Chapter 2
The Impact of Climate Change on Natural Disasters

Sandra Banholzer, James Kossin, and Simon Donner

Abstract This chapter explains what hazards and disasters are, reviews their trends, and assesses the potential impact of changing climate on hazards and extreme events. Observations since 1950 indicate increases in some forms of extreme weather events. The recent Special Report on Extreme Events and Disasters (SREX) by the Intergovernmental Panel on Climate Change (IPCC) predicts further increases in the twenty-first century, including a growing frequency of heat waves, rising wind speed of tropical cyclones, and increasing intensity of droughts. A one-in-20-years "hottest day" event is likely to occur every other year by the end of the twenty-first century. Heavy precipitation events are also on the rise, potentially impacting the frequency of floods and almost certainly affecting landslides. This chapter also examines the science of event attribution, its potential and possible issues. It further outlines the global distribution and impact of natural disasters.

Keywords Climate change impact • Natural hazards • Disasters • Event attribution • Disaster risk distribution • Tropical cyclone

S. Banholzer (✉) • S. Donner
Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC V6T 1Z2, Canada
e-mail: sbanholz@gmail.com; simon.donner@ubc.ca

J. Kossin
NOAA National Climatic Data Center, Asheville, NC, USA

Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, WI, USA
e-mail: james.kossin@noaa.gov

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2.1 Natural Hazards: What Are They?

Disasters like Hurricane Sandy in October 2012 that affected the Caribbean and the East coast of America or floods in the summer 2010 that inundated large parts of Pakistan (see Figs. 2.1, 2.2, and 2.3) dominated the media headlines around the

Fig. 2.1 Hurricane Sandy on October 28, 2012, on 1:45 pm eastern daylight time (Photo from NASA Earth Observatory image by Robert Simmon with data courtesy of the NASA/NOAA GOES project science team)

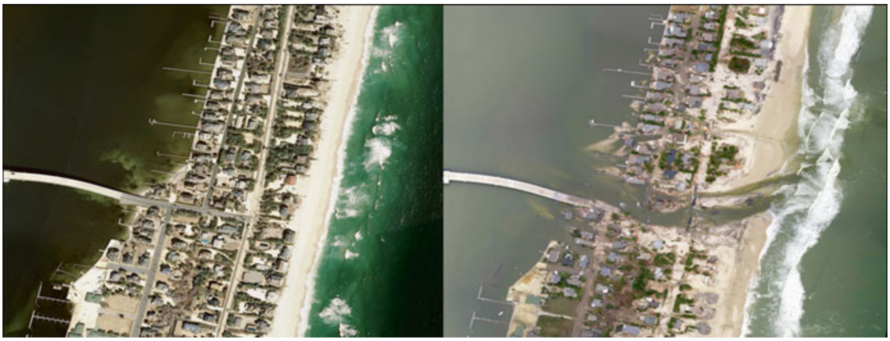

Fig. 2.2 Parts of New Jersey's shoreline before and after Hurricane Sandy hit late October in 2012. Storm surges and winds created a new inlet between the Atlantic Ocean and the Jones Tide Pond. Sandy was the worst storm hitting the northeastern United States since the Great New England hurricane in 1938. Storm surges reached heights of up to 15+ feet in New Jersey (Munich 2013) (Photo from NOAA Remote Sensing Division)

