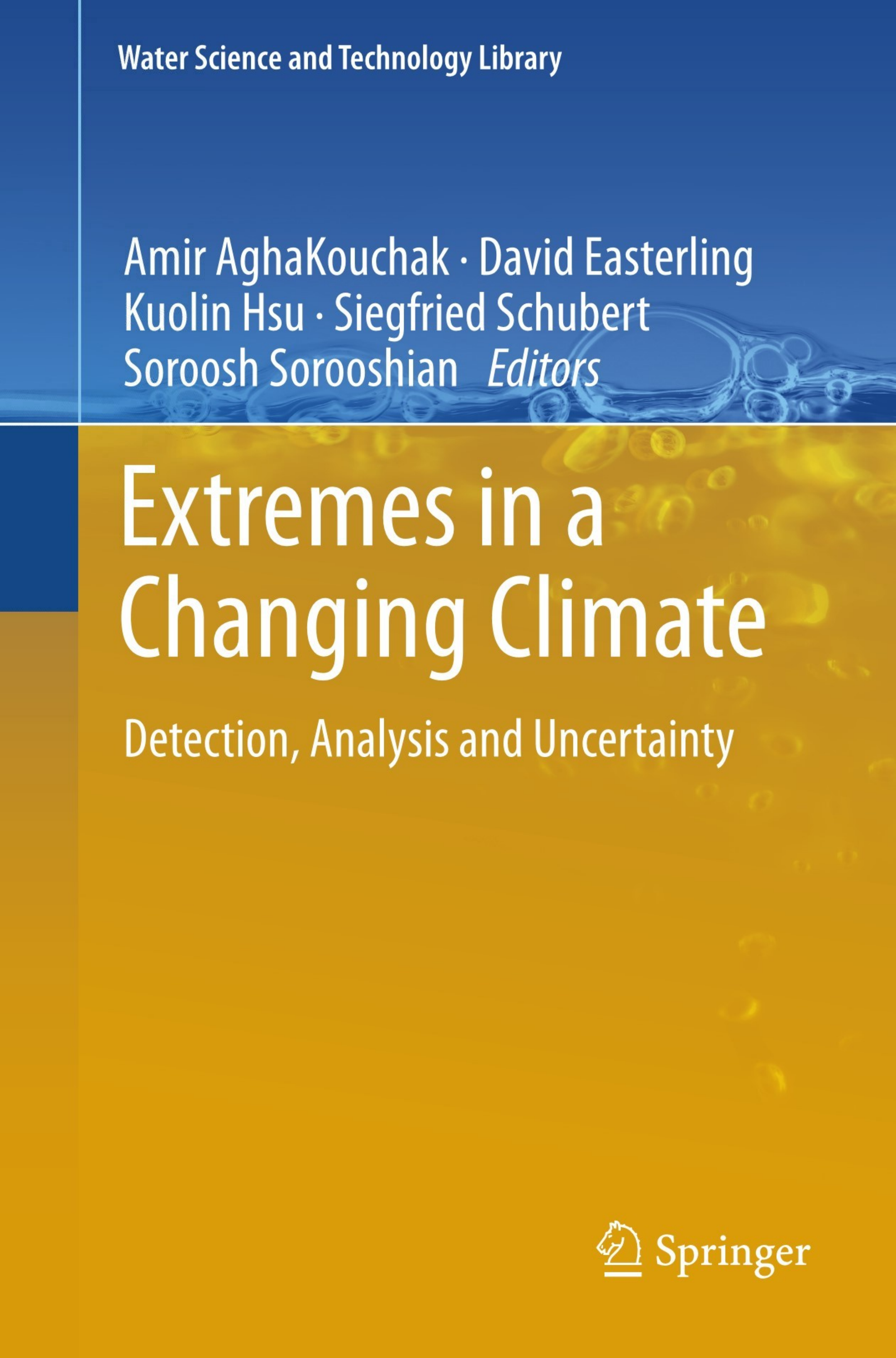

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Amir AghaKouchak · David Easterling
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Extremes in a Changing Climate

Detection, Analysis and Uncertainty

Springer

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Foreword

The climate is changing owing to human activities. The predominant effect is from the changing atmospheric composition mainly from burning of fossil fuels that produces both visible pollution that blocks the sun and carbon dioxide. The particulates have a short lifetime as they are washed out of the atmosphere by rainfall, but carbon dioxide has a very long lifetime: typically over a 100 years and so it builds up and accumulates. Indeed carbon dioxide amounts have increased by over 40% since pre-industrial times and over half of this increase has occurred since 1970. Carbon dioxide is a greenhouse gas and produces a blanketing effect that results in a warming planet.

