factsheet 1

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Extreme weather events in Europe: preparing for climate change adaptation

Factsheet 1 Describing extreme weather: statistics and how to interpret them

Key messages

Probabilities are a key to risk management, and statistics offer a mathematical framework for describing risk factors arising from changes in the intensity and frequency of extreme weather events.

The likelihoods that different temperatures, precipitation and wind speeds will exceed critical values are usually shown in the form of a probability density function. The shapes of probability density functions vary, depending of the underlying physics. The extreme values at either end of the curve are irregular and rare by nature, and are represented by the tails of probability density functions.

Information about the most frequent values is usually robust and gives a good estimate of the long-term mean. Extremes, on the other hand, are both rare and occur on an irregular basis, which makes them very difficult to analyse and forecast. There are, nevertheless, statistical methods that use a wide range of mathematical tools and can be used in risk management.

For climate change, there are methods of explaining to a reasonable level of confidence how the probability of seeing different events and intensities might change in future. The main challenge is to understand how all the probabilities change: what will the probability density functions look like? Climate change reflects the overall changes in Earth system processes, and the probability density functions provide a signature of these processes. When processes change, the probability density functions will shift and their mean values and other properties like their extreme values at either end of the distribution will change accordingly.

There are several ways to predict how probability distributions will change in the future. These work fairly well for some phenomena; however, for others, there is still insufficient information to make predictions about such changes.

Much can be learnt from observations about the way past changes in average conditions have affected extremes. Climate models based on the laws of physics also provide useful guidance for certain types of extremes and their statistical distributions.

Why statistics?

One important factor in risk analysis and management is the estimate of the probability of an extreme event taking place. Extremes events are rare, irregular and associated with intensities near the limits of magnitudes seen in the past. Typically, society is not accustomed to extremely rare events, and it is usually difficult to discern a systematic behaviour of such events. There are, nevertheless, ways to get insight into their recurrence and driving processes. Tools for analysing extremes may include both mathematics and statistics as well as models describing physical and dynamical processes.

Our knowledge about extremes is based on information derived from mathematical description of probabilities, observations and measurements, and our understanding of the physical and dynamical processes. In addition, extremes sometimes leave a direct imprint of their presence, such as flooding events or drought.

Statistical models provide mathematical certainty to uncertain information associated with taking a random data sample (all measurements are for a finite period that in principle represents a random sample in the context of the lifetime of the phenomenon). Hence, given a reliable mathematical framework that constrains the range of possible solutions, it may be possible to make inferences even based on incomplete data samples.

Statistics provide valuable descriptions

An individual extreme weather event is related to a given time and location. However, it is always set into the context of the climatology of such events. In this respect, it is important to distinguish between weather and climate. Statistical methods can be used to describe both weather and climate. Weather can be described as a chronology and information about when and where a certain situation takes place; climate can be understood as the typical weather pattern. Moreover, weather can be described by a series of numbers in chronological order, often referred to as a 'time series', whereas in a climatic perspective, the exact timing of events and the chronology are less important than the question of *how often* we can expect such events. This information is given by the frequency of the event, which is directly related to its probability. The probability of an event taking place, on the other hand, is described by a probability density function, abbreviated as 'pdf'. The relationship between weather and climate is illustrated in Figure 1.

All physical processes that can be described in terms of a specific quantity will have a signature in the shape of a pdf, which makes it possible to get an idea of how often certain conditions recur. The pdfs are key to understanding both extremes and climate change. An extreme event often involves a value near the high end of past values – for example the 'upper tail' in Figure 2 – corresponding to one of the 'wings' of the density function.

Measured quantities can be sorted into different size classes and then counted. The counts in each class are known as a histogram. Histograms and pdfs are closely related. However, histograms are created from an arbitrary sample of measurements or calculated values, whereas the pdf describes an intrinsic theoretical function representing the shape of a histogram if it were based on an infinitely large sample. Histograms are usually used to represent past statistics,

