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Introduction

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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.