As well as increasing temperatures, a warming world is expected to alter precipitation in several ways. A warmer atmosphere can hold more water vapor, and will as long as there is a water supply nearby, as there always is over the oceans. The result is that more atmospheric moisture is pulled into storms resulting in heavier rains – or snows. But where it is not raining, the warmer atmosphere sucks moisture out of the soils and vegetation, promoting drought. Indeed, it is expected that a warming world alters the occurrence and magnitude of extremes such as droughts, heavy rainfalls and floods, as well as the geographic distribution of rain and snow. The winter snow season is likely to get shorter at each end and more precipitation events are apt to be rain. But snow events in winter can also be larger, as long as temperatures remain below about freezing. All of these changes are related to an acceleration of the hydrologic cycle and atmospheric circulation changes, and they include the direct impact of warmer conditions on atmospheric water vapor amounts, rainfall intensity, and snow-to-rain occurrence. However, extremes are inherently rare and difficult to observe reliably. But they are exceedingly important because of their nature and the tremendous damage that can ensue as conditions exceed those previously experienced. Key scientific issues relate to determining the statistics of extremes and how they are changing, and whether those changes are indeed caused by the human-induced changes in climate. These are very much the topic of this book.

A key issue then is what will happen in the future? For this we use climate models along with statistical approaches. But there are questions of how well models are able to handle extremes and how we can improve their capabilities. New improved and updated data sets at high frequency (e.g., hourly) are needed to properly characterize many of these facets of our climate and to allow for assessment against comparable model data sets. Then analyses are required that quantify which changes are consistent with our expectations and how we can best contribute to improving their prediction in a future climate. Confronting models with observationally-based products can lead to new metrics of performance and highlight shortcomings and developmental needs that may focus field programs, process studies, numerical experimentation, and model development. New applications should be developed for improved tracking and warning systems, and assessing changes in risk of drought, floods, river flow, storms, coastal sea level surges, and ocean waves. This book provides a welcome entrée into all of these areas.

Addressing the topic of changes in hydrologic extremes has been and continues to be one of the priorities of the World Climate Research Programme and especially the Global Energy and Water cycle Experiment (GEWEX). Indeed the workshop that is the focus of the material in this book grew directly from these interests.

National Center for Atmospheric Research Kevin E. Trenberth

Preface

The observed increase in weather and hydroclimatological extremes, particularly in the past decade, has brought much needed attention to the subject. In 2011, Texas experienced the driest year on record resulting in economic losses exceeding \$7 billion. The Texas drought was by far the costliest drought on record with an approximately 90% increase from the previous global record set in 2006. In the past few years, major drought events have been recorded in Ethiopia, Australia, United States, Eurasia, Middle East, and southern Europe. At the other end of extreme, in 2010, Pakistan experienced the worst flooding in 80 years resulting in over 2,000 casualties, four million people displaced, and 20 million people affected directly or indirectly. The number of people suffering from this extreme event exceeds the combined total of the Indian Ocean tsunami (2004), Kashmir earthquake (2005), and Haiti earthquake (2010). Similar to droughts, every continent, in the past few years, has experienced major floods. For example, Australia, United States, Thailand, and China have set local records in flooding and the resulting economic losses. New records in terms of number of tornadoes in the United States in 2004 (1817) and 2011 (1691) and heat waves in 2003 (Europe) and 2010 (Russia) suggest that we should get used to climate extremes of all kinds and get more serious about developing better mitigation and adaptation strategies.

A question that has unfortunately become political and controversial is whether the observed changes are due to anthropogenic causes or whether our observations are just within the expected climate variability. Perhaps more important is the question of how climate extremes might change in the future. The first step to address these questions is detecting extremes and their variability. Predicting how weather and climate extremes might change in the future requires an understanding of their changes and behavior in the past. In fact, mitigating climate extremes requires a comprehensive and reliable study of statistics of extremes.

The main motivation for this book stems from the demand for more extensive and reliable methods for analyzing climate extremes in a nonstationary world. Given the limitations in the spatial and temporal resolutions of global climate data records, substantial progress in understanding extremes will largely rely on improvements in stochastic methods suitable for analyzing extremes. This book provides a collection of the state-of-the-art methodologies and approaches suggested for detecting extremes, trend analysis, accounting for nonstationarities, and uncertainties associated with extreme value analysis in a changing climate. This volume is designed so that it can be used as the primary reference on the available methodologies for studying climate extremes.

The first chapter introduces several statistical indices designed for detecting and diagnosing changes in climate extremes. Most statistical methods currently being used in engineering design are based on the stationary assumption (i.e., an unchanging climate in a statistical sense). Chapter 2 describes how extremal distributions can be retained under the nonstationary assumption. Chapter 3 extends the discussion by introducing a Bayesian framework for nonstationary analysis of extremes and their associated uncertainties. The chapter also provides a discussion of the so-called regional parameter concept using Bayesian hierarchical modeling. Chapter 4 is devoted to return-periods and return-levels estimation under climate change. The chapter examines two different definitions of return-period under the nonstationary assumption. Chapter 5 illustrates the application of Copula functions to multivariate extreme value analysis. Chapter 6 presents several parametric and nonparametric methods for tail dependence analysis. Chapter 7 discusses the theoretical framework, observational evidence, and related developments in stochastic modeling of weather and climate extremes. Chapter 8 surveys methods of projecting changes in extreme weather and climate statistics. Chapter 9 examines the simulated and observed short-term climate variability and weather extremes that have occurred over the last three decades with a focus on the winter hemispheres. Chapter 10 explores uncertainties in observed changes in climate extremes. Chapter 11 assesses uncertainties in the projection of future changes in precipitation extremes. Chapter 12 presents various data sets that are suitable for examining changes in extremes in the observed record. Finally, Chap. 13 is devoted to the concept of nonstationarity in extremes and engineering design.

