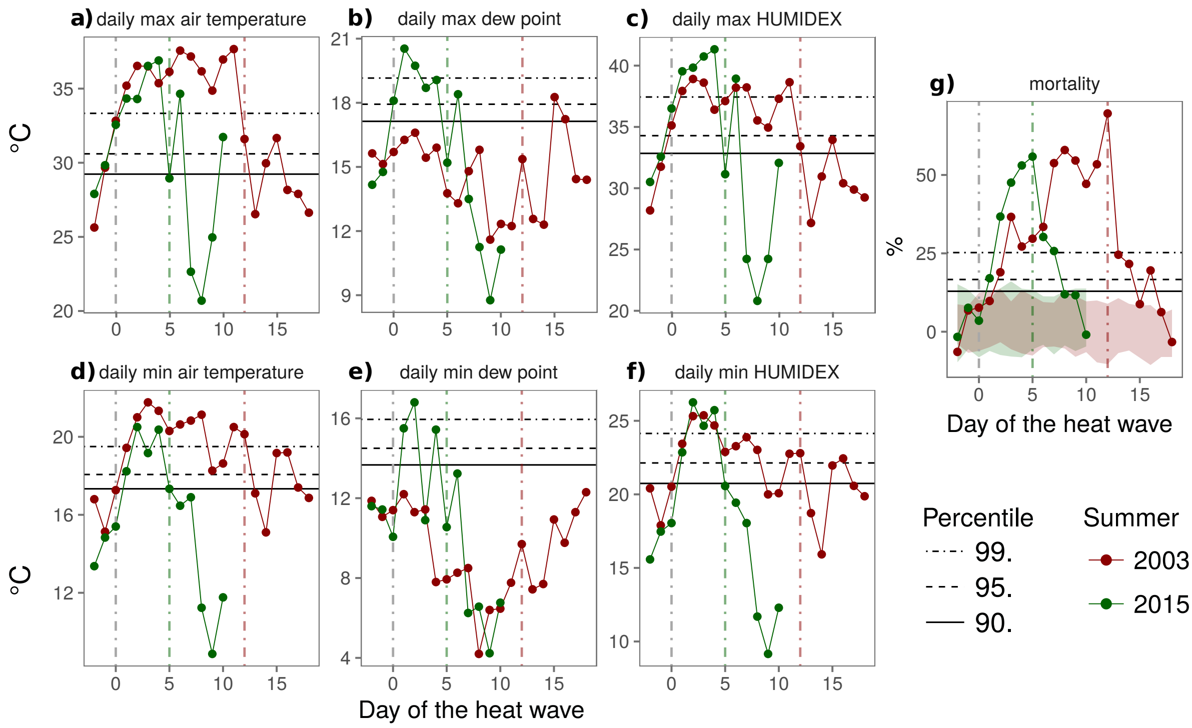

Figure 3. Time series of (**a**–**f**) a number of heat related meteorological parameters and (**g**) daily mortality anomalies (%) for the major heat wave of (red) 2003 and (green) 2015. For each parameter the daily values are displayed together with the 90th, 95th, and 99th percentile threshold calculated over the summer season (JJA) for the period 1971–2000 shown by the horizontal lines. The gray vertical dashed line indicates the beginning of the heat waves; colored vertical dashed lines mark the maximum of the mortality anomalies during the heat wave. (**a**) Daily maximum air temperature (°C); (**b**) daily maximum dew point (°C); (**c**) daily maximum HUMIDEX (°C); (**d**) daily minimum air temperature (°C); (**e**) daily minimum dew point (°C); and (**f**) daily minimum HUMIDEX (°C); (**g**) daily mortality anomalies (%). Shading denotes the background variability in the mortality values estimated for the period 1971–2000, for the time of the year of the 2003 (red) and the 2015 (green) heat wave.

The combined effect of the air temperature and the humidity is described by the HUMIDEX (Figure 3c,f). Accordingly, the higher temperature in 2003 and the higher humidity in 2015 compensate and led to high HUMIDEX values for both events. From the beginning of the heat wave up to one day before the maximum in the mortality data, all daily maximum HUMIDEX values exceeded the 95th percentile threshold for both heat waves (5 and 12 consecutive days for 2015 and 2003, respectively). Furthermore, the daily minimum HUMIDEX passed the 95th percentile for most of the heat wave days. In terms of absolute values, the highest HUMIDEX values were found in 2015, both for the daily maximum and minimum.

