EXTREME EVENTS AND CLIMATE CHANGE

A MULTIDISCIPLINARY APPROACH

EDITED BY

FEDERICO CASTILLO • MICHAEL WEHNER • DÁITHÍ A. STONE

WILEY

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This edition first published 2021

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

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Library of Congress Cataloging-in-Publication Data

Names: Castillo, Federico, editor. | Wehner, Michael F., editor. | Stone, Dáithí A. Stone., editor.
Title: Extreme events and climate change : a multidisciplinary approach / edited by Federico Castillo, Michael Wehner, Dáithí A. Stone.
Description: Hoboken, NJ : Wiley, 2021. | Includes bibliographical references and index.
Identifiers: LCCN 2021003272 (print) | LCCN 2021003273 (ebook) | ISBN 9781119413622 (cloth) | ISBN 9781119413745 (adobe pdf) | ISBN 9781119413646 (epub)
Subjects: LCSH: Severe storms. | Climatic changes.
Classification: LCC QC941 .E97 2021 (print) | LCC QC941 (ebook) | DDC 551.55–dc23
LC record available at https://lccn.loc.gov/2021003272
LC ebook record available at https://lccn.loc.gov/2021003273

Cover Design: Wiley
Cover Image: © NASA

Set in 10/12pt Times New Roman by SPi Global, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

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PREFACE

Climate change has continued unabated since the second assessment report of the Intergovernmental Panel on Climate Change concluded in 1995 that "the balance of evidence suggests a discernible human influence on global climate" (Houghton et al., 1996, p. 4). Since then, confidence in the attribution of the human cause of global warming has increased to the point that by 2018 the Fourth United States National Climate Assessment report found that there is "no convincing evidence that natural variability can account for the amount of global warming observed over the industrial era" and that at best estimate, human changes to the composition of the atmosphere, mainly through the consumption of fossil fuels, accounted for all of that warming (Wuebbles et al., 2017). Because significant climate change is certain to continue into the future, attention to its impacts has become critically important (Field et al., 2014; Jay et al., 2018). As noted in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change:

> Global, regional, and local socioeconomic, environmental, and governance trends indicate that vulnerability and exposure of communities or social-ecological systems to climate hazards related to extreme events are dynamic and thus vary across temporal and spatial scales (high confidence). Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socioeconomic development pathways and the vulnerability and exposure of people.
>
> (Oppenheimer et al., 2014)

Effective risk reduction therefore depends on multidisciplinary research that explores how past, current, and future extreme weather occurrence interacts with risk perceptions, adaptation efforts, and resilience mechanisms. For example, heat wave analysis has emphasized the impacts on health and on health care systems (Guirguis et al., 2014; Ostro et al., 2009; Stoecklin-Marois et al., 2013) whereas the impact of floods, hurricanes, and drought on migration patterns has been mostly undertaken from a social science perspective (Hugo, 2011; Landry et al., 2007; Piguet et al., 2011). The need to approach the impacts of extreme events from a multidisciplinary approach provided the editors with the spark to organize the 2016 AGU Fall Meeting session, "Multidisciplinary Methods to Estimate the Impact of Climate-Related Extreme Events," which is the genesis of this book.

This book presents a selection of contributions concerning the impacts of climate change. The authors are international experts in their fields, and their work represents the state of the art in attribution and socioeconomic impact analysis of extreme events. The work presented in this book is indicative of the multidisciplinary approaches that are needed to have a full assessment of the impact of extreme weather on society.

Chapter 1 by Stone begins our discussion by outlining a detection and attribution approach to the general question of synthesizing the impacts of extreme weather in a changing climate. Using Arctic coast erosion as an example, Stone demonstrates the causal chain that must be developed to attribute individual impacts on anthropogenic climate change. The book then focuses on specific agricultural impacts for five chapters. In Chapter 2 Castillo et al. analyze the impact of heat waves on outdoor labor, particularly on agricultural labor in California. Using a Cobb-Douglas production function approach and drawing from the medical literature, they use crop-specific labor requirements together with climate and socioeconomic variables to determine the impact of heat on labor productivity and its resulting impact on crop productivity. They find that the impact of heat is crop specific, with particularly large impacts on crops that are labor intensive.

In Chapter 3 Grotjahn then takes a more targeted approach asking "What weather extremes affect various agricultural commodities?" He discusses the series of extreme weather events that can set in motion a series of changes affecting agricultural productivity. In Chapter 4 Lu et al. develop a theoretical framework that assesses the impact of extreme events on agricultural production systems. Using a stylized dynamic model, they suggest that an increase in temperatures will result in a geographical shift of agricultural production toward the poles and that there will be a transition from cold-weather crops to hot-weather crops. Despite this, due to the production costs in the new locations, there is a risk of supply shocks in the future. In Chapter 5 Casellas Connors and Janetos explore the teleconnection between regional crop failures finding that mitigation policies, including carbon taxes, will alter the geographic distribution of these impacts. In Chapter 6 Saborío-Rodríguez et al. model adoption of adaptation practices among small bean and corn producers in Honduras and Guatemala in the presence of weather extremes. They find that the implementation of adaptation strategies is positively correlated with perceptions of repeated exposure and frequency of extreme event occurrence as well as human capital capacity building and land tenure regime, among others.

