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Winter storm risk of residential structures – model development and application to the German state of Baden-Württemberg

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Abstract. The derivation of probabilities of high wind speeds and the establishment of risk curves for storm damage is of prime importance in natural hazard risk analysis. Risk curves allow the assessment of damage being exceeded at a given level of probability.

In this paper, a method for the assessment of winter storm damage risk is described in detail and applied to the German state of Baden-Württemberg. Based on meteorological observations of the years 1971–2000 and on damage information of 4 severe storm events, storm hazard and damage risk of residential buildings is calculated on the level of communities. For this purpose, highly resolved simulations of storm wind fields with the Karlsruher Atmospheric Mesoscale Model (KAMM) are performed and a storm damage model is developed.

Risk curves including the quantification of the uncertainties are calculated for every community. Local differences of hazard and risk are presented in state-wide maps. An average annual winter storm damage to residential buildings of minimum 15 million Euro (reference year 2000) for Baden-Württemberg is expected.

1 Introduction

Born from disturbances of low-pressure regions over the Atlantic Ocean and driven by high temperature differences in winter, destructive storms in Europe have rather short return periods of <10 years and often cause widespread, sometimes European-wide damage to persons, buildings, and nature. In Germany, storms are by far the costliest natural catastrophes, causing more than 27% of the economic and more than 45% of the insured damage (Munich Re, 2005[1]) of all catastrophic natural events between 1970 and 2004.

In order to better understand the nature of winter storms and their consequences, a risk analysis is needed that allows to quantify the expected losses. For that purpose, risk is expressed as probability-damage relationship, also known as risk curve representing the damage that is expected to be exceeded at a given annual probability. The corresponding formula is written as (e.g. Petak and Atkisson, 1982)

Risk = Hazard * Vulnerability * Value

implying that risk is the combination of (1) a storm hazard function, defined as the probability of exceedance of a given wind speed, (2) a vulnerability function, combining wind speed and relative damage and (3) a value function calculating the absolute monetary loss. Thus, according to this definition, if one of these latter functions is zero, also the risk function becomes zero. An important derivate of the risk curve is the average annual damage (AAD) that gives the monetary amount that would have to be set aside each year to cover the full range of future losses up to a minimum probability level.

The need for such a risk analysis is evident as no quantification of storm damage risk has been conducted so far for entire Germany. Methods of risk assessment in a single city (Radke and Tetzlaff, 2004) or integral damage assessment in Germany (Klawa and Ulbrich, 2003) are considered first approaches. However, a Germany-wide risk assessment needs methods that ensure a large-scale and high-resolution analysis. Furthermore, the method is limited by the availability and manageability of data.

Concerning storm hazard, in recent years, publications mainly focused on the analysis of individual storm events (Goyette et al., 2001; Ulbrich et al., 2001) and on investigations of climatological aspects (Schiesser et al., 1997;

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Lamb, 1991). Existing hazard maps are predominantly based on wind information from observational weather stations combined with spatial interpolation methods (Klawa, 2001; Kasperski, 2002). Based on data related to the wind energy distribution, a more regionalized and interdisciplinary approach using statistical-dynamical downscaling methods combined with methods from wind engineering became popular (Mann et al., 2002; Troen and Petersen, 1991).

An approach similar to that presented in this paper was chosen by Kalthoff et al. (2003), who combined climatological data from ground-based weather stations with a mesoscale numerical model in order to assess the regional effects of large-scale extreme wind events in the closer surroundings of the Black Forest. Useful climatological sources on a global scale are, for example, the re-analysis projects carried out by the National Centres for Environmental Prediction, the National Centre for Atmospheric Research (NCEP/NCAR) and the European Centre for Medium Range Weather Forecast (ECMWF).

Research on vulnerability functions for the existing building stock basically began in the 1970s with a detailed analysis of damage caused by cyclone Tracey in Australia (Leicester and Reardon, 1976). Since then, a multitude of different functions dividable by the kind of modelling were developed. Most models were acquired empirically by fitting simple functions to damage data (e.g. Sparks et al., 1994; Dorland et al., 1999; Munich Re, 2001). The functions have the disadvantage that extrapolation to higher wind speeds is not satisfactory, as they are not based on physical processes. In contrast to empirical approaches, it was tried to construct deterministic models (e.g. Unanwa et al., 2000; Pinelli et al., 2004). However, these projects only refer to the US and need large amounts of specific building information that is not available on a large scale in Germany. Additionally, stochastic models were proposed (Rootzén and Tajvidi, 1997; Katz, 2003) applicable for the assessment of overall damage distributions. A detailed review of some further damage functions is given in Heneka and Ruck (2004).

Summarizing, it can be stated that for our purpose of a Germany-wide risk assessment neither an existing hazard model nor a vulnerability model can be used without major adoption. In Sect. 2, we describe our methodology towards a countrywide risk analysis. Application to the German state of Baden-Württemberg for hazard and risk assessment is demonstrated in Sect. 3.

2 Storm damage risk model development

According to the above given definition, the storm damage risk model mainly consists of two sub-models: the hazard model and the vulnerability model.

2.1 Hazard model

Detailed climatological information about the occurrence of gusts associated with storms are only available at about 100 weather stations in Germany. In order to gather information at all the other sites, it is assumed that the highest annual wind speed at every site occurs during the strongest annual storm event that affects a region. Due to their large spatial extension, exclusively winter storms (September–April) are analysed. Local storm events such as thunderstorms, tornadoes and severe down-slope winds are not considered.

For each year during the period 1971 to 2000 the strongest events are identified. Instead of simply interpolating measured wind speeds, the corresponding wind fields are modelled by a numerical mesoscale model with a spatial resolution of $1\,\mathrm{km}\times1\,\mathrm{km}$. With the use of extreme value statistics, hazard curves are computed for every grid point of the raster based on the 30 annual maximum wind speeds.

2.1.1 Storm detection

Several years of observational data are necessary to analyse extreme wind events and to detect the strongest past storm events in an area of investigation. For climatological studies, ground-based weather information from synoptic weather stations provide the most powerful data sets of long-term time series. Especially for industrialized countries, a sufficient number of long-term time series are available.

The frequency and intensity of storms during the period 1971 to 2000 are analysed in order to identify the main storm events in the area investigated. This was done by creating an index of storm strength for each storm event. The indices are the sum of the normalized wind speeds measured at the selected weather stations. Normalization was carried out with the maximum wind speed recorded at the respective weather station. Weather stations which data sets lack consistency, in spite of the fact that the routine meteorological observations are presumably performed according to common WMO standards, are not considered.

2.1.2 Modelling of the wind field

The wind close to the earth's surface is strongly influenced by a broad range of associated mechanisms related to orography and land use. The local or regional meteorological variables, especially the wind field over complex terrain, may largely differ from those on the large scale (Whiteman and Doran, 1993; Adrian and Fiedler, 1995). Consequently, during the last decades, mesoscale atmospheric models were developed to study these effects. Whereas the spatial horizontal resolution of global weather models is $>50\,\mathrm{km}$, the resolution of mesoscale models goes down to 1 km or less. Comprehensive reviews of the boundary-layer meteorology and the wind flow over complex terrain are provided by Meroney (1990) and Carruthers and Hunt (1990) among others.

