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Computation of the Probabilities for the Occurrence of Extreme Events
as a Consequence of Climate Change
– Emphasis Germany –

by

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Summary

Data base and method of analysis

Global climate change, detectable also in *Germany*, is with good reasons a focus of public interest. This is why, at least with regard to recent decades, the human impact plays an important role and because the consequences concern ecologic and socioeconomic impacts as a whole. It is evident, that, thereby, extremes are of outstanding importance. So, the urgent question arises, whether extremes have become more frequent or more intensive, respectively, in the context of climate change observed so far.

In consequence, in this study, based on the station network available, monthly and daily *observational data of surface air temperature, precipitation and wind* (only monthly data in the latter case) from Germany or Central Europe, respectively, were analysed for the period 1901-2000 and, based on much more stations, for the period 1951-2000. This was done with respect to variations in the behaviour of extreme events. Two different methods were applied: The method moving in time (method I, chapter 3) is based on defined thresholds. Both, empirical and theoretical frequency distributions were adjusted to the observational data time series. Then, quantities like the distributions of waiting time, repetition time and risk were computed as usual in extreme value statistics.

Alternatively, the structure-oriented time series analysis (method II, chapter 4), again adjusting appropriate frequency distributions, but using all time series data at every step of analysis, looks for significant time series structures in order to evaluate the corresponding probability density function (PDF) parameter time series. This allows to compute time-dependent series specifying the probability that any defined threshold may be exceeded or that the data remain under this threshold.

Results

The method moving in time (*method I*) reveals with regard to monthly precipitation totals that extreme events remaining under lower thresholds become less frequent; this means that relatively dry months have become more seldom. Considering upper thresholds, this means extreme intense precipitation, these events have become less often in Eastern regions and more often in Western regions of Germany. So, in contrast to Western regions, precipitation as a whole has become less extreme in Eastern regions. The analysis of daily precipitation data leads to similar results, however, considerably more depending from the definition of thresholds. This means, the trends of occurrence probability vary as a consequence of this definition. Generally speaking, also in case of daily data a tendency towards more extreme precipitation prevails, especially in Western parts of Germany.

In case of temperature, with only few exceptions, it is found (monthly and daily data) that extreme cold events become less and extreme warm/hot events more frequent as can be expected keeping in mind the background of global warming.

Similarly, the structure-oriented time series analysis (*method II*) indicates that in case of monthly or seasonal temperature data the average is increasing whereas the variance varies only seldom. In consequence, the probability of warm months occurring is increasing, often very significantly (with the exception of autumn, period 1951-2000) and of cold months decreasing. In line with these findings, relatively warm days become more probable, especially in winter and with respect to the daily maximum, and more cold days become less

probable in all seasons, especially in Southern Germany. However, because extreme heat waves occur in summer, a trend to more extreme hot summers is also evident.

In case of precipitation seasonal particularities are dominating. In winter, a trend towards both more precipitation and more variability is detectable with regard to monthly or seasonal data. This means a wide-spread increasing probability of occurring extreme high precipitation in the winter season. In contrast to that, the summer season can be characterized by decreasing precipitation variance so that extreme high monthly or seasonal precipitation become more seldom, not only in Germany but also in most regions of Central Europe. As far as daily precipitation data are concerned, extreme high precipitation (exceeding the upper 10 % or even 5 % and 2 % percentiles) is observed more and more seldom in summer but more frequently in the other seasons (especially winter and South Germany).

The analysis of wind data leads to varying results so that it is not possible to derive clear and generally valid statements. One reason may be a relatively high bias of these data. Under these restrictions it may only be concluded that the probability of extreme strong daily wind velocity shows a prevailing tendency to increase in winter and to decrease in summer.

1 Introduction and aim of the study

Global climate change, in particular the warming of the lower atmosphere observed on a global average since the industrial era, is conceived to be anthropogenically dominated. This is due to the scientific understanding based on both climate modelling, partly in a very sophisticated manner (IPCC 2001) and statistical analysis of observational data (Grieser et al. 2000, Schönwiese 2003) identifying the emission of climate-relevant trace gases (CO₂ etc.) as a main forcing (enhanced greenhouse effect). In turn, this is due to the use of fossil fuels (coal, oil, and gas) and deforestation.

Evidently, this climate change is also detectable in Germany, where the warming was even more pronounced, 1,0 °C within 1901-2000 (Rapp 2000, Schönwiese and Janoschitz 2005) than on a global average (0,7 °C). Note, however, that due to the superposition of fluctuations these numbers vary with the period considered (Germany: 0,8 °C for the period 1891-1990 as well as 1901-2004). In addition, there are outstanding particularities from season to season and pronounced regional structures of climate change even within such a small area as Germany. This holds even more pronounced for precipitation where the increase in winter (concentrated in West Germany) and the decrease in summer, however less pronounced and less systematically, are the outstanding facts.

In this context, there arises the question whether this climate change is connected also with a change of the frequency or probability, respectively, and intensity of extreme events. This is why particularly extreme events have strong effects on ecologic and socio-economic affairs (see also case studies concerning the summer heat wave 2003 and the Elbe flooding in summer 2002, chapter 5). To answer this question, it is necessary to look on the frequency distributions of the climate variables under consideration. In doing this, it is a common statistical technique to adjust theoretical frequency distributions to empirical ones to become independent from such sample peculiarities which may be by chance (Schönwiese 2000) and, in consequence, to come to results which are valid in a more general manner.