The book then turns to the climate change impacts on the more complicated behavioral changes of land use and migration. In Chapter 7 Sanchez Vargas et al. analyze individuals' behavior and the impact of extreme heat when considering socioeconomic and weather variables. Using a Cobb-Douglas utility function framework they find that individuals' socioeconomic characteristics interact well in explaining the impact of extremes on individuals' welfare. In Chapter 8 Tan and Liu use the latest migration theory to analyze the relationship between extreme event occurrence and migration patterns in China and extend it to include the concept of adaptative capacity. They further analyze how an individual's political participation affects his or her migration decision when considered in the context of extreme event occurrence. Their findings suggest that in order for individuals to adapt to weather variability, local governments should provide financial incentives and social assistance programs. Furthermore, Tan and Liu suggest that citizens' participation is key to increasing adaptive capacity in the presence of weather variability. In Chapter 9 Lozano et al. estimate the impact of extreme weather events on internal migration in Guatemala for the 1997–2002 period. They find that drought occurrence in the municipality of origin significantly reduces migration, whereas extreme precipitation increases migration.

In Chapter 10 Vanos et al. then demonstrate that heat exposure is both a physical and mental health risk in many occupations. They further describe the physiological effects of extreme heat and provide metrics for quantifying these effects. In Chapter 11 Collins and Paxton focus on tropical cyclones, the largest and most intense storms on the planet. They begin with outlining the wind and rainfall processes that present danger to coastal and even inland communities, and they conclude with practices that can be undertaken before the storm to mitigate losses as well as techniques after the storm to measure losses. In Chapter 12 Raghavendra and Milrad find a relationship between heat waves in Florida and extreme precipitation events a few days later. The compound nature of such sequential extreme events exacerbates the impacts that would be experienced by just one or the other.

Finally, in Chapter 13 Shaw et al. analyze the impact of weather-related variables on economic activity for 12 sectors of the US economy, including retail, forestry, agriculture, manufacturing, construction, and finance. They use a nonlinear framework to show that increases in temperature improve economic outcomes up to a threshold temperature where economic activity is then negatively affected. Results are particularly strong for construction, forestry, and mining.

This book focuses on the impacts of changes in extreme weather in a warming climate because this is the principal way that climate change directly affects human systems. Climate change impacts on agriculture are particularly apparent, and many of these chapters reflect this. The book is intended to survey topics and methods and is by no means a complete list of the impacts of extreme weather. Readers will find that some of these methods can be transferred from the applications in this book to other climate change impact topics in their own interest.

This book is dedicated to the memory of Professor Anthony Janetos. Tony was an enthusiastic supporter of this book and recognized the urgent need to bring physical and social climate scientists together.

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ACKNOWLEDGMENTS

Support from the National Science Foundation project "EaSM Advancing Extreme Value Analysis of High Impact Climate Change and Weather Events," No. 1243333. and the Regional and Global Model Analysis (RGMA) program in the Biological and Environmental Research division of the Office of Science, United States Department of Energy is gratefully acknowledged by the editors of this book.

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Synthesizing Observed Impacts of Extreme Weather Events Across Systems

Dáithí A. Stone

ABSTRACT

This chapter discusses synthesis assessments of the impacts of extreme weather across multiple types of impacts. It considers existing global synthesis efforts rather than developing a new analysis based on other chapters in this book. It includes discussion of the motivation for such assessments, challenges in performing syntheses related to extremes, and possible methods for assembling a synthesis. The focus is on the detection and attribution of impacts during the past half-century, but implications for predicting and, ultimately, documenting future changes in risk are also discussed. The only synthesis assessment of past impacts related to extreme weather is reviewed, noting that its shortcomings can be overcome only through further developments in a number of areas, including monitoring and process understanding.

1.1. A REASON FOR CONCERN

In 1992, the nations of earth agreed to "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" according to the prescriptions of the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992). The meaning of "dangerous" was not specifically defined, but it was made clear that action should be taken so as "to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." Since 1992, the world's nations have continued developing the UNFCCC, and more recently they noted "the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events . . ." (United Nations, 2015, p. 26). In doing so, the countries recognized that "adverse effects of climate change" will impose "loss and damage," but they remained silent on the conditions under which such adverse effects, loss, and damage might be considered "dangerous." Such conditions might be reached, for instance, once a certain threshold of damage is achieved or if the rate of increase of loss becomes too high. The nature of those conditions might be different for the viability of the insurance industry, the stability of an economy, the reliability of a food supply, or the steadiness of a political system. Hence, whatever might ultimately be designated as dangerous, it will need to be informed by assessment of impacts around the world and across natural, managed, and human systems. This assessment not only needs to note the global and cross-system averages but also the existence of any localized but transformative impacts, such as might occur around an ice-free Arctic Ocean, as well as disparities in impacts, for instance between wealthy and poor populations. In this chapter we will refer to such an assessment as a synthesis.