The presented paper will mainly focus on the spatial distribution of the maximum wind speeds in a high spatial resolution of 1 km. For this purpose, the nonhydrostatic "Karlsruhe Atmospheric Mesoscale Model" (KAMM) is used. The numerical model describes the atmospheric processes based on the three fundamental equations of physics, the equations of momentum, continuity, and energy. Special features of the model are the interrelation to a basic state, the terrain-following eta-coordinate system, and the inelastic approximation for filtering sound waves. Due to the huge computation requirements, the model is implemented on a vector-parallel supercomputer (VPP5000). For more details concerning model architecture and model quality it is referred to Adrian (1994) and Kalthoff et al. (2003).

Modelling the wind fields of past storm events, as noted above, requires the availability of initialization fields of the most important atmospheric variables, such as geostrophic wind, temperature, humidity, pressure and stratification of the atmosphere. Therefore, a basic state is introduced from a large scale model or even more simply from data of radiosondes.. The method is applied to the ERA40 reanalysis data set of the ECMWF. The reanalysis project of ECMWF supplies a comprehensive set of global analyses describing the atmospheric conditions for the time period from 1957 to 2002 with a spatial resolution of 2.5° and a temporal resolution of 6 h. For more details, the reader is referred to the various reports of the ECMWF (e.g. Simmons and Gibson, 2000). The advantage of the ERA40 data set is the global availability of a homogenous data set for a climatologic relevant period and a better spatiotemporal differentiation than using only the information of a single radiosounding. Due to the coarse spatial resolution of the ERA40 dataset compared to current operational global models, it is not possible to cover the dynamical aspects of a storm both in time and space from these initialisation fields. Here, the model is confined to describe stationary conditions and focus only on the wind pattern modified by small-scale terrain variations. The tracks of the individual storms in their temporal evolution and structure are not simulated.

An optimal interpolation procedure is performed to the reanalysis data for generating high-resolved initialisation fields of the model. The low temporal and spatial resolution of the global reanalysis model will likely cause a major problem for the simulation of the wind fields, with respect to both its intensity and spatial distribution. Consequently, nudging technique is used to adjust the wind field to the values measured at weather stations located in the area investigated. Nudging is a weak relaxation towards an atmospheric reference state. The nudging term should be large enough that it has an effect on the solution, but small enough so that it does not dominate over other terms (Stauffer and Seaman, 1990).

The nudging field consists of the basic state and a distance weighted factor resulting from weather stations located in the area investigated. The factor is calculated by the difference between modelled and observed wind speeds. A second simulation is performed for the selected storms where the modelled wind speeds were forced to keep track to the nudging field. The final model output is a highly resolved data set of the wind field at the moment of the strongest winds. Note again, that due to the grid raster of 1km, orography and land use are smoothed and thus, the output wind fields are generalised compared to wind fields over real terrain.

Table 1. Gust factors depending on land use (Used sources: Wieringa, 1986; Drimmel, 1977; DIN 1055-4, 2005).

vegetation	gust factor
water	1.40
rock, sand, wetland	1.45
grassland	1.50
field	1.50
deciduous forest	1.65
mixed forest	1.70
coniferous forest	1.75
built-up area	1.85

2.1.3 Gust wind speed

Mesoscale models are yet not able to reproduce fluctuations of the wind speed. They only represent grid scale wind speeds with averaging times of about 20 min to 1 h (Panofsky and Dutton, 1994). This is due to a common lack of numerical models, where turbulence closure schemes are used to formulate the equations of motion.

There are two main alternative approaches to adapt gust factors to the simulated wind speeds: A physical approach like the method of Brasseur (2001) or empirical gust factors which are proposed in design codes like the German building code (DIN 1055-4, 2005).

As the implementation of Brasseur's method into the numerical model is still under way, preliminary values of gust factors from literature (Wieringa, 1986; Drimmel, 1977; DIN 1055-4, 2005) are connected with the mean wind speeds. These values are adjusted to the available data set of roughness length and are complemented with observed gust factors at several weather stations (Table 1). The roughness length values are derived from the CORINE (CoORdination of INformation on the Environment) land cover data, which gives an European-wide overview of land use with a defined minimum size of 0.25 km^2. The original 44 categories are reduced to 8 main categories. For each grid cell (1 km×1 km), the majority land use category is calculated.

In Table 1, the gust factor is defined as the relationship between the average wind speed over a time period of 20 min from the model and the maximum peak gust averaged over a period of 3 s at 10 m above ground level.

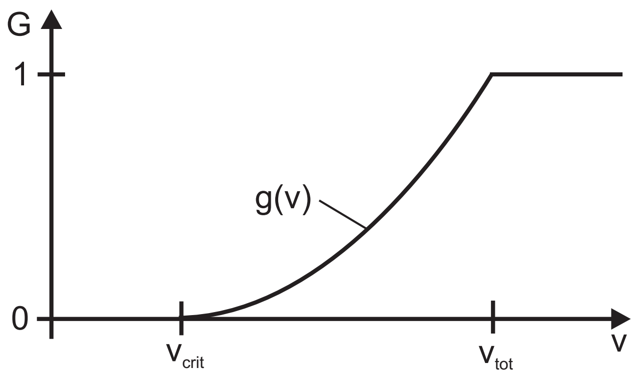

Fig. 1. Ratio of damage to maximum possible damage G for a single residential building as a function of the maximum gust wind speed V during storm events.

2.1.4 Calculation of extreme events

Based on the 30 annual values of maximum wind speed computed at each grid point with KAMM, mesoscale climatology is calculated using the classical extreme value theory. The "Generalized Extreme Value" (GEV) distribution (von Mises, 1954) is a family of continuous probability distributions developed in the extreme value theory to combine the Gumbel, Fréchet, and Weibull families, also known as Fisher-Tippett Type I, II, and III extreme value distributions (Palutikof et al., 1999; Embrechts et al., 2003).

The cumulative distribution function is defined as

$$F(x) = \exp[-(1-ky)^{1/k}], \tag{1}$$

its inverse function is written as

$$v(p) = \beta + \frac{\alpha}{k}\left\{1 - \left[-\ln\left(1-\frac{1}{T}\right)\right]^k\right\} \tag{2}$$

Whereas Type I and Type II are unbounded, Type III is bounded at the upper end. The most common numerical methods to determine the parameters α, β, and k for the inverse cumulative distribution function (Eq. 2) are the Probability Weighted Moments (PWM) and the Maximum Likelihood (ML) solutions. The results may be sensitive to the chosen estimation procedure and distribution.

For the distribution of Gumbel (k=0), the inverse cumulative probability is given by

$$v(p) = \beta - \alpha \ln[-\ln(1-p)], \tag{3}$$

where $v(p)$ is the wind speed that is exceeded at the probability level p during a time period of one year. This relationship is called the wind hazard curve and calculated for every grid point of the area investigated.