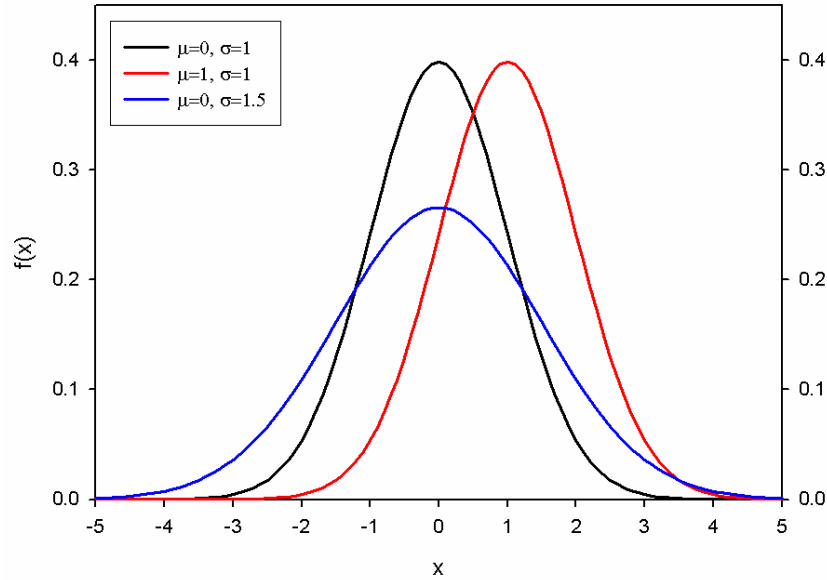


Figure. 1: Probability density function (PDF) of the Gaussian distribution with different parameter combinations (see text).

The most simple type is the Gaussian distribution (normal distribution), see Fig. 1, which is symmetrical with respect to the average μ (in this case also mode, i.e. most frequent value, maximum of PDF). As a consequence of climate change, this distribution may shift in direction to larger x values (transition from the black to the red plot in Fig. 1). Alternatively, it may broaden if the data are dispersed over a larger x range (quantified by the standard deviation σ or variance σ^2 ; transition from the black to the blue plot in Fig. 1). Finally, both average and variance may vary, where, more general, it is usual to address these features by the location parameter (e.g. μ) and the dispersion parameter (e.g. σ). Such variations have their specific effects on extremes which are usually defined to be relatively large or small, respectively, x values. Again with regard to Fig. 1 these may be values $x > 1$ or $x > 2$ (upper thresholds), alternatively $x < -1$ or $x < -2$ (lower thresholds).

If the functions shown in Fig. 1 are standardized, i.e. the integral from $x = -\infty$ to $x = +\infty$ (area “below” each such function) equals 1 or 100%, respectively, for any defined range Δx this integral quantifies the probability that such values occur. In consequence, such a function is called probability density function (PDF). Furthermore, Fig. 1 shows that the probability, defined in this way, data $x > 2$ occurring is much larger in case of the red as well the blue compared to the black plot. Because in Fig. 1 the black plot is characterized by $\mu = 0$ and $\sigma = 1$, in this special case $x=1$, $x=2$ etc. are the thresholds of one times, two times etc. of the standard deviation (called 1σ , 2σ etc. thresholds) as partly used in the following. Alternatively, percentiles are used. Their definition is that above or below, respectively, a certain quantity of data can be found, e.g. 5 % above the upper 5 % percentile or 5 % below the lower 5 % percentile, respectively (where sometimes the upper 5 % percentile is also defined as the 95 % percentile).

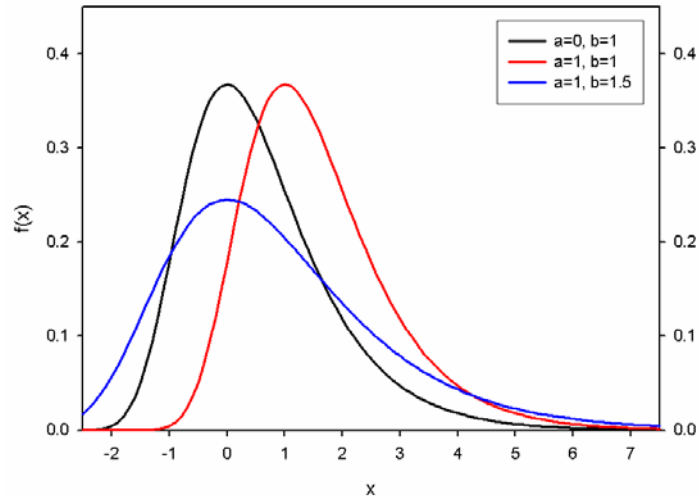


Figure 2: Probability density function (PDF) of the Gumbel distribution with different parameter combinations (see text).