This chapter is concerned with possibilities and challenges of syntheses that might inform the UNFCCC

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Extreme Events and Climate Change: A Multidisciplinary Approach, First Edition. Edited by Federico Castillo, Michael Wehner, and Dáithí A. Stone.

process (and we hope other national and international activities) with specific respect to adverse effects inflicted by extreme weather events. It is not intended to provide a synthesis assessment itself, a major multidisciplinary endeavor. Why the focus on extreme weather? Does it matter whether impacts are a consequence of extreme weather rather than of other manifestations of anthropogenic climate change?

Much contemporary risk management focuses on reducing exposure and vulnerability to, and increasing resilience against, natural disasters. Infrastructure is designed to withstand certain thresholds of extreme weather, and insurance is purchased as a hedge against damage from uncertain but plausible extreme weather. Thus one possible lens for defining "dangerous" is through the definition implicit in current design specifications and in what is considered affordable levels of insurance: in other words, through risks associated with extreme weather. So, to answer the question from the previous paragraph, for some purposes it may indeed be relevant to focus on impacts that are a consequence of extreme weather. This point features in reports from the Intergovernmental Panel on Climate Change (IPCC), the international body tasked with assessing current understanding of anthropogenic climate change in order to inform the UNFCCC process. In its 2001 report, the IPCC identified five "reasons for concern" (RFCs), each "consistent with a paradigm that can be used . . . to help determine what level of climate change is dangerous" (Smith et al., 2001, p. 915). These RFCs have continued to provide synthesizing structure through to the most recent reports (Cramer et al., 2014; Hoegh-Guldberg et al., 2018; Oppenheimer et al., 2014; Smith et al., 2009). One of these RFCs is the relationship between anthropogenic climate change and risks associated with extreme weather events.

In keeping with the use of the RFCs as summary measures for informing the UNFCCC process, this chapter focuses on understanding how synthesis assessments might provide status updates on risks associated with extreme weather events. In particular, the chapter will concentrate on understanding the detection and attribution of recent impacts, that is, evaluating the combined evidence from monitoring and system understanding, including their comparison, in order to document how anthropogenic emissions have already affected various aspects of human, managed, and natural systems around the world via extreme weather. A benefit of the focus on detection and attribution is that it highlights the role of monitoring. Implications for predicting future changes in risk will be discussed at the end, including the role of continued documentation of impacts for monitoring progress toward the UNFCCC objective. One thing to note at this point, though, is that analysis of the past considers impacts, that is, the outcomes of certain risks, whereas in the future we can consider only the risks themselves. For simplicity, in this chapter we will tend to consider impacts, outcomes, and risks to be different facets of the same thing.

The chapter consists of three further sections. The next (second) section will examine various steps involved in generating a synthesis assessment, particularly focusing on challenges. The third section will then review the single existing synthesis assessment of past changes in risk associated with extreme weather. That assessment was conducted as part of the chapter on "Detection and Attribution of Observed Impacts" in the IPCC Fifth Assessment Report (Cramer et al., 2014) in order to document current understanding of the "risks associated with extreme weather events" (their section 18.6.4). Other synthesis approaches will also be mentioned, but as yet they have not been applied to the specific topic of the impacts of extreme weather. The final section will describe implications for predicting future global, cross-sectoral, extreme-weather-related risk.

1.2. OF TRUTHS AND TRIVIALITIES

Niels Bohr, one of the pioneers of quantum mechanics, used to say that it was the task of science to reduce deep truths to trivialities (Pais, 1991). When it comes to informing climate policy, however, the opposite might be a more useful dictum. A substantial component of current disagreement over the impacts associated with extreme weather events comes from a lack of clarity over what is meant by impacts of extreme weather events. This means that trivialities about natural hazards, such as that more intense hurricanes have the potential to induce more damage than do weaker hurricanes, are often taken as truths about impacts of climate change. But the truth is a much more complicated amalgam of weather hazard, policy, economics, community organization, and just plain luck. Understanding this truth will be easier if we clarify exactly what question interests us, what possible tools we have for exploring that question, and what challenges we face in applying those tools. This section discusses some of these issues.

1.2.1. Weather Extremes or Impact Extremes?

We will start first with the distinction between weather and impacts (of weather). Although the distinction is generally commonly understood for long-term impacts of long-term climate changes, this is not the case with extremes. Extreme weather is often confused with natural hazards. For instance, in its review titled *Attribution of Extreme Weather Events in the Context of Climate Change,* the US National Academy of Sciences in fact considered natural hazards including floods and wildfires (National Academies of Sciences, Engineering, and Medicine, 2016). However, in the most recent IPCC assessment report, floods and wildfires are considered to occur outside of the climate system in the hydrological and ecological systems, respectively (Cramer et al., 2014; Settele et al., 2014).

In this chapter we will distinguish between "extreme weather events" and, for lack of a better term (Cramer et al., 2014), "extreme impact events." We will consider an "extreme weather event" to be any event in the climate system that is episodic in nature and is far from average in some standard climatological measure. "Far from average" is ill-defined, but we may consider fairly mundane mid-latitude storms even if they are not all that rare. An "impact event" is something like a flood (hydrological event), wildfire (ecological event), pest outbreak (agricultural event), or stock market crash (economic event), also being episodic and far from average, but occurring outside of the climate system.

