Assessing Vulnerability and Risk to Heat Wave Events in Germany and Building a Basis for Further Modelling

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Abstract

Heat wave events are silent and slow but devastating disasters. The European 2003 summer heat wave event has caused more than 50,000 fatalities within only a few weeks. With worldwide mostly increasing frequency of heat wave events, there is a clear need to find adequate adaptation strategies. For such strategies it is unavoidable to know where vulnerability and risk is at its highest and how it will change in future times. We identified in our fuzzy logic approach major hot spots of heat wave vulnerability and risk that can be used as discussion basis and starting point for further modelling.

1 Introduction

Heat waves events are silent and slow but devastating disasters. The European 2003 summer heat wave event has caused more than 50,000 fatalities within only a few weeks (IPCC 2007). Strongly affected by heat wave events have been persons living in urban areas with negative bioclimatic characteristics (IPCC 2007). With worldwide increasing urban population (UN 2008) and the growing number of elderly people who react particularly sensitive to heat impacts this situation is most likely to get even worse. In addition, in different climate change scenarios the frequency of heat wave events is expected to increase up to a general higher mean (JENDRITZKY & TINZ 2009) but even more important to a higher variability which leads in turn to a higher possibility of heat wave related extremes (SCHAER et al. 2004). Focusing on these three trajectories – increase in urban population, ageing of population, and expected increase in heat waves – it becomes clear that there is a high need for the development of adequate adaption strategies and implementation of these strategies in land development, urban planning and local policies (WOLF et al. 2010, SMITH & LEVERMORE 2008). Identification and quantification of the potential risk of heat impact driven by climate and demographic change is therefore a large challenge. A wide variety of vulnerability/risk definitions and frameworks depending on the type of research or research community exist (BIRKMANN 2006). According to CUTTER (1993) “Vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazard of place (risk and mitigation) with the social profile of communities.” Vulnerability is characterized by system variables including the systems physical environment in terms of “hazard of place” as well as human characteristics defined by “the social profile of communities” (CUTTER 1996). The risk is defined by the UN defi-
nition as “expected losses [...] resulting from interactions between natural or human-induced hazards and vulnerable conditions” (UN 2004). Risk can therefore be seen as a function of vulnerability and hazard (FÜSSEL 2007, WISNER 2004).

On this basis of quantified risk and vulnerability decision makers may then be able to develop strategies for further coping. However, this quantitative research is confronted with the problem of modelling complex systems including not only natural or physical but also human components. Models should therefore be as simple as possible to guarantee on the one hand a transfer to other regions and on the other hand to give decision makers a simple “indicator” which gives a clear idea of expected impacts (KROPP et al. 2006). The challenges in quality and incompleteness of the data seems to be inherent and a restriction to precise and detailed results on vulnerability and risk. In computer science and electronic engineering well established concept is the concept of Fuzzy Logic which deals with not exactly quantifiable data or so called “fuzzy” data (ZADEH 1965). We argue that by using fuzzy approaches the impreciseness of the data can be explicitly integrated into the analysis. Hence, the aim of this study is to develop a simple fuzzy modelling approach to assess vulnerability and risk to heat wave events in Germany.

2 A Fuzzy-logic Approach of Vulnerability and Risk to Heat Wave Events in Germany

2.1 General approach

To develop a model of vulnerability and risk to heat wave events in Germany we first have to determine the key indicators which characterize our system. In this paper, the environmental and biophysical characteristics are represented by “amount of urban area”, “amount of forest areas” and “population density” per statistical entity (Kreise and Kreisfreie Städte). The proxy “amount of urban area” is representing the strength of urban climate effects, mainly urban heat island effects (OKE 1987), secondly reduced water availability and a lack of vegetation resulting in less evapotranspiration (BÖLUND & HUNHAMMAR 1999). This well-known phenomena can have strong influence on local climate systems and frequently results in a negative climate situation with higher temperatures and lower humidity in urban areas having observable influence on human health (ENDLICHER 2008). The proxy “amount of forest areas” is taken as a hint for how “green” a statistical entity is and therefore which opportunities it has to deal with heat. Forest areas have significant cooling effects even on surrounding areas (ROWNTREE 1986, JIM & CHEN 2009). The strength of cooling effects on local climate conditions depends on the size of the forest, the location and the pattern – for example – in urban areas (DIMOUDI & NIKOLOPOULOU 2003, KATAYAMA et al. 1993). The final proxy “population density” represents the housing situation in an entity. We assume: the higher the population density, the higher the building density, which in turn leads to an increase in negative urban climatic effects.