When focusing on the mortality time series, the close relationship between the heat load and the mortality becomes clear. In 2003, the mortality anomalies grew constantly until the maximum of +70% was reached after 11 days (14 August; Figure 3g). After this date, mortality began to decline for four days and almost reached the levels of background variability after 15 days at 19 August. In 2015, mortality increased for five days to a maximum anomaly of +56% (6 July). From this date on, mortality decreased for three days until 9 July. The reduction of the mortality anomalies after the maximum was in both cases very fast.

The extraordinary nature of the health impacts of these two heat waves is highlighted by the fact, that both events cross the 99th percentile of the daily summer (JJA) mortality values for 6 (2015) and 10 (2003) consecutive days. Per definition, less than one day per summer is expected to exceed this threshold in an average summer. With respect to the linear interpolated daily population data, about 1390 additional deaths were counted during the August 2003 heat wave. In the July 2015 heat, about 700 cases above the base line were registered. Both heat waves, therefore, contributed to a great extent to the excess deaths of the corresponding summer season.

Figure 3 furthermore suggest a slight lag between the meteorological conditions and the signal in the mortality data. The mortality anomalies lagged behind the daily maximum HUMIDEX exceeding the 95th percentile by 1 or 2 days, for 2015 and 2003, respectively. Consequently, the maximum in the mortality data occured for both heat waves on days where the meteorological parameters indicate a clear reduction of the heat stress (dashed vertical lines in Figure 3c). These patterns suggest a sustained health effect of the heat wave for at least one day.

3.2. The 2003 and 2015 Heat Waves in the Context of Climate Change

In the context of climate change, the number of heat waves is very likely to increase in the next decades [4]. In the following, we quantify the probability for heat waves comparable to the ones of 2003 and 2015 in the near and far future using RCM simulations.

RCM data is usually not available in a temporal resolution higher than daily means. Therefore, the analysis shown in Figure 3 was repeated using the daily mean HUMIDEX (Figure 4a). This approach led to very comparable results. The heat wave of 2003 was now characterized by 8 consecutive days above the 95th percentile, while for 2015, 5 consecutive days were found. To generalize these findings, we assessed the change in heat wave frequencies for all events where the daily mean HUMIDEX exceeds the 95th percentile for 3 to 10 consecutive days. Therefore, we calculated the 95th temperature percentile for each model separately to reduce the influence of model biases on the analysis [33]. The 95th temperature percentile was calculated using the reference period 1971–2000.

First, the RCM's capability to simulate these heat waves was assessed (Figure 4b). In the reference period the RCMs tend to overestimate the average number of heat waves per year for all durations. Heat waves with a duration of three days, for instance, occured on average every second summer in the observations (0.5 events/yr), while the multi model ensemble median suggest a frequency of about 0.6 events/yr. While for most durations at least a few models simulate frequencies comparable to the observations, the medium-length durations of 5 and 6 days are clearly overestimated by the models. This overestimation of the heat wave persistence in the CORDEX simulations has been discussed earlier [33] and may be attributed to a misrepresentation of land-atmosphere feedbacks (e.g, soil moisture, surface energy fluxes).

The projected changes are calculated separately for each model with respect to the model mean value of the reference period, to reduce some effect of the overestimated persistence. In the near future (2021–2050) and under RCP4.5, a clear increase in the frequency is found for all durations. Short term events (3 days) already increase by 0.9 events/yr (multi-model median). Furthermore, the very strong 10 day events increase by about one event per decade (0.1 events/yr) in comparison to less than one event in 30 yrs in the reference period (multi-model median 0.03 events/yr). No pronounced differences are found between RCP4.5 and RCP8.5 for the near future. Increases are in general slightly larger in RCP8.5, but much smaller than the differences between the models. On this time scale, differences in the emission scenarios have no systematic effect on the heat wave frequencies.

In the far future (2070–2099), however, the differences between the scenarios emerge. For RCP4.5 a further increase is found for all classes. However, at least for the shorter events, a weakening of the trend is found, i.e., the changes 1971–2000 to 2021–2050 are larger than the changes from 2021–2050 to 2070–2099. The three day heat waves, for instance, increase by 1.5 events/yr relative to the reference period (0.6 relative to 2021–2050). In case of the extreme long-lasting heat waves, changes are still small, but nevertheless pronounced. 10 day events may increase by 0.3 events/yr, suggesting one additional extreme heat wave every third summer.