Why care about this syntax? Just as an extreme weather event need not necessarily result in an extreme impact event, an extreme impact event may happen regardless of what the weather is doing. For example, in warmer climates (i.e., where snowmelt is not a factor) inland floods usually occur under conditions of heavy rainfall over some period of time. But it is also possible for floods to occur for other reasons unrelated to rainfall, such as under a controlled dam release for downstream ecological support or when urban water mains or sewer systems fail. Note also that an extreme weather event (or series thereof) may have long-term consequences beyond an immediate impact due to destruction of infrastructure. Is it more appropriate then to focus on weather events or impact events? It depends on the purpose. For instance, although Cramer et al. (2014) generally considered their remit to focus on impact events, the assessment with regards to the extreme RFC was explicitly focused on weather events (and the risk implied by their occurrence). This chapter is motivated by the effects of extreme weather, and so the focus will be on that, but we will keep in mind that extreme weather events do not necessarily equate to extreme impact events.

1.2.2. Detection and Attribution

We should clarify a few points about using detection and attribution for understanding before continuing further, even if the term has little to do with extremes or synthesizing per se. Detection and attribution is used to describe the process of comparing predictions of what should have happened in the past and observations of what has actually happened in order to develop a comprehensive documentation of cause and effect (Hegerl et al., 2010; Stone et al., 2013). The predictions should be made based on some understanding of how the relevant systems operate, perhaps based on explicit numerical modeling of the component processes or through extrapolation of empirical relationships. Importantly, the demand on monitoring and modeling is high, such that conclusions are supported by a full wealth of information. However, the flip side is that confident conclusions are not always possible for any of a variety of reasons, including that a specific impact may not have been monitored. Hence, although confident detection of a climate change influence on something can be taken to mean that indeed climate change is having an influence, the lack of a confident detection does not necessarily mean the opposite (Hansen & Cramer, 2015).

As a case study, we will explore the application of detection and attribution analysis using data on the occurrence and impacts of tornadoes in the United States of America. The data are from the Storm Events Database, Version 3.0 (https://www.ncdc.noaa.gov/stormevents/, downloaded May 24, 2018), and is to our knowledge a unique documentation of extreme weather and its impacts. This database is produced by the US National Oceanic and Atmospheric Administration to document the occurrence of extreme weather events and their effects over the United States. Coverage depends on the type of weather event, with the earliest tornado record noted in January 1950. Data include the type of weather event, the county in which it occurred, the intensity of the event, and quantified impacts. We exclude Alaska and US-dependent territories (e.g., Guam, Puerto Rico, and the US Virgin Islands) from analyses here because of incomplete records or complications from changes in county/borough boundaries. It is important to note that this product is not advertised as being a reliable documentation of trends in extreme weather and their impacts over the past 68 years. We will consider possible issues relating to that later in this section. Nevertheless, the product's focus on extreme weather events, and its documentation of the weather type, location, and impacts, makes it ideal for the demonstrative analyses to be conducted in this chapter.

Figure 1.1 shows a simple way of diagnosing the contributors to the year-to-year variability and long-term trends of two impacts of tornadoes in the United States. The black lines indicate direct injuries to humans and direct human deaths attributed to tornadoes over the 1950–2017 period according to the NOAA database. The colored lines (other than red) indicate variations in various other factors that may also contribute to the variations and trends in deaths and injuries, all adjusted to the same scale as the historical impact data: the tornado frequency (count of segments, which counts twice if an