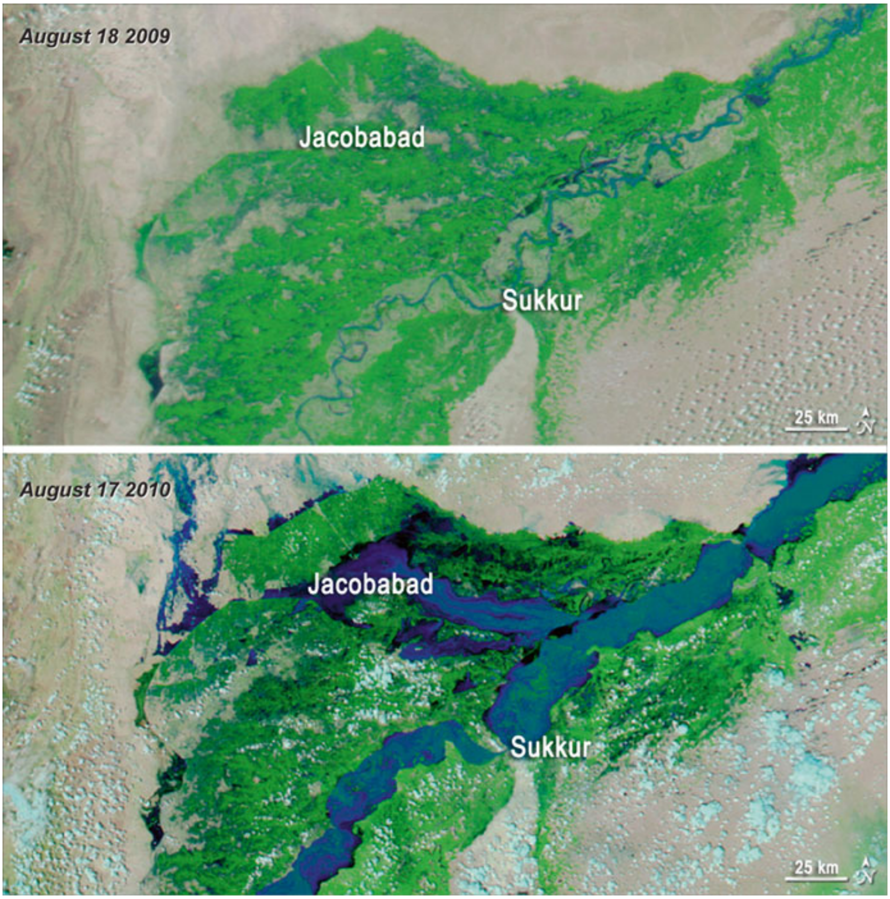

Fig. 2.3 Northwestern Pakistan in August 2009 (*top*) and during the flooding in 2010 (*bottom*): Very strong monsoon rains caused the Indus River to inundate large areas and affecting 15–20 million people causing the worst flooding in a century. This extreme event caused significant damage, in particular to the agriculture sector as more than 6 million ha of agricultural land was inundated. Moreover, the productivity of this submerged land could be severely affected or even lost, causing a long-term impact on the environment and the society (UN 2010) (Photo from UNEP 2010)

world for weeks. These events had disastrous economic, environmental, and social consequences. Hurricane Sandy resulted in $50 billion economic losses, more than $25 billion insured losses, and led indirectly to power outages in 15 states (Munich 2013). The flooding in Pakistan was considered the worst in a century – killed over 1,600 people and left two million homeless (UN 2010).

But what is the difference between a natural hazard, an extreme event, and a disaster? Is a landslide in a deserted mountainous region a disaster? Questions like these require crystal-clear definitions of these terms.

Box 2.1 Definitions

Hazard:

"A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UNISDR 2009a)

Natural hazard:

"Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage" (UNISDR 2009a)

Climate Extreme (extreme weather or climate event):

"The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (IPCC 2012b)

Disaster:

"A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources" (UNISDR 2009a)

2.1.1 Hazards Versus Disasters

The United Nations International Strategy for Disaster Reduction (UNISDR) released a compilation of updated standard terminology related to disaster risk reduction in order to mainstream terms and their definitions (UNISDR 2009a). See Box 2.1 for a definition of hazard, natural hazard, and disaster.

There exist a variety of definitions for extreme events; the definition in Box 2.1 is from the IPCC SREX report (IPCC 2012a). The word *extreme* can be used to describe the impact of the event or physical aspects of the event itself, which can lead to confusion. In general, extreme events, for example related with temperature or precipitation, can be defined by indices describing absolute quantities or the frequency of incidents beyond an absolute or relative threshold or by dimensionless indices (Zwiers et al. 2013). Natural hazards and extreme events fall into the same context and can be used interchangeably.

Disasters and natural hazards/extreme events are often associated with each other but they are not the same. A disaster is the result of the severity of a natural hazard combined with the exposure to the hazard, the preexisting vulnerability, and the inability to cope with the impacts of the hazard (UNISDR 2009a). Examples of common hazards are hurricanes (Figs. 2.1 and 2.2), droughts, floods (Fig. 2.3), and forest fires (Fig. 2.4).