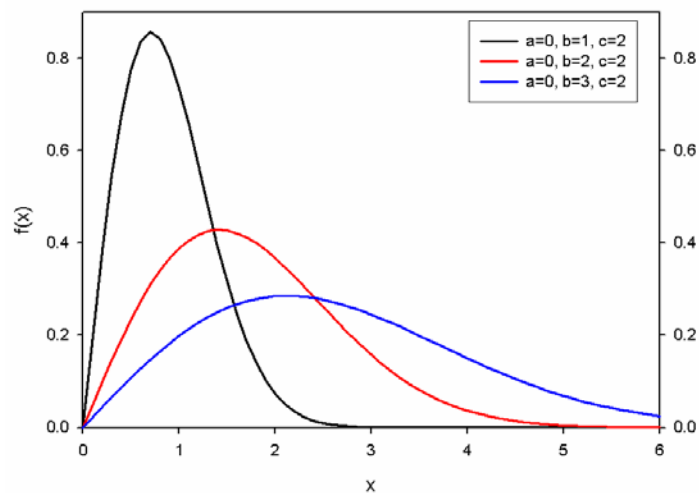


Figure 3: Probability density function (PDF) of the Weibull distribution with different parameter combinations (see text).

Not all data meet a Gaussian PDF, although in case of temperature monthly or annual data this condition is often fulfilled. However, in this study it was found that it is sufficient to use only two alternative PDF, that is Gumbel, see Fig. 2, and Weibull distribution, see Fig. 3. These distributions are not symmetrical where the Gumbel distribution is characterized again by two parameters, that is location parameter a (mode, most frequent value, maximum of PDF) and dispersion parameter b , whereas in case of the Weibull distribution, in addition, a shape parameter c is introduced (and location parameter a is the minimum). So, the Weibull distribution reveals to be very manifold (for more details see text books, e.g. Schönwiese 2000).

In the following, the aim of analysis is, considering surface air temperature, precipitation, and wind as observed in Germany or Central Europe, respectively, within the recent century, to derive the variations in time of the empirical such as adjusted theoretical frequency distributions (PDF). This allows to compute the probability of occurring lower and upper extremes. It cannot be expected, that the results are uniform. So, the analysis is differentiated with regard to seasons and the regional structures of varying probabilities are also presented in terms of charts.

2 Data Base

The data base available for this study is summarized in Table 1. As indicated in this overview, monthly as well as daily data of surface air temperature (Germany), precipitation (Germany and some adjacent regions of Central Europe) are used, period 1901-2000 and based on much more stations period 1951-2000. In case of temperature not only daily averages but also daily maximum and minimum data were available. In contrast to temperature where the analysis was performed for Germany only, precipitation was also considered for adjacent Central European regions to meet the fact of essentially more poor representativeness of this climate element. Moreover, also some recent examples of extreme events which occurred in 2002 and 2003 were interpreted (chapter 5). The wind data which revealed to be not very reliable were also restricted to Germany. These were the number of days within each months where Bft > 8 (Beaufort degree 8 exceeded) and, in addition, monthly averages of wind speed. Figs. 4 and 5 illustrate the station networks used in case of monthly and daily temperature and precipitation data.

Table 1: Overview of the data base (predominantly Germany).

Type of data	Daily data		Monthly data	
	1901-2000	1951-2000	1901-2000	1951-2000
Precipitation	21	301	133 + 79*	-
Temperature	3**	141**	6**/12	141**
Wind	-	-	-	15/72***

*) Central Europe additionally **) average, maximum, and minimum data

***) number of days Bft > 8 (15 stations) and monthly averages of wind speed

Note: All these data are provided by the German Weather Service (Deutscher Wetterdienst, DWD) or the Global Precipitation Climate Center (joined at DWD) in the context of a common DEKLIM project (German Climate Research programme, BMBF).

A striking problem, which cannot be addressed here in detail, is data quality. This holds for both data accuracy and homogeneity where inhomogeneities are due to change of instruments and/or station location; this may lead to variations which are not climatological in nature and must not be misinterpreted. In addition, there are representativeness problems as mentioned above. For a detailed discussion of these problems see Schönwiese and Rapp (1997), Rapp and Schönwiese (1996) and Rapp (2000).

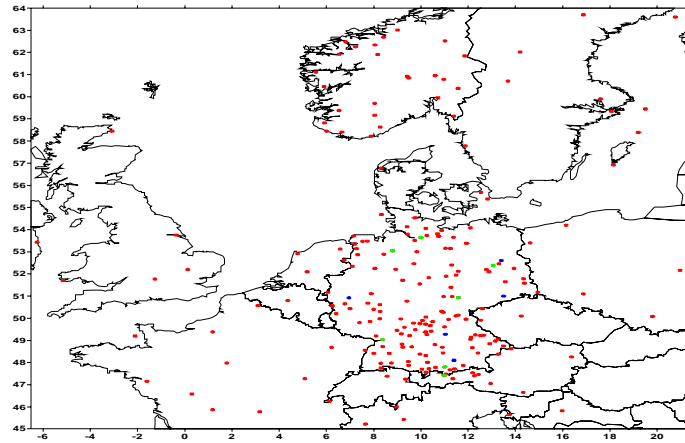


Figure 4: Station network, monthly data 1901-2000; red precipitation, blue temperature, green precipitation and temperature.

