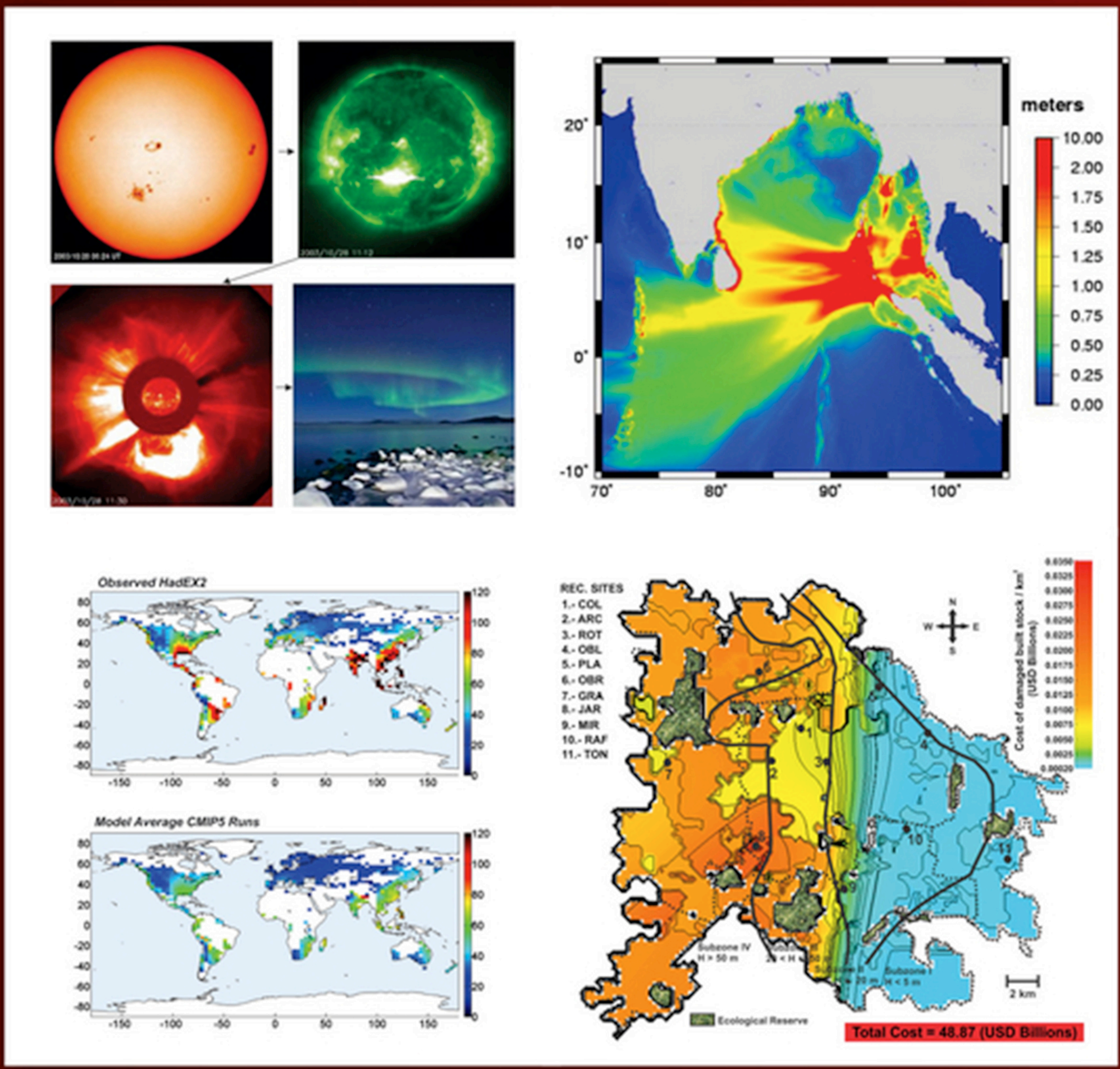
Extreme Events

Observations, Modeling, and Economics



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Geophysical Monograph 214

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Cover images: **Left top panel:** A space weather event registered in October 2003. A large active region (upper left panel) on the Sun erupted with a bright area (upper right panel), followed within minutes by a coronal mass ejection (lower left panel), see http://sohowww:nascom:nasa:gov/hotshots/. In the lower right pannel the aurora borealis due to the event (photograph by *Andy Keen*, http://www.aurorahunters.com). *Rusmaikin et al*. [2016], Drivers of Extreme Space Weather Events: Fast Coronal Mass Ejections, Chapter 7 in this Monograph. **Right top panel:** The 26th of December 2004 a Mw 9.1 to 9.3 magnitude subduction earthquake with epicenter in the Sumatra-Andaman, Indonesia, region, generated a Mega-Tsunami that caused ~ 300,000 casualties. The map shows the maximum Tsunami amplitudes derived from a numerical simulation of this event. *A.Piatanessi*, www.ingv.it/%7eroma/reti/rms/terremoti/estero/indonesia/indonesia.htm. **Left bottom panel:** Global-scale comparison of changes in historical (1901–2010) annual maximum daily precipitation between station observations (compiled in HadEX2) and the suite of global climate models contributing to the fifth phase of the Coupled Model Intercomparison Project (CMIP5). *Asadieh B. and Krakauer N. Y*. [2015], Global trends in extreme precipitation: climate models versus observations, Hydrol. Earth Syst. Sci., 19, 877–891, 2015; www.hydrol-earth-syst-sci.net/19/877/2015/ doi:10.5194/hess-19-877-2015.
Right bottom panel: Modeling of damage cost of one- to three- floor dwelling built stock in Guadalajara, México, for a Mw 8.5 magnitude subduction earthquake scenario. *Chavez et al*. [2016], Extreme Magnitude Earthquakes and their Direct Economic Impacts: A Hybrid Approach, Chapter 17 in this Monograph.

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CONTENTS

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PREFACE

In statistical terms, extreme events can be defined as events that largely deviate from the statistical mean. From the physical point of view, it is widely accepted that such events are generated by systems that are both nonlinear and complex. Due to their infrequent occurrence, on the one hand, and to the complexity of the processes involved, on the other, extreme events have been difficult to study and, even more so, to predict. For these reasons, their analysis has mainly focused on studying their frequency-size distribution, while their prediction has been limited, by-and-large, to applying extreme value theory (EVT) to estimate the expected time intervals for the occurrence of an event that exceeds a certain threshold. It has become clearer and clearer, though, that the applicability of classical EVT theory to complex and nonlinear phenomena may be limited, while novel methods for their study are becoming available.

This monograph aims to present an overview of methods recently developed for the description, understanding and prediction of extreme events across a range of phenomena in the geosciences, with an emphasis on the study of their socio-economic impacts. It is the outcome of four American Geophysical Union sessions on *Extreme Events: Observations, Modeling and Economics*, held in 2007, 2008, 2011 and 2013. The editors of this volume organized these four sessions in order to examine the broad topic of extreme events in the geosciences from an interdisciplinary perspective. The primary objectives of these sessions were to provide an open forum for the theoretical and empirical developments that could improve: (i) the understanding, modeling and prediction of extreme events in the geosciences, as well as (ii) the quantitative evaluation of their economic consequences. Most of the articles in this monograph emerged from these four AGU sessions.

The monograph covers the causes and consequences of extreme geophysical phenomena like space weather, asteroid impacts, climatic change, earthquakes, tsunamis, hurricanes, landslides, volcanoes, and flooding; it also addresses their associated socio-economic impacts, locally, regionally and globally. The understanding and modeling of these phenomena is critical to the development of timely strategies worldwide for the prediction of natural and anthropogenic extreme events, in order to mitigate their adverse consequences.

We would like to dedicate this Monograph to the memory of V. Keilis-Borok (1921–2013) and of Emilio Rosenblueth Deutsch (1926–1994) for their visionary contributions in the geosciences and in seismic risk engineering.