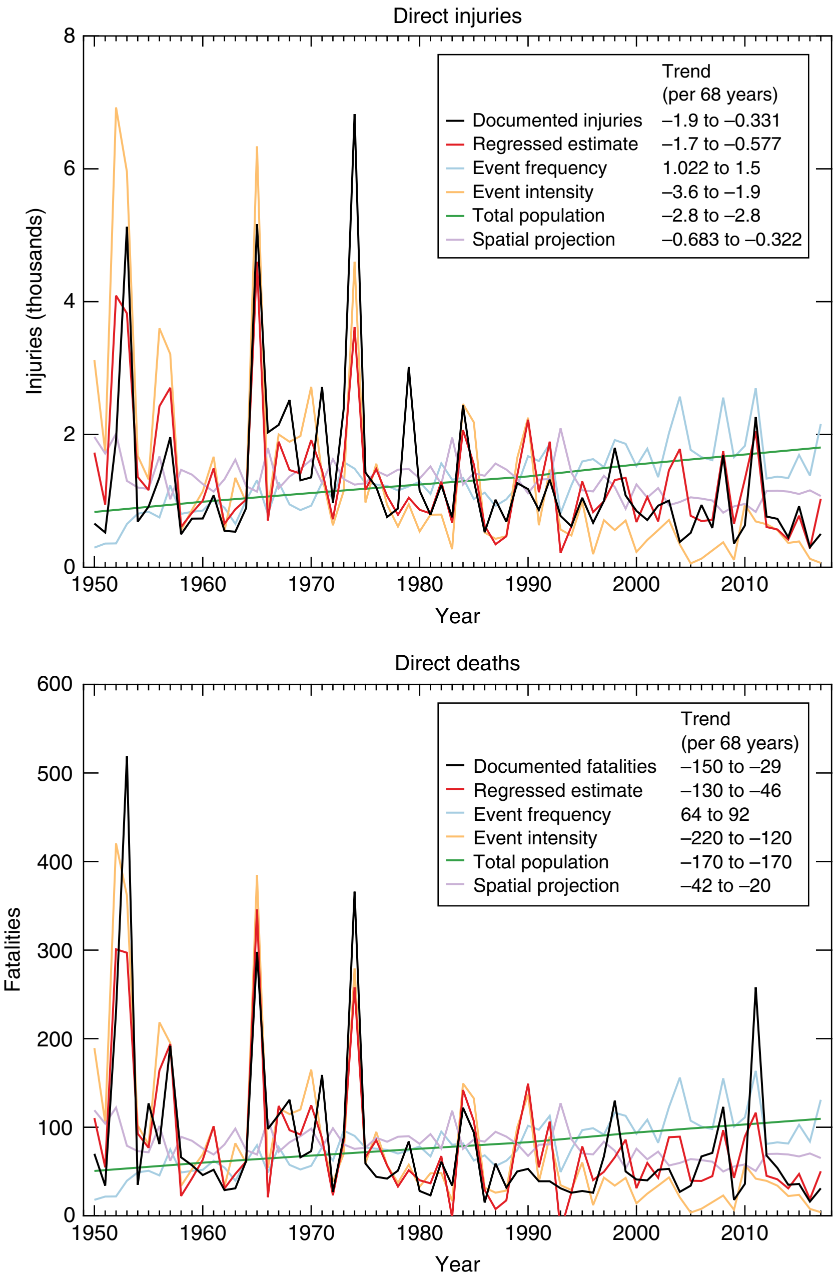

Figure 1.1 Annual variations in fatality and injury impacts from tornadoes in the United States between 1950 and 2017. Documented fatality and injury impacts are shown in black. Tornado frequency and a measure of average tornado intensity (the ratio of the frequencies of F-scale 4 to F-scale 1 tornadoes) are also plotted as measures of the climate hazard, while the total US population and the spatial projection of tornado frequency onto population (at the county scale) are plotted as measures of exposure (Manson et al., 2017). A regression of the documented impacts against the measures of hazard and exposure is plotted in red. The uncertainty ranges of the contributed trends from the various regressed measures of hazard and exposure are estimated by removing the linear least-squares trends from all regressed time series, resampling the residuals using 1,000 bootstrap samples, adding the linear trends back to these samples, calculating their linear trends, and then taking the 5th to 95th percentile range of the trends. All time series are scaled to the same units as the documented fatality and injury data. Tornado data are from the NOAA Storm Events Database (https://www.ncdc.noaa.gov/stormevents/).

individual tornado crosses a county boundary or touches down twice), the tornado intensity (approximated by the ratio of the counts of F4 over F1 intensity tornadoes), the national human population (for the states included in the analysis), and the projection of the spatial pattern of tornado incidence onto human population (labeled "spatial pattern" in the figure, reflecting both spatial shifts in human population and shifts in tornado location). A multiple linear regression of observed impacts onto these four driving factors is shown in red.

The regression is dominated by the tornado intensity index for both impacts. Visually, the intensity peaks in 1953, 1965, and 1974 closely match the injury and death peaks in those years. However, the decline in injuries since 1980, and the lack of a long-term trend in deaths, is not matched by the large(r) decline in intensity, which is mainly compensated for by the long-term trends in event frequency and (in a nonsensical negative sense) by population. Note though that the long-term behavior of the impacts and hazard data should be treated with caution because of long-term changes in reporting practice and technology (Gall et al., 2009). For example, the widespread deployment of weather radar in the early 1990s corresponds to an increase in event counts; if radar increased the detection rate of weaker tornadoes, that would also have induced a downward shift in our intensity measure.

There are, however, some broad conclusions we can still take from this analysis. First, tornado intensity is the dominant factor influencing year-to-year variations in injuries and fatality risk. Second, year-to-year causal relationships may not be the major determinant of long-term trends in risk; at the very least, population has little short-term variability but could have doubled the impacts over this period. Finally, the missing driving factor in these plots, namely vulnerability, has likely decreased substantially over this period. Given that suspected biases in the underlying data might have induced a bias toward increasing trends, that population has approximately doubled, and that there is no upward trend in either impact, it stands to reason that a decrease in vulnerability has also played a role. From this cursory analysis we might conclude that there is evidence that trends in tornado behavior have not been a major factor in driving long-term trends in tornado-related fatality and injury.