Not every extreme event has to lead to a disaster; it largely depends on the prevailing conditions (IPCC 2012a). The prevailing conditions are determined by the level of vulnerability and exposure of populations. Exposure and vulnerability are

Fig. 2.4 Wildfires in December 2010 burned large areas near Mt. Carmel, south of Haifa, and were described as the largest so far in Israel. A report by the Israel's Ministry of Environment pointed out that fires like these are projected to be more common with the impacts of climate change on more intense and longer dry seasons (IME 2010) (Photo from UNEP 2011)

not static. A variety of factors influence vulnerability and exposure such as social, economic, and geographic factors but also governance plays a role. Further, vulnerability and exposure can be dependent on the season or on co-occurrence of other extreme events. Socioeconomic variables, such as income, education, and age, will not influence the occurrence of climate extremes but they can impact the way populations are able to prepare for, withstand, and recover from the impacts (IPCC 2012a).

For example, as explained in Sen's (1981) widely cited book about the connection between poverty and famine, drought is not the only cause of a disastrous famine. Precipitation decrease may be a contributing factor but prevailing factors such as poverty and the system behind food exchange are dominating. The focus should lie on exchange entitlement and not on declining food availability (Sen 1981). A recent study by the Chatham House (2013) about managing famine risk also points out that a major problem with droughts is that the early warnings are not followed by adequate actions to prevent a disastrous famine. The barriers are usually from political, institutional, and organizational nature (Chatham House 2013).

Another example that demonstrates how natural hazards can turn into disasters is the Hurricane Katrina that devastated New Orleans in 2005. The hurricane itself was considered a natural hazard, the flooding of the ninth ward (a neighborhood of New Orleans) however led to a disaster but arguably not a natural disaster. The disastrous outcome was caused by both: the natural hazard (the hurricane) and human-made factors such as the inadequate preparedness level (e.g., levees) or existing differential social vulnerabilities (Cutter and Emrich 2006).

In other words, prevailing factors like these mentioned in regard with famine or Hurricane Katrina can contribute to explain the severity of the impact of a natural hazard. A natural hazard like a landslide in a deserted mountainous region is hence not a natural disaster as it is lacking the human involvement. Based on these definitions of hazards and disasters, disaster risk is a function of the prevailing conditions (exposure and vulnerability) as well as the extreme event itself (UNISDR 2011a). The concept of human vulnerability will be further discussed in Chap. 5.

2.1.2 Categories of Natural Hazards and Problems with Definitions

Natural hazards can be further categorized into sudden- and slow-onset "creeping" threats (UNEP 2012a). Sudden-onset hazards are, for example, geological hazards (e.g., earthquakes, mudslides) and hydrometeorological hazards (e.g., floods, except droughts). Slow-onset hazards are droughts, coastal erosion, and poor air quality, among others (UNEP 2012a).

Slow- and sudden-onset hazards can cause temporary as well as long-lasting disruption to the environment as well as the societies. For example, slow-onset threats like droughts have wide reaching impacts. The most visible impact of droughts is the effect on agriculture. Within the agriculture sector, poor rural farmers dependent on rain-fed subsistence agriculture are specifically affected (UNISDR 2011a). However, problems in the agriculture sector then cascade into the economic and social sectors (e.g., famine) and can last beyond the duration of a drought (UNISDR 2011a). Similarly with sudden-onset hazards, the destructive force and the impact of, for example, a flood is more obvious and faster detected than the impact of poor air quality. Even though the waters might recede soon, the impacts can have similar long-lasting consequences that affect several sectors. In the example of the floods in Pakistan in 2010, the agricultural production of the inundated land was severely decreased and potentially lost forever.