Vladimir I. Keilis-Borok

Keilis-Borok was a Russian mathematical geophysicist and seismologist. He was the founding Director of the International Institute of Earthquake Prediction Theory and Mathematical Geophysics of the Soviet, and then Russian, Academy of Sciences in Moscow. His major contributions to the geosciences included, at first, important studies of seismic-signal propagation and of Earth structure. The second part of his research life was dedicated to applying concepts and methods from the theory of nonlinear and complex systems to the prediction of both natural and socio-economic crises. Starting with the study of premonitory seismic patterns, he and his numerous and diverse collaborators applied related methodologies to make socio-economic predictions with notable success. The mathematics of pattern recognition was thus brought to bear to correctly predict the popular vote winner of presidential elections in the United States, as well as to predicting rises in murder rates in Los Angeles, recessions, spikes in unemployment and terrorist attacks.

Keilis-Borok served as the President of the International Union of Geodesy and Geophysics (1987–1991), Chair of the Mathematics and Natural Sciences Section, International Council of Scientific Unions (1988–1991), Founding Chairman, International Committee for Geophysical Theory and Computers (1964–1979), and an Expert for the Soviet side in the technical meetings on the Nuclear Test Ban Treaty (1960–1990). He was elected to the American Academy of Arts and Sciences (1969), Austrian Academy of Sciences (1992), U.S. National Academy Sciences (1971), Pontifical Academy of Sciences (1994), Soviet Academy of Sciences (1988), and the Academia Europaea (1999). He received the first L.F. Richardson Medal of the European Geosciences Union, a Doctorate Honoris Causa from the Institut de Physique du Globe, Paris, and the 21st Century Collaborative Activity Award for Studying Complex Systems from the McDonnell Foundation. He was also an exceptionally warm and supportive colleague and human being.

Emilio Rosenblueth Deutsch

Rosenblueth Deutsch was a Mexican civil engineer and professor of the Universidad Nacional Autonoma de Mexico (UNAM, Institute of Engineering). His published work, characterised by conceptual formulation of rational frameworks and probabilistic theories, the use of innovative mathematical models and of their application, mainly in seismic engineering, had a major influence on developments in seismic risk and design worldwide. His and coauthored books and over 300 publications, reveal his original thoughts on risk analysis, concepts of reliability, optimisation in seismic design, education, and ethics in technology.

His contributions were recognized worldwide, among others by the National Academy of Sciences of the United States, the American Academy of Arts and Sciences, the American Society of Civil Engineers (ASCE), the American Concrete Institute, and the International Association for Earthquake Engineering. He was a member of the Colegio Nacional of Mexico, and President of the current Mexican Academy of Sciences. Academic honors conferred on Rosenblueth Deutsch, to name only a few, include the Freudenthal Medal and the Newmark medal of the ASCE, the Prince of Asturias Prize from Spain, the Bernardo Hussay Interamerican Science Prize, the Huber Research Prize, the Moiseff Award, the National Science and Arts Prize of Mexico, and honorary doctorates from the University of Waterloo, the Carnegie Mellon University and the UNAM.

Incidentally, Emilio Rosenblueth Deutsch, was the co-editor (with Cinna Lomnitz) of the book *Seismic Risk and Engineering Decisions*, Elsevier (1976), for which Jim Brune wrote a chapter on *The Physics of Earthquake Ground Motions* in which he followed fundamental results on the seismic source suggested by Keilis-Borok in 1959 (Ann. Geofis. 12, 205-214), and therefore the latter indirectly also contributed to the book. Thus, the present monograph's being dedicated to their memory brings them together again …

M. Chavez, M. Ghil, J. Urrutia-Fucugauchi

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1
Introduction

Mario Chavez,[1] Michael Ghil,[2,3] and Jaime Urrutia-Fucugauchi[4]

The recent occurrence of events like the European 2003 heat wave, the Sumatra 2004 earthquake, the 2005 Hurricane Katrina, the Tohoku 2011 earthquake, the 2012 Hurricane Sandy, and the Nepal 2015 earthquake represented not only climatic or geophysical extremes, but they have had or will have large and long-lasting consequences in large segments of the world population. In each case, these events impacted systemic, structural, and socioeconomic weaknesses in the societies found in their path. The common characteristic of these events is that they reached larger intensities, durations or both, when compared with previous observations of the same phenomena; they also had or still have an impact on health, infrastructures, ecosystems, or the economy of the world region where they occurred. It is relevant, moreover, to mention that high-impact geophysical events may be qualified as being extreme by a society, although a similar event occurring in a different region or under different conditions would not have the same impact and thus would not be qualified as an extreme event by the same or a different society.

Taking into account the characteristics of geophysical extreme events, this book focuses on the aspects that are related to their observation and their modeling, as well as to estimating their socioeconomic impacts. The book brings together different communities of researchers and practitioners in the fields of the climate sciences and geophysics, mathematics and statistics, economy, and sociology; it gathers, in a unified setting, 21 representative related to extreme events research, many of which include applications to their impact on society or the environment.

Most of the 21 chapters included deal with novel methodologies and their applications for the study of extreme events and their impacts. The chapters are grouped into six themes. Part I is composed of five chapters on fundamentals and theory, one covering the statistical analysis of environmental and temperature data, two on dynamical system approaches to the analysis of extreme events, another one on climate tipping points, and the fifth one on a delay differential equation study of the El Niño–Southern Oscillation (ENSO). Part II has two chapters related to extreme events in Earth's space environment: one chapter analyzes extreme events in space weather, and the other the Chicxulub asteroid impact associated with the mass extinction at the K/T boundary.

Part III deals with climate and weather extremes, and it contains four chapters: one on extreme flooding in the midwest of the United States, the second one on the impacts of the 2005 Hurricane Wilma, the third on observations and modeling of damages caused by the 2004 Indian Ocean tsunami, and the fourth chapter on rogue wave events in a laboratory setting of capillary waves. Part IV is dedicated to extreme events in the solid

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earth and it includes three chapters, the first on a multi-proxy approach for great magnitude earthquakes and tsunamis, the second on landslide risks in Italy, and the third one on an extreme event approach to volcanic eruptions.

Part V addresses, in four chapters, the socioeconomic impacts of extreme events: the first of these uses classical extreme value theory to study the economic impact of extreme events and in particular of hurricanes, the second chapter relies on a hybrid approach to assess the direct economic impacts of extreme-magnitude earthquakes, the third chapter is on tropical cyclones and their socioeconomic impacts, and the fourth one is on natural disasters and their impacts on a dynamic, nonequilibrium economy. Finally, in Part VI, three chapters deal with the very difficult and controversial issue of predicting extreme events and with the closely related one of preparedness: the first chapter treats extreme tsunami events in the Mediterranean region and their impact on the Algerian coasts, the second analyzes the complexity surrounding high-technology extreme events, in particular, the 2011 failure of the Fukushima nuclear power plant, while the third paper reviews a group effort on the predictive understanding of extreme events and its applications to disaster preparedness. We summarize here the main contributions of each of these chapters.

1.1. PART I: FUNDAMENTALS AND THEORY

In Chapter 2, G. Toulemonde and colleagues argue that the classical statistical assumption in analyzing extreme events, namely that of independence in space, time, or both, may not be valid in the geosciences in most cases. Furthermore, the statistical modeling of such dependences is complex and different modeling roads should be explored. First, the authors present some basic concepts of univariate and multivariate extreme value theory (EVT), followed by a series of examples on how this theory can help the practitioner to make inferences about extreme quantiles in a multivariate context.

In Chapter 3, C. Nicolis and G. Nicolis propose a deterministic dynamical systems approach to identify the principal signatures of the statistical properties of extremes. Then, the authors derive analytical expressions for n-fold cumulative distributions and their associated densities, for the exceedance probabilities and for the spatial propagation of extremes. Numerical simulations that exhibit substantial differences from classical EVT theory complement these analytical results. These differences are illustrated for dynamical systems giving rise to quasi-periodic behavior, intermittent chaos, and fully developed chaos, respectively.

