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Only in the Heat of the Moment? A Study of the Relation between Weather and Mortality in Germany

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Abstract

In this study we analyze the relationship between heat events and mortality in Germany. The main research questions are: Does heat lead to rising mortality and if yes, are the effects persistent or compensated for in the near future? Furthermore, we consider differences between heat effects in urban and rural environments. Cause specific daily mortality and meteorological data were connected on the county level. We allow for static as well as dynamic relations between extreme temperatures and mortality and compare different panel data estimation approaches. We find that heat has a significant positive impact on mortality. The strongest effects can be observed on the same day and the first week afterwards. The mortality increase ranges between 0.003 and 3.5 per 100,000 inhabitants depending on the particular death cause. We do not find a significant negative, and thus compensating, impact in the medium term, which is contrary to the Harvesting Hypothesis. Using a value of statistical life approach we estimate that each additional hot day in Germany induces a total loss of €1,861M. Moreover, the environment plays an important role. The heat induced increase in mortality is significantly higher in urban areas.

Key Words: Climate Change, Harvesting Hypothesis, Heat Waves, Mortality, Urban Heat Island effect
JEL Classification: I10; Q51; Q54;

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1 Introduction

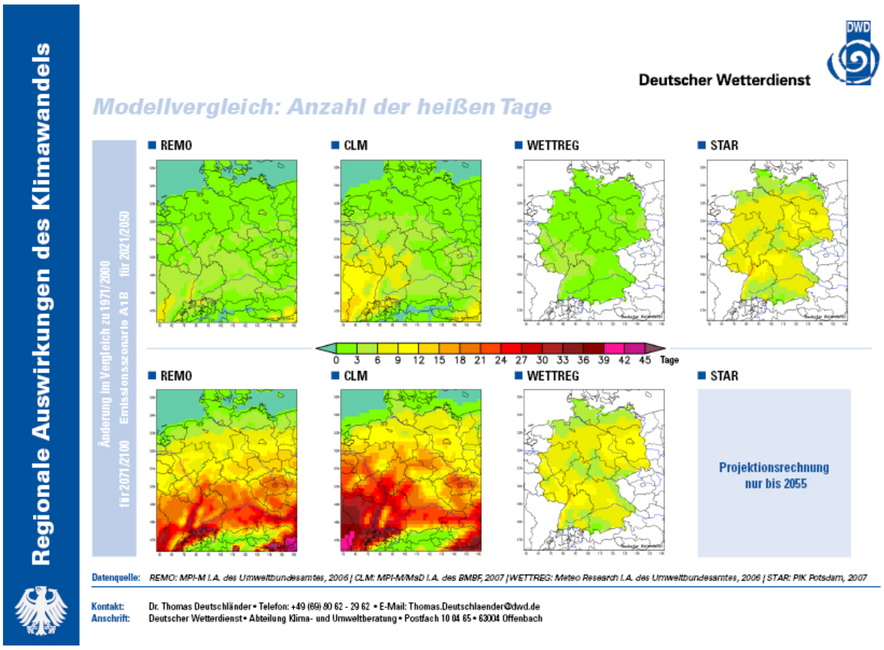
Climate change is one of the most formidable challenges of modern society. It can be expected that its foregoing progress will affect several sectors of the economy. For instance, agriculture can be influenced by climate induced crop losses or the transport sector might have to deal with limitations caused by floods or storms that become more intense. In this paper, we focus on the implications for public health.

The impact of climate change on public health is apparently important. According to newspaper articles it was estimated that the heat wave in 2003 claimed about 3,500 victims in Germany. For comparison in the same year 6,613 people died in road accidents.

According to meteorological scientists, one consequence of climate change is a shift in the distribution of temperatures (Stern, 2007). This shift is predicted to occur in two different ways. Firstly, average temperatures are rising. This aspect is generally known as *Global Warming*. According to the most recent estimates[1], the world's average temperature has already risen by 0.74 °C over the past 100 years. For Germany the average increase was even higher, at a level of 1.1 °C [2]. This trend can be expected to progress in the future. Future rising of average temperatures in Germany until the end of this century, for example, is predicted at a range between 2 °C and 4 °C.

Secondly, the distribution of temperatures shifts in the sense that the probability of more frequent and intense extreme temperature events increases. Using meteorological models to simulate future climate scenarios, the German Weather Service predicts that at the end of the 21st century the average number of extreme hot days, where the air temperature rises above 30 °C, can end up at a level which is twice as high as at the end of the 20 century. An illustration of this phenomenon is shown in Figure 1[3], which was provided by the German Weather Service. Four different regional simulation models were used to calculate the predicted average number of hot days in Germany. It can be seen that the average number of hot days, will increase significantly up to the end of the 21st century, especially in the south of the country.

Figure 1: Future Scenarios: Yearly Number of Hot Days



Through its temperature regulation, the human body is closely linked with the environment. To hold the body heat on a constant level, it has to react very sensitively to changes in the temperature of its surroundings. Thus, events of extreme heat lead to hard thermal stress which give rise to an increase in mortality rates. This impact has been verified in several studies[4]. However, there remain open issues in the literature. Firstly, the relation has not been estimated using high frequent census data on mortality in Germany over long period. Secondly, additional weather determinants that might affect the intensity of thermal stress are most often disregarded in empirical analysis. Thirdly, by now there is still no common position about the time structure of the relation between heat and mortality. The results of this study might shed some hint on these issues.

We connected daily data on weather and mortality at the county level[5] and implemented a panel data analysis. The goals of our study can be summarized in three points: Firstly, we wanted to clarify whether extreme temperature events have an immediatly increasing effect on mortality rates and thus, a negative impact on public health in Germany. Secondly, it was our aim to describe the character of the connection. In this part, we focused on the time structure of the impacts. Here the question is if extreme temperatures induce a shift in the mortality distribution, meaning that mortality rates increase or if estimated immediate effects are compensated for in the frame of a longer time horizon. This issue concerns the so called

Harvesting Hypothesis, which will be discussed in more detail later on. Thirdly, we analysed the impact of urbanization and the question whether measured effects are higher in urban areas, as proposed by the *Urban Heat Island Hypothesis*.

The paper is organized as follows: Before the main content of the analysis is provided, a short overview of existing literature and an embedding of the work in a theoretical setting will be given. In section three, a closer look at the indicators used for climate change and health, i.e. the temperature and mortality variables, is provided. Special features of each will be described and their possible connection will be taken into account, to build a framework for the following empirical analysis in section four. A description of the methodology used and assumptions needed, as well as the presentation of the empirical results for the analysis of each research question, is included. Finally, section five gives the conclusion of the analysis, a discussion of economic implications of the results and an outlook for future research.

2 Literature Review

In this section we provide a literature review and highlight some of the main controversies and open issues. Since our analysis has a special focus on Germany, this overview will concentrate on research on industrialized countries.

Previous results on the extreme temperature mortality nexus were, in most cases, obtained using time series or panel data analysis. The studies can be differentiated into two groups: Firstly, the connection can be analyzed in a more general framework by studying the link of heat waves and aggregated mortality rates. For industrialized countries, many empirical studies verify that extreme heat induces a significant increase in mortality rates. Vaneckova et al. (2010) found temperature to be a significant modifier of daily mortality, especially for elderly people, using Australian data. Ostro et al. (2009) came to similar results for the United States. For the 2006 California heat wave, they found a negative impact of high temperatures on mortality. Their estimates show that mortality in this time was even higher than assumed by medical institutions. This could imply that previous estimates of heat induced mortality have been too low and that the effects, which we have to calculate with, are even higher than previously thought. It should also be mentioned that there are very few studies which did not find a positive impact of heat on mortality. Donaldson et al. (2003), for example, provide a comparative study of the impact of heat waves for three climatically diverse regions, namely North Carolina, South Finland, and Southeast England, during the period from 1971 to 1997. In fact, they estimated falling excess mortality when temperatures increased.

Additionally, the temperature mortality nexus can be further characterized by analyzing the specific impact on mortality by different causes. Studies have been implemented for the United States, Australia and several European countries. The main result is that a positive impact of extreme temperatures on mortality can be confirmed and that people aged over 65 years or people with cardiovascular or respiratory diseases are more strongly affected than people in good health (Deschenes and Moretti, 2009; Huynen et al., 2001; Ishigami et al., 2008; Medina-Ramn et al., 2006; Rey et al., 2007; Vaneckova et al., 2008).

Nevertheless, there is no consensus about the time structure of these effects. The hypothesis of the *Harvesting Effect* is that the rising mortality induced by extreme temperatures is only a contemporary effect. But if a longer time horizon is regarded, the effect is not persistent and mortality could even decrease so that the net impact of high temperatures on mortality disappears. This would imply that heat waves only have an impact on the time structure of mortality rates but not on their levels. Deschenes and Moretti (2009), for example, give evidence for the existence of the *Harvesting Effect*, but Rey et al. (2007) reach the opposite conclusion.

Moreover an empirical analysis should allow for the possibility that effects are heterogeneous. It has been found in several studies that during a heat wave, mortality is significantly higher in urban areas than in rural environments[6]. The hypothesis of an *Urban Heat Islands Effect* can be found, for example, in the early work of Clarke (1972). Thus, the day time differences in temperatures between urban and rural areas are very small, but at night there is often significant variation: in cities it is significantly warmer than in rural areas. This leads to a situation where people living in metropolitan areas have less possibility to recover during the nights and are thus exposed to higher thermal stress.

Finally, other weather factors that could also determine the intensity of heat induced stress, like wind speed or humidity, vary between different environments and therefore, could also influence the heat-mortality nexus.