To account for vulnerability, we follow MATTHIES et al. (2008) and KOPPE (2004a) and identify elderly people as well as very young people as vulnerable groups. Hence we select the following variables: “percentage of people older than 65 years”, “percentage of people older than 75 years” and “percentage of people younger than 3 years”. The higher the percentage of these groups the higher the vulnerability of the entity.
To assess the risk, the specific hazard – a heat wave event – of an entity has to be represented by a proper proxy as well. There is no general definition what a heat wave is or what temperature can be harmful for people, because it differs from region to region. However, in central Europe and North America a generally used threshold is a daily maximum temperature of 30 °C which shows a clear coherence with mortality (HAJAT 2002). To estimate the heat days, climate data is analyzed in the time period 1991 to 2010. The mean number of heat days per year is calculated and used as proxy for the thermal load of a station.

We apply this vulnerability and risk approach to the study area of Germany, which will be described in more detail now.

2.2 Study area and regional Climate Change

Germany lies in central Europe and with nearly 82 billion inhabitants it is the largest state in Europe in terms of population. As a federal system, Germany is divided into 16 federal states, which then are divided into altogether 465 Kreise und kreisfreie Städte.

Germany’s location in central Europe is typical for moderate west coast maritime climates. The eastern parts, especially Brandenburg can be semi-continental. The central German uplands are close to 1000 m high in elevation and therefore have sub-alpine climates. The German Alps reach up to nearly 3000 m in elevation and therefore show alpine conditions. A special climatic situation is found in the Rhine valley in southern Germany. Caused by special topographic situations and a Mediterranean influence the average temperature can be quite higher than in the surrounding areas what is best visible in the excellent wine planting conditions.

Like all European countries, Germany is facing some challenges related to global climate change: a shift in the occurrence of heat days and a related higher frequency of extreme heat wave events is expected in several scenarios (JACOB et al. 2008). As seen in the 2003 summer heat wave, impacts of heat wave events can lead to significant higher mortality rates (IPCC, 2007) even in moderate climates like Germany (KOPPE et al. 2004b). In Figure 1 the increase in temperature is projected for the period 2071 – 2100 for different scenarios.

Fig. 1: Possible changes in the amount of heat wave days for Germany in the period 2071 – 2100 compared to the baseline 1961 – 1990 using different scenarios: B1, B2, A2, A1B (Source: Helmholtz Gemeinschaft – UFZ, 2010; Tage = days).
Even in the best-case scenario (B1), 15 and more heat days in summer will be likely. The worst-case scenario has a projected increase of up to 40 and more heat days. In all scenarios a north-south gradient is apparent with Southern Germany facing a higher increase in heat waves. Northern Germany is showing lower change rates but still an increase between 10 and 30 days per year.

2.3 Data

The described variables in this approach are covered by different sources. The population data is provided by the Statistisches Bundesamt Deutschland (German Statistical Office), the basic geometry of the Kreise und Kreisfreie Städte as well as the population density is provided by the Deutsches Bundesamt für Kartographie und Geodäsie (German cartography and geodetic office) and the land use data is generated from the European CORINE land cover project by the European Environmental Agency.

As population variables, the percentage of elderly older than 65 and 75 as well as the percentage of children younger than 3 years is used. The percentage is calculated by the ratio of the absolute number of people older/younger the specific age and the total population in one entity. The density is calculated using the provided area of an entity in people per square kilometres. In the CORINE grid data set forest and urban classes are selected and converted to vector data. Then the amount of forest and urban area is calculated for every entity. The forest data is then finally transformed to the variable “lack of forest area” by calculating the non-forest area (therefore 100 % – x % of forest area). In Table 1 all variables are listed with data source and their mean.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of elderly (65+)</td>
<td><em>Statistisches Bundesamt Deutschland</em></td>
<td>11.87 %</td>
</tr>
<tr>
<td>Percentage of elderly (75+)</td>
<td><em>Statistisches Bundesamt Deutschland</em></td>
<td>8.76 %</td>
</tr>
<tr>
<td>Percentage of children (up to 3)</td>
<td><em>Statistisches Bundesamt Deutschland</em></td>
<td>2.38 %</td>
</tr>
<tr>
<td>Percentage of urban areas</td>
<td>Europ. Environmental Agency</td>
<td>9.66 %</td>
</tr>
<tr>
<td>Lack of forests</td>
<td>Europ. Environmental Agency</td>
<td>97.37 %</td>
</tr>
<tr>
<td>Population density</td>
<td><em>Bundesamt für Kartographie und Geodäsie</em></td>
<td>595.3 p/sqkm</td>
</tr>
</tbody>
</table>