Acknowledgment

Completing this book could not have been accomplished without the assistance and support of many individuals. First and foremost, the Editors wish to express sincere appreciation to the authors who shared their knowledge and expertise in climate extremes. We thank Kevin Trenberth for his thoughtful views on Extremes in a Changing Climate. We convey our gratitude to Professor Vijay Singh, Editor-in-Chief of the Springer's *Water Science and Technology Library*, and the members of the Editorial Advisory Board. Without their encouragement and support this work would not have been realized. We offer special thanks to the many reviewers of the book for their thoughtful comments and suggestions which led to improvements in the quality of the book. Appreciation is expressed to Scott Sellars and Andrea Thorstensen for reviewing some of the manuscripts and offering suggestions for improvement. We praise the professional service provided by the publication

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Chapter 1
Statistical Indices for the Diagnosing and Detecting Changes in Extremes

Xuebin Zhang and Francis W. Zwiers

Abstract This chapter introduces statistical indices that have been used to quantify the past changes in weather and climate extremes. These indices can also be used to assess changes in future extremes as projected by climate models. We also present examples in which the influence of anthropogenic climate change has been identified on extreme daily temperature, extreme daily precipitation, and the probability of occurrence for a specific extreme event.

1.1 Introduction

Weather and climate extremes have always played an important role in shaping the natural environment and pose significant challenges to society. For example, extremely cold winter temperatures strongly regulate over-winter survival of the spruce beetle in the Yukon and the mountain pine beetle in British Columbia, Canada. The insect freezes and dies below a threshold temperature of about –40°C, therefore, the occurrence of such very cold temperature events in winter affects the abundance of the beetle population in the following spring. Another example is the availability of water: too much or too little water can both pose strong challenges to society. As climate changes, weather and climate extremes will also change. Given their importance and the prospect of changes in the future, it is very important to understand how and why weather and climate extremes have changed in the past,

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and how they will change in the future. One approach towards such an understanding would be to develop metrics with which weather and climate extremes can be characterized, quantified and monitored. However, there are no universally accepted metrics for such a purpose.

The word “extreme” can refer to many different things in the climate literature, and consequently, there is no unique climatological definition for extreme (Stephenson 2008). This occurs in part because the word “extreme” can be used to describe either a characteristic of a climate variable or that of an impact. In the case of a climate variable, such as surface air temperature or precipitation, an extreme can be reasonably well defined referring to values in the tails of the variable’s distribution that would be expected to occur infrequently. In the case of an impact, an extreme may be less well defined since there may not be a unique way to quantify the impact. The linkage between an extreme event in the sense of a climate variable and an extreme event in the sense of the impact of a climate or weather event is not straightforward. A rare weather or climate event may not necessarily cause damages. For example, a strong wind associated with a tropical cyclone over the ocean may not result in any damage if there are no ships nearby. Similarly, not all damages are caused by rare weather and climate events. For instance, while the 2011 Thailand flood caused more than eight billion US dollars in insured damages, the amount of rain that fell in the region was not very unusual (van Oldenborgh et al. 2012).

In this chapter, we define some indices that can be derived from daily weather data. These indices allow the characterization of historical and future changes in extremes of weather variables. We will also provide some examples in which anthropogenic influence on weather and climate extremes can be detected and attributed. Our discussion will focus on weather and climate variables rather than impacts resulting from weather or climate events.

1.2 Indices of Extremes for Weather and Climate Variables

The Intergovernmental Panel on Climate Change in its 4th Assessment (Hegerl et al. 2007) defines an extreme climatic event as one that is rare at a particular place and time. The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation refines this definition, stating that “an extreme (weather of climate) event is generally defined as the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable” (Seneviratne et al. 2012). The idea of defining extremes as events in the tail(s) of a probability distribution is illustrated in Fig. 1.1. Figure 1.1 also shows, schematically, how warm or cold extremes are affected by changes in the mean or standard deviation of daily temperature and how extreme precipitation is affected by an increase in precipitation intensity. Exactly what constitutes an extreme event will depend on the context of usage.