In order to calculate the precision of the estimated distribution parameters and the confidence intervals of the hazard curves the method of bootstrapping described by Efron and Tibshirani (1993) is applied to the modelled wind speeds of the 30 storm simulations. The method estimates the sampling distribution of an estimator by resampling with replacement from the original sample.

2.2 Vulnerability model

The vulnerability of a structure is the link between the storm event and the consequent damage to specific structures and is expressed by damage functions. Generally, meteorological, structural, topographical, and social factors are of prime importance for storm damage. As damage information are mainly given by insurances, additionally, economic and actuarial parameters affecting seriously the amount of loss have to be taken into account. It is most common to use the wind speed as a variable and other factors as parameters in damage functions. However, due to the limited data available, most damage models published do not have additional parameters.

2.2.1 Storm damage model

In this section, a statistical approach in order to relate wind speed and damage is presented which is similar to the statistic-deterministic storm damage model of Sill and Kozlowski (1997). For two damage values, 1.) the ratio of affected buildings (RAB; affected buildings to total number of buildings within a region) and 2.) the damage ratio (DR; monetary damage to total value of buildings within a region), a calculation method based on logical assumptions is developed.

The wind damage model is based on the following hypothesis: Let v be the maximum wind speed during a storm event. A structure suffers damage, if v is higher than the critical wind speed v_{crit}. The latter is the wind speed, at which damage to a structure occurs for the first time. Maximum damage is reached at wind speeds higher than the structure's total wind speed v_{tot}. At wind speeds between these limits, damage can be expressed by a function $g(v)$. For every single building, the damage ratio G (Fig. 1) is therefore written in sections as

$$G(v, v_{\text{crit}}, v_{\text{tot}}) = \begin{cases} 0, & v < v_{\text{crit}} \\ g(v), & v_{\text{crit}} \le v < v_{\text{tot}} \\ 1, & v_{\text{tot}} \le v \end{cases} \tag{4}$$

For reasons of simplicity, the damage propagation function $g(v)$ is supposed to be proportional to the wind flow with a power coefficient α. In Eq. (5) at α=2, damage would be proportional to the force of the wind flow. At α=3, it would be proportional to the energy of the wind flow. In general, any more sophisticated function $g(v)$ could be used when further information on damage propagation is available.

$$g(v, v_{\text{crit}}, v_{\text{tot}}) = \left(\frac{v - v_{\text{crit}}}{v_{\text{tot}} - v_{\text{crit}}}\right)^{\alpha} \tag{5}$$

Due to variable building quality and maintenance, the critical wind speeds of buildings within a population of buildings will not be equal. They will rather be distributed somehow. In our case, it is assumed that v_{crit} follows a normal distribution $f(v_{\text{crit}})$ with a mean critical wind speed μ_{crit} and a standard deviation σ_{crit} – in contrast to Sill and Kozlowski (1997) who used triangular distributions to estimate this variability. Thus, the ratio of affected buildings to the total number of buildings is calculated as

$$RAB(v, f(v_{\text{crit}})) = \int_{-\infty}^{v} f(v_{\text{crit}})\, dv_{\text{crit}} \tag{6}$$

which equals the cumulative density function (CDF) of f (Fig. 2). In this distribution, μ_{crit} corresponds to the gust wind speed at which 50% of the buildings in the population are damaged. The two parameters of the distribution have to be adapted to fit the damage data available.

The total wind speeds v_{tot} are also distributed, for simplicity we assume a distribution correlated to v_{crit} in such a way that v_{tot}–v_{crit}=Δv is constant for every building. Further on, assuming the same damage propagation characteristics and an average value of the maximum damage for all buildings, the damage ratio DR for an amount of buildings as a function of the maximum gust wind speed v can be calculated to

$$DR(v, f(v_{\text{crit}}), \Delta v, \alpha) = \int_{-\infty}^{v} f(v_{\text{crit}})\, G(v)\, dv_{\text{crit}} \tag{7}$$

Here, the parameter Δv has to be adapted to fit the damage data, assuming that α in Eq. (5) is fixed. In order to obtain the total number of damaged buildings and the damage sum, RAB and DR have to be multiplied by the total number of buildings and the total value, respectively. The total value of private residential buildings in communities is estimated by Kleist et al. (2006) and equals the replacement costs with reference to the year 2000.

Again, the damage propagation function $g(v)$ and distribution function f chosen for v_{crit} are first approaches and, hence, subject to inaccuracies. Within this mathematical framework, any function or distribution can be used.

2.2.2 Implementation of further parameters

To describe damage in more detail, it would be desirable to have different damage functions for different types of buildings or different exposures. The influence of these additional parameters has to be quantified. For example, Sill and Kozlowski (1997) and Khanduri and Morrow (2003) proposed additional curves for different types of buildings, Schraft et al. (1993) for storm duration.

In our model, μ_{crit}, σ_{crit} and Δv will simply have to be adapted to fit the data classified by the parameters investigated.

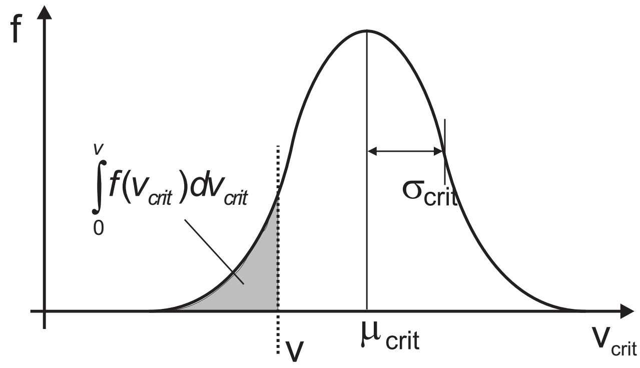

Fig. 2. Assumed normal distribution of critical wind speeds in a population of buildings. At a given maximum gust wind speed v, the ratio of affected buildings is computed as the grey area.

2.3 Risk calculation

Risk is defined as 1.) the number of damaged buildings and 2.) the monetary damage to buildings within a population of residential buildings (in our case we compute the risk for communities as smallest administrative areas in Germany) that is exceeded at a certain level of probability during one year. In Eq. (8), the risk R is calculated for each community, combining the specific hazard curve $v(p)$ with the community's vulnerability function DR and total assets A (number or total value of buildings).

$$R(p) = DR(v(p))\ A \tag{8}$$

As a result, a specific risk curve is assigned to every community. The area of a community is small enough to assume constant storm hazard (also possible are postal code areas). However, for a risk assessment for larger areas such as districts, one would have to use other methods (e.g. Huang, 2001) in order to take into account the probability of the spatial extend of wind speeds. For instance, storm events generally consist of wind speeds of varying local exceedance probabilities.

Another basic risk value is the Average Annual Damage (AAD) which is calculated by integrating the risk curve R over the annual exceedance probabilities.

$$AAD = \int_{p=p_{\min}}^{1} R(p)dp \tag{9}$$

This sum has to be spent every year to account for all future losses up to an individual event probability $p_{\min}$. This lower probability level depends on the available storm hazard curves. Thus, more extreme events with lower probabilities are not taken into account. Note that within these simple risk definitions, neither financial nor actuarial aspects are considered.