The climate data is provided by the Deutsche Wetterdienst (DWD). We use the data (daily maximum temperature) of 45 climate stations in the time period 1991 to 2010 to count all days with a maximum temperature above 30 °C using a Python script. For each station, the number of heat days is then divided by the overall number of days in the time period to get an average value.
2.4 Method

We apply three different fuzzy approaches to derive the vulnerability and risk to heat waves in Germany. Since there exists no distinct threshold whether vulnerability or risk is high or low, neither is there data to train our model, we chose a fuzzy set (RASHED & WEEKS 2003):

$$A = \{(x, \mu_A(x) \mid x \in X)\}$$

with $\mu_A(x)$ being a membership function that expresses the degree of membership of a certain variable. This membership function can be of linear, exponential, sinusoidal or other gradual shape and allows dealing with fuzzy transitions because no exact threshold is necessary. In our case study, we argue that there is a simple linear relation: The higher the value, the higher the influence. Hence, the resulting membership function is:

$$\mu_{\text{High}}(x) = \frac{(x - \text{min})}{(\text{max} - \text{min})}$$

In case of low values (e.g. below the mean) the resulting value, however, can be relatively high. This situation would be given if the distribution of a variable is extremely right skewed. To avoid this, we suppose that if the value of the variable is smaller than the average, the variable has no influence, but if the value is higher than the average, the influence increases linear:

$$\mu_{\text{High}}(x) = \begin{cases} 0 & \text{if } x < \text{average} \\ \frac{(x - \text{average})}{(\text{max} - \text{average})} & \text{if } \text{average} > x \end{cases}$$

The third membership function we define is to argue that a variable’s influence is small if the variable is low, but if it gets near or above the average, the influence rises rapidly growing up to a certain point where the growth slows down and reaches 1 asymptotically:

$$\mu_{\text{High}}(x) = \frac{1}{2} \left(1 - \cos \left(\pi \cdot \frac{x}{100}\right)\right)$$

These three different membership functions are used to calculate the degree of membership of all variables to the category “high”.

After fuzzyfying all variables, the fuzzy sets have to be integrated to one single index offering information about heat wave vulnerability of each entity. Since there exists no precise information about the variable with the highest influence on vulnerability, we approach a basic integration using equal weighting and summarize the weighted fuzzy sets. The results – ranging between 0 and 1 – will then be classified using quintile classification.

To determine the average heat load per entity, the calculated heat load per station is interpolated using Ordinary Kriging (DALY 2006, ZIMMERMAN et al. 1999). The interpolation using a Gaussian function shows an overall good fit with a standardized root-mean-square error of 1.005. To aggregate the interpolated data to the level of Kreise und kreisfreie Städte, the area weighted mean per entity is calculated.

We follow the definition of risk as a function of vulnerability and hazard. $\{\text{Risk}_{\text{high}}\}$ is hence represented by the logical clause:
IF \{Vulnerability_{high}\} \text{ AND } \{Hazard_{high}\} \text{ THEN } \{Risk_{high}\}.

The vulnerability is higher if each vulnerability variable is higher. The Hazard is standardized by the three membership functions mentioned above. The logical clause to determine the risk is represented by the following:

\{Risk_{high}\} = \min \{Vulnerability(x), Hazard(x)\}

3 Results and Discussion

3.1 Vulnerability to heat waves in Germany

Figure 2 shows the three results of the vulnerability analysis. All in all, the three approaches differ from each other only little. The central lands of south-east Lower Saxony, Thuringia and Saxony show medium to high vulnerability to heat waves in all approaches. The Ruhr-Area shows an overall high vulnerability. Rhineland-Palatinate and the Rhine-Valley down to South Baden-Württemberg show a medium to high vulnerability. Noticeable is the high overall vulnerability of cities and urban areas (e.g. Berlin, Munich, Frankfurt a. M.). The large German Forests (Black Forest, Vosges Mountains, German Alps, Bavarian Forests) show an overall low vulnerability. More remote and agricultural areas (e.g. Brandenburg, Mecklenburg-Western Pomerania) do so too. The Northern end (Schleswig-Holstein) shows a medium to high vulnerability. Noticeable differences can be found in northern Lower Saxony where we find a low vulnerability in the first approach and a high vulnerability in the third one. Also parts of Bavaria (West Lower Bavaria and North Upper Bavaria) do show such differences.