When designing infrastructure, the engineering community accounts for climate extremes that occur only infrequently and are generally not expected to recur each year. Examples include the estimates of long period return values of annual maximum amount of rainfall within 5, 20 min, or within 1, 2, 6, 12, and 24 h to derive design rainfalls for sewage systems, or of annual maximum wind gust speed or annual maximum (accumulated) snow depth to derive codes for building design. In this case, the concept of extremes corresponds well to that used in statistical science, and thus powerful statistical tools based on extreme value theory are available to aid in the analysis of historical and future extremes (e.g. Coles 2001; Katz et al. 2002). Such tools were developed to infer extreme values that might occur beyond the range of the observed sample, such as the problem of estimating the 100 year return value on the basis of a 30-year sample. Increasingly, these tools are being used in the evaluation of extreme events simulated in climate models (e.g. Kharin et al. 2007; Wehner et al. 2010), in the characterization of the influence of large scale atmospheric circulation variations on extreme rainfall (Zhang et al. 2010), and in the detection of anthropogenic influence on temperature extremes (Zwiers et al. 2011).

To address the needs of various aspects of climate research on extremes as illustrated above, and to facilitate the monitoring of extremes, the Joint CCl[1]/CLIVAR[2]/JCOMM[3] Expert Team on Climate Change Detection and Indices (ETCCDI) defined a set of descriptive indices of extremes (Frich et al. 2002; Alexander et al. 2006; Klein Tank et al. 2009; Zhang et al. 2011). The indices were based on the European Climate Assessment indices (Klein Tank and Können 2003). They were chosen to sample a wide variety of climates and included indicators such as the total number of days annually with frost and the maximum number of consecutive dry days in a year (see Table 1.1). They can be derived from daily values of maximum and minimum temperatures, and daily precipitation amounts, and are designed to be easily updatable as more data become available, so as to facilitate monitoring. When developing those indices, it was realized they need to be as comparable as possible across different regions. Some of these indices have been used for the detection and attribution of changes in extremes.

The ETCCDI indices generally fall into three different types. One type of index measures the monthly and/or annual maxima or minima of daily temperature or annual maximum daily precipitation amounts. These types of extreme indices, like annual maximum 12 or 24 h precipitation amounts mentioned earlier, have been widely used in engineering applications to infer design values for engineered structures. Another type of index involves the calculation of the number of days

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[1] The World Meteorological Organization (WMO) Commission for Climatology (CCl).

[2] The World Climate Research Program (WCRP) Climate Variability and Predictability Project (CLIVAR).

[3] The WMO and the UNESCO's Intergovernmental Oceanographic Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM).

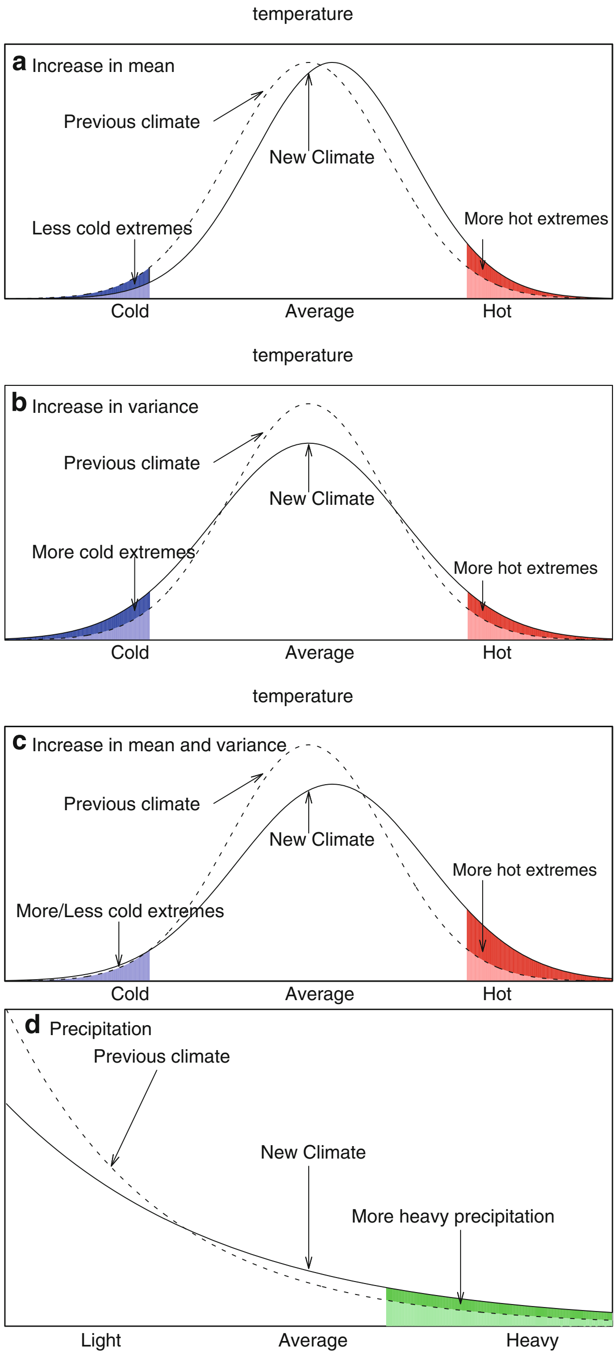

Fig. 1.1 (continued)