The aim of this study is to identify the potential impact of extreme temperatures on mortality in Germany and, after an analysis of the immediate effects, to have have a special focus on both the *Harvesting* and the *Urban Heat Island Hypothesis*. Moreover, we seek to give an economic interpretation to our results. One perspective which was often missing in previous work was the economic implication of empirical findings. In the work of Hübler et al. (2008), a first step was taken. They estimated costs induced by climate change in Germany at the end of this century. Simulated future climate scenarios were used to calculate health care costs and losses in productivity. As a result, they predicted an increase in casualty, an increase in hospitalization costs and a decrease in productivity. Another sector which may be strongly affected is the insurance industry. In the discussion of the empirical analysis we will come back to this point in more detail.

3 Mortality and Temperatures - a closer view

In this section we provide summary statistics of the data.

3.1 The Mortality Variable

As our main dependent variable, we used daily mortality rates per 100,000 inhabitants[7] on the county level over the period from 1996 to 2006. We refer to these normalized rates as *mortality* in the following. Deaths are distinguished by age, gender and cause[8]. Descriptive statistics are given in Table (1) below.

We consider six different different dependent variables. Firstly, the entire population and all death causes are considered. The mortality rate reached, on average, a daily number of nearly 3 deaths per 100,000 inhabitants (13 for older people). Additionally, we constructed four particular subgroups of death causes. These are: respiratory and cardiovascular diseases, neoplasms and infectious diseases. According to previous research, they can be assumed to be influenced by extreme temperature events more strongly than overall mortality. For these variables the average of daily mortality ranged between nearly 0.03 and 1.32. All these

Table 1: Descriptive Statistics on Mortality Rates

Variable	Mean	Std	Min	Max
All death causes	2.820	1.589	0	22.704
Age 65 years and older	13.077	7.984	0	105.153
Respiratory diseases	0.182	0.394	0	7.942
Cardiovascular diseases	1.320	1.079	0	15.849
Neoplasm	0.723	0.774	0	11.409
Infectious diseases	0.033	0.163	0	4.943

Notes: Mortality is calculated as daily mortality per 100,000 inhabitants on the county level. Descriptive statistics for each death cause separately. The number of observations is 1,526,840 which is equal to the number of counties(380)[9] multiplied by the number of days (4018).

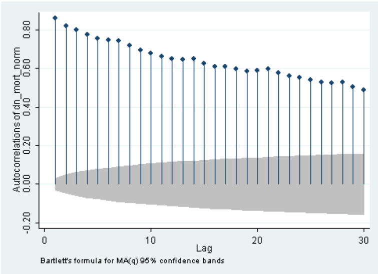
subgroups will be analyzed separately in section 4.

One special feature of daily mortality is that it exhibits a strong positive autocorrelation. In Figure (2), the estimated[10] intertemporal correlation of daily mortaity in Germany is illustrated for each of the six dependend variables. In all cases we identified a positive intertemporal correlation. Except for death caused by neoplasms, a clear picture emerged for all groups: a significant positive but decreasing autocorrelation. The starting values varied between nearly one for the population aged over 65 years and 0.4 in the case of infectious diseases. In all groups the mortality rate today is still significantly correlated with the rate of 30 days before.

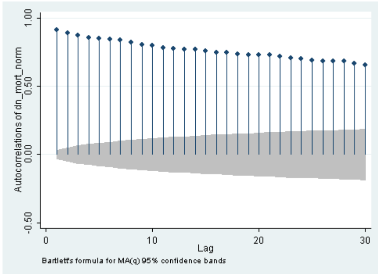
We assume that the observed positive intertemporal correlation comes from two sources. Firstly, a clear *seasonal pattern* of the mortality rates can be identified. It is well-documented in previous research on mortality rates in European countries and in the United states[11] that a U-shaped distribution is obtained, which has peaks at the beginning and the end of the year, and is lowest in the middle of summer. As it is illustrated in Figure (3), we estimated the trend for all samples which will be considered in the empirical analysis and identified a clear U-shaped pattern for four of the six dependent variables.

The second conceivable reason for autocorrelation in daily mortality rates is the *time trend*. The estimated[12] trend was not equal for all groups of analysis, as illustrated in Figure (4). For the entire population, no clear time trend emerged from our data. In the case of the population aged over 65 years, demographic change is clearly discernible, since daily mortality

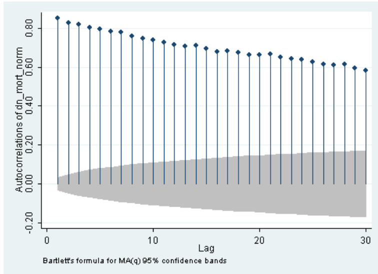
Figure 2: Autocorrelation of Mortality Rates



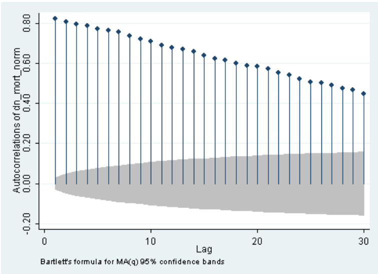
(a) All death causes



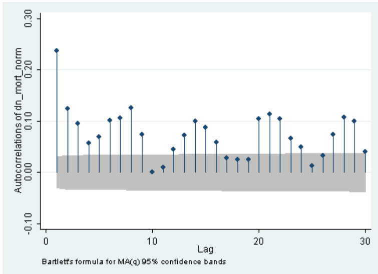
(b) Age 65 years and older



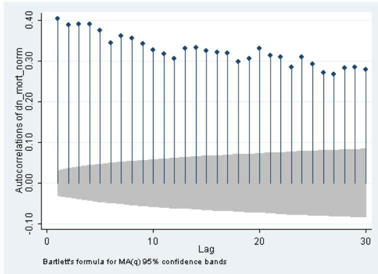
(c) Cardiovascular diseases



(d) Respiratory diseases



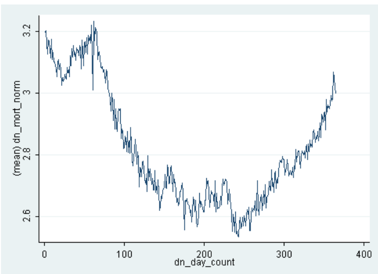
(e) Neoplasm



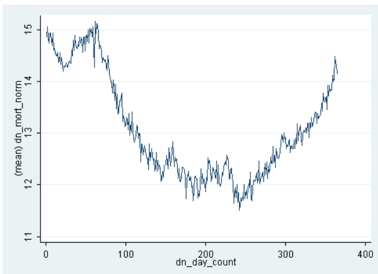
(f) Infectious diseases

Notes: Estimated autocorrelations for each sample separately. Daily mortality per 100,000 inhabitants was averaged over whole Germany. Grey shading illustrates significance on the 5% level.

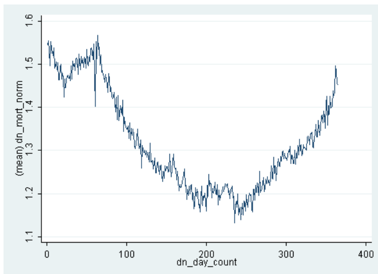
Figure 3: Seasonal Trend of Mortality Rates



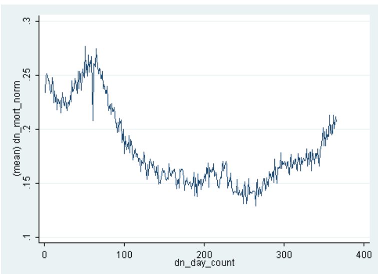
(a) All death causes



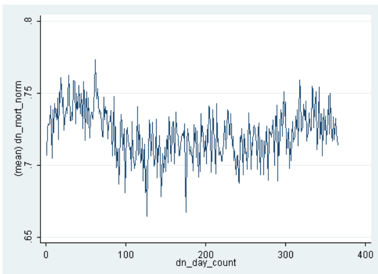
(b) Age 65 years and older



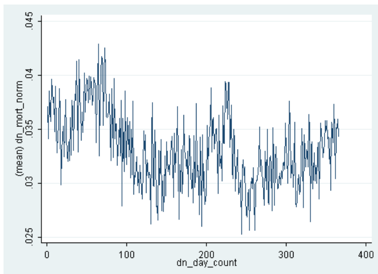
(c) Cardiovascular diseases



(d) Respiratory diseases



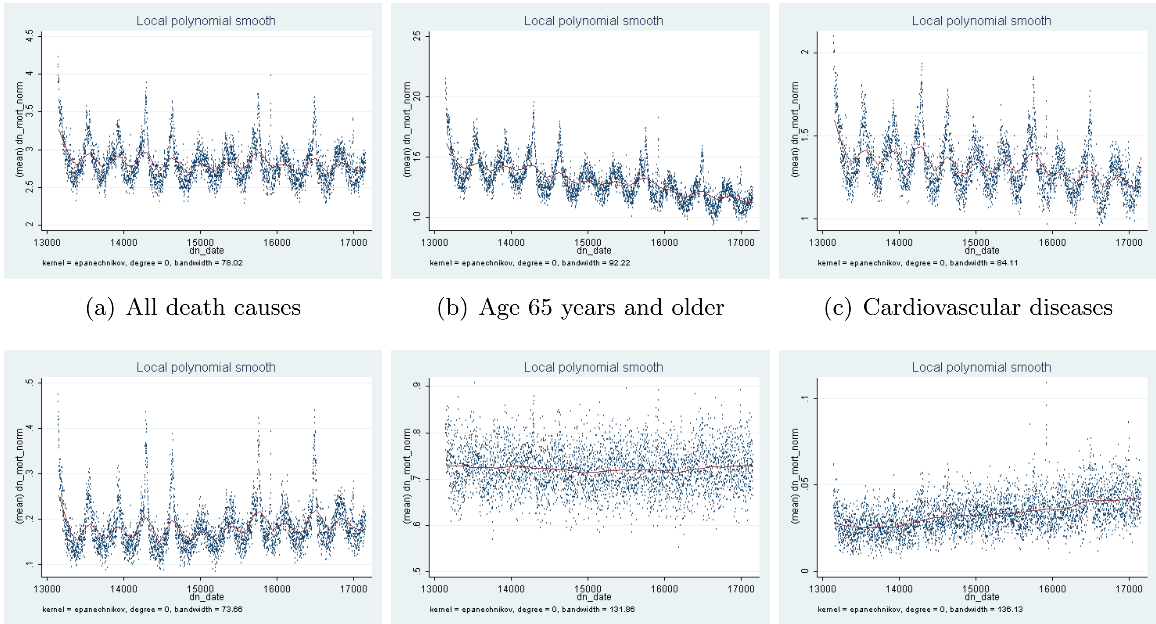
(e) Neoplasm



(f) Infectious diseases

Notes: Estimated seasonal pattern for each sample separately. Daily mortality per 100,000 inhabitants of each day of the year was averaged over Germany. The days of one year are counted from 1 to 365 and plotted on the x-axis.