![Fig. 2: Results of the vulnerability analysis: Mean-Max fuzzification (left), Min-Max fuzzification (mid) and sinusoidal fuzzification (right). The classification is based on quintiles.](image-url)
3.2 Risk of heat waves in Germany

In Figure 3 the results of the risk approaches are shown. The risk approaches show a generally different picture compared to the vulnerability approaches. In contrast to scattered patterns in the vulnerability approach, larger clusters of high risk can be identified here. Three major hot spots of potential high-risk regions are identified: (1) Rhineland-Palatinate, Baden-Württemberg and South-Hessen, (2) The Berlin-Brandenburg Area and Saxony and (3) the Ruhr-Area. North and Central Germany show an overall very low to low risk with the exception of some urban regions in the first approach. Bavaria is only partly at higher risk. Mostly all urban regions in southern Germany (e.g. Nuremberg, Freiburg, Karlsruhe, Kaiserslautern, and Stuttgart) show a very high risk in at least two approaches.

![Fig. 3: Comparison of risk approaches. Classification is based on quintiles](image)

3.3 Comparison of the three approaches

Overall, we can find a broad accordance between all three approaches, mainly due to underlying data and similarities in the membership functions. The mean-maximum approach shows lowest values in the vulnerability and risk assessment, the min-max and sinusoidal approach show general high agreement. In the min-max risk approach urban areas (e.g. Berlin, Dresden, and Hannover) are detected as high-risk regions. Urban areas are identified, frequently surrounded by rural areas with low risk.

Summing up in Figure 4 we can see regions that have been analysed to be at high vulnerability and risk in all three or at least two approaches. Regions that have been detected multiply can be assumed to be a quite certain hot spot. Highly vulnerable areas are identified in The Ruhr-Area, Saxony, Schleswig-Holstein (Husum and Heide), greater Hannover area and single big urban settlements (e.g. Munich, Berlin, Frankfurt a. M.). High-risk re-
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Regions are located in the Rhine-Valley (Baden-Wurttemberg), Stuttgart region, Frankfurt a. M. region, Nurnberg and North-Bavaria, the Ruhr-Area as well as Berlin and Potsdam.

*Fig. 4*: Regions of triple or double vulnerability (left) and risk (right) identified as secured hot spots

However, we are well aware of the restrictions of our approach: The simple model, few selected variables, challenges in choosing membership functions and different aggregation methods are clear limitations.

4 Conclusions and Outlook

In this paper we applied a fuzzy logic approach to assess heat wave vulnerability and heat wave risk on a country-wide scale. Results indicate which regions are, compared to other regions, at higher vulnerability or risk. By varying the fuzzy logic memberships, we achieve a deeper insight and higher level of security of the results.

The identified high-risk regions are mainly expected outcomes. So we identified large urban, highly compacted areas and typically “hot-climate” areas. In the 2003 summer heat wave, the mortality has been expectable high in Baden-Wurttemberg (KOPPE et al. 2004b). Also in Berlin-Brandenburg, an increase in mortality has been detected in the 2003 as well as in the 1994 heat wave (GABRIEL 2010). However, the increase did not reach the Baden-
Württemberg one in 2003. There is only few data about mortality changes available caused by heat waves in Germany. Hence we cannot verify our model empirically, but the research done on mortality changes indicates that some hot spot regions have been identified correctly. Without such a validation dataset available, there is a need to develop the knowledge-based approach and integrate more expert knowledge on weighting and aggregation. The use of additional data also has to be discussed in further work: How can the regional GDP influence the adaption strategies? How adequate is the availability of medical service?

The last but important role takes the approach regarding further modelling. Therefore all data can be seen as changing temporally, projections of input data can be used to analyse future vulnerability and risk. Also monitoring can be an opportunity to detect changes and find correct regional to local adaption concepts. We believe that such models can be a concrete step towards regional to national adaption planning and risk reduction measures.

References

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