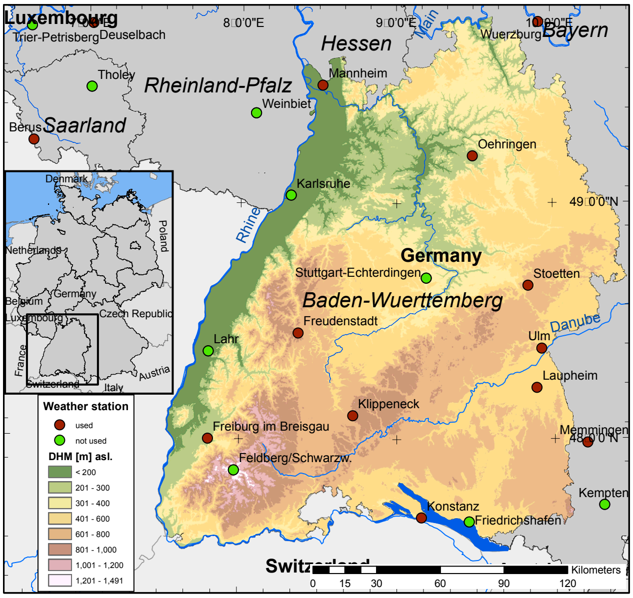

Fig. 3. The area under investigation in south-west Germany.

3 Application of the model to the German state of Baden-Württemberg

3.1 Hazard assessment

Due to the large extensions of storms and the limited calculating capacity, the investigated area of Germany is divided into 6 sub-regions. Each sub-region has a size of approx. 300×300 grid points. Each grid point represents an area of 1 km×1 km. The method described in Sect. 2.1 is first applied to the state of Baden-Württemberg situated in Southwest Germany. This region is characterised by complex terrain with two low mountain regions with elevations up to 1500 m above sea level (Fig. 3).

3.1.1 Storm detection

The German Weather Service (DWD) provides data of the daily maximum gust speed at about 20 different stations from 1971 to 2000 in the area investigated. Additionally, hourly data of these stations as well as data from radiosoundings in Stuttgart are taken into account. The data were thoroughly analysed in order to exclude error measurements and gusts associated with other storm types such as thunderstorms. Additionally, stations showing severe inhomogeneities are not considered. Nearly all weather stations are affected by inhomogenities like changes in measurement levels, the replacement of old instruments, relocation of the weather station and roughness changes in the nearer surrounding of the station. The most severe ones are relocations (e.g. Ulm from the edge to the top of the Kuhberg) and the change in measurement level (e.g. Karlsruhe from 10 m height to 48 m height).

Table 2. List of the strongest storm events per year in southwest Germany with respect to the applied normalisation method.

Normalisation: maximum wind speed			Normalisation: 98%-percentil		
Rank	Index	Date	Rank	Index	Date
1	12.9	28 Feb 1990	1	27.5	28 Feb 1990
2	12.6	26 Dec 1999	2	27.1	26 Dec 1999
3	12.3	13 Nov 1972	4	25.1	13 Nov 1972
4	12.1	01 Feb 1983	5	24.7	01 Feb 1983
5	12.0	02 Jan 1976	7	24.6	02 Jan 1976
6	12.0	09 Dec 1993	6	24.7	09 Dec 1993
7	11.9	23 Nov 1984	3	25.2	23 Nov 1984
8	11.0	24 Mar 1986	12	22.2	24 Mar 1986
9	10.7	13 Mar 1992	14	21.7	13 Mar 1992
10	10.6	10 Dec 1979	8	22.7	10 Dec 1979
11	10.6	26 Jan 1995	9	22.4	26 Jan 1995
12	10.5	16 Jan 1974	11	22.2	16 Jan 1974
13	10.5	28 Jan 1994	16	21.4	28 Jan 1994
14	10.3	28 Oct 1998	10	22.4	28 Oct 1998
15	10.3	16 Dec 1982	13	21.9	16 Dec 1982
16	9.6	18 Nov 1971	15	21.5	18 Nov 1971
17	9.5	25 Mar 1988	20	20.4	25 Mar 1988
18	9.1	29 Oct 1996	22	19.8	29 Oct 1996
19	9.0	12 Nov 1977	21	20.4	12 Nov 1977
20	8.8	03 Jan 1981	17	21.2	03 Jan 1981
21	8.3	**03 Feb 1980**	28	16.3	**29 Mar 1980**
22	8.0	29 Jan 2000	23	18.4	29 Jan 2000
23	8.0	25 Feb 1997	27	16.6	25 Feb 1997
24	8.0	12 Nov 1973	26	16.7	12 Nov 1973
25	7.4	03 Jan 1978	24	18.2	03 Jan 1978
26	6.8	28 Mar 1987	25	17.0	28 Mar 1987
27	6.8	14 Dec 1989	19	20.5	14 Dec 1989
28	5.6	**03 Jan 1991**	18	21.0	**19 Dec 1991**
29	5.5	05 Nov 1985	29	15.5	05 Nov 1985
30	5.0	**29 Nov 1975**	30	12.4	**07 Jan 1975**

From these data, the frequency and intensity of storms are analyzed to identify the main storm event for each year. In Table 2, the strongest storm events in Baden-Württemberg from 1971 to 2000 are shown. The most severe storm identified is gale "Wiebke" in 1990. It outmatches the more damaging event "Lothar" in 1999 because of the larger extension of the storm field. For comparison also the storms, their ratings and indices produced using the 98% percentile values for the normalisation are shown. The detected storms for the whole period only disagree in 3 of the 30 years for the two different methods. In this work, the normalisation with the maximum wind speed is preferred. For this reason, the impact of the strongest event to the total sum is the same for all weather stations.

Almost all detected events exhibit wind directions ranging from northwest to southwest. No relevant storm event with easterly wind directions was detected in that period.

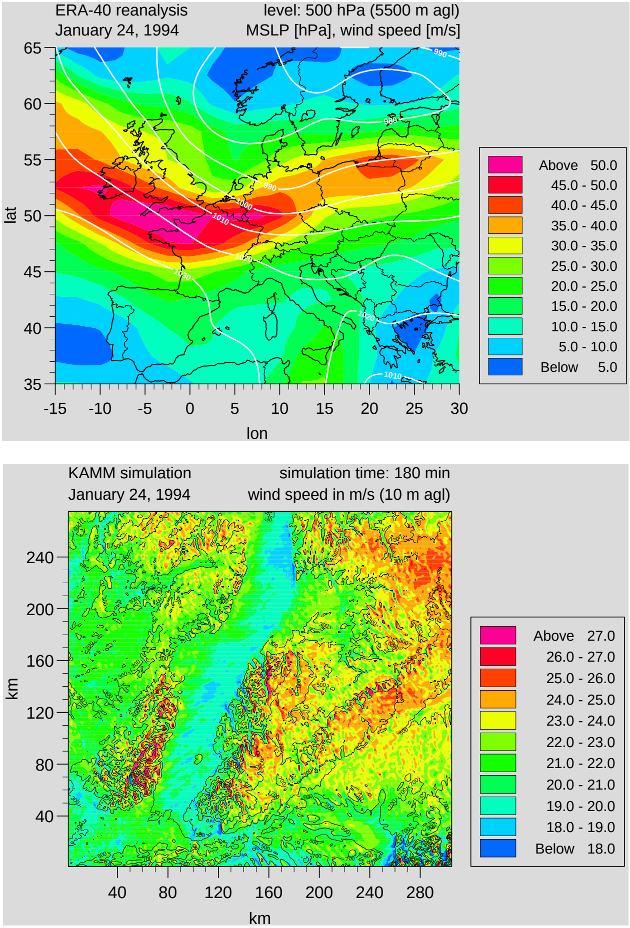

Fig. 4. The model simulation by KAMM (above) is subject to the boundary conditions of the ECMWF global model (bottom).