Figure 4: Time Trend of Mortality Rates



(a) All death causes (b) Age 65 years and older (c) Cardiovascular diseases

(d) Respiratory diseases (e) Neoplasm (f) Infectious diseases

Notes: Estimated time trend of average daily mortality by 100,000 inhabitants on the county level for each dependent variable separately. Stata date variable from 1996 to 2006 on the x-axis.

rates decrease in the long run. Also, a decreasing time trend was estimated for mortality caused by cardiovascular diseases. In contrast, a weak positive time trend in daily mortality can be observed for respiratory and infectious diseases.

These two patterns, time trend and seasonal dynamic, are assumed to be reasons for the intertemporal correlation in the mortality data. Thus, we have to take it into account in the empirical analysis which follows. Furthermore, we detrended the data by using a fixed effects regression of the mortality rates. Firstly, we regressed them on month and year dummy variables which lead to a weaker but still positive autocorrelation in the data. This characteristic will play an important role when the time structure of the impact of extreme heat on mortality is considered in the *Harvesting Analysis* later on. Therefore, the focus is on the dynamic relation between heat and mortality. As an alternative, we used a polynomial of the day variable to detrend the data. We found that the higher the degree of the polynomial used in the regression, the less autocorrelation was left in the mortality data. This leads to the conclusion that the main part of the intertemporal dependence in daily mortality is driven by seasonal patterns.

3.2 The Temperature Variable

For our analysis we used the occurrence of heat waves as an indicator of climate change. Compared to other variables influencing health, temperatures have the main advantage that they are naturally exogenous. Admittedly we can affect the climate by our behavior and therefore the shifting temperatures in some sense, but the period between our action and the implied changes is so long that it can be disregarded in the short term analysis conducted in this study. Thus, from an econometric point of view we can assume that there is no endogeneity bias in the results of our regression analysis. However, if heat events have a significant negative impact on human health, it can be assumed that people will adapt their behavior to weaken these implications. The induced changes in behavior are in turn connected with welfare losses. Consequently, avoidance behavior could be seen as an omitted variable in this case and has to be kept in mind when economic implications are evaluated.

The weather data was provided by the German Weather Service. It includes the information collected at 1,045 meteorological stations which are distributed over the whole area of Germany. Table (2) shows the descriptive statistics of the observed daily temperature variables.

Table 2: Descriptive Statistics of Daily Temperatures

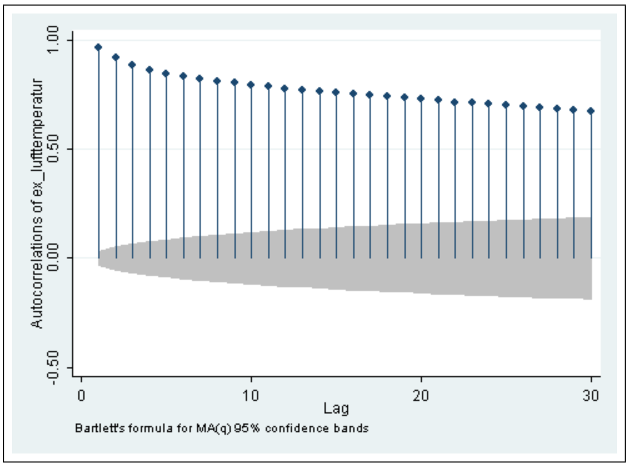
Variable	Mean	Std.Dev.	Min	Max
average air temperature	9.243	7.478	-20.150	30.500
minimal air temperature	5.292	6.716	-28.000	24.194
maximal air temperature	13.508	8.720	-15.375	39.468

Notes: Temperatures measured in degree centigrade. Descriptive statistic for calculated daily averages over Germany.

In the period of analysis the mean daily air temperature in Germany is about 9 $^\circ$C, averaged over the whole period and area. Minimum temperatures varied in a range between -28 $^\circ$C and 24.2 $^\circ$C. The maximum daily temperatures ranged from -15.4 $^\circ$C on the coldest days up to nearly 40 $^\circ$C on hot summer days.

One particular feature of the temperature variable is the strong autocorrelation of the daily values. An illustration of the dynamic in our sample is shown in Figure (5).

Figure 5: Autocorrelation of Daily Temperatures

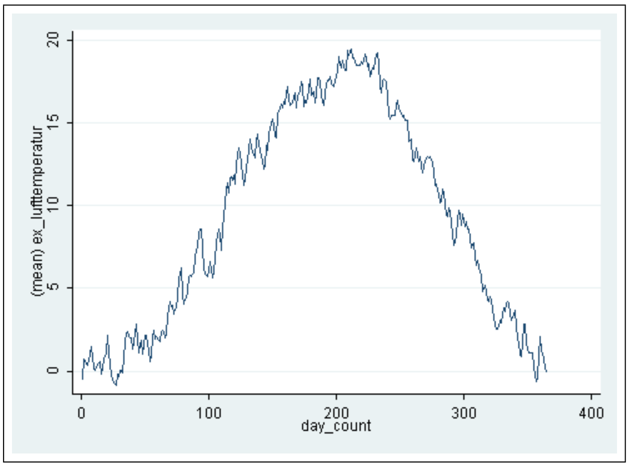


Notes: Estimated autocorrelation of daily average temperatures over Germany. Grey shading illustrates significance on the 5 % level.

The autocorrelation starts at a very high and significant value of almost one and decreases the more days we go backwards. A significant connection is estimated for all of the 30 lags included. This strong positive autocorrelation clearly implies that if lags have a direct impact on current mortality - then estimates will be upward biased if they are left out of the regression. Whether estimated effects go in the same direction or vary for different points in time can give evidence for the hypothesis of the *Harvesting Effect* later on.

The strong autocorrelation in the weather data may has two main explanations. As in the case of mortality rates, a clear seasonal trend of the average air temperatures over the whole year can be observed. As presented in Figure (6), the typical European picture evolves where average daily temperatures start very low in January at a level around 0 ° C, then rise over the months until mid of summer where they attain values around 20 ° C on average and afterwards decrease until December where they end up at their low starting values. In other words, we can identify the opposite curvature in the distribution of average temperatures over the year than that we have shown for daily mortality above.

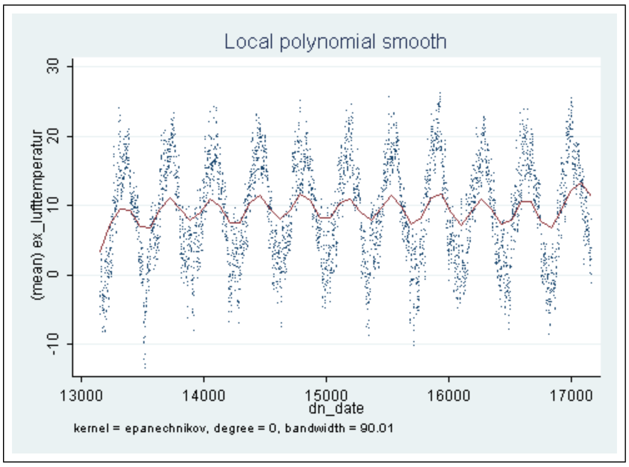
Figure 6: Seasonal Trend of Daily Temperatures



Notes: Estimated distribution of daily average temperatures over the year in Germany. The days of one year are counted from 1 to 365 and plotted on the x-axis.

A second possible reason for the strong autocorrelation is the time trend in temperatures associated with *Global Warming*. It is predicted that average temperatures will rise in the long run. In Figure (7), the time trend in the data from 1996 to 2006 is presented. Only a very weak tendency of rising temperatures is visible.

Figure 7: Time Trend of Daily Temperatures



Notes: Estimated time trend of average daily temperatures over Germany from 1996 to 2006. Stata date variable from 1996 to 2006 on the x-axis.