in a year exceeding specific thresholds that are relative to a fixed base period climatology. An example of this type of index is the number of days with daily minimum temperature below the long-term 10th percentile in the 1961–1990 base period for the respective calendar days. As the 10th percentile differs from one calendar day to another, extremes defined this way are a relative characteristic. Therefore, a minimum temperature of −10°C in Toronto in winter would not be considered as an extreme, but the same event would be very extreme in other seasons. Applying such a definition to data makes it possible to compare the indices from different places with different climates as the same part of the probability distribution of daily temperature is sampled at each location. A third type of index involves the calculation of the number of days in a year exceeding specific thresholds that are fixed across the space. The thresholds are typically impacts related. An example is the number of frost days per year (i.e., minimum temperature below 0°C). The phenomena may in itself not be an extreme in either the absolute or relative sense. The number of frost days and the number of growing season days are such examples. While such indices may not be applicable everywhere on the earth, and the phenomena may not occur in some places on the earth (e.g. a frost day would never occur in the tropics except perhaps in high mountains), they have a long history in many applications such as agriculture in many places.

1.3 Detection and Attribution of Changes in Climate Extremes

The identification of past changes in climate extremes is important. Understanding the possible causes of those changes is even more important. For example, understanding whether external forcing of the climate system, such as that due to human induced greenhouse gas emissions, had caused an observed change in extremes would affect confidence in the projection of future changes that are obtained from climate models that are driven with future emissions scenarios. One would have a

Fig. 1.1 Schematic representations of the probability density function of daily temperature, which tends to be approximately Gaussian (exceptions can be caused by soil freezing, energy balance constraints, and other factors such as snow or soil moisture feedbacks, e.g. Fischer and Schär 2009; Hirschi et al. 2011), and daily precipitation, which has a skewed distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. In the case of temperature, changes in the frequencies of extremes are affected by changes in the mean, in the variance, and in both the mean and the variance. In a skewed distribution such as that of precipitation, a change in the mean of the distribution generally affects its variability or spread, and thus an increase in mean precipitation would also likely imply an increase in heavy precipitation extremes, and vice-versa. In addition, the shape of the right hand tail could also change, affecting extremes. Furthermore, climate change may alter the frequency of precipitation and the duration of dry spells between precipitation events. Figure 1.1a, b, c modified from Folland et al. (2001) and Fig. 1.1d modified from Peterson et al. (2008)

Table 1.1 The extreme temperature and precipitation indices recommended by the ETCCDI (some user defined indices are not shown). Precise definitions are given at http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.html

ID	Indicator name	Indicator definitions	Units
TXx	Max Tmax	Monthly maximum value of daily max temperature	°C
TNx	Max Tmin	Monthly maximum value of daily min temperature	°C
TXn	Min Tmax	Monthly minimum value of daily max temperature	°C
TNn	Min Tmin	Monthly minimum value of daily min temperature	°C
TN10p	Cool nights	Percentage of time when daily min temperature <10th percentile	%
TX10p	Cool days	Percentage of time when daily max temperature <10th percentile	%
TN90p	Warm nights	Percentage of time when daily min temperature >90th percentile	%
TX90p	Warm days	Percentage of time when daily max temperature >90th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between daily max and min temperature	°C
GSL	Growing season length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with $TG > 5°C$ and first span after July 1 (January 1 in SH) of 6 days with $TG < 5°C$	days
FD0	Frost days	Annual count when daily minimum temperature <0°C	days
SU25	Summer days	Annual count when daily max temperature >25°C	days
TR20	Tropical nights	Annual count when daily min temperature >20°C	days
WSDI	Warm spell duration indicator	Annual count when at least 6 consecutive days of max temperature >90th percentile	days
CSDI	Cold spell duration indicator	Annual count when at least 6 consecutive days of min temperature <10th percentile	days

(continued)

Table 1.1 (continued)

ID	Indicator name	Indicator definitions	Units
CSDI	Cold spell duration indicator	Annual count when at least 6 consecutive days of min temperature <10th percentile	days
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	The ratio of annual total precipitation to the number of wet days ($\geq$ 1 mm)	mm/day
R10	Number of heavy precipitation days	Annual count when precipitation $\geq$10 mm	days
R20	Number of very heavy precipitation days	Annual count when precipitation $\geq$20 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days when precipitation <1 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days when precipitation $\geq$1 mm	days
R95p	Very wet days	Annual total precipitation from days >95th percentile	mm
R99p	Extremely wet days	Annual total precipitation from days >99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total precipitation from days $\geq$1 mm	mm

good reason to expect a change in extremes to continue in the future if the underlying cause of the change is well understood and is expected to continue into the future. In the climate literature, the identification of the changes and attribution to possible causes is usually termed detection and attribution. The good practice guidance paper on detection and attribution that was developed for the use by lead authors for the Intergovernmental Panel on Climate Change assessments (Hegerl et al. 2010) provides detailed definitions and outlines standard procedures for detection and attribution.

Detection is defined as the process of demonstrating that the climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to variability generated by the climate system itself alone is determined to be small, for example, less than 10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence. Identification of a statistically significant trend in a time series of climate observations is a simple example of detection. Attribution is usually more complicated and can be conducted in several ways, though confidence in attribution will be differ from one approach to anther.