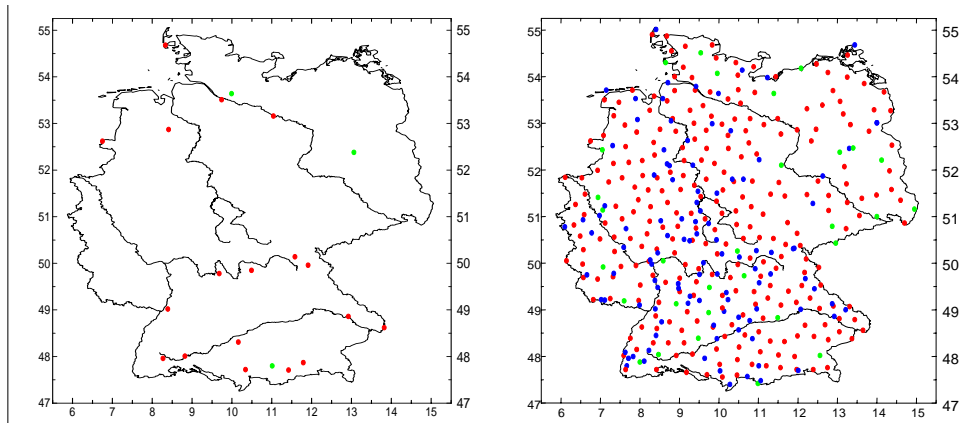


Figure 5: Station network, daily data, left 1901-2000, right 1951-2000; colour code as in Fig. 4.

3 Extreme value analysis moving in time

3.1 Method

First, the method was used which is conventional and recommended by IPCC (2001). All data are available in terms of time series as specified in Table 1 with regard to climate elements and number of stations. The initial step is the determination of the empirical frequency distribution and the adjusting of one of the theoretical distributions (PDF) as described in chapter 1 where the confidence of adjusting is tested as usual by a means of the Kolmogoroff-Smirnoff and a χ^2 test. The next step is the choice of thresholds and window widths. Thereby, the thresholds are oriented at σ factors (e.g. $\mu \pm 1\sigma$, 2σ , and 3σ in case of precipitation monthly data; $\mu \pm 1.25\sigma$, ..., 2σ in case of temperature daily data) or percentiles (e.g. 95, 98, 99, 99.5 % in case of precipitation daily data) where the choice of these criteria is an empirical optimization taking into account the different dispersion (scattering) of temperature and precipitation data. The window width is the time subinterval which is object of the computations. A 10 yr (120months) width was used moved in 1 yr steps, so that in case of the total period 1901-2000 the computations were performed for 1901-1910, 1902-1911 etc. ..., 1991-2000.

This analysis is continued by the computation of the empirical and theoretical probabilities of exceeding or remaining under the thresholds selected for all windows so that series of these probabilities result. This, furthermore, is the basis to compute the related distributions of waiting time, repetition time and risk of extremes. If the expected value is the mode of any distribution, then the waiting time is defined as the time interval from any time step t_1 until time step t_2 where the considered (threshold-dependent) extreme event occurs for the first time. Then the waiting time distribution quantifies the probability that one has to wait from time step t_1 to time step t_2 until the considered extreme occurs for the first time. The repetition time is the expected value of the waiting time distribution, that means the sum of all possible waiting times multiplied by the probability that exactly after this time interval the considered extreme occurs for the first time. So, the repetition time is a measure how often a considered event occurs within the time interval from t_1 to t_2 . Finally, the risk is the probability that within any defined time interval the considered extreme occurs at least once. As a supplementary analysis dry spells and precipitation events were considered with regard to clustering, i.e. it is analysed how often none or very low precipitation rates occur within any defined window (using different window widths in this case).

3.2 Results

The manifold results can be summarized as follows.

- *Precipitation, monthly data*

The Gumbel distribution reveals to be best appropriate for the consideration of upper thresholds. Lower thresholds are problematical because of the strong positive skewness of this distribution (see Fig. 2). ***In Western Germany a trend towards shorter repetition times of upper extremes prevails, in Eastern Germany the opposite is the case. So, roughly seen, the risk of extreme high precipitation increases in the West whereas decreases in the East.*** Some details of these results are shown in Fig. 6.