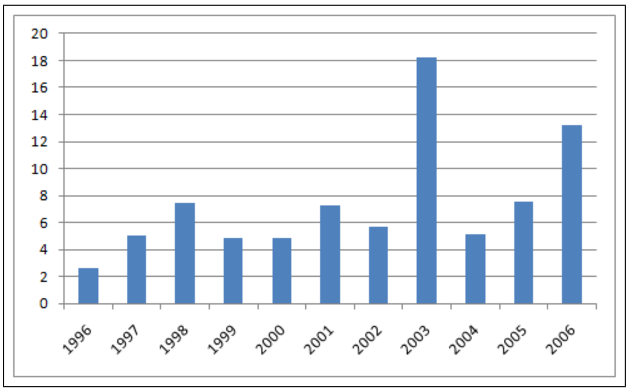
3.3 Definition of a Heat Event in the Mortality Nexus

One weakness in previous studies that addressed the impact of extreme temperatures on mortality is the narrow definition of a heat event. The simplest way to define a day of extreme heat is to look at a general threshold value of temperature. Deschenes and Moretti (2009), for example, analyzed mortality on days where the maximum temperature was higher than 80 °F (26.67 °C)or 90 °F (32.22 °C). Theories of the medical meteorology give reason to criticize this approach: to evaluate the intensity of thermal stress on human bodies, other relevant environmental factors besides the ambient air temperature have to be considered. Several indexes have been developed to deal with this problem. The generally accepted standard technique which is used in medical meteorological science, for example in the heat warning system of the German Weather Service, is the so called *Klima-Michel-Modell*. In this model the *perceived* temperature is calculated based on the work of Jendritzky et al. (1979). The perceived temperature is the temperature level that would induce the same thermal feeling in an average reference environment. To calculate it, the actual air temperature and several other meteorological, geographical and personal factors are combined. The weather related factors are: dew point or relative humidity, wind speed, air pressure, rainfall, sunshine duration and cloud coverage characteristics. Furthermore, information on the geographical position of the weather station and an individual with average clothing and physical activity has to be considered.

Until now there are only a few studies that have taken this point into account. For instance, Hübler et al. (2008) used the perceived temperature for their future scenario calculations. More basic approaches are the model of apparent temperature[13] and the Humidex[14] where air temperature and humidity are combined. Barnett et al. (2010) provides an overview of the attemps. He looked at the issue of what temperature measure is best to predict mortality rates but could not identify a dominating strategy in previous research. The question whether the additional meteorological factors are mediators, i.e. affected by climate change, or confounders, meaning that they are not affected by climate change themselves but correlated with temperatures, has not been answered yet. In the second case, it is important to include them in the empirical analysis to avoid biased estimates. In this paper, we controlled for the additional factors of the *Klima-Michel-Modell* that might influence the intensity of the heat impact on human bodies.

To identify heat waves in our study, we used a definition from the German Weather Service. A day is defined as hot, in the sense of inducing thermal stress[15] for human bodies, if the maximum temperature reaches or exceeds the level of 30 ˚ C. Figure (8) shows the average number of hot days per year in Germany.

Figure 8: Average Number of Hot Days per Year



Notes: A day was defined as hot if the max temperature exceeded 30 ˚ C. For each year the average number of days was calculated over Germany.

As expected, the number of hot days was highest in the years 2003 and 2006, which brought extreme hot periods over Europe. In these years, the total number was at nearly 18 and 14 hot days, respectively.

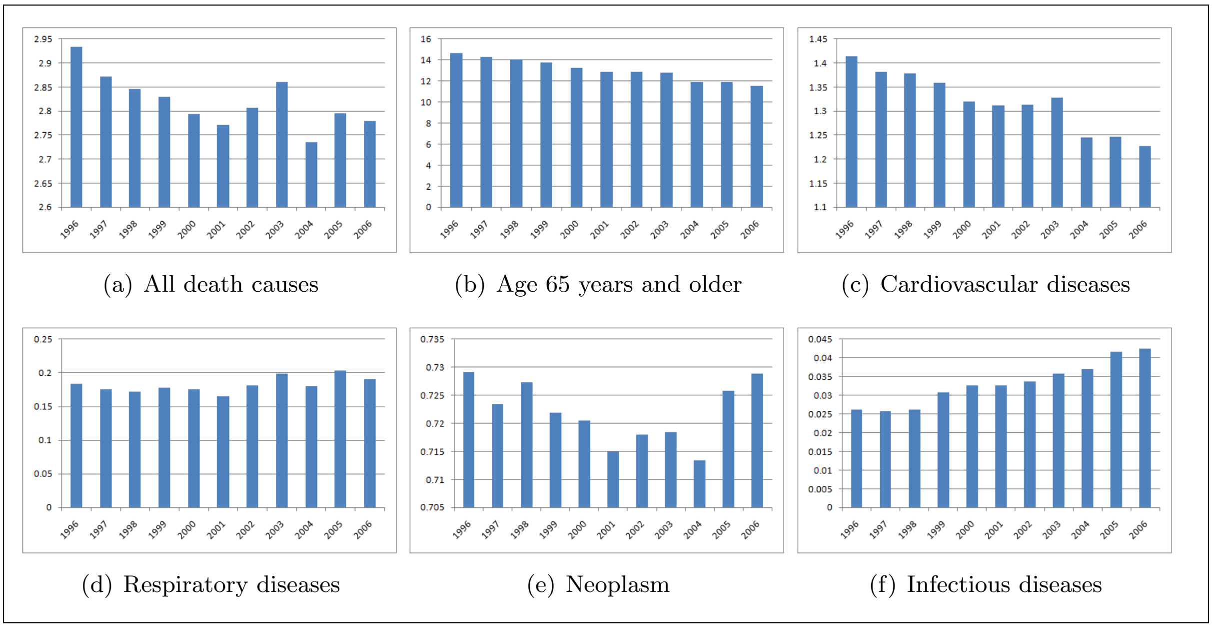
4 Empirical Analysis

In this section, we present the results of our statistical analysis by which we want to answer the three main research questions described above: Does heat lead to immediately rising mortality rates? Are the effects persistent or does the *Harvesting Hypothesis* hold true? Are there differences in heat related mortality in urban and rural areas? The different modeling approaches implemented, and their respective results, will be presented separately in what follows.

4.1 Preliminary Analysis

As a first step, we calculated average mortality rates for each year to have a first impression of the possible impact of heat waves. In Figure (9), the results are presented for every death cause considered in our analysis. Here, no obvious increase in average mortality was indicated

Figure 9: Average Mortality per Year



(a) All death causes (b) Age 65 years and older (c) Cardiovascular diseases

(d) Respiratory diseases (e) Neoplasm (f) Infectious diseases

Notes: Averages of daily mortality per 100,000 inhabitants calculated by county and year

in the years 2003 and 2006, in which extreme heat occured in the summer months[16]).

Secondly, we calculated average mortality on days when heat did and did not occur. Results are reported in Table (3). For all dependent variables, the average mortality was weakly smaller on days with moderate temperatures. The significance of this difference will be analysed in section 4.3 and the following ones.

Table 3: Average Mortality on Hot vs Temperate Days

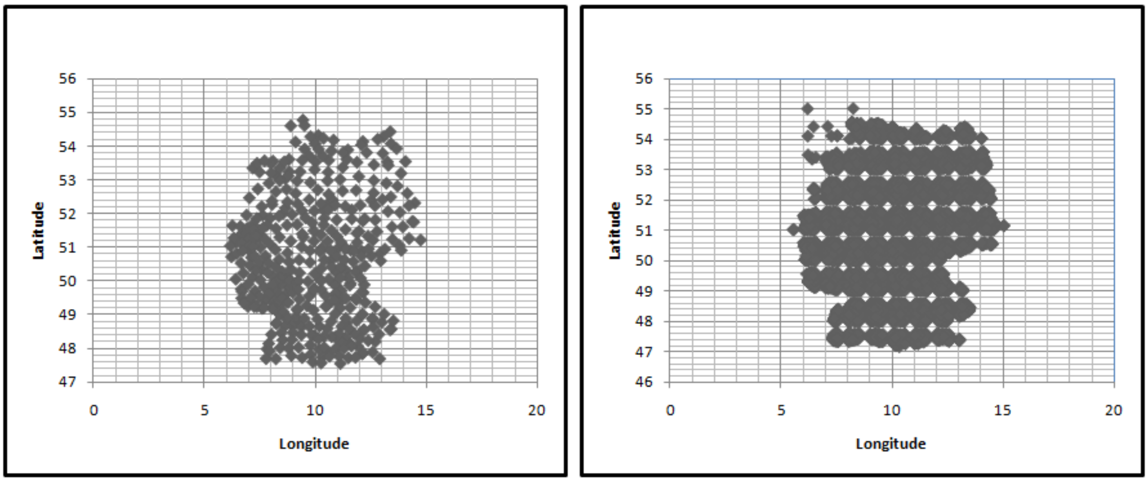
	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
temperate days	2.82	13.07	0.18	1.32	0.72	0.03
hot days	2.98	13.52	0.20	1.34	0.77	0.05

Notes: Mortality is calculated as daily mortality per 100,000 inhabitants on the county level. Calculated average for each sample separately. Day is defined as *hot* when daily max temperature reached or exceeded 30 ° C.

4.2 Connecting Meteorological and Mortality Data

The geographical unit of our analysis is the county. We connected frequently collected data on weather variables and mortality rates. Today there are 413 counties in Germany. Due to

Figure 10: Geographical Positions of Data Collection



(a) County Central Points (b) Meteorological Stations

Notes: Geographical county centroids and position of meteorological stations described by degree of latitude and longitude. Mortality data was available by county, weather data was collected by meteorological stations distributed over whole Germany.

local government reorganizations between 1996 and 2006, we ended up with 380 counties for which mortality data was available for each day over the whole period. The population in the counties ranged from 35,058 to 3,466,524 when all age groups were considered. Population of people aged 65 years older was between 6,129 and 609,989.

Information about weather conditions was available from 1,045 meteorological stations. In Figure (10) the geographical distribution of both is illustrated.

One difficulty before we could implement the empirical analysis was the interpolation of the two datasets. We followed the study of Hanigan et al. (2006), in which different approaches of how to calculate population exposure estimates of daily weather are compared. The geographical centroid of each county was used as a key to merge weather and mortality observations. The weather conditions for every county and day were then calculated as an inverse distance weighted average[17] of all meteorological measurement stations that were within a distance of 50km around the county centroid[18]. Thus, we obtained a balanced panel dataset with daily observations of mortality and weather for each of the 380 counties over a period of 11 years as basis of our analysis.

