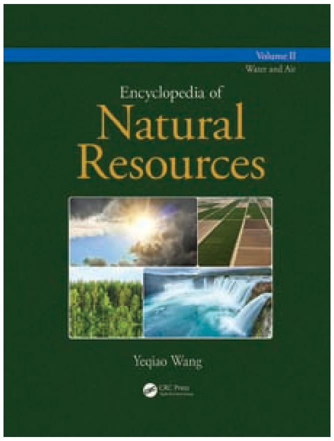

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Climate: Extreme Events

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Abstract
One very important topic in climatology, meteorology, and related fields is the understanding of extremes in a changing climate. There is broad consensus that some of the most hazardous effects of climate change are due to a potential increase (in frequency and/or intensity) of extreme weather and climate events. This entry reviews the basic statistical definitions of weather and climate extremes, discusses how they are sampled and commonly used, and provides a brief overview on how extremes are expected to change in a warming climate.

INTRODUCTION

Extreme events in weather and climate are by definition scarce, but they can have a significant physical and socioeconomic impact on people and countries in the affected regions. Alongside the intuitive knowledge that hurricanes, tornados, severe storms and rain, droughts, floods, and extreme temperatures might qualify, how can we define extreme events more quantitatively? There are several approaches used in climate research. One often-used [e.g., by the Intergovernmental Panel on Climate Change (IPCC)] definition of an extreme event of the variable under consideration is based on the tails of its climatological (i.e., reference) probability density function (PDF) at a particular geographical location. Extreme events would normally be as rare as or rarer than the, for example, 5^{th} and 95^{th} percentiles. The specific percentile values are not rigorously defined, so often other, more or less stringent, ranges are used (e.g., the 1^{st} and 99^{th} or 10^{th} and 90^{th} percentiles), depending on the particular application. Another routinely used definition of extreme events is that of block maxima or minima. Block maxima/minima are the highest/lowest values attained at a specified location during a given time interval (e.g., daily, monthly, seasonal, or annual). If the interval is the whole period for which observations are available, a block maximum/minimum is called the "absolute extreme." Note that both definitions do not depend on the particular shape (e.g., Gaussian or non-Gaussian) of the PDF. Yet the Gaussian distribution is very often used to estimate the odds of extreme events, neglecting the non-Gaussianity of real world observations. Therefore, an extreme event can also be defined as the non-Gaussian tail of the data's PDF. This definition implies that a high amplitude event does not qualify as extreme if it is described by Gaussian statistics. In a nutshell, because there are different definitions, it is important to be aware of the one being used in a particular application.

Whichever definition is used, understanding extremes has become an important objective in weather and climate research because weather and climate risk assessment depends on knowing and understanding the statistics of the tails of PDFs. At this point it is essential to define weather and climate. As described in almost all fundamental meteorological textbooks,[1,2] weather is varying on timescales of hours, days, to a few weeks, whereas climate varies on longer timescales of months, years, and decades. There is, of course, a certain overlap and the terms weather and climate are typically used in a loose way, specifying the timescales as needed for particular applications. It should be noted that nonlinear multi-scale interactions render a strict separation of timescales unfeasible, making it all put impossible to attribute an individual extreme event to a changing climate.

There is broad consensus that some of the most hazardous effects of climate change are related to a potential increase (in frequency and/or intensity) of extreme weather and climate events. (A notable exception is gradual sea level rise, which will result in the inundation of large densely populated regions; by our definition this is not an extreme event, but it is surely catastrophic.) The overarching goal of studying extremes is, therefore, to understand and then manage the risks of extreme events and related disasters to advance strategies for efficient climate change adaption. Although numerous important studies have focused on changes in mean values under global warming, such as mean global temperature (one of the key variables in almost every discussion of climate change; see, for example, reports from the IPCC available at http://www.ipcc.ch), the interest in how extreme values are altered by a changing climate is a relatively new topic in climate research. The reasons for that are primarily twofold. First, for a comprehensive statistical analysis of extreme events, high-quality and high-resolution (in space and time) observational data sets are needed. It is only recently that global

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high-quality daily observations became available to the international research community. Second, we need extensive simulations of high-resolution climate models to (hopefully) simulate realistic climate variability. Again, only recently long enough high-resolution numerical simulations of climate variability became feasible to study extreme events in some detail.