The observed climate variations, such as those that are seen by monitoring indices of extremes, generally reflect both natural variations internal to the climate system and the responses to external forcing such as changes in solar radiation and human induced changes in greenhouse gases. As the observed climate is only one realization of the climate system, it is difficult to separate internal variation from the response to external forcing using observations alone (Hegerl and Zwiers 2011). However, a climate model can be used to generate many realizations of the climate under the same forcing, enabling the estimation of both the response to external forcing, or signals, and the spatial and temporal structure of natural internal variation of the climate as represented by the climate model. As a result, a typical detection and attribution analysis involves the comparison of signals simulated by multiple climate models with the observations. A standard statistical approach to the detection and attribution problem is the optimal fingerprinting method (e.g., Allen and Stott 2003). This method is essentially a generalized regression, in which observed climate variations are regressed onto model simulated signals with the residual compared with model simulated variability.

Detection and attribution methods were first developed to consider changes in the mean of the distribution of climate variability, and because extremes are events that occur in the tails of such distribution, the detection and attribution of changes in extremes creates new challenges. Approaches that have been used either transfer the data into a form that allows the standard optimal fingerprinting method to be used, or explicitly considers the distributional properties of the extremes being analyzed. In the following, we illustrate, through examples, some detection/attribution approaches that have been employed in the context of extremes.

1.3.1 Changes in Extreme Temperatures

Zwiers et al. (2011) evaluated whether there has been an anthropogenic influence on long return period daily temperature extremes. In this study, they used observed 1961–2000 annual extreme temperatures, including annual maximum values of daily maximum (TXx) and daily minimum (TNx) temperatures, and annual minimum values of daily maximum (TXn) and daily minimum (TNn) temperatures, to characterize past changes in extreme temperatures. Recognizing that the real response to external forcing may have a different magnitude but similar spatial-temporal patterns to that simulated by climate models and that the distribution of annual maxima or minima temperatures is reasonably well approximated by the Generalized Extreme Value (GEV) distribution, they fit non-stationary GEV distributions (see Chap. 2 for details) for extreme temperatures with location parameters that vary in time according to climate model simulated responses. They found that the climate model simulated pattern of warming response to historical anthropogenic forcing in cold extremes fits observations best when its amplitude is scaled up by a factor greater than one, and that in warm extremes the fit to observations is best when the amplitude is scaled down. They quantified that globally, waiting times for extreme annual minimum daily minimum and daily maximum temperature events that were expected to recur once every 20 years in the 1960s are now estimated to exceed 35 and 30 years, respectively. In contrast, waiting times for circa 1960s 20-years extremes of annual maximum daily minimum and daily maximum temperatures are estimated to have decreased to fewer than 10 and 15 years, respectively. Figure 1.2 displays estimated return periods and their 5 and 95% uncertainty limits for circa 1960s 20-year return values of annual extreme daily temperatures in the 1990s climate for many sub-continental regions and the global land area in total.

Morak et al. (2012) analyzed global and regional long-term trends in the frequency of hot and cold temperature extremes defined as the number of days exceeding the 90th percentile or not reaching the 10th percentile of daily minimum (TN90, TN10, see Table 1.1 for definitions) and daily maximum (TX90 and TX10) temperatures. They compared the observed trends with those simulated by a climate model using the optimal fingerprinting method. The signals (or fingerprints) were obtained from an ensemble of historical forcing simulations conducted with a climate model developed at the UK Met Service Hadley Centre (HadGEM1). Both observations and the means of ensemble simulations under combined natural and anthropogenic forcings show an increase in the frequency of warm extreme and a decrease in cold extremes in both boreal warm and cold seasons, though there are regional differences. They also found that anthropogenic influence is detectable in the frequency of warm and cold temperatures.

1.3.2 Anthropogenic Influence on Annual Maximum 1- or 5-Day Precipitation

Detection and attribution of possible anthropogenic influence on extreme precipitation has proven to be a substantially bigger challenge. Observed daily precipitation is highly variable from place to place, and exhibits spatial scales of variations that are smaller than climate models can represent. This means that large numbers of densely spaced precipitation observing stations are required to be able to isolate the component of observed precipitation that is directly comparable to simulations. Unfortunately, there are few regions globally with a sufficiently dense observing network to enable this kind of comparison. Min et al. (2011) therefore tried to circumnavigate this scale issue by transforming the observed and simulated annual maximum 1- or 5-day precipitation amounts into probability based indices (PI) before applying the standard optimal detection method. To do this they used separate transformations based on the GEV distribution for observations and model output, thereby bringing both onto a dimensionless scale on the unit interval.