4.3 Immediate Effects of Extreme Heat on Mortality

4.3.1 Methods

To estimate the impact of temperature shocks on cause specific mortality in Germany, we used a simple static model which is a common approach of economic studies in this field[19]. The model is described in equation (1).

$$Y_{it} = \alpha + \beta\, H_{it} + \theta\, X_{it} + \sum_{j=1}^{11} \sigma_j\, month_{jt} + \sum_{k=1996}^{2005} \eta_k\, year_{kt} + \nu_i + \epsilon_{it} \qquad (1)$$

Y_{it} :	denotes the mortality rate per 100,000 inhabitants[20] in county i at time t.
H_{it} :	describes the occurrence of a heat event, which is a dummy variable that is equal to one in the case of daily maximum temperatures higher than 30 ° C.
β :	is the coefficient of interest, capturing the effect of extreme heat on mortality.
X_{it} :	is a vector that includes all other relevant meteorological factors according to the *Klima-Michel-Modell* as described in section 3. These time varying factors are cloud coverage[21], humidity[22], air pressure[23], wind speed[24], rainfall[25] and sunshine duration[26]. All of them are calculated as daily averages except rainfall and sunshine duration, which are cumulative measures over the day[27].
$month_{jt}$	dummy variables for every month to controle for seasonal effects.
$year_{kt}$	dummy variables for every year to control for time trend.
ν_i :	fixed county specific effects.
ϵ_{it} :	time varying stochastic error term.

4.3.2 Results

Estimation was carried out with and without the additional meteorological determinants X_{it} to assess the importance of including them in the analysis. In Table (4) the results are presented. As described above, we conducted our analysis for the entire population, and all death causes, as well as separately for different groups of death cause to observe whether people with a bad health status are more sensitive to thermal stress.

Table 4: Immediate Impact of a Heat Event

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
heat separated	0.372***	1.803***	0.042***	0.166***	0.068***	0.012***
CI (95%)	[0.351; 0.394]	[1.702; 1.905]	[0.037; 0.048]	[0.152; 0.18]	[0.06; 0.077]	[0.009; 0.014]
heat	0.356***	1.747***	0.042***	0.160***	0.068***	0.011***
CI (95%)	[0.334; 0.377]	[1.644; 1.85]	[0.036; .048]	[0.146; 0.174]	[0.059; 0.076]	[0.009; 0.013]
effect in %	12.62%	13.36%	23.33%	12.12%	9.44%	36.67%
Cloud coverage	0.007***	0.035***	0.001**	0.003***	0.001*	0.000
Humidity	-0.001*	-0.003*	-0.000*	-0.000	-0.000	-0.000**
Air pressure	-0.002***	-0.009***	-0.000**	-0.001***	-0.000**	-0.000
Wind speed	-0.001	-0.004	-0.000*	-0.000	-0.000	0.000
Rainfall	0.002***	0.006***	0.000	0.001***	0.001**	-0.000
Sunshine	0.005***	0.020***	0.000	0.002***	0.001	-0.000
constant	4.415***	21.200***	0.303***	2.069***	0.964***	0.051***
$R^2 within$	0.016	0.031	0.009	0.015	0.000	0.001
Fraction	1	0.803	0.063	0.467	0.257	0.012

Notes: Panel data fixed effects estimates of equation (1) with robust errors clustered on the county level. The unit of analysis is the county. The dependent variable is daily mortality of the specific death cause per 100,000 inhabitants. The independent variable of interest is the *heat event* which equals one if daily max temperature reach or exceed 30 ° C. Percentage changes calculated using average mortality on moderate days reported in Table(3). Each column reports results of seperate regression for specific cause. The first row includes estimates when additional meteoroliogical controls (X_{it}) are excluded. From the second row on, results for the complete model are reported. The last row presents prevalence of each death cause calculated as the total number of cause specific death devided by the total number of all cause mortality over the whole period. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Through all specifications, a significant positive impact of extreme heat on mortality was observed. There is some evidence that without additional meteorological determinants, the effect on mortality tends to be overestimated. In addition, for most of the meteorological factors, a weak but highly significant impact on mortality was observed and using F-Tests, the joint significant impact was validated. Hence, the additional meteorological determinants will be included in all following specifications. The immediate increase in daily mortality, when maximum temperatures reached or exceeded 30 ° C, was estimated by our model to range between 0.011 and 1.747. For the entire population and all death causes, we observed that there are 0.356 additional deaths on days when heat occurs, which corresponds on average to a 12.62% higher mortality rate than on days with moderate temperatures. For people of age 65 and older, the effect was, as one would expect, clearly higher at a level of 1.747 heat induced deaths. The cause specific immediate impacts of heat where all significantly positive and in the range between 0.011

and 0.16 additional deaths. It has to be considered that a cause specific impact plays a more important role in relative terms, when the prevalence of the cause of death is smaller. Thus, the estimated heat impact on mortality was highest for infectious and respiratory diseases, where the calculated increase was 36.67% and 23.33% respectively.

4.4 Testing the ***Harvesting Hypothesis***

The second step of our analysis was to get a closer view of the time structure of the heat effect. As described in section 2, a special debate evolved around the hypothesis of the *Harvesting Effect*. We will now focus on this hypothesis.

Harvesting Analysis - Part 1

To estimate whether the measured immediate impact on mortality is persistent or compensated in a longer time horizon, we extended the static approach of the previous section. One main feature has to be considered in the analysis of time displacement: as described in section 3, we found a strong positive autocorrelation in daily temperatures as well as in the mortality rates. Both could influence the time structure of the heat mortality relation. As a consequence, we now additionally control for the autocorrelation that is not captured by seasonal effects and time trend. In particular, the impact of previous heat events is of main interest for the *Harvesting Effect*. Thus, we now take a closer look at the occurrence of heat in previous days. Later we also consider the impact of lagged mortality rates by switching to a dynamic model.

To capture delayed effects of a heat event, we extended the model of equation (1) by including lags of the heat variable. We distinguished between three lag lengths. 7, 14 and 30 days preceding a heat event where considered. The term $\sum_{j=1}^{l} \gamma_j \, H_{i,t-j}$ describes this in equation (2) where l is the number of included lags.

$$Y_{it} = \alpha + \beta \, H_{it} + \sum_{j=1}^{l} \gamma_j \, H_{i,t-j} + \theta \, X_{it} + \sum_{j=1}^{11} \sigma_j \, month_{jt} + \sum_{k=1996}^{2005} \eta_k \, year_{kt} + \nu_i + \epsilon_{it} \qquad (2)$$

If the *Harvesting Hypothesis* holds true, estimated coefficients of the lagged heat variables γ_j

should be significantly negative, such that immediate positive effects are smoothed and in sum there is a zero net effect of extreme heat on mortality. We estimated the relation of equation (2) seperately for each combination of death cause and lag length. Results are reported in Table (5) and Figure (11).

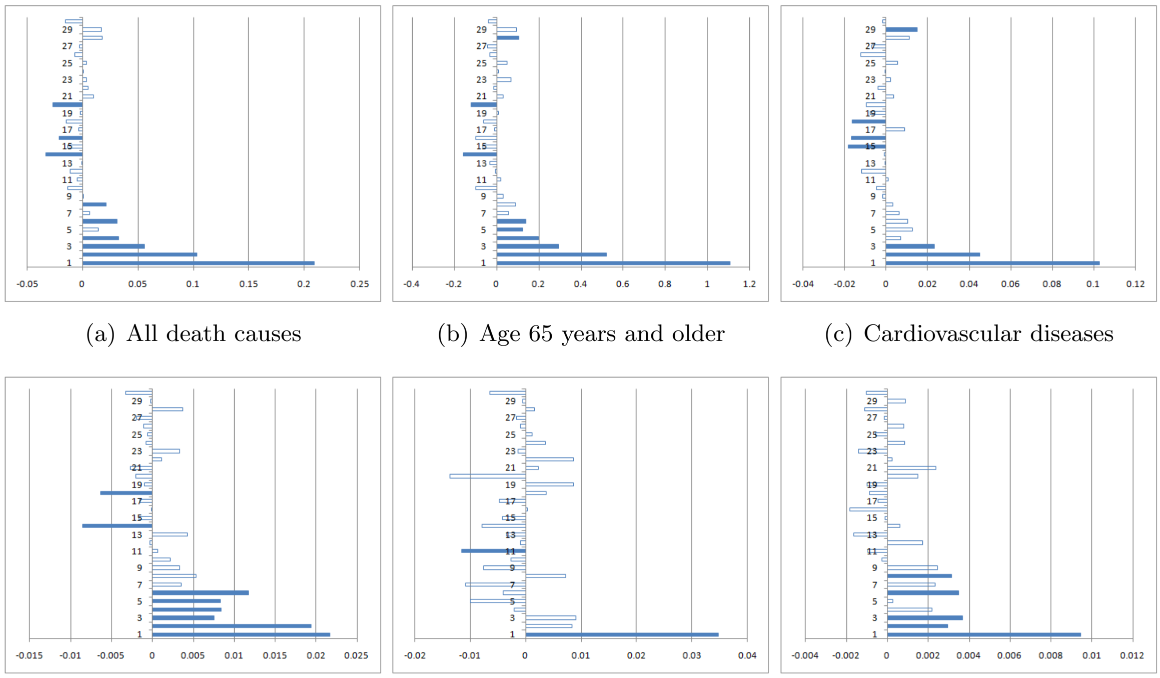
Table 5: Immediate and Harvesting Effect of a Heat Event