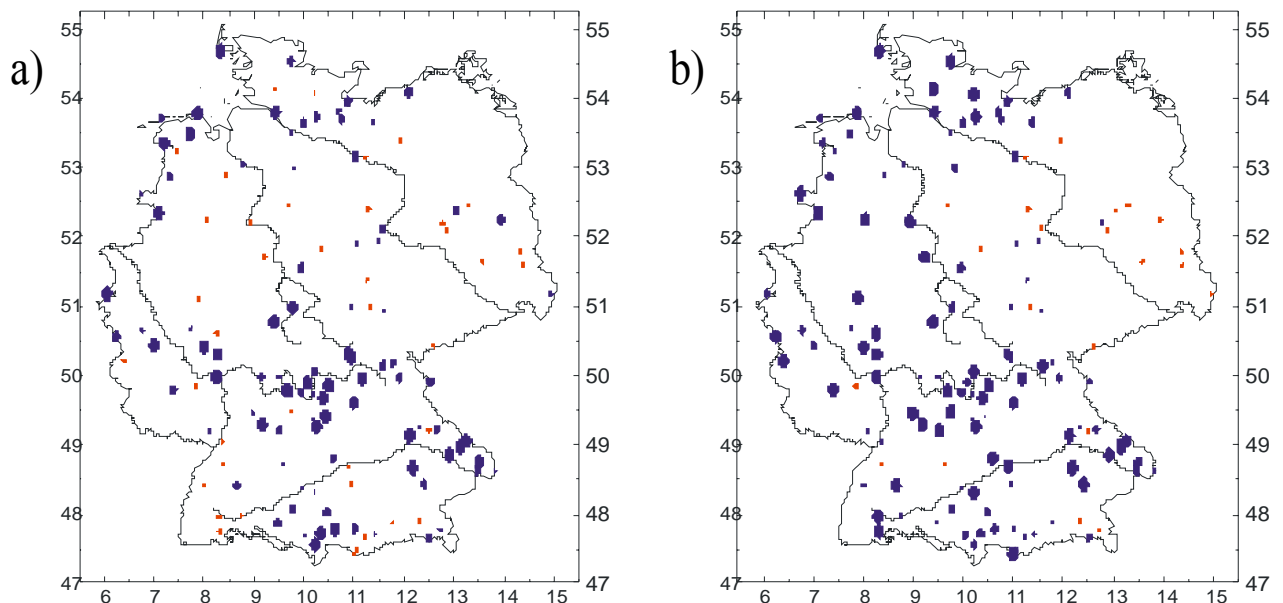


Figure 6: Precipitation, monthly data 1901-2000, trends of repetition time of data exceeding the 2σ threshold a) empirical, b) Gumbel distribution adjusted; red increasing, blue decreasing (more extreme), symbol size proportional to the magnitude of the trends.

- **Precipitation, daily data**

The tendency towards more or less extreme precipitation events, respectively, in case of daily data, depends much more from the thresholds than in case of monthly data. So, the results are different. *Generally spoken, in winter a wide-spread increase of dispersion is observed, in summer, however, a decrease, so that – as a predominant effect – the probability of extreme high winter precipitation increases (especially in Western and Southern regions of Germany).* Some details are available from Fig. 7 where it is worth noting that in Eastern and Northern regions of Germany the probability trend changes its sign if different percentile thresholds are underlying. *As far as dry spells are concerned, in Western Germany a trend towards more frequent occurrence prevails (all over the year) whereas, however, the maximum length of dry episodes seems to decrease.*

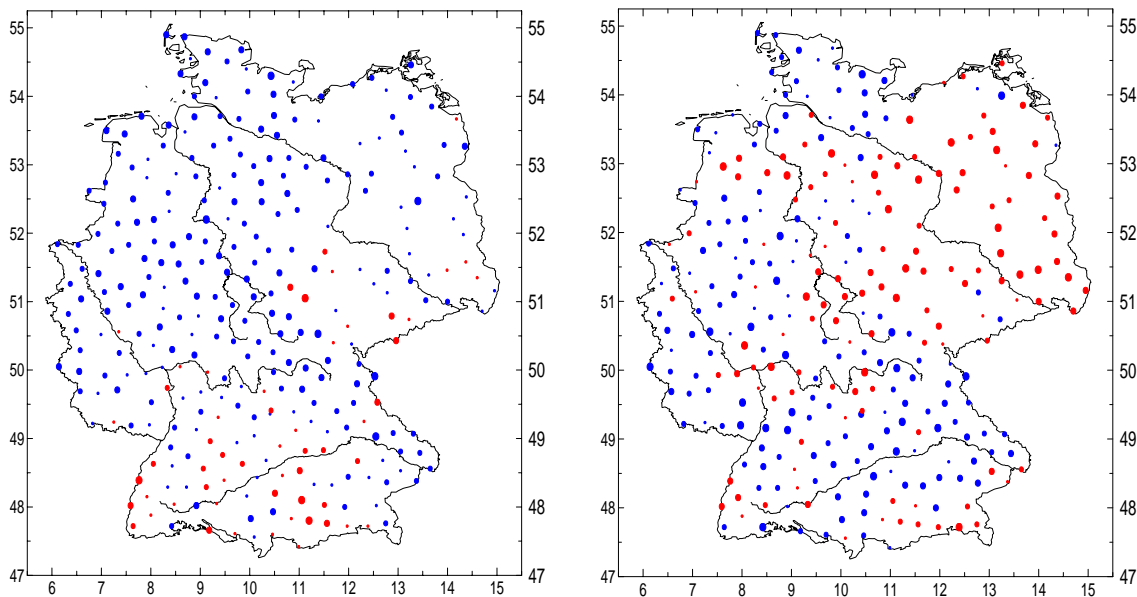


Figure 7: Precipitation, daily data 1951-2000, trends of repetition time, left 95 % percentile, right 99.5 % percentile exceeded; red increasing, blue decreasing where the size of the colour symbols is proportional to the trend magnitude.

- **Temperature, monthly data**

The Gaussian distribution is appropriate, however, sometimes the Weibull distribution meets better. Regional structures are not detectable due to the poor data base (very few stations).

- **Temperature, daily data**

Daily averages and maximum data are often Gumbel-distributed, in case of minimum data adjusting of any theoretical distribution fails. The probability of occurring cold days decreases at a higher magnitude as the probability of warm days increases. *So global warming shows in Germany more the effect of decreasing probabilities of extreme cold days than increasing probabilities of extreme warm days.*

An analysis of wind data was not performed by means of this method.

4 Structure-oriented time series analysis

4.1 Method

This alternative method of analysis (from Trömel 2005) is based on the fact that, in general, climate time series are non-stationary. This means, the statistical moments like average (location parameter), variance (dispersion parameter) and so on vary in time. In consequence, the climate time series under consideration is separated into a number of significant structures. Such structures are: trend (linear or non-linear), seasonal component (annual cycle where phase or amplitude may vary), further cyclical components (here not considered in detail), the low-frequent component (in contrast to cyclical only very few relative maxima/minima) and the residuum. By means of a stepwise regression a solution is looked for which represents best the time series considered by a superposition of these components.