SAMPLING

The general problem of understanding extremes is, of course, their scarcity: it is very hard to obtain reliable (if any) statistics of those events from a finite observational record. Therefore, the general task is to somehow extrapolate from the well-sampled center of a PDF to the scarcely or unsampled tails. The extrapolation into the more or less uncharted tails of a distribution can be roughly divided into four major, by no means mutually exclusive categories. In fact, the study of extreme events in weather and climate is most often done by combining the strategies of the following methods.[3,4]

The *statistical approach* (*extreme value theory*) is solely based on mathematical arguments.[3,5–8] It provides methods to extrapolate from the well-sampled center to the scarcely or unsampled tails of a PDF using mathematical tools. The key point of the statistical approach is that, in place of an empirical or physical basis, asymptotic arguments are used to justify the extreme value model. In particular, the generalized extreme value (GEV) distribution is a family of PDFs for the block maxima (or minima) of a large sample of independent random variables drawn from the same arbitrary distribution. Although the statistical approach is based on sound mathematical arguments, it does not provide much insight into the physics of extreme events. Extreme value theory is, however, widely used to explore climate extremes.[9–11] In fact, the foundation of extreme value theory is very closely related to the study of extreme values in meteorological data.[7,8] Nowadays this is very often done in conjunction with the numerical modelling approach discussed below. That is, model output is analyzed using extreme value theory to see if statistics are altered in a changing climate.

The *empirical–physical approach* uses empirical knowledge and/or physical reasoning to provide a basis for an extreme value model. The key point here is that, in contrast to the purely statistical method that primarily uses asymptotic mathematical arguments to model only the tail of a PDF, empirical and/or physical reasoning is employed to model the entire PDF. The empirical–physical method can itself be further split into either empirical or physical strategies (or both), focusing on the empirical or physical aspects of the problem, respectively. For example, a purely empirical approach would simply fit a suitable PDF to given data, whereas a more physical ansatz would also determine the physical plausibility of a specific PDF. However, often a clear distinction between the physical and empirical aspects is impossible. The empirical–physical method lacks the mathematical rigor of the statistical method, but it provides valuable physical insight into relevant real world problems. An example for an empirical–physical application is the Gamma distribution, which is often used to describe atmospheric variables that are markedly asymmetric and skewed to the right. Often skewness occurs when there is a physical limit that is near the range of data.[6] Well-known applications are precipitation and wind speed, which are physically constrained to be non-negative. It should be noted that the empirical–physical approach can be, in principle, put on a more rigorous foundation using the principle of maximum entropy.[12–14] That is, given some physical information (i.e., constraints) of a process, the PDF that maximizes the information entropy under the imposed constraints is the one most likely found in nature (i.e., the least biased given the constraints). However, not all PDFs commonly used to explain weather and climate data can be justified this way. For example, the Gamma and Weibull distributions can be obtained by the principle of maximum entropy, but the constraints are not necessarily physically meaningful.[15]

The *numerical modelling* approach aims to estimate the statistics of extreme events by integrating a general circulation model (GCM) for a very long period.[16–18] That is, this approach tries to effectively lengthen the limited observational record with proxy data from a GCM, filling the unsampled tails of the observed PDF with probabilities from model data. Numerical modelling allows for a detailed analysis of the physics (at least model-physics) of extreme events. In addition, the statistical and empirical–physical methods can also be applied to model data, validating (or invalidating) the quality of the model. It is obvious that the efforts by the IPCC to understand and forecast the statistics of extreme weather and climate events in a changing climate fall into this category. Because very long model runs are needed to sample the tails of a PDF, global GCMs used for that purpose are currently run at a relatively coarse spatial resolution and are, therefore, unable to resolve important sub-grid scale features such as clouds, tornadoes, and local topography. Because of that, GCMs cannot be used for very localized studies of extreme events. To overcome this problem downscaling methods are commonly used, for which the prediction of extremes is not based on direct GCM output but on subsequent statistical or dynamical models to link the coarse GCM output to local events.[19]