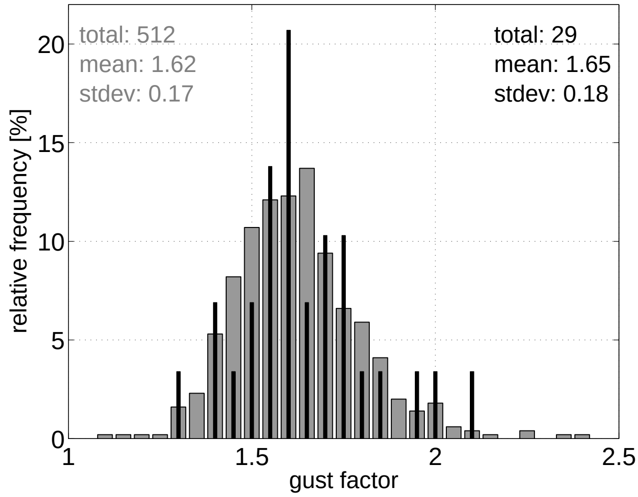

Fig. 5. Relative frequency of gust factors at the weather station of Stötten during extreme storm events in the years 1952–2004 (grey bars) and during the most severe storms per year in the period from 1971 to 2000 (black bars).

3.1.2 Modelling of the wind field

The spatial distributions of the maximum wind speeds are simulated for the annual strongest storm events. Typical time steps of the simulations are in the range of a few seconds.

An example of a model result is shown in Fig. 4. The initial values of the ERA40 data of gale "Lore" on 28 October 1994 can be seen in the left part of the figure, whereas the right part shows the model result of KAMM. The data refer to a height of 10 m for the model simulation and a height of about 5500 m (500 hPa) for the ERA40 data. The wind field pattern from KAMM is highly influenced by the orography and the initial wind field pattern of the reanalysis data. Hence, the highest wind speeds are simulated over the north and over the low-range mountains. For the nudging field, information from the weather stations of Stuttgart, Trier, and Feldberg are used in order to adjust the wind field to the values measured at these locations. At weather stations used for validation, the typical values of the simulated to the observed wind speed are in the range of 40% to 150%. When applying the nudging technique, the differences are reduced and range between 75% and 125%.

3.1.3 Gust wind speed

The output of the mesoscale model are average wind speeds. The maximum gusts are calculated using the gust factors of Table 1. The problem of using these gust factors is obvious from Fig. 5. The values of the gust factors at the weather station Stötten cover a broad range during various storm events. There are no relevant differences in observed gust factors between the consideration of the extreme storm events in the years 1952 to 2004 and the most severe storms per year in the period from 1971 to 2000. Predominantly land use at the station Stötten is grassland. The theoretical roughness parameter with a value of 1.5 (Table 1) slightly underestimates the observed one (1.62). As the hazard model is subjected to uncertainties that are due to the application of coarse spatiotemporal data and the model representation of the storms, quantification of uncertainties is a key issue in assessing the quality of the modelled wind speeds. To check the robustness of the hazard model, a total of 420 samples are taken for comparing the simulated with the measured gust speeds at ground-based observation stations. For the measured wind speeds the maximum daily gust are used. In general, the simulations and observations are in good agreement (Fig. 6). Low wind speeds are overestimated by the model. Remarkable is the overestimation of a chain of samples showing simulated wind speeds in the range of 26 m/s to 34 m/s. This anomaly refers to the station of Freudenstadt and is discussed in detail in the next section.

3.1.4 Calculation of extreme events

To determine the extreme wind climatology for the area of Baden-Württemberg, the Gumbel distribution function is

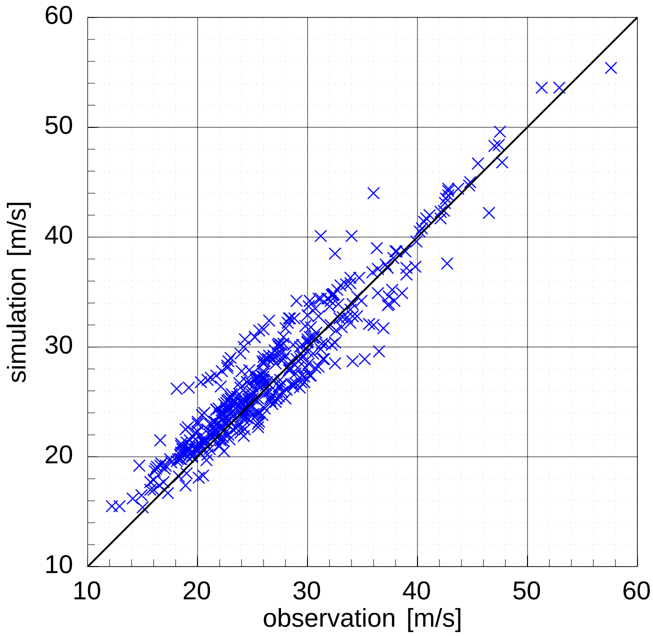

Fig. 6. Comparison of 420 samples with respect to the gust speeds measured at 14 ground-based weather stations and modelled gust speeds of the nearest located grid point.

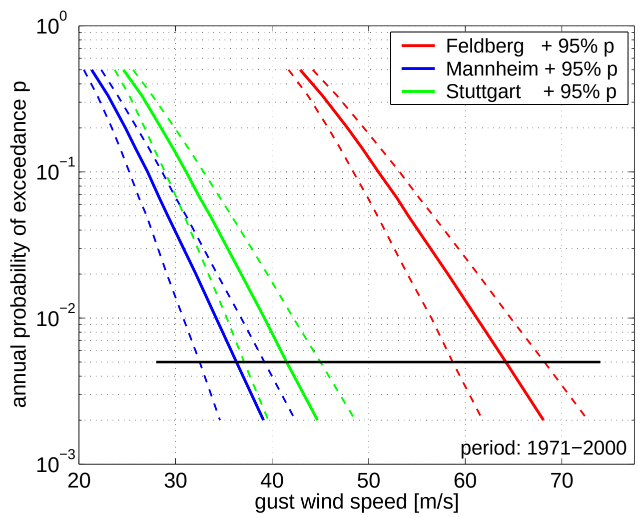

Fig. 7. Gust speeds depending on the annual exceedance probability below p=0.002 threshold for the locations of Feldberg, Mannheim, and Stuttgart. The solid black line shows the lower end of the curves corresponding to the p=0.005 level used for the hazard and risk calculations.