1.2.3. Finding a Common Currency

If we want to synthesize across multiple regions and types of impacts, then we need to have a common metric that is applicable to all of those regions and types of impacts. In one of the tornado impact analyses just given we used the human fatality rate. Human fatality impacts are a standard and obvious metric, because under the ethical and judicial standards of most countries all human deaths are equivalent. The use of the injury metric in the other tornado analysis is less clear-cut, however: some injuries may be more severe and consequential than others. And neither of those metrics is applicable for impacts outside of human health. A starting point might be money, considering that so much of our lives is spent using it as a universal currency. But can we put a monetary value on a species going extinct? Or on various aspects of livelihoods and culture?

A partial way around this challenge is to use a qualitative measure of relative change instead of a quantitative metric (Cramer et al., 2014; Oppenheimer et al., 2014; Smith et al., 2001, 2009). For instance, in their synthesis assessment of the detection and attribution of changes in risk associated with extreme weather, Cramer et al. (2014) synthesized only across like systems (e.g., bleaching/stress/mortality of warm water corals) when assigning a level of confidence to the evaluation of whether observed climate trends had played a major or minor role in an observed change. Hence, their summary statement highlighted "High-temperature spells have impacted one system with high confidence (coral reefs), indicating Risks Associated with Extreme Weather Events. Elsewhere, extreme events have caused increasing impacts and economic losses, but there is only low confidence in attribution to climate change for these" (Cramer et al., 2014, p. 983) but included no cross-system synthesis. However, these system-specific conclusions were then aggregated into a past-to-future assessment of the qualitative change in risk by Oppenheimer et al. (2014). Synthesizing across qualitative, rather than quantitative, outputs of detection and attribution analyses means that the synthesis is more flexible in the types of detection and attribution analyses it can include. For instance, a multiple linear regression analysis may be appropriate for a system that behaves fairly linearly to external perturbations, but another type of analysis may be required for a system with a highly nonlinear response. In a quantitative synthesis it would be hard to include the output parameters of both analyses in a consistent way. Similarly, being able to include more disparate types of analyses of each component input (e.g., different studies of butterfly range shifts using different techniques) means that a qualitative synthesis can incorporate a more robust representation of uncertainty. However, the trade-off is a lack of transparency over technical details that may be important.

An alternative approach is to convert results of individual studies into a binary metric, such as "predictions consistent with observations" versus "predictions inconsistent with observations" (Rosenzweig et al., 2007, 2008; Savo et al., 2016). For predictions of future risks, a possible binary metric might be based on a threshold for losses or damages or based on a threshold for relative importance in relation to predicted effects of other factors. With some loss of information about severity, this approach can in practice produce a single synthesis measure. However, it has several important assumptions (Stone et al., 2013). Most important, by assuming that each unit of study (for which a binary result is assigned) is equivalently important, it is still assigning value. Such an approach has yet to be applied specifically to impacts related to extreme weather.

1.2.4. The Arithmetic of Synthesis

There are two possible dimensions in which one can conduct a synthesis analysis: horizontally, across like systems, or vertically, along the causative chain. Figure 1.2 shows a simple example from Cramer et al. (2014) in which both dimensions were explicitly invoked in developing a synthesis conclusion of the detection and attribution of "increased erosion of Arctic coasts." Vertically, synthesis assessments of individual steps in the causal chain, from "decreasing Arctic sea ice cover in summer" through "lack of sea ice protection from wind storms" were used to build the final assessment.

Alternatively, the final assessment can be seen as the horizontal synthesis across multiple like systems, in this case across the Arctic regions of Asia, Alaska, and Canada. Although the various causative steps of the regional assessments were not listed in the published report, they were necessarily implicit in the development of the regional assessments; similarly, the various Arctic-wide assessments were developed from regional information. Thus in fact this figure should appear more as a grid, with only certain cells having published assessments.

The nature of synthesis across the two dimensions differs. Sensibly, confidence along the vertical causal chain, in the existence of a trend in the first step and of causation in the last two steps, decreases as the assessment proceeds through the impact chain. Along the horizontal regional dimension, though, confidence in the Arctic-wide assessment is the same as for the regional assessments. This is sensible enough, but what if the assessment for Asia had been for "very low confidence"? Basing the Arctic-wide assessment on the more or less confident result would mean that the existing synthesis assessment would not be representative of the entire Arctic (Stone et al., 2013). However, taking some qualitative average (i.e., "low confidence") would hide the existence of "medium confidence" in at least some impacts. Cramer et al. (2014) attempted to deal with this issue by adopting the practice of assigning confidence to carefully worded synthesis statements, with the explanation that "the confidence statements refer to a globally balanced assessment" (p. 1014). So for instance, the assessment of "changes in flood frequency and magnitude in non-snowmelt-fed rivers" referred to changes of any nature, not applicable to all non-snowmelt-fed rivers around the planet but rather to the existence of such changes in at least a major river in most continents.