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
7 lags						
heat	0.215***	0.999***	0.022***	0.094***	0.051***	0.004***
CI (95%)	[0.195; 0.236]	[0.900; 1.100]	[0.016; 0.027]	[0.080; 0.109]	[0.041; 0.061]	[0.002; 0.006]
harvesting	0.461***	2.504***	0.087***	0.207***	0.022**	0.027***
total	0.676	3.503	0.109	0.301	0.073	0.031
effect in %	23.97	26.80	60.56	22.80	10.14	103.33
14 lags						
heat	0.214***	0.995***	0.021***	0.094***	0.051***	0.004***
CI (95%)	[0.194; 0.234]	[0.896; 1.094]	[0.016; 0.027]	[0.079; 0.109]	[0.041; 0.061]	[0.002; 0.007]
harvesting	0.397***	2.244***	0.086***	0.177***	-0.004	0.029***
30 lags						
heat	0.215***	1.000***	0.022***	0.095***	0.051***	0.004***
CI (95%)	[0.195; 0.235]	[0.901; 1.099]	[0.016; 0.027]	[0.081; 0.110]	[0.041; 0.061]	[0.002; 0.006]
harvesting	0.363***	2.171***	0.072***	0.146***	-0.006	0.028***

Notes: Panel data fixed effects estimation of equation (2) with robust errors clustered on the county level. The unit of analysis is the county. The dependent variable is daily mortality per 100,000 inhabitants. We distinguished by the number of included heat lags which was 7, 14 and 30 previous days. First row always reports immidiate effects of heat when for lagged heat events is controled. The second row presents cumulative ($\sum_{j=1}^{k} \gamma_j$) effects of heat occurence in the previous k days. The third row reports the total effect, calculated as the sum of both. Significance is tested using *t-test*. Each column includes results of cause specific regression analysis. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Again we found a significant increase in mortality on days of extreme heat. There are no significant differences in the results for the different numbers of included lags, which leads to the conclusion that the first week after the heat event is important. The estimated number of additional deaths on days of extreme heat ranged between 0.004 an 0.999 depending on the specific cause. Through all models the estimated immediate effect of heat today was

Figure 11: Impact of Previous Heat Events



(a) All death causes (b) Age 65 years and older (c) Cardiovascular diseases

(d) Respiratory diseases (e) Neoplasm (f) Infectious diseases

Notes: On the horizontal axis the estimated regression coefficients are assigned. The vertical axis presents the included lags from day one up to day 30 before the actual heat event. Filled bars stand for significant estimated effects at least on the 5% significance level

significantly smaller compared to the results of the contemporary analysis[28] when no lagged heat events were included. But the overall effect, calculated as the sum of immediate and harvesting effect, was higher. In conclusion, the analysis of contemporary effects estimates the true direction of the heat impact but the amount of immediate and overall effect tends to misspecified. Therefore, lagged heat events can be seen as omitted variables in the initial model. Moreover, including heat lags in the relation can be seen as an option to control for the abruptness of the occurrence of heat. The amount of harvesting in the relation was analyzed by two properties. First, the aggregated amount of harvesting was calculated by adding up estimated coefficients of all lagged heat variables, i.e. from lag 1 to lag k while k equals 7, 14 or 30. For all outcomes, a positive cumulative delayed effect of extreme heat on mortality was observed, and it was highly significant except for death caused by neoplasm. Secondly, one can consider particular estimated effects of lagged heat events. In Figure (11), the impact of lagged heat is illustrated for the model where 30 lagged heat events were included[29]. The effects vary over the period of the previous 30 days. Up to one week before, heat events tend to increase current mortality significantly. This means that heat also has a positive impact on mortality in the days after its occurrence. If we go further back, the heat effect tends to become negative for the 10 to 20 days before the actual date but in most cases very weakly, and not significantly. Afterwards, the estimated impact becomes again weakly positive. Again, the only exception where effects turned out to be not that clear was in the case of death caused by neoplasms. If most of the heat lag coefficients, and at least their sum, would have had a significant negative sign, we would have found an indication that the *Harvesting Hypothesis* holds true. To the contrary, we found that lagged heat events, especially in the week before, even lead to an additional increase in mortality today and this cannot be compensated for by the weak negative impact of heat events further back in the past. Thus, we have found a reversed *Harvesting Effect*, meaning that the impact of heat on mortality in a longer time horizon is still positive. We can conclude that heat events in fact increase mortality, i.e. shift their distribution, and do not only lead to a short time displacement. The *Harvesting Hypothesis* can therefore be rejected.

Harvesting Analysis - Part 2

As it was shown in section 3, not only are temperatures significantly autocorrelated, but mortality data is also characterized by a strong intertemporal dependence. Hence, when the time structure of the heat mortality nexus is considered, lagged mortality should also be included in the empirical analysis. Therefore, we now estimate a dynamic estimation approach by extending the initial model in equation (1) by including lagged heat events as well as lagged mortality rates. In equation (3) they are captured by the terms $\sum_{j=1}^{k} \gamma_j \, H_{i,t-j}$ and $\lambda_j \, Y_{i,t-j}$.

$$Y_{it} = \alpha + \beta \, H_{it} + \sum_{j=1}^{k} \gamma_j \, H_{i,t-j} + \sum_{j=1}^{k} \lambda_j \, Y_{i,t-j} + \theta \, X_{it} + \sum_{j=1}^{11} \sigma_j \, month_{jt} + \sum_{k=1996}^{2005} \eta_k \, year_{kt} + \nu_i + \epsilon_{it} \tag{3}$$

We implement the model for different numbers of lags $k = 1, ..., 7$, since this period was shown above to be most relevant. We again used a panel data fixed effects approach and estimated equation (3) for each $k = 1, ..., 7$ and each death cause sample seperately. For standard panel data with a large number of individuals, and a relatively small number of time periods this method could lead to bias in the estimated coefficients. But if T goes to infinity, this bias converges to zero[30]. In our dataset, 4,018 periods are included. Thus, we assume T to be large enough such that there is no substantial bias left in our results. Moreover, OLS and Fixed

Effects Regression results define the upper and lower bounds of a dynamic estimation approach. To check the validity of our results, we implemented the model for each combination of death cause and lag length and number of lagged mortality and temperature, also using OLS. We found very similar results in all cases, which suggests that the bias is very small.

For each cause of death, we obtained seven particular estimates. Our discussion is, at this point, restricted to the results for the entire population and all death causes. Estimations for specific causes were very similar. Table (6) reports the effects of heat today on current mortality. Estimated effects of specific heat and mortality lags are shown in Table (7) and (8).

Table 6: Harvesting Effect with Control for Lagged Mortality

Variable	1 lag	2 lags	3 lags	4 lags	5lags	6 lags	7 lags
heat	0.231***	0.222***	0.217***	0.215***	0.215***	0.214***	0.214***
CI (95%)	[0.211; 0.252]	[0.202; 0.243]	[0.197; 0.237]	[0.194; 0.235]	[0.194; 0.235]	[0.194; 0.234]	[0.194; 0.234]

Notes: Panel data fixed effects estimation of equation (3) with robust errors clustered on the county level. The unit of analysis is the county. The dependent variable is daily all cause mortality per 100,000. In the first row the heat effect of the harvesting model is reported. Each column represents estimates with specific number of lagged heat events and mortality rates included. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Through all dynamic models, we again obtained a significant increase in mortality on days of extreme heat. There is sparse variation in the effects distinguished by the number of lags we additionally included. In all cases they are in the range between 0.231 and 0.214 additional deaths per 100,000 inhabitants on the day of heat occurrence. This is similar to the estimates of the first step of the harvesting analysis[31] but significantly smaller than the estimated impact of 0.37 in the analysis of contemporary effects[32]. This discrepancy is caused by the omitted variable bias induced by excluding lagged temperatures as described in the previous step. In Table (7), the particular effect of each lagged heat event is listed.

All estimated effects of lagged heat events are significantly positive, which leads us to the same conclusion as in the first step of the *Harvesting Analysis*: Heat events have a positive impact on current mortality and also on mortality on the following days. The more days we go backwards,

Table 7: Effects of Lagged Heat Events

effect of lag	1	2	3	4	5	6	7
included lags							
1	0.272***						
2	0.214***	0.134***					
3	0.211***	0.104***	0.069***				
4	0.209***	0.102***	0.051***	0.038***			
5	0.207***	0.101***	0.050***	0.028*	0.021*		
6	0.207***	0.099***	0.049***	0.027*	0.008	0.027*	
7	0.207***	0.099***	0.049***	0.026*	0.008	0.025*	0.002

Notes: Addition to Table (6). Particular results of lagged heat event coefficients (γ_j) from estimation of equation (3). Each column represents estimates with spicific number of lagged heat events and mortality rates included. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

the smaller the estimated impact. When the number of included heat lags goes beyond 7, lagged heat events tend to become insignificant. Furthermore, if the amount of harvesting is calculated in analogy to the previous step as the sum of lagged heat coefficients, we observe positive values in each case. Thus, we found that heat increases mortality significantly and that the main impact is on the day of occurrence and the first week afterwards. Our results can again be interpreted as a reversed *Harvesting Effect.* These results have also been verified by the estimation of the model for each of the specific causes which will not be reported separately.

The second possible reason why the estimated impact of heat on mortality might be biased in the static analysis, is the strong positive autocorrelation in mortality. We considered this also in the second step of our analysis of the *Harvesting Effect.* If the *Harvesting Hypothesis* held true, we should have found higher coefficients of heat today than in the analysis of contemporary effects, meaning that lagged mortality would have had a negative impact on mortality today and thus, the heat effect would be weakened by a longer time horizon. But to the contrary, we estimated significantly smaller impacts of heat on mortality. Results are reported in Table (8).