used to fit hazard curves to each grid point using the data of the simulated wind fields. It should be pointed out that any conclusion from the statistical analysis is subject to the uncertainties of the extrapolation and the physical limits. Taking into account this certainty and the limited length of the data series of 30 years, it is not reasonable to extrapolate to

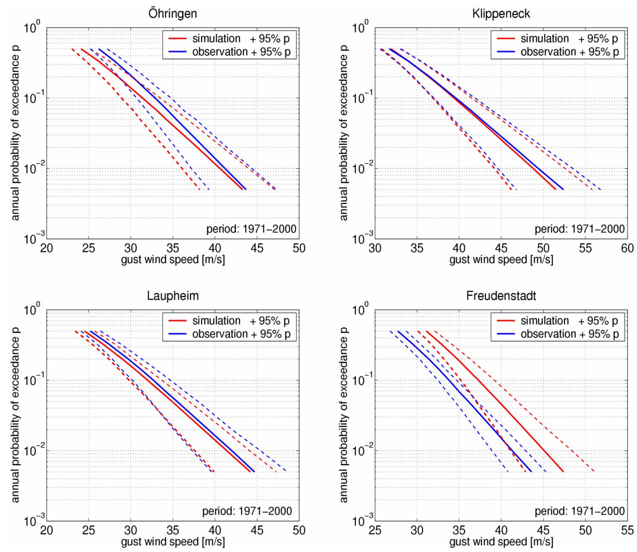

Fig. 8. Wind speed exceedance probabilities for four locations in Baden-Württemberg. The red lines refer to the calculation of the simulated values, the blue lines refer to the calculation of the measured values. Additionally, the 95% confidence bounds are plotted. For comparison, the nearest located grid point to the weather station is used.

exceedance probabilities smaller than p=0.005 (Fig. 7). A detailed comparison between simulation and model data is presented in Fig. 8. Whereas the hazard curves of both data at the stations of Laupheim, Öhringen, and Klippeneck are in good agreement, which is not the case for Freudenstadt. Both hazard curves are even located outside the confidence intervals of the other ones. This is an indication of overestimated simulated wind speeds downstream of the Black Forest mountains. The reason for this is a systematic overestimation of the wind speed in the lee of the Black Forest mountains which may be a consequence of the large nesting step performed to the ERA40 reanalysis data set.

The hazard map (Fig. 9) displays the spatial distribution of the maximum wind speed with an exceedance probability of 0.02 per year (this equals a mean return period of 50 years). Regions with statistically very high wind speeds are over the low-range mountains and especially at the top of the hills as well as along ridges, where the values are often above 50 m/s. The lowest wind speeds with values below 28 m/s are expected in the valleys of the Black Forest.

3.2 Vulnerability assessment

3.2.1 Calibration

In order to use the vulnerability model for damage assessment in Baden-Württemberg, it is calibrated with recorded loss data of four past storm events (Lothar, 26 December 1999; Lore, 28 January 1994; Wiebke, 1 March 1990; Winter

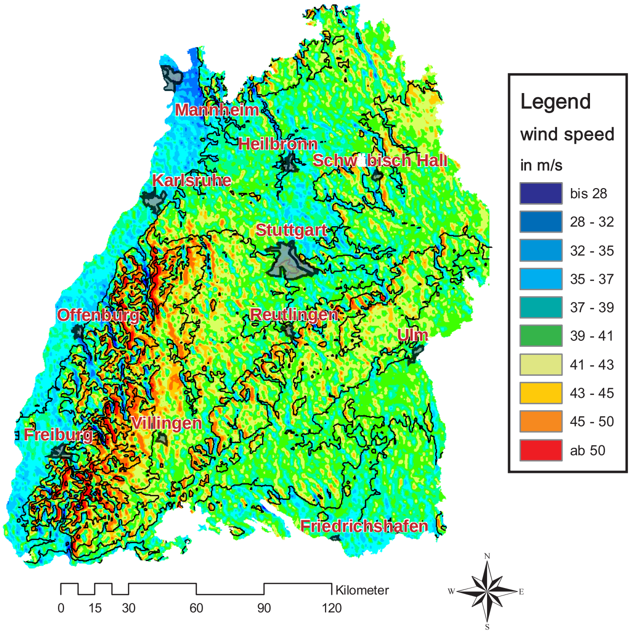

Fig. 9. Maximum gust speeds in Baden-Württemberg with an exceedance probability of 0.02 per year (equals a mean return period of 50 years).

storm 24 March 1986) provided by the SV building insurance company Stuttgart. The data reflect the number of claims and the losses due to storm damage of residential buildings for every postal code zone and storm. As a storm insurance was obligatory in Baden-Württemberg and offered exclusively by the monopolist up to 1994, the data available are sufficiently representative. This holds also for the 1999 storm as the SV Stuttgart still held by far the largest share in terms of storm insurance cover.

All values are adjusted with respect to inflation and development of the total number of buildings. The dimensionless values of damage ratio (DR) and ratio of affected buildings (RAB) are defined as follows

$$DR = \frac{\text{Loss} + \text{deductibles}}{\text{Total insured sum}} \tag{10}$$

$$RAB = \frac{\text{Claims}}{\text{Total number of buildings}} \tag{11}$$

In these equations, all losses and claims that occurred during the storms are assumed to have been recorded. Additionally, deductibles paid by the insured are considered in the calculation of the damage ratio in order to estimate the total damage.

The gust wind speeds for every postal code area and storm are calculated with KAMM and taken directly in the build-up areas.

The coefficients μ_{crit}, σ_{crit}, and Δv for the model are obtained by least-square regression (Table 3). The model is adjusted to fit the total damage of the storm as well as possible.

Table 3. Coefficients for the storm damage model (standard deviation in brackets).

μ_{crit}	σ_{crit}	Δv	a
50.4 m/s (2.5)	7.8 m/s	78 m/s	2

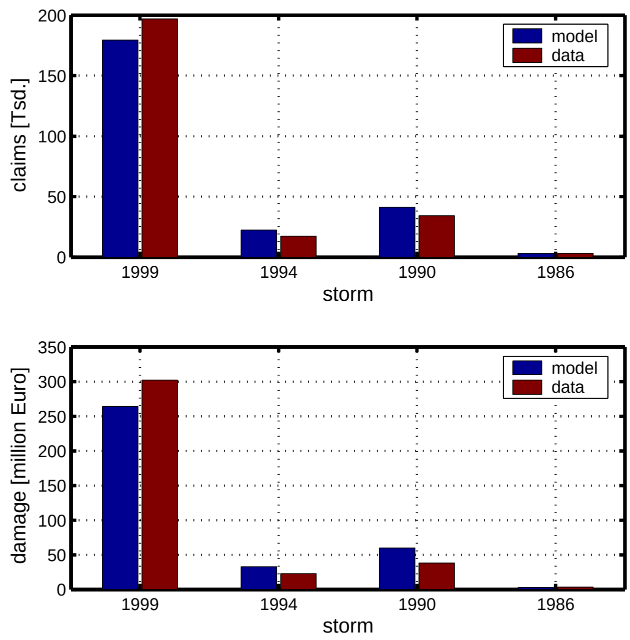

Fig. 10. Total number of claims and total damage in Baden-Württemberg for the investigated storm events as provided by insurance data and by model output.