On this basis time-dependent PDF (using the best adjusting) parameter functions can be derived (see chapter 1). This is in case of a Gaussian distribution the variation of average μ (location parameter), which means trend, and the standard deviation σ (dispersion parameter), in case of a Gumbel distribution location parameter a and dispersion parameter b , in case of a Weibull distribution additionally shape parameter c . When these features are known, for any time the PDF can be computed and, in turn, the probability that data exceed or remain under any defined (upper or lower) threshold.

4.2 Results

Applying this alternative method, again the results are very manifold. In the following it is tried to summarize where in case of precipitation not only Germany but also the adjacent regions of Central Europe were roughly included.

- *Precipitation, monthly data*

The Gumbel distribution reveals to be appropriate. In winter, positive trends of the location and dispersion parameter prevail (more precipitation and at the same time more variance). ***This means that especially the probability of extreme high precipitation has increased, especially in winter. On the contrary, in summer often negative trends of the dispersion parameter are found which leads to a decrease of extreme high precipitation.*** Fig. 8 shows two examples for this behaviour in terms of probabilities.

- *Precipitation, daily data*

These data can better be adjusted by a Weibull distribution. ***The number of days where extreme high precipitation occurs mostly increases in winter and autumn whereas in summer a decrease prevails.*** Some details are shown in Fig. 9. The increase probably concerns both short-term convective precipitation (showers) and more long-term precipitation due to uplift processes (warm fronts) without that any statement about the related frequencies and their change is possible on the base of this statistical analysis. However, in summer a long term (climatological) increase of the sea surface pressure may be a cause of the observed precipitation decrease. Actually, pressure trend charts available for Europe (Schönwiese and Rapp, 1997, related to the period 1891-1990) indicate such an increase in Central Europe during spring and summer whereas during winter a decrease was found (autumn no uniform trend within Central Europe).

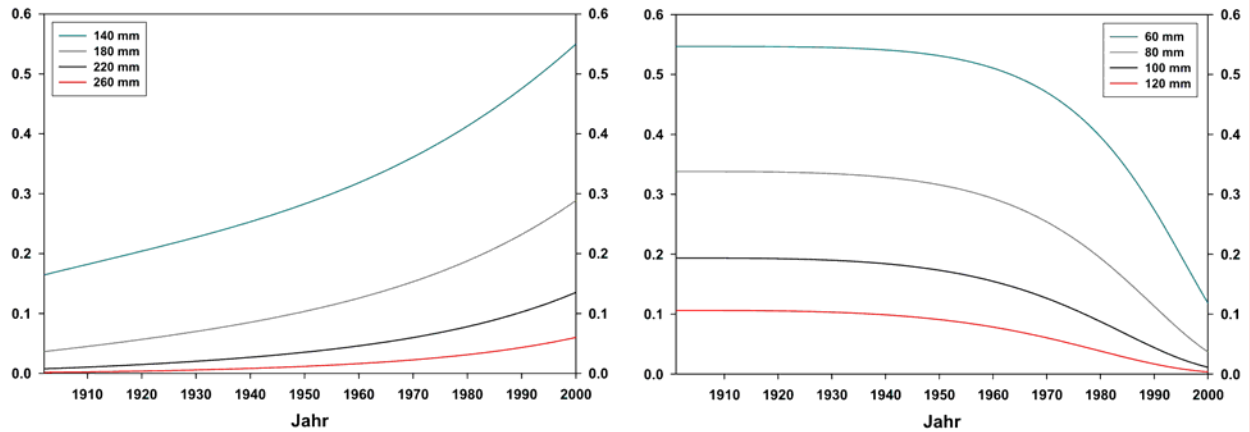


Figure 8: Left probability variation of the occurrence of the winter upper thresholds as indicated at station Mainz, right same for August precipitation at station Kitzingen.

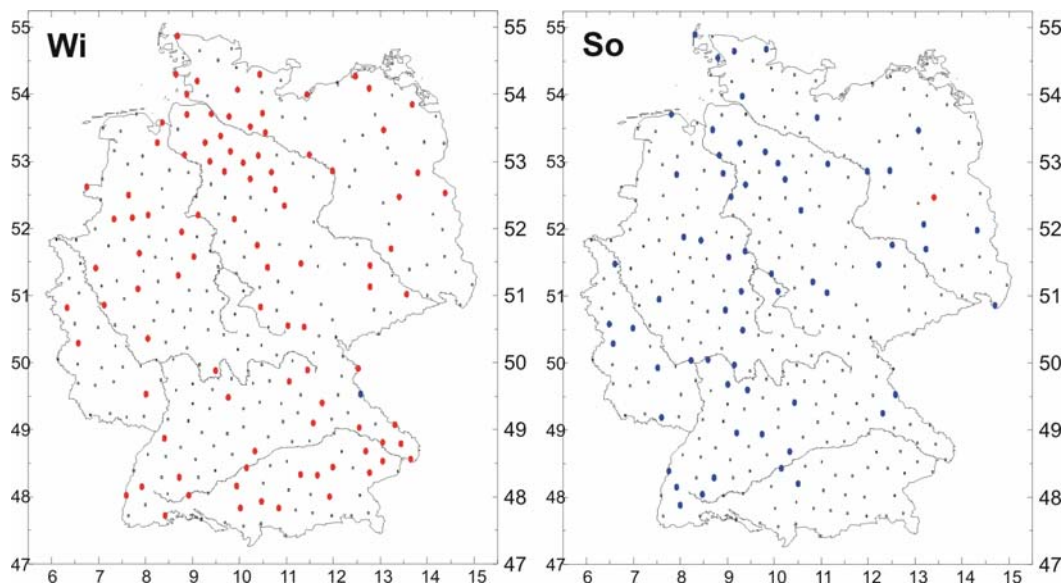


Figure 9: Trend of the probability of exceeding the upper 10 % percentile of daily precipitation totals (1951-2000); red significantly positive, blue significantly negative, black not significant.