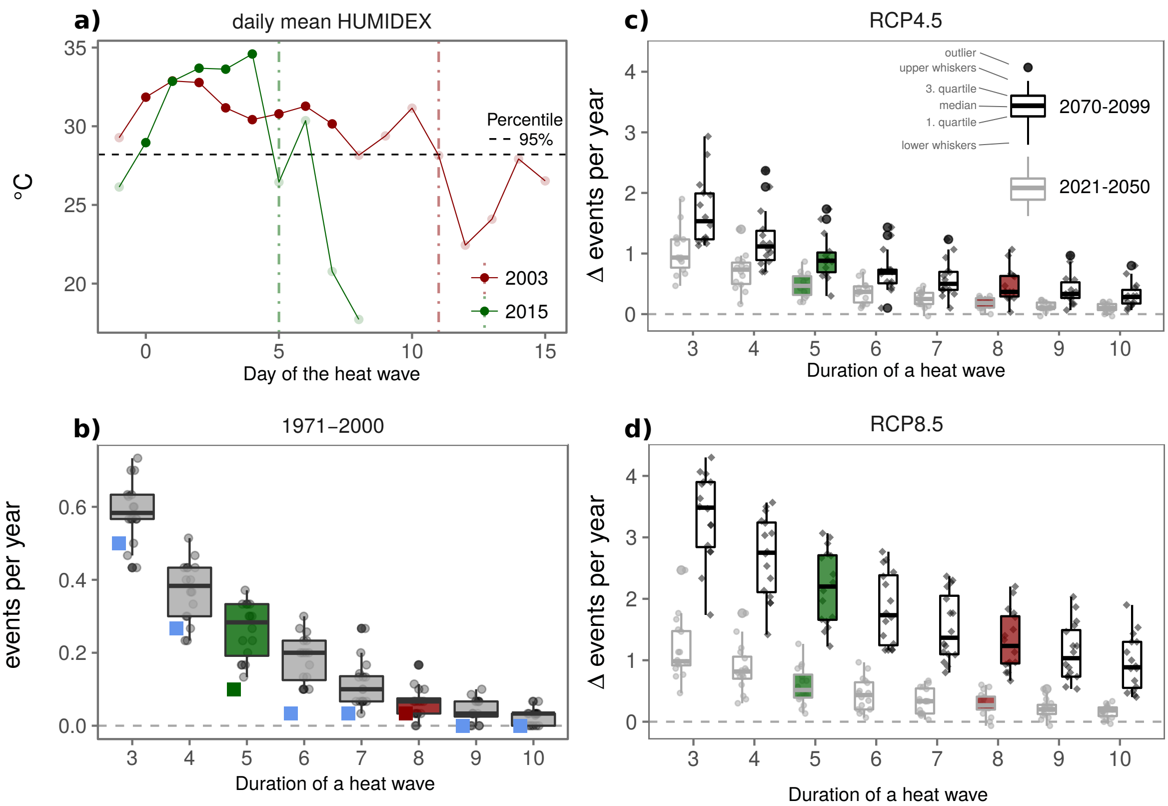

Figure 4. (**a**) Similar to Figure 3 but for the daily mean HUMIDEX; (**b**) Boxplot statistics for number of heat waves per year in the RCM simulations. Heat waves are defined by 3 to 10 consecutive days with a daily mean HUMIDEX above the 95th percentile. Dots resemble the results from the individual simulations; colored squares denote the number of events per year derived from observations. The events of 2003 (8 consecutive days) and 2015 (5 consecutive days) are highlighted by the red and green color; (**c**) Boxplot statistics for the change of heat waves frequencies with a duration between 3 and 10 days in the near (2021–2050) and far (2070–2099) future for the RCP4.5 scenario relative to the model mean value for 1971–2000. Dots resemble the individual RCM simulations; (**d**) Same as (**c**), but for RCP8.5.

Still, in comparison to the RCP8.5 the changes found for RCP4.5 are moderate. For all duration the intensification is always larger than the changes from 1971–2000 to 2021–2050. 3 day heat waves increase by 3.5 events/yr, the 2015-like events with 5 day duration increase by 2.2 events/yr (two additional 2015-like heat waves in every summer), and a 2003-like event is also likely to take place once a summer (multi-model median increase by 1.2 events/yr). The strongest 10 day heat wave, finally, increases by 0.9 events/yr until the end of the 21th century.