In Chapter 4, S. Siegert and associates discuss the application of a physical weather model and a simple data-based model to probabilistic predictions of extreme temperature anomalies; the comparison between the two uses the concept of skill scores. The authors found that, although the result confirms the expectation that the computationally much more expensive weather model outperforms the simple data-based model, the performance of the latter is surprisingly good. Furthermore, they assert that over a certain parameter range, the simple data-based model is even better than the uncalibrated weather model. They propose the use of receiver operating characteristic (ROC) statistics to measure the performance of the predictors, and find that using this type of scoring, the conclusions about model performance partly change, which illustrates that predictive power depends on its exact definition.

In Chapter 5, T. Lenton and V. Livina apply concepts from dynamical systems theory to study extreme events in the climate system. In particular, they focus on “tipping points” or discontinuities, previously known as bifurcations in a system’s large-scale behavior, and on the prospects for providing early warning for their imminent occurrence. The authors describe general methods for detecting and anticipating tipping points, for systems with a high level of internal variability that sample multiple states in time, as well as for systems with less variability that reside in a single state. They apply those methods to the ice-core record of abrupt climate changes in Greenland during the last ice age. Finally, they discuss the limitations of the general methods, and suggest combining them with system-specific vulnerability indicators and process-based models, to help assess the future vulnerability of different tipping elements in the climate system.

In Chapter 6, M. Ghil and I. Zaliapin study a delay differential equation (DDE) for ENSO in the relatively novel setting of non-autonomous dynamical systems and of their pullback attractors. This setting provides deeper insights into the variability of the sea surface temperature T in the Tropical Pacific. Their model includes three essential ENSO mechanisms: the seasonal forcing, the negative feedback due to the oceanic waves, and the delay caused by their propagation across the Tropical Pacific. Two regimes of model variability, stable and unstable, are analyzed. In the unstable regime and in the presence of a given, purely periodic, seasonal forcing, spontaneous transitions occur in the mean T, in the period, and in the extreme annual values. They conclude, among other findings, that the model’s behavior exhibits phase locking to the seasonal cycle, namely the local maxima and minima of T tend to occur at the same time of year, which is a characteristic feature of the observed El Niño (warm) and La Niña (cold) events.

1.2. PART II: EXTREME EVENTS IN EARTH'S SPACE ENVIRONMENT

In Chapter 7, A. Ruzmaikin and co-authors apply the Max Spectrum statistical method, which is based on the scaling properties of speed maxima, to study the Sun's fast coronal mass ejections (CMEs). This kind of extreme space weather event is a disturbance in the space environment that presents hazards to the operation of spacecraft systems, instruments, or lives of astronauts. Empirical studies have shown that the speed distribution of CMEs is non-Gaussian. By applying the Max Spectrum technique to CMEs observations, the authors identified the range of speeds, of about 700–2000 km/s, that separates extreme CMEs from typical events. From their investigation of the temporal behavior of fast CMEs, it was concluded that they were not independent, but arrived in clusters and thus can be described by a compound Poisson process.

In Chapter 8, J. Urrutia-Fucugauchi and L. Pérez-Cruz analyzed the highly exceptional Chicxulub asteroid impact event at the Cretaceous/Paleogene boundary, and its effects on the Earth's climate, environment and life-support systems. This boundary marks one of the major extinction events in the Phanerozoic, which affected about 75% of species on Earth. First, the authors examined the impact event and the cratering in Mexico's Yucatán Peninsula and the waters off it, the timescales involved and the energy released. Then, they assessed the impact's regional and global effects, which involved major perturbations in the ocean and atmosphere. Finally, the authors discussed how and to what extent life-support systems are affected by extremely large impact events, and what the fossil record reveals about the extinction event and biotic turnover. In particular, they examined how sudden and extended the processes involved are, as well as the temporal records of extinction and recovery.

1.3. PART III: CLIMATE AND WEATHER EXTREMES

In Chapter 9, A. W. Robertson and colleagues studied Midwestern floods and, in particular, the April 2011 flooding event in the Ohio River Basin. The authors used a K-means clustering algorithm for daily circulation types during the March–May spring season to infer relationships between flooding events and circulation types, as well as relationships between these types and climate drivers; the drivers in this study included the interannual ENSO and the intraseasonal Madden-Julian oscillation (MJO). Their results suggest that anomalous southerly fluxes of moisture from the Gulf of Mexico are associated with weather types that occur in connection with the floods, while two of these circulation types are preferentially associated with La Niña. Statistically significant lagged relationships between the frequency of occurrence of these regimes and the MJO were also identified, and they are associated with convection propagating from the Indian Ocean to the Maritime Continent. Implications for prediction across timescales are also discussed.

In Chapter 10, E. Mendoza and associates analyze and model the observations of the record-breaking category 5 Hurricane Wilma of October 2005. This extreme meteorological event generated direct looses of about 2 billion USD in Cancún, Mexico. The authors assessed the hazards and vulnerability to tropical cyclones of this overdeveloped beach-lagoon system. Among other results, the authors showed that before tourist development started in the 1970s, the beach-lagoon system in Cancún functioned as a metastable beach, with erosion-accretion cycles and evidence of natural breaching in places. But the rapid, disorganized tourist development that has taken place, mainly in the last five decades, has degraded this system, increasing its vulnerability to extreme weather events and dramatically reducing its resilience. Hence the effects of Hurricane Wilma on Cancún beach cannot be ascribed only to climatic variability: they bear witness also to the anthropogenic activity that had already degraded the system over recent decades.

In Chapter 11, K. Goto and colleagues relied on field observations, satellite image analyses, and high-resolution numerical modeling to investigate details of local inundation due to the 2004 Indian Ocean tsunami; these multiple data sets also allowed them to make quantitative estimates of the damage generated by the tsunami that was generated by the Sumatra-Andaman earthquake. In particular, the authors investigated the damage to coastal morphology, marine ecosystems, and mangroves at Pakarang Cape, Thailand, and to structures, humans, and mangroves at Banda Aceh city, Indonesia. Their high-resolution numerical modeling of the tsunami hydrodynamics (i.e., inundation depth, hydraulic force, and current velocity) allowed them to generate fragility functions, which explained the observations of the local tsunami inundation and the damage generation, including the damage incurred to the coral communities. The authors suggest that their quantitative damage estimates represent an important step forward for tsunami risk assessment in high-risk, tsunami-prone countries worldwide.

In Chapter 12, M. G. Shats and co-authors argue that extreme wave events on small-scale water surfaces can be used as laboratory analogues of rogue or freak waves in the ocean. The latter ocean waves have heights and steepness much greater than expected from the sea state level and are responsible for a large number of maritime disasters. The authors also emphasize that the generation of rogue waves in the ocean is associated with a distinct tail in the probability density function (PDF) of wave heights. As observations of such rogue waves are rather scarce, the authors performed laboratory studies that consisted of periodically shaking the fluid container in the vertical direction. This shaking produces extreme wave events when capillary-gravity waves are excited at the frequency of the first subharmonic of the driving frequency. The latter laboratory waves appear to be unstable to amplitude modulation, and this instability leads to the decomposition of wave packets into ensembles of interacting oscillatory solitons called "oscillons." The wavefield dynamics is determined by the oscillon interactions, which include their merger, annihilation, and collision. Strikingly, collisions of same-phase oscillons lead to generation of extreme events that can be called "capillary rogue waves."

1.4. PART IV: EXTREME EVENTS IN THE SOLID EARTH

In Chapter 13, M.-T. Ramírez-Herrera and colleagues propose a multiproxy approach, which includes geological, microfossil, magnetic-property, geochemical, historical, ethnographic, instrumental data, and theoretical modeling analyses, to expand our knowledge about extreme-magnitude seismic events beyond the short instrumental record, and therewith to reduce the tsunami hazard to coastal communities. The authors focused their study on the coast of the Guerrero region, located in the Mexican subduction zone, where the occurrence of historical earthquakes and of the associated tsunamis is relatively well documented since the 16th century. Their main result shows that the Guerrero coast region has been exposed to large-magnitude destructive earthquakes and tsunamis, in addition to the AD 1979 and AD 1985 events, at least to a third one, in 3400 BP and that the latter reached 5 km inland. The authors highlight the need to carry out these types of studies in the Mexican subduction zone, to assess the hazard in this region to create resilient coastal communities.