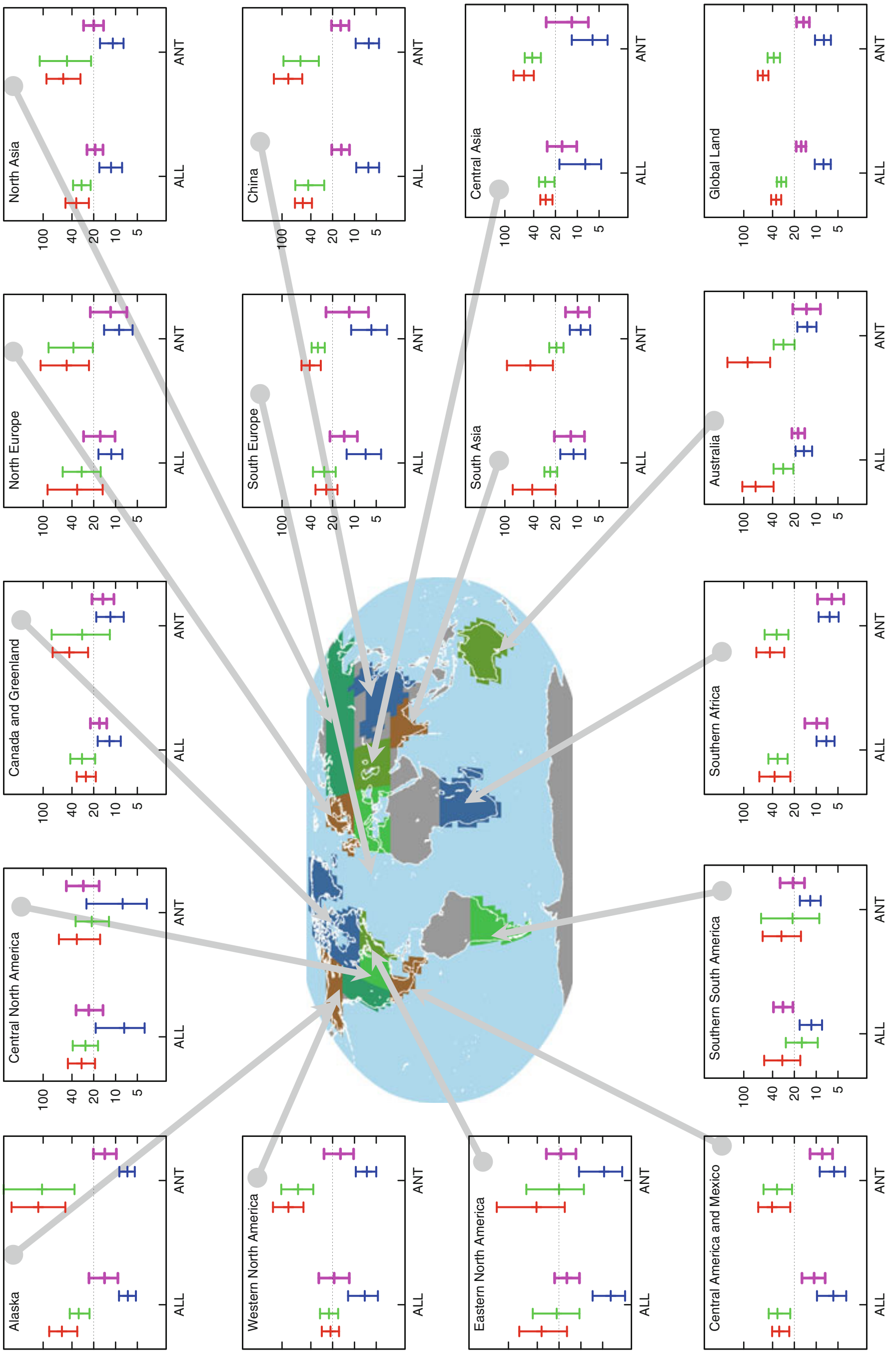

Fig. 1.2 (continued)

Figure 1.3 shows trends of extreme precipitation indices for annual maximum 1-day precipitation amounts during 1951–1999 from observations, and from model simulations under anthropogenic forcing or under combined effect of anthropogenic and natural forcings. They found evidence of human influence in observed changes in precipitation extremes during the latter half of the twentieth century .It was found that a best fit with observations required that the magnitude of the climate model simulated responses to external forcing be increased by a large factor, which limits confidence in the attribution of observed changes.

1.3.3 Event Attribution

When a rare and catastrophic meteorological extreme event occurs, a question that is often posed is whether such an event is due to anthropogenic influence. Because it is very difficult to rule out the occurrence of low probability events in an unchanged climate, and because the occurrence of such events usually involves multiple factors, it is very difficult to attribute an individual event to specific causes (Hegerl et al. 2007). However, in this case, it may nevertheless be possible to estimate the influence of external forcing on the likelihood of occurrence of such an event. Such estimates of how the likelihood of events has changed are especially useful from risk management point of view. The infamous 2003 European heat wave caused huge impacts in Europe, with an estimated 40,000 heat related deaths García-Herrera et al. 2010). To address the question whether anthropogenic contributed to the severity/occurrence of the 2004 European heat wave, Stott et al. (2004) used an event attribution method. With this method, they first detected anthropogenic influence on mean summer temperature in southern Europe; they then estimated the effect of anthropogenic forcing on the likelihood of a warm summer, and finally inferred an anthropogenic influence on the likelihood of the 2003 European heat wave. Note that the attribution result for one event may not necessarily extend to another event. Using another method, Dole et al. (2011) suggest that the 2010 Russian heatwave could have occurred without anthropogenic influence. This finding is not necessarily inconsistent with the possibility that human influence may have increased the odds of this occurrence of the event.