The *non-Gaussian stochastic approach* makes use of stochastic theory to evaluate extreme events and the physics that governs these events.[4] Assuming that weather and climate dynamics are split into a slow (i.e., slowly decorrelating) and a fast (i.e., rapidly decorrelating) contribution, weather and climate variability can be approximated by a stochastic system with a predictable deterministic component and an unpredictable noise component. In general, the deterministic part is non-linear and the stochastic part is state dependent. The stochastic approach takes advantage of the non-Gaussian structure of the PDF by linking a stochastic model to the observed non-Gaussianity. This can be done in two conceptually different ways. On the one hand, if the deterministic component is non-linear and the stochastic component is state independent, the non-Gaussianity is due to the non-linear deterministic part. On the other hand, if the deterministic component is linear and the stochastic component is state dependent, the non-Gaussianity is due to the state dependent noise. Of course, any combination of the two mechanisms is also possible. Although the non-linear approach with state-independent noise captures some types of non-Gaussian climate variability well,[20,21] it recently became clear that state-dependent (or multiplicative) noise plays a major role in describing weather and climate extremes.[4] The physical significance of multiplicative noise is that it has the potential to produce non-Gaussian statistics in linear systems. In particular, Sura and Sardeshmukh,[22] Sardeshmukh and Sura,[23] and Sura[4] attribute extreme anomalies to stochastically forced linear dynamics, where the strength of the stochastic forcing depends linearly on the flow itself (i.e., linear multiplicative noise). Most important, because the theory makes clear and testable predictions about non-Gaussian variability, it can be verified by analyzing the detailed non-Gaussian statistics of oceanic and atmospheric variability.

What do these approaches have in common? Every approach effectively extrapolates from the known to the scarcely known (or unknown) using certain assumptions and, therefore, requires a leap of faith. For the statistical approach the assumptions are purely mathematical. For example, the assumption of classical extreme value theory, that the extreme events are independent and drawn from the same distribution, and that sufficient data are available for convergence to a limiting distribution (the GEV distribution) may not be met.[5,6] The potential drawback of the empirical–physical approach is its lack of mathematical rigor (with the exception of the principle of maximum entropy); it primarily depends on empirical knowledge and physical arguments. The weakness of numerical modelling (including downscaling) lies in the largely unknown ability of a model to reproduce the correct statistics of extreme events. Currently, GCMs are calibrated to reproduce the observed first and second moments (mean and variance) of the general circulation of the ocean and atmosphere. Very little is known about the credibility of GCMs to reproduce the statistics of extreme events. Likewise, the non-Gaussian stochastic approach relies on the assumption that weather and climate variability can be modelled by a stochastic process. It has to be concluded that the common methods to study extreme events have some limitations and that the study of extreme weather and climate events is largely empirical. In particular, there exists no closed quantitative theory on how the statistics of weather and climate extremes might change in a warming climate.

CLIMATE CHANGE

What can be said about likely changes in frequency or intensity of climate extremes in a warming climate? Overall, not very much. In fact, there are only few processes we understand well enough to have some confidence in projected changes.[24] At the top of the list is an increase in the number of extremely warm days and heat waves. In fact, many land areas are already experiencing significant increases in maximum temperatures. This is also consistent with projected temperature changes obtained from GCM projections. Because warm air can hold more water, there is also an agreement that the intensity (mean and variability) of the hydrological cycle increases with increasing temperatures.[25] Given a more intense hydrological cycle, larger amounts of rainfall will come from heavy showers and more intense thunderstorms. Of course, more intense precipitation increases the likelihood of severe floods. Somewhat counter intuitively, the likelihood of severe drought will also increase in a warmer climate because, with a more intense hydrological cycle, a larger proportion of rain will fall in the more extreme events. In addition, higher temperatures will result in increased evaporation reducing the amount of moisture available at the surface. Note that the global spatial distribution of temperature and precipitation extremes (and the probability of droughts) is highly variable.[24,26] Of course, many people are mostly interested in the projected change of severe winds. Unfortunately, we have very little definite knowledge about how the strength and frequency of hurricanes and severe mid-latitude storms might change under global warming. The reason for that is, that the genesis of tropical and mid-altitude storms is controlled by many physical processes, including the large-scale atmospheric flow, whose interactions we currently do not fully understand. Also, there is a large uncertainty with regard to how our global climate models are capable of simulating the plethora of small-scale processes. That is also the reason why we cannot make a definitive projection for small-scale events such as tornadoes, hail, and thunderstorms.

CONCLUSION

Knowing the tails of weather and climate PDFs is an important goal in the atmospheric and ocean sciences because weather and climate risk assessment depends on understanding extremes. Although the commonly used definitions of extremes, and their conceptual implementation in a meteorological framework, are straightforward, it is very hard to obtain statistically significant information of extreme weather and climate events from scarce data. In particular, we only have a very limited physical and statistical understanding of how extremes are going to be altered in a changing climate. Many climate projections just look into the change of the mean and the variance, that is, assuming Gaussian statistics. However, the non-Gaussian statistics (the shape of the distribution) will most likely also be altered in a changing climate. More research (more observations, better theoretical and numerical models) is needed to improve our understanding of how a PDF might change in the future.

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