In Chapter 14, P. Salvati and associates propose a new approach, based on the modeling of empirical distributions of landslide events with a Zipf distribution, to investigate landslide risk to the population of Italy over time. The authors present an updated version of an Italian historical catalog of landslide events with human consequences that cover the period 91 BC to AD 2011. Still, to overcome problems due to gaps in the updated catalog, they rely mainly on the information available for the 1861–2010 period. They studied the temporal and geographical variation of landslide risk in five subzones of the north, the center, and the south of Italy for three subintervals: 1861–1909, 1910–1959, and 1960–2010. The authors conclude that their new societal landslide risk level estimates are an important step for increasing awareness of the problems posed by this type of extreme events among Italian administrators and citizens.

In Chapter 15, S. De la Cruz-Reyna and A. T. Mendoza-Rosas apply a three-step procedure to assess the volcanic hazard posed by potential extreme eruptive sequences of individual volcanoes or groups of volcanoes. The first step consists of expanding the, usually incomplete, historical eruptive series of a volcano by eruptive synthetic series constructed from any available geological-time eruption data. This step assumes a scaling, self-similar relationship between the eruption size and the occurrence rate of the latter. In the second step, a Weibull-model analysis of the distribution of quiescent times between successive eruptions is carried out to estimate their time dependence, if any. Finally, the eruption series are analyzed using EVT theory for a nonhomogeneous Poisson process with a generalized Pareto distribution as intensity function. From the results of this analysis, the probabilities of future eruptions can be estimated. Examples of the application of the proposed procedure to the Colima, El Chichon, and the Popocatepetl volcanoes of Mexico conclude the chapter.

1.5. PART V: SOCIOECONOMIC IMPACTS OF EXTREME EVENTS

In Chapter 16, R. Katz states that considerable effort has been dedicated to the statistics of extreme geophysical phenomena, while not much is known about the corresponding distribution of economic damage, due largely to the scarcity of data. He applies EVT to help explain the differences between upper-tail behavior of the economic-damage distribution and that of the underlying geophysical phenomenon. Based on physical considerations, the author proposes a damage function in the form of a power law, and concludes that a "penultimate" (or second-order) approximation of EVT is required to replace the standard asymptotic (or "ultimate") theory. This formulation implies, at least under a wide range of plausible conditions, that the distribution of economic damage can be heavy-tailed, even when the upper tail of storm intensity distribution, say, is bounded. These theoretical considerations are applied to the economic-damage distribution due to hurricanes and its relationship to storm intensity, as measured by maximum wind speed at landfall.

In Chapter 17, M. Chavez and co-authors formulate a hybrid approach to estimate the probability of exceedances of the intensities (PEIs) of extreme-magnitude earthquakes (EMEs) and the probability of exceedance of direct economic consequences (PEDECs) that arise from the damages to spatially distributed infrastructure within a site. The PEIs are obtained from samples of 3D-synthetic seismograms associated with EME scenarios by applying a machine learning technique. The PEDECs are computed by combining appropriate cadastral, direct economic costs and seismic vulnerability functions of the infrastructure and the spatial distribution of the intensities of the EME scenario. Truncated PDFs for the marginal distributions and copula models are applied to obtain the independent and joint probability distributions of the PEI and the PEDEC; these distributions, in turn, can be used to derive the associated return period for decision-making purposes. This hybrid approach is applied to obtain preliminary upper bounds on the probable maximum losses (PMLs)of the direct costs associated with the damage to the typical, one to three floor dwellings of Mexico City and Guadalajara, based on scenarios of an extreme, M_w 8.5 magnitude subduction earthquake. The preliminary PMLs obtained vary from 0.7 to 18 billion USD for Mexico City, and from 37 to 61 billion USD for Guadalajara. If ex-ante mitigation actions are taken to retrofit dwelling constructions and thus reduce their vulnerabilities, roughly 52,000 and 250,000 dwellings could be spared in Mexico City and Guadalajara, respectively, by investing ~0.8 and 6 billion USD, versus potential PMLs of 7 and 22 billion USD, in each city, respectively.

In Chapter 18, S. J. Camargo and S. M. Hsiang summarize the current knowledge on the link between tropical cyclones (TCs) and climate at various timescales, from subseasonal to anthropogenic warming, and on the quantitative modeling of the TCs' socioeconomic impact. They argue that the improvements in computational capabilities have enabled the representation of TCs in models of the global atmosphere and ocean to become much more realistic, especially by increasing the models' horizontal resolution; still, deficiencies remain in modeling storm intensity. With respect to the socioeconomic issues, the authors mention that the advancements in geospatial analysis have enabled researchers to link meteorological observations with socioeconomic data, and thus measure the effect that TC exposure has on numerous human outcomes. The authors conclude that the TCs' socioeconomic impact is larger than previously thought. Hence, the rational management of current and future TC risk must leverage policies and institutions, such as insurance coverage and infrastructure investments. The efficiency and value of the latter can only be determined through continued, systematic evaluation of the TCs' social cost.

In Chapter 19, A. Groth and colleagues combine the study of a dynamic, nonequilibrium model (NEDyM) of business cycles with that of time series of macroeconomic indicators to address the interactions between natural and socioeconomic phenomena. NEDyM simulates fairly realistic, endogenous business cycle, with an average periodicity of 5–6 years marked by slow expansions and rapid recessions. This model predicts that the macroeconomic response to natural disasters, under nonequilibrium conditions, is more severe during expansions than during recessions. This prediction contradicts the assessment of climate change damages or natural disaster losses that are based purely on long-term growth models, in which there is no asymmetry between expansions and contractions of the economy. To verify this NEDyM prediction, the authors analyze cyclic behavior in the U.S. economy, using nine aggregate indicators for the 1954–2005 interval. The analysis relies on multivariate singular spectrum analysis and finds that the behavior of the U.S. economy changes significantly between intervals of growth and recession, with higher volatility during expansions, as expected from the NEDyM model predictions.

1.6. PART VI: PREDICTION AND PREPAREDNESS

In Chapter 20, L. Amir and collaborators applied tsunami modeling to assess the hazard due to extreme-magnitude earthquakes and submarine slides causing tsunami events along the Mediterranean coasts of Algeria. Among other results, they found that tsunami water heights triggered by extreme, magnitude-7.5 earthquake scenarios with epicenters near the Oran and Algiers coasts are up to 2 m in height, while for submarine-slide sources the water heights can reach above 5 m along the western part of the Algerian coast. The authors discuss the challenges that Algeria would face due to the economic impact of such extreme tsunami and earthquake events on their coastal infrastructure. Finally, the chapter highlights the importance of the urgent and full implementation of the North-East Atlantic and Mediterranean Seas Tsunami Warning System (NEAMTWS) for the prevention and awareness of tsunami hazard and risk in the Mediterranean earthquake-prone region.

In Chapter 21, H. Castaños and C. Lomnitz analyze the aftermath of the extreme, M_w 9 magnitude Tohoku earthquake and its associated mega-tsunami, which led to the Fukushima nuclear catastrophe. Based on a detailed analysis of the available information on the old (~40 years) and current protocols applied worldwide for the design and operation of nuclear power plants, especially on those used for the Fukushima and Oyster Creek nuclear power plants, the authors argue that the Fukushima nuclear power plant was designed under a strategy known as "defense in depth," a military strategy consisting of delaying the progress of an enemy force by trading casualties for space. This strategy, when it is applied to the design of nuclear power plants, consists on adding subsystems construed as layers of redundant technology around the reactor core. This approach implies that nuclear safety is conditioned by a risky constellation of subordinated technologies, which combined with the occurrence of extreme geophysical events, such as the Tohoku megatsunami, results in a complex system whose behavior cannot be fully predicted. It is concluded that high-tech extreme events, such as the Fukushima, will continue to occur, mainly because of previously unforeseen weaknesses in their redundant subsystems.