- *Temperature, monthly data*

The Gaussian distribution is fulfilled in good approximation. In all seasons, except autumn and period 1951-2000, positive trends in average are found and nearly no variation of variance. ***This leads to increasing probabilities of warm months and decreasing probabilities of cold months occurring.***

- *Temperature, daily data*

As in case of precipitation daily data the Weibull distribution is appropriate. ***The most striking result is an enormous speed-up of increasing probabilities of extreme warm days since roughly 1970 (particularly concerning maximum temperatures in winter) and corresponding decreasing probabilities of extreme cold days (especially in Southern Germany).*** Two examples are presented in Fig. 10.

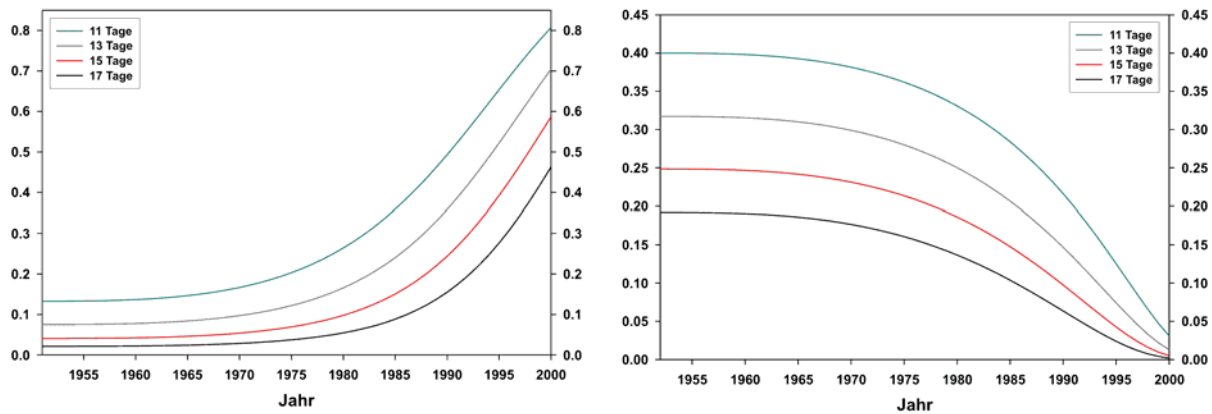


Figure 10: Left probability variation of the occurrence of the number of days indicated with a maximum temperature exceeding the upper 10 % percentile (in this case 28.5 °C) at station Euskirchen (Western Germany), right of a winter temperature below the lower 10 % percentile at station Erlangen (South Eastern Germany).

- Wind

The analysis of wind data leads hardly to results which may be interpreted in a systematic manner. One reason may be the relatively high bias of these data, another the outstanding variability of this climate element in time and space. Nevertheless, with caution, it may be stated that the probability of extreme maxima (BFT > 8) in winter increases (with the exception of coastal areas) and in summer decreases (with the exception of Southern Germany).

5 Case studies

Two case studies shall be briefly mentioned here: the *summer heat wave 2003* and the Elbe flooding in summer 2002. The summer 2003 (average of months June, July, and August) was extreme hot in Central Europe, concentrated in France and Switzerland, and mostly also very dry. *In Germany, it was the hottest summer since 1761 with an average surface air temperature of 19.6 °C*; this value is 3.4 °C higher than the 1961-1990 average corresponding to a deviation in terms of standard deviation by a factor of 3.8 (3.8 σ ; compare also black plot in Fig. 1 where this situation would correspond to 3.8 x). This enormous anomaly is so outstanding that it cannot be explained only by a summer warming trend as observed since approximately 1900. And it is also worth noting that the record summer temperatures observed so far (1947, 1983, 1992, 1994 and in earlier time 1859, 1834, 1826) were considerably exceeded by the 2003 event, see Fig. 11 (Schönwiese et al. 2004).

If one applies the method described in chapter 4 on these German summer temperature data, so reveals an increase of the probability that such an event (temperature anomaly ≥ 3.4 °C) occurs from $p < 0.0001$ (corresponding to a waiting time of more than 10,000 yr. i.e. on a statistical average such an event would be expected one times within 10,000 years) in 1960/1970 to $p \approx 0.0022$ in 2003 (waiting time c. 455 yr, i.e. expected now one times within 455 years). *This means a very extreme event even in 2003 but an probability increase by a factor of 20. Climate model simulations based on scenarios of human impact (anthropogenic enhanced greenhouse effect) project a similar further enormous increase of this heat wave probability in the next decades* (Schär et al. 2004). By the way, this extreme hot summer 2003 was not only characterized by a very high area-average surface air temperature, especially in August, but also by a new record of the number of heat days (daily

maximum $> 30\text{ }^{\circ}\text{C}$) and extreme heat days (daily maximum $> 35\text{ }^{\circ}\text{C}$), for example in Karlsruhe: 53 (record so far 44 in summer 1947) or 16 (record so far 9 in 1947 and 10 in 1952), respectively.