Figure 10 shows a data-model comparison of the total damage in Baden-Württemberg for every storm. The strongest storm event is slightly underestimated, while the two medium events are overestimated. The corresponding damage functions are presented in Fig. 11. Here, also the median and the 5% and 95% percentiles of the insurance damage data are shown. The two percentiles limit the region in which 90% of the data points are located. This gives an impression of the large variability of the damage data. The damage model fits the median data very well. By introducing an artificial uncertainty – by random variation of the parameter μ_{crit} –, also the percentiles can be estimated sufficiently for both RAB and DR.

3.2.2 Parameters other than wind

It would be desirable to introduce additional parameters in the wind damage model in order to explain the variation of the damage data. Unfortunately, no quantitative information was available for most of the typical parameters, e.g. building type or age, storm duration or precipitation. For the influence

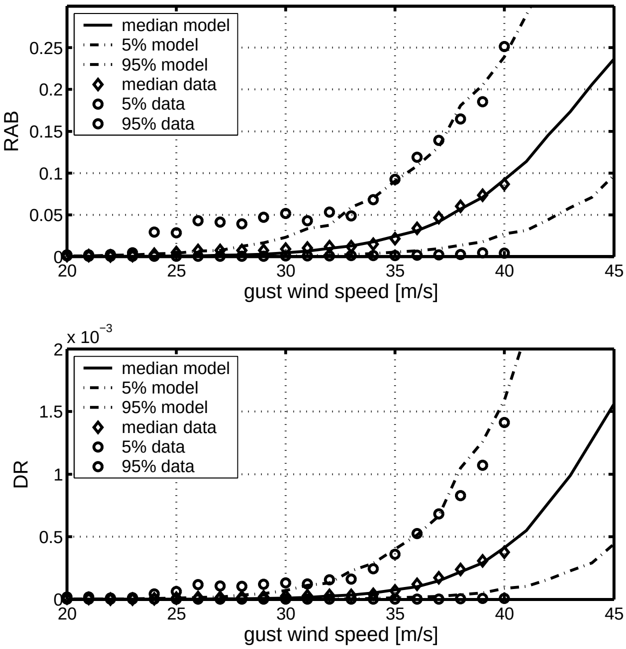

Fig. 11. Storm damage functions for the ratio of affected buildings (RAB) and the damage ratio (DR) in relation to gust speed. The model is marked by the lines, the insurance data by diamonds and circles. Note the strongly increasing trend of damage with higher wind speeds and the large variability of the damage data.

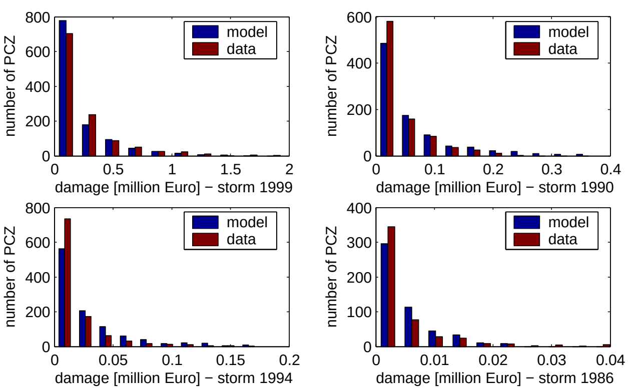

Fig. 12. Comparison of model output and damage data in damage histograms for 4 storm events in Baden-Württemberg.

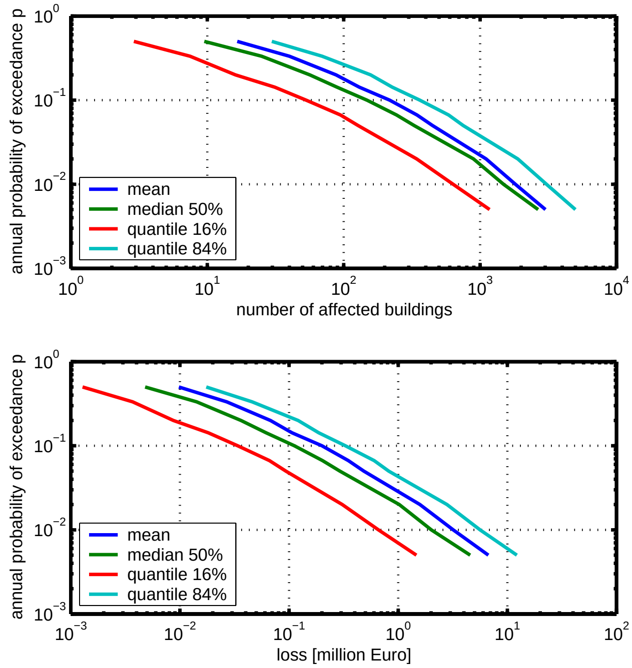

Fig. 13. Example of risk curves for the number of affected buildings and loss for the city of Tübingen. Only private residential buildings are considered. Below an exceedance probability of p=0.005 (equals to a mean return period of 200 years), the extrapolation is not applicable due to the limited historical data (30 years of wind speed data).

of topography, the damage data were analyzed and a relationship between topographic exposure and damage was found (Heneka and Ruck, 2006[2]). However, as the majority of communities are situated in topographically neutral terrain, the results did not significantly increase the accuracy of the model. This is mainly due to the fact that the most important parameters (e.g. type of buildings) could not be considered.

For this project, vulnerability is reduced to the relationship between gust wind speed and median damage to private buildings, with an additional estimate being given for the model uncertainty.

3.2.3 Derivatives from the model output

For the validation of the model, it is useful to compare derivatives from the output directly with the insurance data. The damage histograms of the 4 investigated storm events are plotted in Fig. 12. The number of postal code zones in the damage classes of the model and the data correspond well and give an impression of how damage of storm events is distributed. Most of the damage is light. The correlation of the distribution of observed and simulated damage for the ratio of affected buildings (damage ratio) for the 1999 event is 0.75 (0.61), for the 1994 event 0.23 (0.12), for the 1990 event 0.38 (0.29) and for the 1986 event 0.21 (0.19). The correlation of DR is always below RAB. For the major event 1999, wind speed as model variable already explains 75% (61%) of the variability. However, for the minor events, the correlation is fairly satisfying. The reason for this behaviour is that it is not possible to determine exactly the start of damage at lower wind speeds what is resulting in larger differences between observed and simulated damage. At higher wind speeds, the influence of this error becomes smaller.

[2]Heneka, P. and Ruck, B.: Topography effects and storm damage – an analysis of storm damage of past storm events, J. Wind Eng. Ind. Aerod., in review, 2006.