In Chapter 22, V. Keilis-Borok and colleagues describe a uniform approach for predicting extreme events, also known as critical phenomena, disasters, or crises in a variety of fields. The basic assumption of the approach is that a pervasive class of hierarchical dissipative complex systems generates such events. This kind of system has the property that, after coarse-graining, it exhibits regular behavior patterns that include premonitory patterns signaling the approach of an extreme event. The authors also propose a methodology, based on optimal control theory, for assisting disaster management, in choosing an optimal set of disaster preparedness measures undertaken in response to a prediction. The chapter includes examples of the application of the uniform approach of premonitory patterns to the prediction of the occurrence of earthquakes, U.S. presidential elections, surges in unemployment, U.S. economic recessions, homicide surges, as well as examples related to disaster preparedness.

1.7. SUMMARY AND CONCLUSIONS

The 21 chapters discussed so far use a variety of mathematical, numerical, and statistical techniques to expand our understanding of extreme geophysical and climatic events, as well as the risks they impose on society. The physical and economic comprehension of these risks, as well as the current techniques to cope with them, has improved recently to a considerable extent. It appears that understanding, and hence predicting, extreme events might be possible in some cases. However, as shown in this book, the tools to estimate their probability distributions are already available in a number of areas of the geosciences. These recent advancements create a lot of opportunities and challenges for the researcher in and practioner of extremology, the science of extreme events, and their consequences.

Part I
Fundamentals and Theory

2

Applications of Extreme Value Theory to Environmental Data Analysis

Gwladys Toulemonde,[1] Pierre Ribereau,[1] and Philippe Naveau[2]

ABSTRACT

When analyzing extreme events, assuming independence in space and/or time may not correspond to a valid hypothesis in geosciences. The statistical modeling of such dependences is complex and different modeling roads can be explored. In this chapter, some basic concepts about univariate and multivariate extreme value theory will be first recalled. Then a series of examples will be treated to exemplify how this probability theory can help the practitioner to make inferences about extreme quantiles within a multivariate context.

2.1. INTRODUCTION: UNIVARIATE EXTREME VALUE THEORY

Extreme events are, almost by definition, rare and unexpected. Consequently, it is very difficult to deal with them. Examples include the study of record droughts, annual maxima of temperature, wind, and precipitation. Climate sciences is one of the main fields of applications of extreme value theory (EVT), but we can also mention hydrology [*Katz et al.*, 2002], finance, and assurance [*Embrechts et al*., 1997], among others. Even if the probability of extreme events occurrence decreases rapidly, the damage caused increases rapidly and so does the cost of protection against them. The policymakers' summary of the 2007 Intergovernmental Panel on Climate Change clearly states that it *is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent* and that *precipitation is highly variable spatially and temporally.*

From a probabilistic point of view, let us consider a sample of n independent and identically distributed (i.i.d.) random variables (r.v.) $X_1, X_2, \ldots, X_n$ from a distribution function F. In the same way that we have the central limit theorem (CLT) concerning the mean value of this sample, asymptotic results are available from EVT about the limit distribution of the rescaled sample's maximum value $X_{n,n} = \max_{i=1,\ldots,n} X_i$ as the sample size n increases. Indeed, according to the classical EVT [*Embrechts et al*., 1997; *Coles*, 2001; *Beirlant et al*., 2004; *de Haan and Ferreira*, 2006], the correctly rescaled sample's maximum is, under suitable conditions, asymptotically distributed according to one of the three extreme value distributions named Gumbel, Fréchet, or Weibull.

More precisely if there exists sequences of constants $\{a_n\}$ and $\{b_n > 0\}$ and a nondegenerate distribution function G such that

$$\lim_{n \to +\infty} \mathbb{P}\left(\frac{X_{n,n} - a_n}{b_n} \le x \right) = G(x)$$

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then G belongs to one of the following families (with $\alpha > 0$):

1. Gumbel:

$$G(x) = \Lambda(x) = e^{-e^{-(x-a/b)}} \quad \text{with} x \in \mathbb{R}$$

2. Fréchet:

$$G(x) = \Phi_\alpha(x) = \begin{cases} 0 & \text{if } x \le a \\ e^{-((x-a/b))^{-\alpha}} & \text{if } x > a \end{cases}$$

3. Weibull:

$$G(x) = \Psi_\alpha(x) = \begin{cases} e^{-(-(x-a/b))^{\alpha}} & \text{if } x \le a \\ 1 & \text{if } x > a \end{cases}$$

A specificity of these three distributions is their max-stability property. Furthermore, they are the only max-stable distributions. A distribution G is max-stable if G is invariant, up to affine transformations, that is, up to location and scale parameters. In other words, we say that G is max-stable if there exists sequences $\{d_n\}$ and $\{c_n > 0\}$ such that, for all $n \ge 2$, the sample's maximum $X_{n,n}$ is equal in distribution to $c_n X + d_n$ with X following the same distribution G, what can be written as follows:

$$G^n(x) = G\left(\frac{x - d_n}{c_n}\right).$$

From a statistical point of view, the interest of this fundamental theorem is limited. Indeed each situation corresponds to different tail behavior of the underlying distribution F. The Fréchet distribution corresponds to the limit of maxima coming from heavy-tailed distributions like the Pareto distribution. The Weibull distribution is associated with distributions with a finite endpoint like the uniform distribution. The particular case of the Gumbel distribution has a special importance in EVT because it occurs as the limit of maxima from light-tailed distributions, for example, from the Gaussian distribution. Moreover, empirically, the Gumbel distribution fits particularly well in a wide range of applications especially in atmospheric sciences.

In practice we have to adopt one of the three families but we don't have any information about F. That's why a unified approach would be very appreciated in order to characterize the limit distribution of maxima.

The previous theorem could be reformulated in a unified way by using the generalized extreme value (GEV) distribution. If there exists sequences of constants $\{a_n\}$ and $\{b_n > 0\}$ and a nondegenerate distribution function G such that

$$\lim_{n\to+\infty} \mathbb{P}\left(\frac{X_{n,n} - a_n}{b_n} \le x\right) = G_{\mu,\sigma,\gamma}(x)$$

then $G_{\mu,\sigma,\gamma}$ belongs to the GEV family

$$G_{\mu,\sigma,\gamma}(x) = \exp\left(-\left[1 + \gamma\frac{x-\mu}{\sigma}\right]^{-1/\gamma}\right)$$

with $x \in \left\{z : 1 + \gamma\frac{x-\mu}{\sigma} > 0\right\}$.

It is easy to remark that $G_{\mu,\sigma,\gamma}$ merges all univariate max-stable distributions previously introduced. It depends on an essential parameter γ characterizing the shape of the F-distribution tail. Since a strictly positive γ corresponds to the Fréchet family, this case corresponds to heavy-tailed distributions. Otherwise a strictly negative γ is associated with the Weibull family. For γ tends to 0, the function $G_{\mu,\sigma,\gamma}$ tends to the Gumbel one.

Practically, in order to assess and predict extreme events, one often works with the so-called block maxima, that is, with the maximum value of the data within a certain time interval including k observations. The maximum can be assumed to be GEV distributed in the case where k is large enough. If we obtain a sufficient number of maxima and if these maxima can be considered as an i.i.d. sample, estimation values for the GEV unknown parameters can be obtained with maximum likelihood procedure or probability weighted moments (PWM) for instance. The asymptotic behaviors of these estimators have been established [*Hosking et al.*, 1985; *Smith*, 1985; *Diebolt et al.*, 2008].