Fig. 1.2 Estimated return periods (years) and their 5 and 95% uncertainty limits for 1960s 20-years return values of annual extreme daily temperatures in the 1990s climate (see text for more details). *ANT* refers to model simulated responses with only anthropogenic forcing and *ALL* is both natural and anthropogenic forcing. Error bars are for annual minimum daily minimum temperature (*red*: TNn), annual minimum daily maximum temperature (*green*: TXn), annual maximum daily minimum temperature (*blue*: TNx), and annual maximum daily maximum temperature (*pink*: TXx), respectively. *Grey* areas have insufficient data

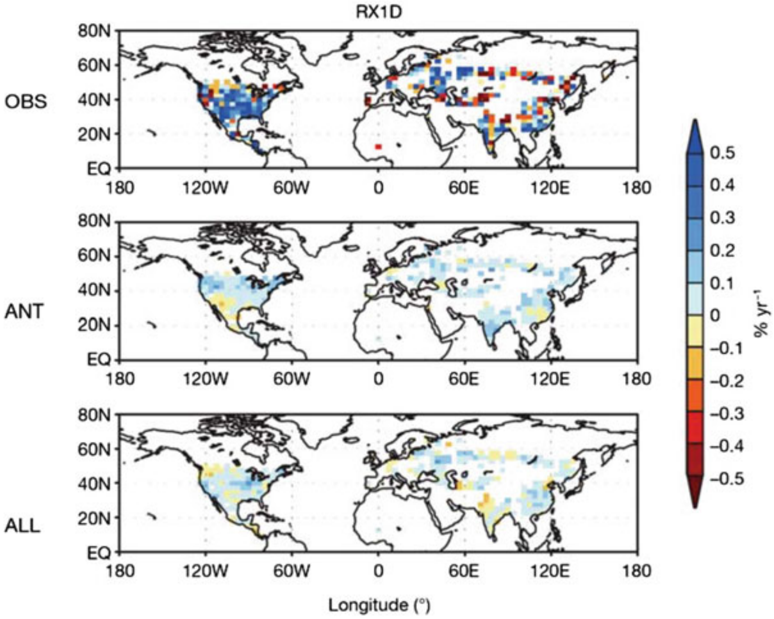

Fig. 1.3 Geographical distribution of trends of extreme precipitation indices (PI) for annual maximum daily precipitation amounts (*RX1D*) during 1951–99. Observations (*OBS*); model simulations with anthropogenic (*ANT*) forcing; model simulations with anthropogenic plus natural (*ALL*) forcing. For models, ensemble means of trends from individual simulations are displayed. Units: per cent probability per year (From Min et al. (2011; see paper for details))

1.4 Summary

In this chapter, we introduced some concepts for definition of statistical indices with which past changes in weather and climate extremes may be quantified. These indices can also be used to monitor ongoing changes in extremes, and they can be used to assess changes in future extremes as projected by climate models. We also present a few examples in which influence of anthropogenic climate changes on extremes has been identified. It should be noted that there appears to be no unique method to define what constitutes a weather or a climate extreme. While it is vastly important to understand how and why weather and climate extremes may have changed in the past and how they will behave in the future, there are significant challenges towards a full understanding.

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Chapter 2
Statistical Methods for Nonstationary Extremes

Richard W. Katz

Abstract There is a long tradition of the use of methods based on the statistical theory of extreme values in hydrology, particular for engineering design (e.g., for the proverbial "100-yr flood"). For the most part, these methods are based on the assumption of stationarity (i.e., an unchanging climate in a statistical sense). The focus of this chapter is on how the familiar distributions that arise in extreme value theory, namely the generalized extreme value (GEV) and generalized Pareto (GP) distributions, can be retained under nonstationarity. But now the extremal distribution is allowed to gradually shift by introducing time as a covariate; that is, expressing one or more of the parameters of the distribution as a function of time. At least for the parameter estimation technique of maximum likelihood, it is straightforward to fit such statistical models. Some detailed examples are provided of how the proposed methods can be applied to the detection and statistical modeling of trends in hydrologic extremes, such as for stream flow and precipitation.

2.1 Introduction

There is a long tradition of the use of methods based on the statistical theory of extreme values in hydrology, particular for engineering design (e.g., for the proverbial "100-yr flood"). For the most part, these methods are based on the assumption of stationarity (i.e., an unchanging climate in a statistical sense). In recent years, the specter of global climate change has been raised in conjunction with the enhanced greenhouse effect. Physical considerations suggest an intensification of the hydrologic cycle, with increases in the frequency and intensity of extreme high

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