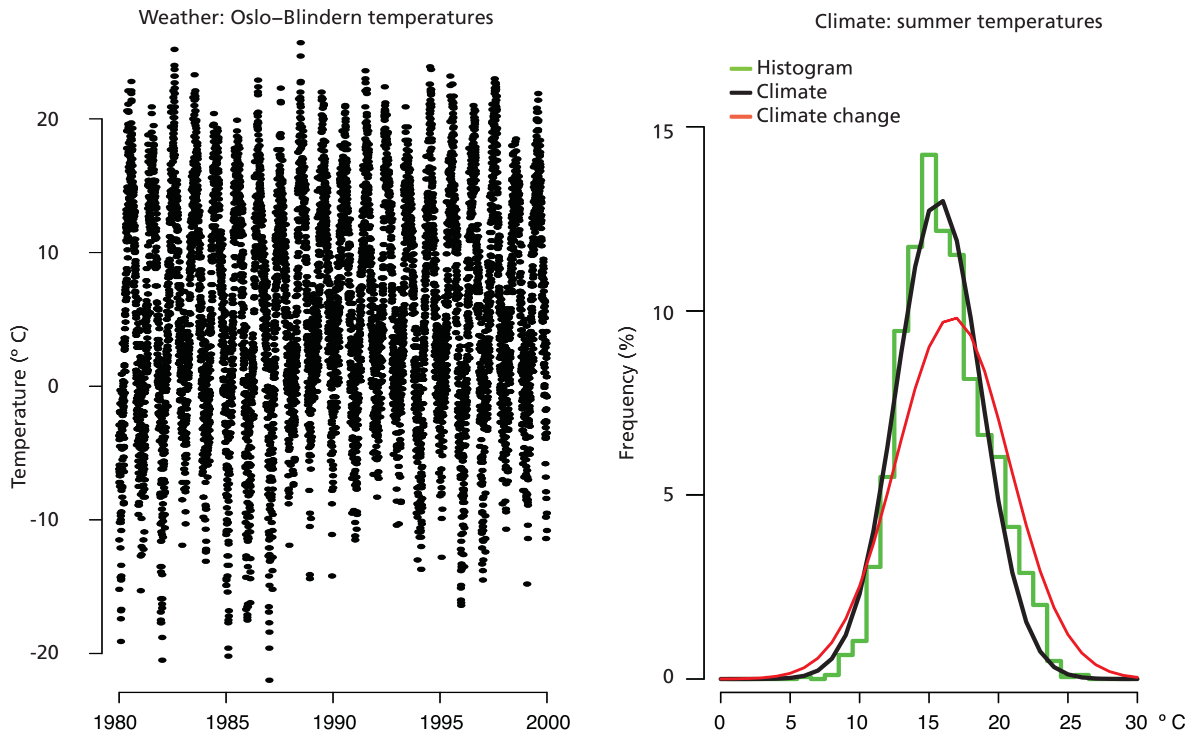

Figure 1 Typical time series for temperature (left) and histograms (right) showing how often different temperatures occur

The probability density function (pdf) is shown in black and provides a description of the past and present climate. A climate change implies a shift in the pdf, and a hypothetical case is shown as a red line.

and, in a stationary climate where the pdf does not change over time, the histograms will also provide useful information about probabilities for the future. As expected from its definition, however, climate change involves changes in the pdfs, and it is therefore important to predict their future shapes. Typically, return-value analyses made for the past – such as the once in a 100-year flood – assume stationary pdfs, which will not be valid for the future.

The term 'percentile' refers to the rank of the magnitudes in the data sample. The 50^{th} percentile has a value that is greater than 50 % of the data (the median), and the 99^{th} percentile is greater than 99 % of the data.

Types of extremes

Extremes can be characterised by intensity, spatial extent, duration and frequency. A common feature is their rare recurrence and irregular nature. Other important aspects of extremes are whether they tend to come in clusters or exhibit long-term trends, and the degree of randomness in their recurrence.

Extremes include heavy precipitation, high winds, heat waves, cold snaps, droughts, flooding, hurricanes, storms, storm surges, tornadoes, hail, lightning, avalanches and landslides. Extreme weather is part of our natural climate, and, from time to time, extreme weather conditions occur. Their frequency and severity, however, are affected by changes in climate. The recurrence of record-breaking events can be used as an indicator of the changing character of the extreme events.

Extremes are often local phenomena, and are frequently not captured by measurements. Whereas the statistical sample of extremes is often small and subject to sampling fluctuations, the modelling of extremes is based on a well-defined mathematical framework.

Identifying and tracking storms provides one method for describing extremes. Extreme precipitation, heat waves, flooding and wind speeds can be modelled statistically based on pdfs. In some cases, such as precipitation, it may even be possible to predict how the shape of the distribution may change in the future.