In the first considered example, we dispose of temperature daily maxima during 30 years in Colmar, a city in the east of France. We consider monthly maxima for the summer months: June, July, and August (see Figure 2.1). This way we avoid a seasonality in the data.

The choice of the block size denoted in the sequel by r, such as a year or a month, can be justified in many cases by geophysical considerations but this choice has actual consequences on estimation tools. In an environmental context, if we can often consider annual maxima as an i.i.d. sample, this hypothesis is stronger when we deal with monthly or weekly maxima for instance. Indeed in these latter cases we have typically a seasonality in the data so we are in a nonstationary context.

Coming back to our application, when the GEV distribution ($G_{\mu,\sigma,\gamma}$) is fitted by maximum likelihood directly on the sample of $k = 90$ monthly maxima on summer (3×30 years), we obtain $\hat{\mu} = 31.502$, $\hat{\sigma} = 2.456$, and $\hat{\gamma} = -0.256$. The corresponding 95%-confidence intervals are [30.943; 32.060], [2.058; 2.853], and $[-0.383; -0.128]$. The quantile plot in Figure 2.2 is close to the unit diagonal indicating a good fit of data (*Empirical*) by a GEV distribution

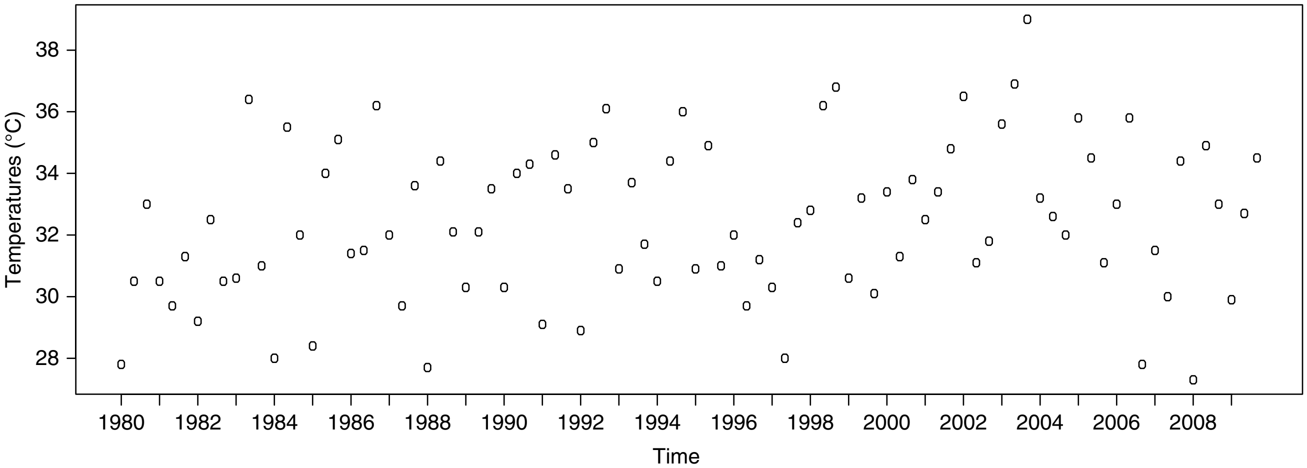

Figure 2.1 The y-axis corresponds to temperature maxima (in °C) for the months of June, July, and August from 1980 to 2009 (x-axis) recorded at Colmar (France).

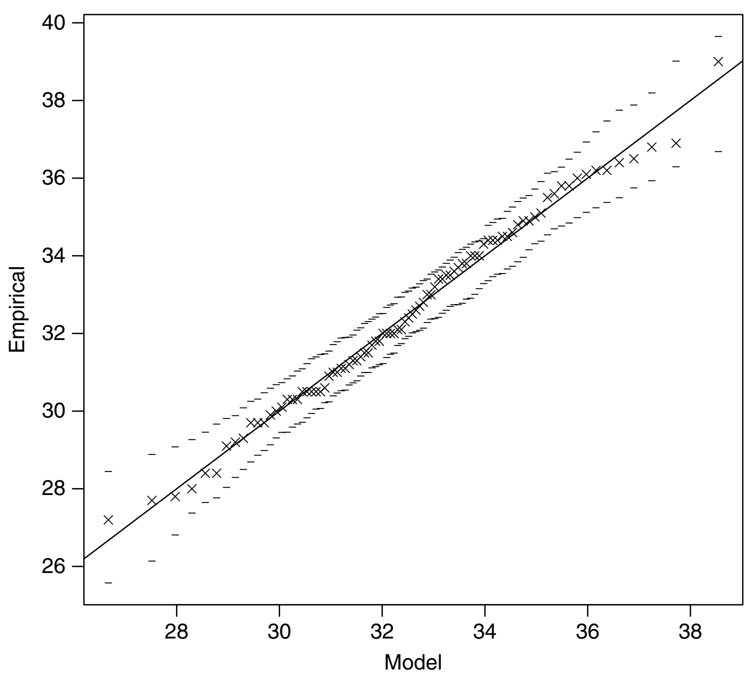

Figure 2.2 Quantile Plot for the GEV distribution—Colmar data.

(*Model*). The results on the GEV fitting must be taken with care. Indeed, taking the maxima only on 30 measures may lead to unexpected results [see *de Haan and Ferreira*, 2006]. Here, the limiting distribution of the maxima may be the Gumbel one even if the estimation of γ is negative (e.g., if the original variables are Gaussian distributed, the effective gamma is approximately $-1/(2\log k)$, where k is the block size).

A question of interest in this kind of application concerns the estimation of extreme quantiles of the maxima distribution on a period (a block). In other words, we are looking for $z_{1/p}$ such that $\mathbb{P}(X_{r,r} \leq z_{1/p}) = 1 - p$.

Since we have $\mathbb{P}(X_{k,k} \leq z_{1/p}) \approx G_{\mu,\sigma,\gamma}(z_{1/p})$, we obtain

$$\begin{aligned} z_{1/p} &\approx \mu - \frac{\sigma}{\gamma}\left[1 - \left(-\log(1-p)\right)^{-\gamma}\right] && \text{if } \gamma \neq 0 \\ &\approx \mu - \sigma \log\left(-\log(1-p)\right) && \text{if } \gamma = 0. \end{aligned}$$

The quantity z_T is called "return level" associated with a return period $T = (1/p)$. The level z_T is expected to be exceeded on average once every $T = (1/p)$ blocks (e.g., months).

We use the following estimator $\hat{z}_T$:

$$\begin{aligned} \hat{z}_T &= \hat{\mu} - \frac{\hat{\sigma}}{\hat{\gamma}}\left[1-\left(-\log(1-p)\right)^{-\hat{\gamma}}\right] & \text{if } \gamma \neq 0 \\ &= \hat{\mu} - \hat{\sigma}\log\left(-\log(1-p)\right) & \text{if } \gamma = 0. \end{aligned}$$

Starting from the asymptotic behavior of the GEV parameters' vector estimator, it is possible to deduce, thanks to the δ-method [*Van der Vaart*, 1998], the asymptotic behavior of $\hat{z}_T$ leading us to associated confidence intervals.

Coming back to our example, we would like to compute the return level associated with the return period $T = 3 \times 50$ months corresponding to 50 years as we consider only 3 months a year. We easily obtain a return level $\hat{z}_{150} = 38.43$ and a 95%-confidence interval [37.107; 39.758]. This means that considering only summer periods, the temperature 38.43°C is expected to be exceeded on average once every 50 years. So thanks to EVT we are able to estimate a return level corresponding to 50 years, whereas we only consider data since 30 years.