For all numbers of included mortality lags we found a weak but significantly positive impact on mortality today. The value decreases as we go backwards. Regarding the estimated impact of heat on mortality, we can conclude that a part of the increase in mortality when extreme heat occurs is captured by previous mortality rates and that the effect is overestimated in the separated analysis of contemporary effects. Therefore, we can still reject the *Harvesting Hypothesis.*

Table 8: Effects of Lagged Mortality

effect of lag	1	2	3	4	5	6	7
included lags							
1	0.015***						
2	0.015***	0.011***					
3	0.015***	0.011***	0.012***				
4	0.014***	0.011***	0.012***	0.010***			
5	0.014***	0.010***	0.011***	0.010***	0.010***		
6	0.014***	0.010***	0.011***	0.010***	0.009***	0.010***	
7	0.014***	0.010***	0.011***	0.010***	0.009***	0.010***	0.008***

Notes: Addition to Table (6). Results of lagged mortality coefficients (λ_j) from estimation of equation (3). Each column represents estimates with spicific number of lagged temperature and mortality. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Overall, the conclusion of the *Harvesting Analysis* is that mortality increases on days of extreme heat. This effect will not be compensated in a longer time horizon and leads to a shift in the distribution of mortality rates. Comparing the results of both steps of this section, we do not find significant differences. Thus, we can conclude that leaving out lagged heat events overestimates the heat impact. On the other hand, we have shown that the impact of heat is higher the more previous days also where extreme hot and that the duration of heat waves is important to measure the impact on mortality. To capture the pure effect it is not as necessary to also include lagged mortality since the heat effect did not change significantly in the second step of the *Harvesting Analysis*.

4.5 Testing the *Urban Heat Island Hypothesis*

As outlined in section 2, there is a special debate around the issue if living environments affect the amount of heat wave induced deaths. The *Urban Heat Island Hypothesis* states that temperature levels in the city are in the day time more or less equal to those in the rural environment, but the decrease in temperatures at night is considerably less s.t. thermal stress on human bodies is higher. As a consequence, heat induced mortality should be higher in the cities. In addition, it is assumed that other meteorological factors like wind speed and humidity, for instance, vary between cities and rural environments, by which the heat mortality nexus can be affected. In order to test this, we used the classification of the Federal Statistical Office to define urban and rural counties in our sample. Overall, we identified 214 urban[33] and 166 rural[34] counties in Germany. As a first step, we compared the average temperatures during days of extreme heat in both samples. As reported in Table (9), no significant difference was measured. In rural, as well as in urban counties, the temperatures were about 32 ˚C during heat waves. Unfortunately, there is no available data of night-temperatures. Hence, we are not able to test the second assumption of the *Urban Heat Island Hypothesis*, according to which there is a stronger temperature decrease at night outside the cities.

Table 9: Average Air Temperature During Heat Waves

max temperature	Mean	Std. Dev.	Min	Max
All counties	31.90	1.60	30.00	39.60
urban counties	31.91	1.62	30.00	39.60
rural counties	31.85	1.54	30.00	39.2

Notes: Descriptive statistic of average temperatures in ˚C on hot days for whole Germany and for urban and rural counties seperately.

In a second step, we assessed the effect of heat on mortality by estimating the initial model described in equation (1) seperatly for both samples. In addition we implemented the model for the sample of all counties and extended equation (1) by an interaction term of heat and urban county characteristic. Since the main interest is now on the differences in the heat impact between urban and rural areas and not on the amount of the effect itself, the *Harvesting Theory* not considered in this part. Results are presented in Table (10).

Through all estimations and for all county types, except for the sample of infectious diseases in rural areas, we estimated a strong positive impact of heat on daily mortality. Including an interaction term between heat and urban county characteristics shows that mortality on hot days is significantly larger in cities than in the rural environment. This effect ranges depending on the specific death cause between 0.06 and 0.506. Again, a very strong effect shows up for the population aged over 65 years. The estimation of the particular effects in urban respectively rural counties verify this result. The increase in mortality was significantly larger in urban counties. This difference again varied depending on the specific causes. Regarding the estimated test statistics, it can be concluded that the difference between urban and rural counties, in each case, is significant. If we now compare the results with those of the initial analysis[35], it was

Table 10: Heat Effect in Urban vs Rural Counties

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
heat	0.297***	1.426***	0.031***	0.134***	0.062***	0.007***
heat x urban	0.092***	0.506***	0.017**	0.041**	0.008	0.006**
$heat_{urban}$	0.392***	1.918***	0.048***	0.173***	0.072***	0.013***
$heat_{rural}$	0.294***	1.446***	0.031***	0.137***	0.061***	0.007***
t-test	-3695.27	-3739.60	-2291.2	-1999.74	-977.71	-2161.04
Significance	***	***	***	***	***	***

Notes: Panel data fixed effects estimation with robust errors clustered on the county level. The unit of analysis is the county. The dependent variable is daily mortality per 100,000 inhabitants. First two rows presents estimated effect of heat in interaction with urban county characteristic using the data of all counties. In the third and fourth row results for subsamples including only urban, respectively rural counties are presented. Last two rows present test statistic of independet two sample t-test between heat coefficients in urban vs rural counties and significance of differences. Each column includes results of cause specific regression analysis. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

found that for all samples the effect in urban counties was higher, and in rural areas was lower, than the results for all counties together. Whether the *Urban Heat Island Hypothesis* holds true, i.e. higher mortality in urban areas is induced by lower temperature decreases during the nights cannot be answered yet. There might be other time varying factors that significantly differ between urban and rural counties and are not included in this study. To give an answer to this question, additional research is necessary. At the current state of knowledge, we can conclude that mortality during heat waves is significantly higher in urban counties. And we can assume that the differences are not induced by additional meteorological determinants since we control for them in our model.

4.6 Robustness checks

To corroborate our results, we implemented further specifications of the model. Firstly, we included dummy variables for every week instead of month dummies to control for seasonal effects. The main results were consistent with our previous estimations: heat leads to an immediate significant increase in mortality and also has a significant positive effect on the following days. Also the harvesting hypothesis still could be rejected. Also the higher heat induced mortality in urban areas was observed using the more careful season and time trend controls.

As a second robustness check, we estimated all of the models using alternative definitions of the temperature threshold: a heat event was defined by maximum temperatures exceeding 26 °C and 32 °C respectively. We observed what one would have expected after our empirical analysis: Estimated effects had the same direction but were weaker using the lower temperature value and stronger in the case of the higher threshold. In both cases the harvesting hypothesis could be rejected.

Thirdly, we analyzed the relation between heat events and mortality on an aggregated level. Therefore, we added up mortality for each county and year and regressed it on the number of hot days in the county. Results are presented in Table (11).

Table 11: Effect of Hot Days per Year on Aggregated Mortality

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
hot days	-0.547	2.521***	0.968***	-2.738***	-0.287	0.378***

Notes: Panel data fixed effects regression of the number of hot days per year on mortality rates per year and county. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The effects differ depending on the specific causes of death. Regarding the entire population and all causes of death the estimated effect is negative, which was not the case for cause specific mortality. We interpret this as an indication that an analysis of impacts on mortality rates should be distinguished by particular population groups and death causes. For people of age 65 and older, we found that in years with many hot days significantly more people die. This underlines our result that heat induces an upward shift in the distribution of mortality of the elderly. The same result was observed for death caused by respiratory and infectious diseases. This is a very relevant point for our analysis. For these causes of death the largest effects were observed in our analysis and can now be verified by this robustness check. For the other particular causes we found different results: a decrease in mortality from cardiovascular diseases and no significant effect for death due to neoplasms. This makes sense, since the strong positive heat impact on mortality caused by respiratory and infectious diseases at the year level has to be compensated so that there remains no mortality effect for the overall population when all death causes are regarded.

Furthermore, one could argue, that the impact of heat on mortality depends on whether temperatures rise slowly or jumpy. In particular it might be expected that in a sequence of hot days the mortality increase is highest at the first hot day after a period with moderate temperatures and decreases when there was already heat on previous days. Regarding our results of the *harvesting analysis* we already concluded that heat induced mortality increases the more hot days occur after another. As an additional robustness check we estimated equation (1) with an interaction term of heat today and heat on previous days. Results are reported in Table(12). Interaction of heat today and the days before is significantly positive for all cause specific mortality rates. This implies that heat on the day before does not lead to a weaker effect today due to adaptation, but contrary even to an increase in heat induced mortality today.

Table 12: Interaction Effects of Heat Events

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
heat	0.186***	0.899***	0.016***	0.089***	0.046***	0.001
interact1	0.176***	0.917***	0.019***	0.088***	0.027***	0.011***
interact2	0.261***	1.246***	0.053***	0.088***	0.023**	0.014***

Notes: Panel data fixed effects estimation of equation (1) extended by interaction terms with robust errors clustered on the county level. The unit of analysis is the county. The dependent variable is daily mortality per 100,000 inhabitants. First rows presents estimated immediate effect of heat. Second and third row report estiomated coefficients of heat today and yesterday and the day before respectively. Each column includes results of cause specific regression analysis. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

As a last robustness check we widened the harvesting analysis to a longer time window. Using the same approach as in section 4.4., we implemented the model extended by 60 and 90 lagged heat events. Results are presented in Table(13). Except in the case of death caused by neoplasm the estimated immediate as well as the cumulative harvesting effect are significantly positive.

This verifies our results of the harvesting hypothesis, meaning that even in a longer time window the initial heat induced increase in mortality is not compensated by following decreasing rates. In conclusion the distribution of mortality rates indeed is shifted.