4. Discussion and Conclusions

12 years after the extra ordinary heat wave of 2003, another serious heat wave took place in Central Europe. Similar to 2003, the 2015 event lead to a very exceptional increase of the mortality. While in 2003 persistent extreme high air temperature lead to high heat loads, the 2015 event was moreover characterized by high dew point temperatures, causing very sultry conditions.

Similar to 2003, the heat wave of 2015 was not limited to South-West Germany. For large parts of Western Europe exceptional high temperatures and humidity values were observed in 2015 and an increase of the mortality is likely to be found also in other countries. In Switzerland, a comparable mortality increase of +6.9 and +5.4% was reported for summer 2003 and 2015, respectively [34].

For both heat waves our results show, that the maximum in the mortality values occurred one day after the maximum of the wave, when the meteorological parameters indicated a clear reduction of the heat stress. An explanation for this effect can be found in the up to two-day lag, between outdoor heat stress and the indoor conditions [35]. In particular, since many people, especially elderly or sick people which are most vulnerable to heat stress, typically spend a large part of their time inside buildings. Heat warning systems should therefore consider the indoor thermal conditions as well and heat-intervention strategies should focus also to the days following a heat wave.

In this study we applied the HUMIDEX, a combined index which considers the thermal effects of air temperature and humidity. Heat stress perceived by human beings, however, is not only governed by these two parameters. Therefore, the applied HUMIDEX may not cover all possible heat stress situations. This caveat may be avoided by the application of complex human-biometeorological indices, e.g., the Perceived Temperature [36]. In this study, when using RCM simulations to project future changes in heat waves, a heat stress indicator based on temperature and humidity only is a more reliable index, since more sophisticated indices rely on additional input parameters (wind speed, short-wave and long-wave radiation fluxes or cloud cover), which are associated with larger biases in RCMs (e.g., [37]) and are often not available in an appropriate temporal resolution.

Two main differences between the two heat waves should be mentioned. Firstly, the duration of the events. The health impact of heat waves increases with the duration (e.g., [29,38,39]). In this context, the 2003 heat wave, with a duration of two weeks, was very exceptional. Secondly, the timing of a heat wave is important. Heat waves occurring early during the season cause stronger health impacts than heat wave towards the end of the season [32,40,41], due to short-term acclimatisation effects. This is an additional factor explaining the health effects of the 2015 heat wave, which took place in early July, about one months earlier than the 2003 heat wave.

Furthermore the sensitivity of the population to heat stress is not stationary in time. In our study, for instance, where the mortality data was normalized by the population size, a change in the age structure may have changed the sensitivity of the population to heat waves. Between 2003 and 2015, the ratio of elderly (65 years and more), which are more vulnerable to heat stress, has increases from about 17 to 20%. Consequently, the same heat wave is expected to lead to a higher health impact in 2015 in comparison to 2003, if no adaptation has taken place.

One adaptation measure, which was implemented after the 2003 event, is the German HHWS. From 30 June to 7 July 2015 warnings of strong and extreme heat stress were issued by the German Meteorological Service (DWD) for large parts of Germany. A quantification of the influence of these warnings on the heat related mortality in 2015, however, is currently not possible, given the societal changes and the differences between the heat waves with respect to the duration, the time of the year, and the meteorological conditions. More work is needed to quantify this aspect.

For the projected change in heat related mortality, long-term adaptation needs to be considered [42,43] and several different methods exists, to assess long-term adaptation to heat stress for the future [44]. Estimates of long-term adaption for long-lasting heat waves, however, are associated with large uncertainties, given the fact that heat waves with a duration of more than 5 days occured only once or less during the reference period. Therefore, we did not transfer the projected increase in heat wave frequencies into an increase in the heat related mortality. Some long-term adaptation might reduce the future health impact, in particular for the shorter heat waves. The projected increase for all heat waves duration—and in particular the pronounced increases in very long lasting events—and for all scenarios in the near and far future, however demands for an intensification of climate change mitigation and adaptation efforts.

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Author Contributions: Stefan Muthers conceived and designed the study. Stefan Muthers and Gudrun Laschewski gathered data and performed the analysis. Stefan Muthers, Gudrun Laschewski, and Andreas Matzarakis wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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