We have supposed that maxima constitute an i.i.d. sample, which is reasonable with regard to Figure 2.1. A likelihood ratio test indicates no trend in our data. To support this aim we fit a GEV distribution with a linear trend in the localization parameter ($G_{\mu(t),\sigma,\gamma}$). We obtain with the likelihood procedure $\hat{\mu}(t) = 30.635 + 0.059t$, $\hat{\sigma} = 2.439$, and $\hat{\gamma} = -0.281$. The corresponding likelihood ratio test statistic is $D = 2 \times (209.82 - 207.91) = 3.82$. This value is small when compared to the χ_1^2 distribution, suggesting that the simple model (without trend) is adequate for these data. Other estimation procedures have been developed in the nonstationary context. For example, *Maraun et al.* [2010] have proposed various models to describe the influence of covariates (possible nonlinearities in the covariates and seasonality) on UK daily precipitation extremes. In the same way, *Ribereau et al.* [2008] extend the PWM method in order to take into account temporal covariates and provide accurate GEV-based return levels. This technique is particularly adapted for small sample sizes and permits, for example, to consider seasonality in data.

If block sizes are sufficiently large and even if the stationary hypothesis is not always satisfied, the independence one remains very often valid. On the contrary, even if the series could be considered as stationary, the independence hypothesis is not always satisfied if we consider too small block size, like daily maxima.

As an example, Figure 2.3 represents a series of daily maxima of CO_2 (in part per million), a greenhouse gas recorded from 1981 to 2002 in Gif sur Yvette, a city of

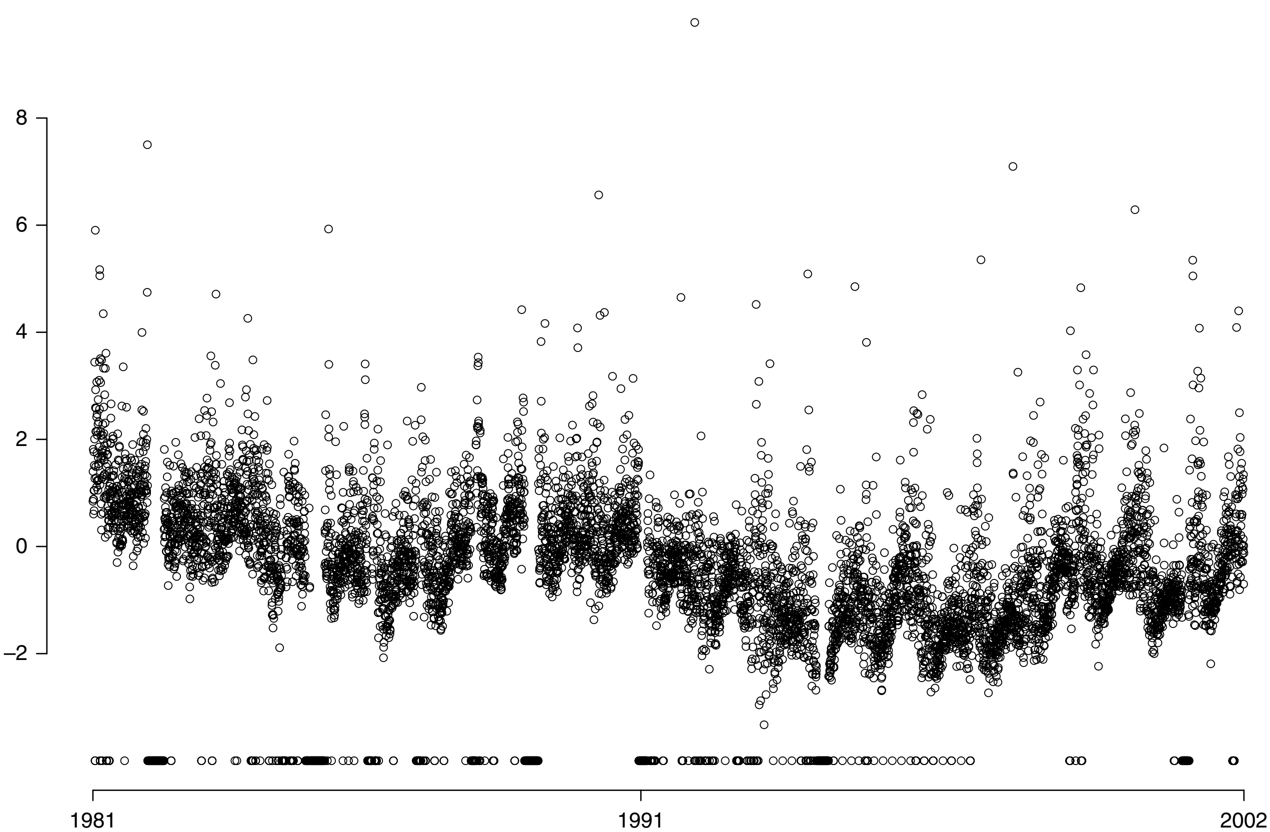

Figure 2.3 Series of daily maxima of carbon dioxide.

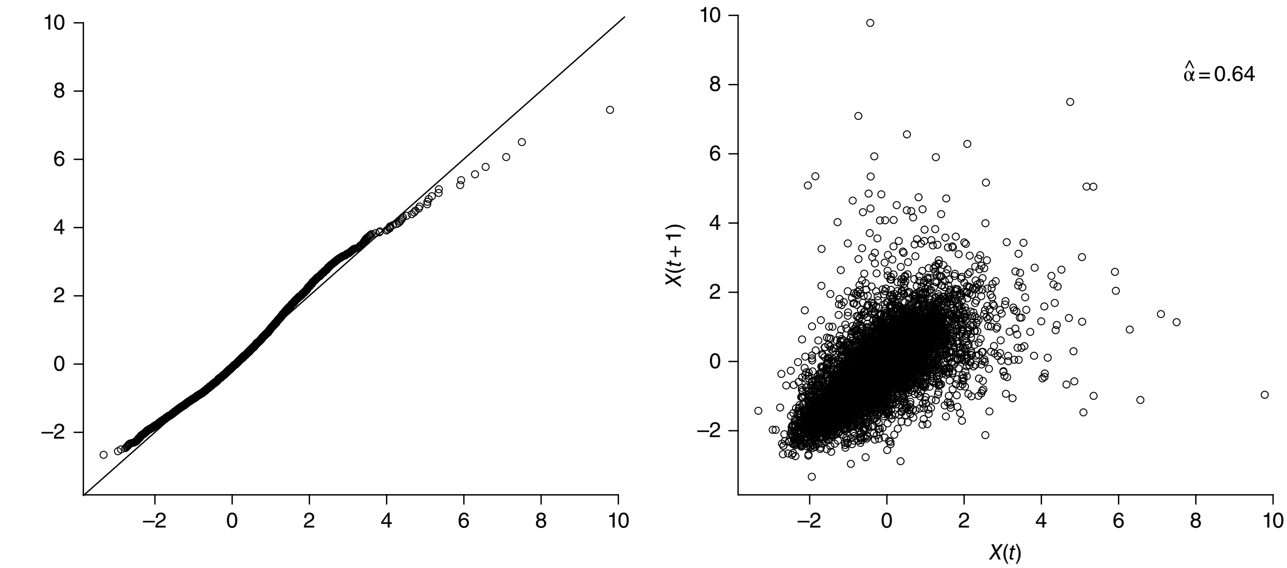

Figure 2.4 Gumbel QQplot (left) and scatter plot of successive values (right) corresponding to daily maxima of carbon dioxide.

France. The trend in the series has been removed in order to consider a stationary series.

This example illustrates the connection between light-tailed maxima and the Gumbel distribution. Indeed, if we fit a Gumbel distribution on the daily CO_2 maxima, we see on the Gumbel Quantile Quantile (QQ-)plot (see left part of Figure 2.4) that it is quite reasonable to suppose that these data are Gumbel distributed (with $\hat{\mu} = -0.44$ and $\hat{\sigma} = 0.76$). But in this practical case, the length of our observations is too short to study yearly maxima, or even monthly maxima. As a consequence, when studying daily maxima it is natural to observe some day-to-day memories. The scatter plot of successive values (see right part of Figure 2.4) confirms this short-term temporal dependence.