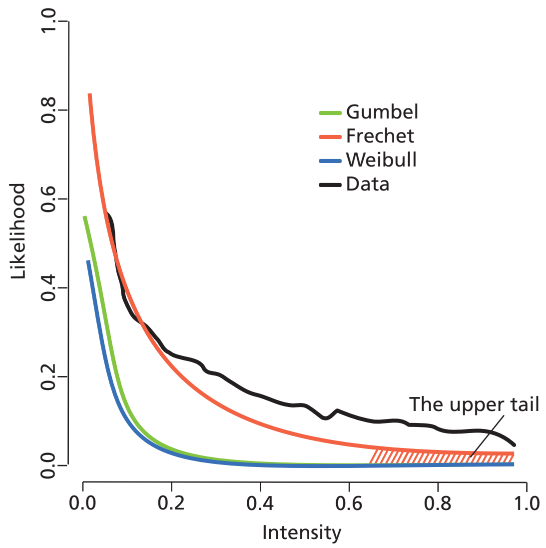

Figure 2 Different pdfs often used to describe extreme values

These pdfs provide curves with different shapes, and choosing which to use depends on the properties of the specific data (black curve). The upper part of the pdfs, for example the red hatched area under the red curve, is referred to as 'the upper tail' of the pdf and is used to represent the extreme values.

How to model extremes

The shape of the pdfs is inferred by a curve-fit to the data. The fit involves a much larger sample than just the most extreme cases. It is assumed that the pdfs are continuous and smooth functions, and that their shape can be constrained by data from both upper and lower ends.

Once the extreme value distribution is known, it is possible to infer the probability of exceeding an extreme threshold value. The probability is closely related to the return interval and return value for a process. A long time is expected on average between extreme events with very low probabilities. It is important, however, to keep in mind that the recurrence is often irregular, and that the timing between events will vary.

How often do extreme events take place? The answer to this question is often addressed through extreme value distributions. The probability can only have values between 0 and 1, where 0 means it never happens, and 1 means it happens all the time. For example, the probability (Pr) of exceeding a threshold value *x* defining the 'upper tail' in Figure 2 is the fraction of the red-hatched area under the red pdf curve, which is the same as $\Pr(X > x) = 1 - \Pr(X < x)$.

Sometimes, extreme events may 'cluster' in time, where several extremes follow each other after short times despite low overall probability. Possible reasons for this may be that the extremes are influenced by varying external conditions and are not independent events.

Extremes and climate change

Traditional return-value analysis assumes that the pdf for a process remains constant, and that the pdf is assumed to be stationary. A climate change, however, is by definition a change in the pdf (illustrated by the red line in the right-hand panel of Figure 1). Non-stationarity implies that a 100-year event at the present time may become, for instance, a 50-year event in the future. There are simple methods for assessing whether a pdf is stationary. A pdf usually assumes that the data are mutually independent and identically distributed (IID). A simple IID test can indicate whether the pdf is changing by examining the recurrence of record-breaking events. For stationary pdfs, there is a mathematical rule for how the probability of a record-breaking event diminishes as the data sample grows in time. This can be used to infer whether the wings of the pdf are changing over time.

Global climate models do not represent local extreme conditions well, but can provide a picture of the large-scale conditions on which the extremes may depend. Various methods for downscaling can extract useful information from descriptions of large-scale conditions, where Bayesian statistics exploit the dependency between weather types and probability. Monte Carlo simulations and numerical experiments may also shed light on extremes. A proper evaluation of all models is a requisite.

Geographical and seasonal distributions reveal dependencies. Extremes may have a systematic local character, where turbulence is influenced by the local environment. Urbanisation may affect temperatures. Furthermore, aspects such as the proximity to oceans affect the exposure to some types of extremes. Different degrees of exposure provide a basis for spatial maps of probabilities and risks.

Extremes in risk analysis

Extremes are often conditions outside the range to which we are accustomed. Their irregularity and severity can bring surprises for societies accustomed to more normal conditions, and hence catastrophes. Risk analyses are important means for managing such threats, and the probability of an event taking place is an important factor in the risk analysis.

Risk can be quantified and defined in mathematical terms, which provides a useful tool for risk management. The convention is often based on notations from statistics, where a variable X describes a condition such as precipitation amount or wind speed. Given the probability $\Pr(X > x)$ that the precipitation, for example, exceeds a certain threshold (x) and the consequence $C(X)$ associated with this condition, the risk can be calculated according to $R(X) = \Pr(X > x) \times C(X)$, the likelihood of occurrence multiplied by the level of consequences should it occur.

Statistics-based climatological studies may provide the probabilities needed for quantifying risks. The consequence may in some cases be quantified, based on the estimated cost, for example of rebuilding. For many cases, however, the consequences are difficult to quantify, for example in the case of mortalities or ecological impacts.

Risk analysis provides tools for climate change adaptation, for example by providing information on the design standards required for infrastructure to meet future climatic conditions and in guiding the premiums for insurance policies. However, in any particular case, risk management will need to account for a range of different conditions and associated risks.

Conclusion

Extreme value statistics represent an important tool for describing uncertainties and for providing the risk analyses needed for adaptation to climate.

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