This issue of "horizontal arithmetic" does not only apply to the confidence measure used by Cramer et al. (2014). For the binary synthesis approach previously described, Rosenzweig et al. (2007) consider if one

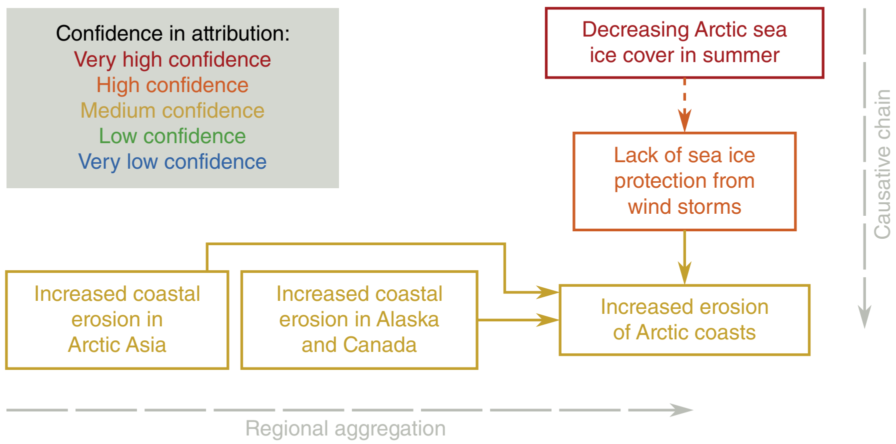

Figure 1.2 Synthesis assessments from the IPCC AR5 concerning the attribution of increased erosion of Arctic coasts. In Cramer et al. (2014) synthesis assessments were made for various aspects of the information feeding the overall assessment. The overall assessment can be viewed as being developed through a causative chain or as aggregation across regional assessments. Confidence is given for the existence of a trend for "decreasing sea ice cover in summer" and for a "major role" in causing trends along the arrows from one box to another.

assessment concluded no impact or an impact in the opposite sense of another region (e.g., decreased erosion for the preceding example). A high "no-impact" count implies a lesser overall combined impact, even though this is by no means necessarily the case. However, given uncertainty in the assessments, picking the most extreme case would be biased, because it would produce a large combined impact estimate even in the absence of climate change. At the other extreme, the fact that one particular system is not being affected may have little overall relevance, and so it should not be selected as representative (Stone et al., 2013).

1.2.5. Is There Power in Numbers?

A final concern is in understanding the uncertainty in any final synthesis measure. This depends not only on the described factors but also on interdependence of the individual studies contributing to the synthesis (Cramer et al., 2014). For example, in synthesis studies of shifts in the geographic ranges of multiple species it is assumed that each species shifts its range independently of others (e.g., Hockey et al., 2011; Parmesan et al., 2011; Rosenzweig & Neofotis, 2003). In that case the addition of observations of the range shift of an additional species adds substantial new information to the synthesis. However, the independence is hard to confirm when species are shifting their ranges as part of a general relocation of an entire ecosystem: observations for a species that is simply following its food (with the observations of that species already included) will lend confidence to the observations of its food but will not truly add a new item within the synthesis.

1.3. SYNTHESIZING ACROSS EVERYTHING

In the previous section we listed some of the challenges involved in developing a cross-system synthesis assessment of the impacts of climate change mediated through extreme weather. Although some qualitative extreme-specific syntheses have been developed for predictions for the coming century (Oppenheimer et al., 2014; Smith et al., 2001, 2009), only one such exercise has been attempted for the historical period, performed as part of the IPCC Fifth Assessment Report. It comprised two main steps: a number of synthesis assessments, each across similar impacts (Cramer et al., 2014), and a collective synthesis across all impacts (Oppenheimer et al., 2014).

The first step is illustrated in Figure 1.3. The position on the vertical axis indicates the degree of confidence (Mastrandrea et al., 2010) in the attribution of a role of observed climate change in an observed impact. The position on the horizontal axis indicates the confidence of a long-term trend in the relevant climate drivers. Some impacts have multiple climate drivers, being represented by multiple symbols connected by a line. The different types of impacts are denoted by different colors, with identification of a major role (it is a dominant factor) or a minor role (it may be involved but is not dominant) of observed climate change.