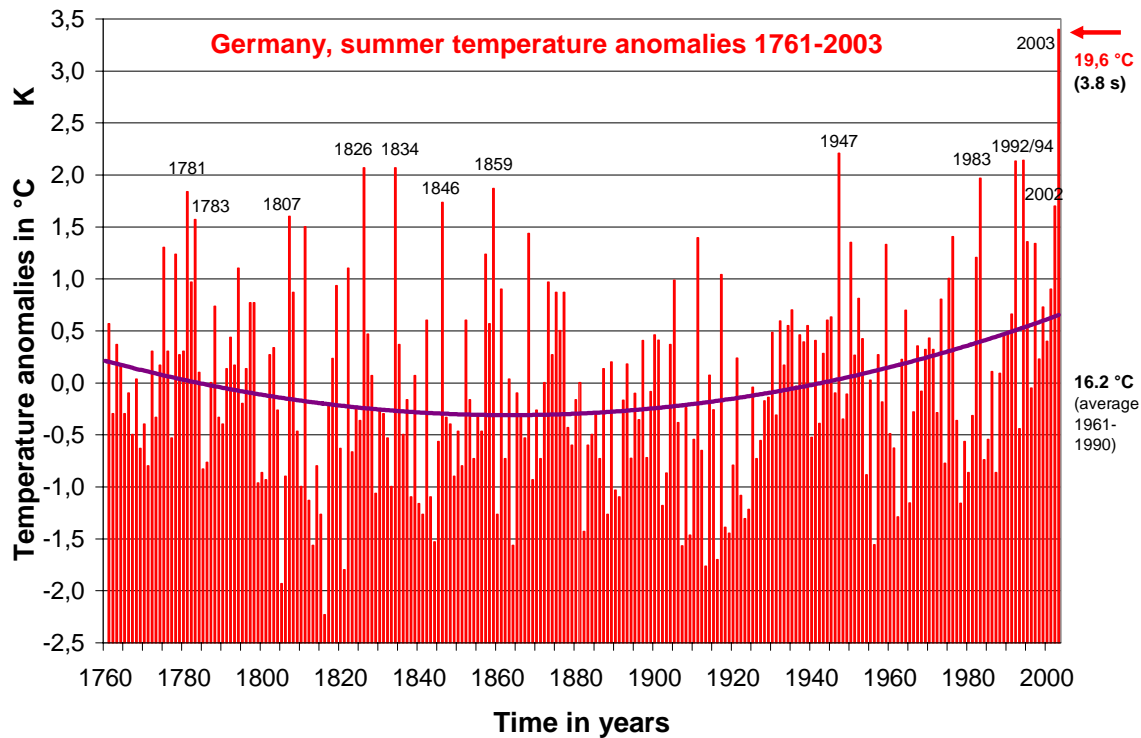


Figure 11: Summer air temperature anomalies (average of months June, July, and August, deviations from the average 1961-1990) 1761-2003, representative for the area of Germany, trend curve (violet plot) and year indications of some selected extreme hot summers included. Note that the extreme value 2003 is outstanding (hottest summer so far; data source: Rapp, 2000; German Weather Service; analysis Schönwiese et al., 2004).

Quite another situation has to be realized concerning the summer 2002 flooding in the Elbe river region (DWD 2003). Indeed, this summer has seen new record values of documented precipitation totals (in particular station Zinnwald-Georgenfeld, Ore Mountains, Saxonia, Eastern Germany, 312 mm on 12.8.2002; record so far 260 mm on 7.7.1954 in Stein near Rosenheim, Bavaria, South East Germany, and same value on 6.7.1906 in Zeithain, again Saxonia). However, on the other hand, water-gauge and run-off time series from the Elbe river in Dresden show a significant decreasing trend (approximately since 1860, but also on longer time scales; Mudelsee et al. 2003). In contrast to that, the water-gauge measurements from the river Rhein in Cologne show increasing values although superimposed by considerable fluctuations. If one differentiates also seasonally, there is a link with increasing winter precipitation in Western and Southern Germany and decreasing summer precipitation in Eastern Germany.

6 Conclusions

This study shows that the observed climate change within the industrial era mostly seen under the aspect of long-term trends is connected also with a change of the frequency and the intensity of extremes. However, the detailed probability analysis – performed for Germany, in case of precipitation also for adjacent Central European regions – and presented here reveals

outstanding particularities with respect to seasons and considerable regional structures. So, a simple statement that German climate is becoming more extreme in a very general sense is not justified. Rather, some details are important and have to be taken into account.

In case of temperature the warming trend, mostly without variation of variance, is the most striking fact. This means, *although there exists the exception of autumn within recent decades, keeping in mind the anthropogenically forced climate change, a further warming trend in all seasons should be expected linked with a probability increase of occurring warm/hot days and corresponding decrease of occurring cold days.*

In case of precipitation the conclusions have to be drawn in a much more differentiated manner because not only trends (of average or mode) but also an increase of variance is detected leading to a “really” more extreme climate. *The most outstanding risks derived in this context are extreme high precipitation events in winter and dryness in summer both with increasing probability of occurrence.* Such results of observational statistics of the past are also important for climate model projections into the future if one agrees that the anthropogenic climate change signal is already existent within the observational climate data of the industrial era.

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