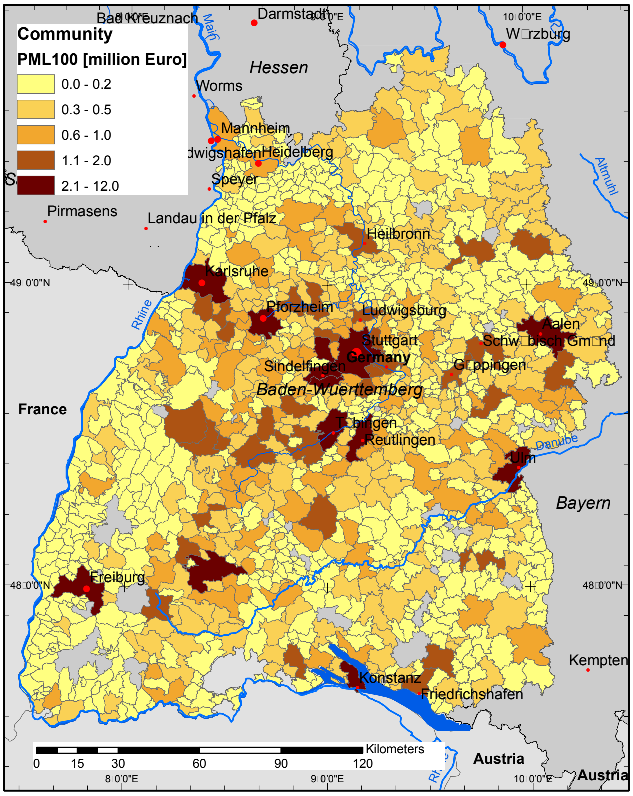

Fig. 14. Storm risk map of private residential buildings in Baden-Württemberg. The map shows the loss in million Euro at an annual probability level of p=0.01. This means, there is a 1% chance of the given value being exceeded during a period of one year.

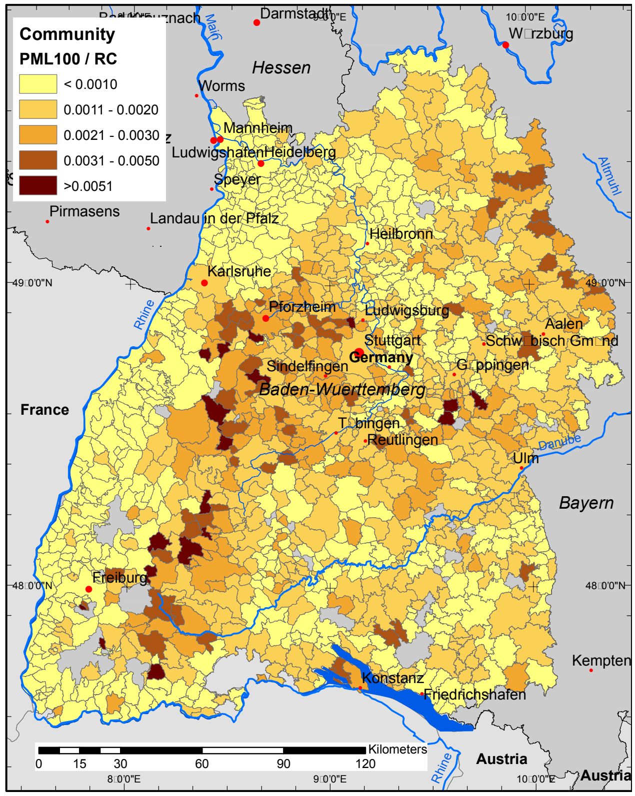

Fig. 15. Same as Fig. 14 with normalisation of values with the replacement costs in every community.

The fact of light damages is also reflected by the average damage for a building. For the three events in 1999, 1994, and 1990, the average damage was between 1350 and 1550 Euros, while the model calculates 1500 Euros. For the 1986 event the model slightly overestimates (1100 Euros) the average damage of 1000 Euros.

These calculations show that the model already provides a good estimate for the overall damage values. However, the estimate of single communities still is subjected to partly large uncertainties.

3.3 Risk assessment

In a final step, risk curves are calculated for every community. Risk curves combine the exceedance probability of hazard curves with the associated damage of the vulnerability model. Thus, they provide the damage to private residential buildings in communities caused by severe wind gusts exceeding a certain level of probability.

For the calculation, a Monte Carlo error propagation technique is used in order to additionally estimate the uncertainty. Input parameters for every probability level are the hazard wind speed $v(p)$ and the critical wind speed μ_{crit}. The variation of these parameters is simulated as a random process following normal distributions. The Monte Carlo simulation is repeated 1000 times for every level of probability.

An example of a risk curve is shown in Fig. 13. The median curve represents the most probable damage estimate. Concerning the uncertainty, with a chance of 16 and 84%, respectively, the percentile curves are the estimates for the upper damage bounds.

As an example of a risk map of Baden-Württemberg (Fig. 14), the average loss is visualized, which is exceeded with an annual probability of p=0.01 within a time period of one year. The damage reaches from several 10 000 Euros to more than 10 million Euros depending on the hazard exposure and the total assets of residential buildings. As most assets are concentrated in urban city areas, loss is highest in these communities.

Figure 15 shows the ratio of the annual loss with the exceedance probability p=0.01 to the total assets of residential buildings. Consequently, the overwhelming effect of the amount of assets present at the various locations is ruled out. The northern and eastern part of the Black Forest as well as the north-east of Baden-Württemberg are the regions with highest storm damage risk.

The annual average damage for every community is calculated according to Eq. (9). As the risk curves do not go beyond the probability of p=0.005, it is also calculated with this probability level. Consequently, the average annual damage is underestimated as less probable events are not considered. The aggregation of all AAD of the communities in the state of Baden-Württemberg results in an overall annual damage of 15 million Euros. As the state hosts approximately one seventh of the total assets of Germany, a Germany-wide AAD of 100 million Euros can be estimated roughly (as mentioned above, this is a lower bound for this damage estimation).

Klawa and Ulbrich (2003) give an average annual loss of 600 million Euros for winter storms in Germany. However, this sum includes all insurance types connected with storm events and not only private buildings. As our minimum estimate lies in this order of magnitude, it may be concluded that the calculation method is satisfactory.

4 Conclusion

This paper describes the development of a storm damage risk model and the first application to the German state of Baden-Württemberg solely based on meteorological data of 30 years of observation and on damage data of 4 past storm events. Highly resolved spatial loss information is provided as well as the approximation of the corresponding uncertainty. The final hazard and risk map points out the critical regions of potential high wind speeds and potential losses, respectively. It may be concluded that the newly developed method works satisfactorily and is applicable to the rest of Germany and potentially also to other countries.

Considering the large variability of damage at the same gust wind speeds, it seems to be obvious that additional parameters should be implemented in the vulnerability model in order to increase the precision. Unfortunately, more precise damage data – detailed information about the type of damage, location, type of structure is needed – was not available. However, for the purpose of this large-scale Germany-wide project, average damage estimation with the indication of uncertainties is sufficient. As our damage model calculates only direct damage, it is necessary to include economic and actuarial parameters in the value function in order to assess the monetary impact for e.g. insurances.

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