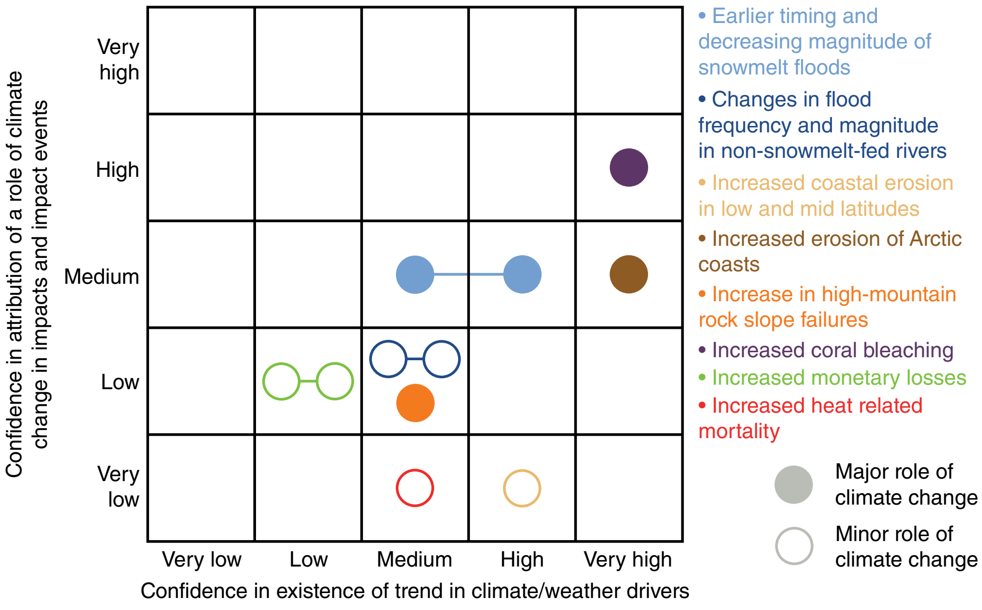

Figure 1.3 Confidence in attribution of observed trends in impacts related to extreme weather. Graphical interpretation of the table in Cramer et al. (2014) documenting the synthesis of evidence of an effect of historical trends in extreme weather on various natural, managed, and human systems.

In the figure, confidence in the impact is necessarily no higher than confidence in the relevant climate driver, because the latter is a component of the former. Note that no assessment was made about whether the climate trends were driven by human activities or represent some natural fluctuation. Hansen and Stone (2016) did examine the role of humans in trends in climate averages that they considered relevant for the extreme weather, and they provided some indication of the robustness of some assessments that included attribution to human activities. In general, the snowmelt flood and coral bleaching assessments ought to be unaffected, whereas the effect on the Arctic coastal erosion assessment depends on the balance between the importance of thermofrost degradation (unaffected) versus regional sea ice retreat (strongly affected). Hansen and Stone (2016) did not examine the human role in other climate trends listed in this figure.

There are three main observations one may make from this illustration. The most obvious is that not that many impacts were covered and many included were limited to very specific statements (for instance, the distinction between erosion of Arctic versus non-Arctic coasts). The synthesis was conducted for two types of impacts: broad synthesis statements of general interest (e.g., monetary losses) or assessments of a more narrow set of impacts selected on the basis of whether strong evidence existed one way or the other (e.g., Arctic coastal erosion). In this sense, the assessment fell short of a full global synthesis across all systems, at least in part because it was conducted under the framework of detection and attribution.

The second observation is that the figure is an amalgam of trends in impacts related to extreme weather, but these trends are not necessarily due to trends in the extreme weather itself. For instance, the evidence of increased erosion of Arctic coasts is based on understanding that storms can now erode the coast more easily because the summer permafrost has disappeared and is no longer providing structural strength and because there is a much longer distance for waves to grow in the space vacated from retreating sea ice. In other words, the erosion occurs during the storms, but the storms themselves are not changing, only the way they interact with the coast is because of more gradual changes.

The third, more arguable, observation is that there are two types of conclusions present. The assessments for coral bleaching, snowmelt floods, and Arctic coastal erosion are all of at least medium confidence of a major role of climate change (which is mostly unaffected when extended to a major role of anthropogenic climate change). The other assessments are of lower confidence and apply only to the existence of a role of climate change. The former group arise because large-scale warming is a simple direct driver, warming is the most visible manifestation of recent climate change, the warming and impacts have been fairly well monitored, and the systems are relatively sensitive to temperature (e.g., the snow line on mountains or the sea ice edge). One or more of these factors is lacking in the second group.

1.4. IMPLICATIONS FOR THE FUTURE

This chapter has focused mainly on the past, specifically about detection and attribution of changes. This places heavy burdens on the evidence base that has the advantage of producing coherent, strongly supported conclusions, but it also has the disadvantage of being unable to provide information on some types of impacts. Does this matter when predicting future risk? After all, predictions concerning risks related to the extreme RFC were made many years before the first assessments of changes in past risks.

First, as time elapses further from the initiation of the UNFCCC process in 1992, we need to know whether we are meeting the UNFCCC's objective of preventing "dangerous anthropogenic interference with the climate system." In other words, we will need to continually update our documentation of how anthropogenic emissions are affecting various aspects of human, managed, and natural systems around the world. This is fundamentally the detection and attribution problem, and hence not only requires understanding of how the world works but also monitoring how everything is (or is not) changing.

As for the relevance for predicting the future, it helps to consider conditions under which detection and attribution analysis provides inconclusive results and to consider those conditions in the context of understanding future risks. There are three possible reasons for detection and attribution analysis to provide inconclusive results: poor monitoring, poor understanding of how the system operates, or bad luck (the observations and understanding do not match because of a statistical fluke). Poor understanding will be just as relevant for errors in predicting the future as they are for the past, in fact, perhaps more so because those errors are likely to be amplified as the climate change signal and other signals become stronger. Statistical flukes occur because the analysis is inherently probabilistic in nature but ought to happen rarely. It does remind us that specific aspects of the predicted future may not materialize in the end simply because the climate and various impact systems are inherently chaotic. Poor monitoring is also relevant, though, because if we do not have a reliably observed baseline and if we do not obtain reliable observations of future states, then we will lack an important input in the process of refining later predictions. The ability to calibrate predictions by evaluating against past behavior, that is, through detection and attribution analysis, will be especially important for our assessment of risk in cases where understanding remains poor in the future.