A very simple approach in the time series analysis would be to consider linear autoregressive (AR) models. Classical hypotheses are noise Gaussianity and model linearity. But in an extreme value context, if X_t is a maximum, then one expects X_t to follow a GEV distribution and it is impossible to satisfy this distributional constraint with a Gaussian additive AR process.

That's why *Toulemonde et al.* [2010] have proposed a linear AR process adapted to the Gumbel distribution. This model is based on an additive relationship between Gumbel and positive α-stable variables (A random variable S is said to be stable if for all nonnegative real numbers c_1, c_2, there exists a positive real a and a real b such that $c_1S_1 + c_2S_2$ is equal in distribution to $aS + b$, where S_1, S_2 are i.i.d. copies of S.) [see *Hougaard*, 1986; *Crowder*, 1989; *Tawn*, 1990; *Fougères et al.*, 2009].

First, let us consider $S_{t,\alpha}$ being i.i.d. positive asymmetric α-stable r.v. defined by its Laplace transform for any $t \in \mathbb{Z}$

$$\mathbb{E}\left(\exp\left(-uS_{t,\alpha}\right)\right) = \exp\left(-u^{\alpha}\right), \text{for all } u \geq 0 \text{ and for } \alpha \in \left]0,1\right[. \tag{2.1}$$

Let $\{X_t, t \in \mathbb{Z}\}$ be a stochastic process defined by the recursive relationship

$$X_t = \alpha \ X_{t-1} + \alpha \ \sigma \ \log S_{t,\alpha} \tag{2.2}$$

where $\sigma > 0$. It has been proved first that Equation (2.2) has a unique strictly stationary solution,

$$X_t = \sigma \sum_{j=0}^{\infty} \alpha^{j+1} \log S_{t-j,\alpha} \tag{2.3}$$

and second that X_t follows a Gumbel distribution with parameters $(0, \sigma)$.

This model is a linear AR model and has consequently the associated advantages such that their conceptual simplicity and their flexibility for modeling quasi-periodic phenomena (e.g., sunspots time series) and short-term dependencies (e.g., day-to-day memories in weather systems). Whereas one drawback of current linear AR models is that they are unable to represent the distributional behavior of maxima, a key point of parameterization (2.2) is that X_t follows a Gumbel distribution. In other words this process is suitable for maxima data coming from light-tailed distributions. Even if our process is

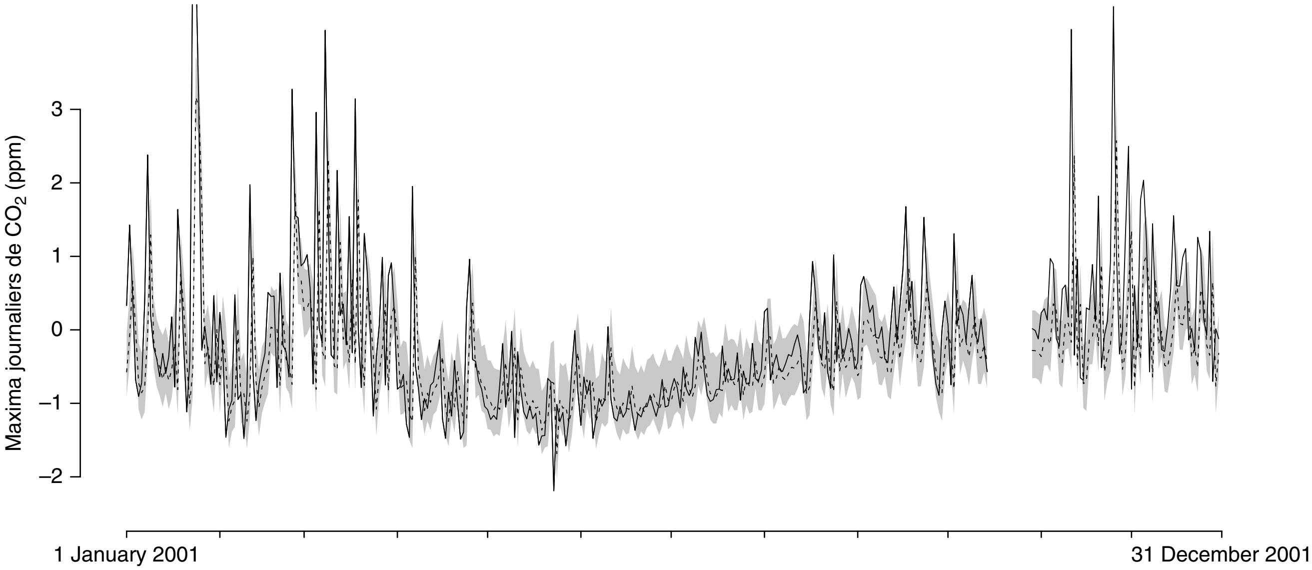

Figure 2.5 One-day previsions of daily maxima of CO_2 (y-axis) in the year 2001 (x-axis). The black line corresponds to the observed series and the dotted line corresponds to the estimated series (median). The gray area is delimited by the first and third empirical quartiles.

specific to the Gumbel distribution, it is possible to extend it for maxima coming from bounded or heavy-tailed distribution. Nevertheless this leads to a process which is not additive anymore.

Coming back to our example, identifying the temporal structure among the largest CO_2 measurements is of primary interest for the atmospheric chemist because this can help to predict future maxima of CO_2 at a specific location. As an illustration, Figure 2.5 presents one-step previsions of CO_2 daily maxima in the year 2001.

This method, presented in *Toulemonde et al.* [2010] is exemplified in their paper on daily maxima series of two other greenhouse gas, the methane (CH_4) and the oxide nitrous (N_2O) recorded at LSCE (Laboratoire des Sciences du Climat et de l'Environnement) in Gif-sur-Yvette (France). Since the beginning of 2007, the LSCE has proceeded to record daily maxima of CH_4 but has stopped the regular recordings of N_2O daily maxima. That's why in a recent paper, *Toulemonde et al.* [2013] proposed a method adapted to maxima from light-tailed distribution able to reconstruct a hidden series. In this state-space context, they take advantage of particle filtering methods. In an extreme adapted model, they compute optimal weights for the use of the auxiliary filter [*Pitt and Shepard*, 1999] and they denote this filter by APF-Opt. Based on observations of CH_4 and N_2O from 2002 to the middle of 2006, they obtained similar results than those presented in Figure 2.6 for the reconstruction of N_2O daily maxima.

Concerning inference procedure, as usually in the block maxima approach, only the maxima are used. To remove this drawback, another technique consists of modeling exceedances above a given threshold u. In the so-called Peaks-over-Threshold (PoT) approach, the distributions of these exceedances are also characterized by asymptotic results.

Let $X_1, \ldots, X_n$ a sample of n i.i.d. r.v. from a distribution function F. We consider the N_u of them which are over the threshold u. The exceedance Y_i corresponding to the variable X_i is defined by $X_i - u$ if $X_i > u$.

The distribution function F_u of an exceedance Y over a threshold u is given for $y > 0$ by

$$F_u(y) = \mathbb{P}(Y \le y \mid X > u) = \mathbb{P}(X - u \le y \mid X > u)$$
$$= \frac{\mathbb{P}(u < X \le u + y)}{\mathbb{P}(X > u)} = \frac{F(u+y) - F(u)}{1 - F(u)}.$$

If the threshold is sufficiently high, we can approximate this quantity by the distribution function of the generalized Pareto distribution $H_{\gamma,\sigma}(y)$. We defined its survival function as follows

$$\bar{H}_{\gamma,\sigma}(y) = \left(1 + \gamma \frac{y}{\sigma}\right)^{-1/\gamma} \quad \text{if } \gamma \ne 0$$
$$= \exp\left(-\frac{y}{\sigma}\right) \quad \text{otherwise.}$$

This function is defined on $\mathbb{R}^+$ if $\gamma \ge 0$ or on $[0; -\sigma/\gamma[$ if $\gamma < 0$ where $\sigma > 0$ is a scale parameter and $\gamma \in \mathbb{R}$ a shape parameter.