Table 13: Heat Effects in a Longer Time Window

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
60 lags						
heat	0.214***	0.995***	0.022***	0.095***	0.050***	0.004***
harvesting	0.387***	2.509***	0.062***	0.165***	-0.004	0.024***
90 lags						
heat	0.186***	0.899***	0.016***	0.089***	0.046***	0.001
harvesting	0.280***	2.198***	0.061***	0.086*	-0.022	0.018***

Notes: Panel data fixed effects regression of equation(2) using 60 and 90 heat lag windows. Coefficients of heat represent the immediate effect. The harvesting effect is calculated as the sum of estimated coefficients of all lagged heat events. Each column includes results of cause specific regression analysis. Significance level: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5 Conclusion

Summary of empirical results

In this paper, we analyzed the impact of extreme heat on the distribution of mortality rates on the county level in Germany. We estimated several panel data models for the entire population and all cause mortality as well as for specific death causes. Our results can be summarized as follows. Firstly, we found that mortality is significantly higher on days of extreme heat and in turn there is a negative impact on health. It has been manifested in all specifications for all particular death causes. Additional deaths on the day when hot temperatures occur were measured in a range of approximately 0.03 to 3.5 per 100,000 inhabitants[36]. In particular for the elderly population, a very strong impact of heat has been observed. This effect will be more important in the progress of population aging. If the elderly population in Germany increases as predicted, it can be assumed that the overall heat induced mortality has been underestimated. Cause specific effects where highest for respiratory and infectious diseases. These two causes became more relevant in recent years and if the increase in mortality continues, the overall heat effect might also increase.

Secondly, after a detailed analysis of the time structure of the heat effect, we could reject the *Harvesting Hypothesis*. Following our results, besides the immediate increase in mortality, heat on previous days also leads to higher mortality. Thus, the distribution of mortality rates is shifted by extreme temperatures and not compensated in a longer time horizon. Contrary to the *Harvesting Hypothesis*, we observed a *reversed Harvesting Effect*, meaning that heat events today also increase mortality in near future.

Finally, differences in the heat effect for urban and rural counties were considered. We found that the increase in mortality on days of extreme heat is significantly larger in cities than in the urban environment. This result is not induced by different values of observable meteorological factors for which we have controlled in the estimation. In consequence, it might be an indicator for the validity of the *Urban Heat Island Hypothesis* suggested in previous research, meaning that higher mortality in cities occurs because of a smaller decrease in temperatures during the nights.

Economic relevance

From an economic point of view, the estimated health shock induces welfare losses. There is a wide range of literature which discusses theoretical models and estimation techniques to calculate a monetary measure of lost lives. Such a calculation is not the focus of this analysis, but used to embed the empirical results in an economic framework. To evaluate heat induced excess mortality we used the findings of Alberini et al. (2006). They focused on benefits that would have been realized by the avoidance of heat induced mortality during the 2003 summer heat wave in the city of Rome. Using behavioral study techniques they estimate a value per statistical death avoided of €3,345,213. One could argue that the Value of statistical life might depend on health status or age of individuals. By now there is no common solution provided by theoretical models[37]. For instance, Alberini et al. (2004) did not find a relation between willingness to pay and age. Considering people with chronic diseases Krupnick et al. (2002) conclude that willingness to pay to reduce mort risk tends to be weakly higher than for respondents which are in good health. This would imply that the reported calculations using our empirical results are even underestimated. However, we applied the statistical life value of Alberini et al. (2006) to our estimations and ended up with the following results that are reported in Table (14).

Table 14: Statistical Value of Lives Lost

Variable	Entire population	Elderly population	Respir. diseases	Cardiovas. diseases	Neoplasm	Infectious diseases
mortality increase per 100,000	0.676	3.503	0.109	0.301	0.073	0.03
effect in %	23.97	26.80	60.56	22.80	10.14	103.33
monetary value in m €	1,861	1,113	300	829	201	83

Notes: First row reports estimated heat induced additional deaths listed in Table (5), where a period of 7 days is considered. Second row includes mortality percentage change of average mortality on temperate days. The last row reports monetary value of lost lives, assuming a value of € 3,345,213[38] per statistical death avoided. To aggregate the effect per 100,000 inhabitants on whole Germany the relevant population size from the year 2006 of 82,314,906 (9,496,708 for people of age 65 and older) was assumed. Each column includes results of specific death cause.

Regarding the entire population the welfare losses in monetary terms that occur from mortality induced by one additional hot day have an estimated value of m € 1,861. For sure, this calculation is very rough, but even so, one thing remains clear: Meteorological experts predict up to twice as many hot days per year in Germany at the end of this century. Combining this with the value of heat induced lives lost, the economic relevance of the effect will be considerably large.

To reduce these costs, society has to be prepared for forthcoming climate change and to its implications. This can happen in two ways: Firstly, policy makers can take action of mitigation, like is done, for example, by the *United Nations Framework Convention on Climate Change*, which has the goal to jointly stop Global Warming. 194 states meet every year for conferences to agree on action plans to stop climate change. The most prominent agreement is the *Kyoto Protocol*. Secondly, actions of adaptation can be taken such that health implications of climate change are abated. Here a distinction can be made between passive and active adaptation. By the term passive, we mean adaptation in an evolutional sense. Humans adapt to a changeing environment such that the increasing occurrence of extreme temperatures and therefore the negative impact on health might decreases. On the other hand, active adaptation can take place, i.e. actions reducing the intensity of thermal stress on human bodies during heat waves. These can be the implementation of heat warning systems, enlighment of the population on prevention behavior or hospital action plans during heat waves, to mention only a few. Research like the study of Teisberg et al. (2004) give evidence for the success of general action plans, in the sense that mortality during heat waves could be reduced significantly. The empirical results of this study underline the need for a general health care plan in Germany to reduce the impact on mortality and thus the induced welfare loss for society.

Besides this general discussion we want to point out that in an economic sense the climate health nexus is mostly relevant for the health care system. Several actors will be affected, for example health service providers, the insurance industry and insured individuals. In this study we observed a shift in the distribution of mortality rates, which is primarily important for the insurance sector and in particular for life insurances and pension funds. Their payment flow depends on life length and the premium system is built on life tables which are determined by the long term distribution of mortality. In general, assumptions about this distribution are based on historical data which could potentially be misleading to the extent that it is distorted by a changing climate.

Limitations of the study and scope for future research

The main limitation of this study is that the estimated positive impact of extreme heat on mortality in the future could be sensitive to the avoidance behavior of the population and structural changes. On the one hand, the process of climate change might be mitigated, such that predictions of meteorological experts might not be realized. On the other hand, the impact of extreme temperatures can be weakened by passive and active adaptation. Both aspects might compensate for the negative health impact and to predict future welfare losses arising they should ideally be considered in the empirical analysis. In addition, it has to be kept in mind that changes in society also determine costs, like demographic change, medical progress or sectoral structure. Finally, three promising topics for future research would be: Firstly, the definition of the heat event could be based directly on the perceived temperature. Secondly, the methodological approach capturing the relation between mortality and temperatures could be extended, for example, in the framework of a competing risks model. As it was shown in our aggregated analysis, the population at risk might changes during heat waves, which illustrates the need for such a framework. Thirdly, it would be an interesting question whether the geographical distribution of hospital and emergencies determine the intensity of thermal stress and thus, the amount of heat induced mortality. Finally, the analysis of the *Urban Heat Island Hypothesis* could be expanded by an analysis of the night temperature differences in urban and rural counties to identify why mortality increases during heat waves differ.

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Notes

[1]Compare to the the report from the World Health Organization in 2008

[2]Compare to Deutscher-Wetterdienst and Umweltbundesamt (2010)

[3]The graphic can be downloaded from the web page of the German Weather Service: http://www.dwd.de/

[4]Compare for example Barnett et al. (2010) which gives an overview of the outcomes

[5]A county is the German *Kreis*, which is the administrative unit between the administrative region and the municipality in a state.

[6]Compare for example McGeehin and Mirabelli (2001) or Sheridan and Dolney (2003)

[7]We used yearly observed county population numbers to normalize the absolute mortality rates. The Federal Statistical Office of Germany provides precise census data, which is a big advantage for our study. For the subsample in which only the elderly population is considered, we used age specific population numbers

[8]Death cause specific distinction was made using ICD 10 keys

[9]How the number of included counties came up is discussed in section 4.2

[10]The Bartlett's formula was used to calculate autocorrelation

[11]Compare for example Deschenes and Moretti (2009)

[12]Calculation using Kernel Polynomial Smoothing

[13]Compare to Zanobetti and Schwartz (2008)

[14]Compare to Conti et al. (2005)

[15]Moderate thermal stress up to a temperature value of 32 $^\circ$ C and hard thermal stress for higher values.

[16]Compare to Figure (8

[17]The use of this approach implies that measurements of a meteorological stations become less important the farer they are away from the county centroid

[18]In the case that there was not a single weather station in this area, the next closest station has been used

[19]Compare for example Deschenes and Moretti (2009)

[20]To calculate the normalized mortality rates, we used the amount of county population observed once every year. The required data was available from the *GENESIS Online* data base of the German Federal Statistical Office.

[21]Cloud Coverage measured in eights

[22]Humidity measured as relative humidity in %

[23]Air Pressure measured in hectopascal

[24]Windspeed classified in levels of the Beaufort scale

[25]Rainfall measured in millimeter per day

[26]Sunshine duration measured in hours

[27]Additionally, several other geographical factors and individual conditions like clothing and physical fitness, determine the effective intensity of a heat event as it was described in section 3. These variables are assumed to be fixed in each county and therefore, they cancel out in the Fixed Effects specification we used for our analysis.

[28]Compare to results of the contemporary analysis without lagged heat in Table (4)

[29]A similar result was observed for the models where 7 and 14 lagged heat events were included

[30]Compare to Nickel (1981)

[31]Compare to Table (5) first column

[32]Compare to Table (4) first column

[33]Urban counties are *Kernstaedte* and *Staedtische Kreise*

[34]Rural counties are *laendliche Kreise* and *Kreise im laendlichen Raum*

[35]Compare to Table (4)

[36]Total effects reported in Table(5)

[37]Compare to Alberini et al. (2006)

[38]Compare to Alberini et al. (2006)