Definitions of individual hazards vary widely depending on their focus. Drought, for example, is characterized by the climate science community as "[a] period of abnormally dry weather long enough to cause serious hydrological imbalance [...]" (IPCC 2012b). Depending on the organization, drought can also be defined with a meteorological (e.g., precipitation), agricultural (e.g., soil moisture), hydrological (e.g., water cycle), or socioeconomic (e.g., impact on society and economy) focus (UNEP United Nations Environment Programme 2012a). The World Meteorological Organization (WMO) however chose the Standardized Precipitation Index (SPI) as a global standard to identify droughts (UNISDR 2011a). Definitions of other hazards are similarly varied. As a consequence, the classification/typology of individual disasters can differ between disaster recording agencies (Tschoegl et al. 2006). Due to this lack of common classification, the number and severity of extreme events reported varies with the definition and the agency (e.g., NatCatSERVICE (Munich RE) recorded events vs. recorded events of the Emergency Event Database (EM-DAT maintained by the Centre for Research on the Epidemiology of Disasters (CRED))) and tracking the incidents is hence difficult (IPCC 2012a; Tschoegl et al. 2006). In order to overcome this deficiency, in 2007, CRED and Munich RE started an initiative to create a common "Disaster Category Classification and Peril Terminology for Operational Databases." This ongoing initiative marks a first step toward a standardized and internationally recognized classification and so far brought together CRED, Munich RE, Swiss RE, Asian Disaster Reduction Centre, and United Nations Development Programme (UNDP) (Munich 2011; Below et al. 2009).

The next section will summarize the main findings regarding the influence that climate change has had on past trends and might have on future projections.

2.2 Impact of Climate Change on Future Hazards

Natural hazards that lead to disasters can cause tremendous impacts on societies, the environment, and economic wealth of the affected countries. Sectors that are closely related to climate, such as agriculture, tourism, and water, are facing a great burden by extreme events (IPCC 2012a). Some forms of climate extreme events have been on the rise over the last few decades. What is their link to human-caused climate change and how will a changing climate affect the occurrence of hazards in the future? Are past disasters going to be the future's norm? This section draws largely from the special report on extreme events (SREX) (IPCC 2012a) as well as from the Working Group I contribution to the 5th IPCC Assessment Report (2013). This chapter also features a focus on tropical cyclones and their relationship with climate change.

2.2.1 Extreme Climate and Weather Events

The Intergovernmental Panel on Climate Change (IPCC) released a special report on extreme events and disasters in 2012 (IPCC SREX). In this report, IPCC assessed the impact of climate change on extreme events and the consequences of these events for the society and the environment as well as the implications on risk management (IPCC 2012a). Expertise from climate change science and disaster risk management was combined with scientists with knowledge in adaptation, vulnerability and impact analysis. This 592-page document is a cross-disciplinary contribution from over 200 authors from 62 countries; it cites thousands of scientific studies and has undergone three review rounds by experts and governments making sure that the results are scientific sound and transparent (IPCC 2012a).

This report concludes that climate extremes are a natural part of the climate system, however "[a] changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events" (IPCC 2012b).

Extreme events can therefore be a consequence of a shift in the mean climate, the variance, or the probability. A shift in the mean of, for example, temperature distribution could increase extreme hot weather and reduce extreme cold weather. Increased variability could lead to an increase in both extreme hot and cold weather (see Fig. 2.5). Percentage wise the greatest change is recorded in the tails of the probability distribution function of climate variables (Trenberth 2011) where the climate extremes are recorded.

Along this analysis of a shifting probability distribution, Hansen et al. (2012) illustrate the shift in global temperature anomaly distribution in the last 30 years by analyzing past summer temperatures and expressing them in standard deviation units. They illustrate how the anomaly distribution has broadened over the past three decades relative to the 1951–1980 mean, making extreme hot summers more frequent. They also found that the percentage of global land area that is experiencing extreme hot summer outliers of $+3\sigma$ has increased substantially, by more than an order of magnitude (Hansen et al. 2012).

Extreme events happen by definition seldom (IPCC 2012a); identifying long-term trends and making projections for the future are hence complicated. However, certain past trends and future predictions can be established with varying confidence (see Sects. 2.2.2 and 2.2.3).

2.2.2 Past Trends

An increase in the number of hazardous events over the last few decades has been noted by major insurance companies (e.g., Munich 2012), international disaster databases (EM-DAT 2011, UNISDR (see Fig. 2.6)), as well as by the scientific community (IPCC 2012a).

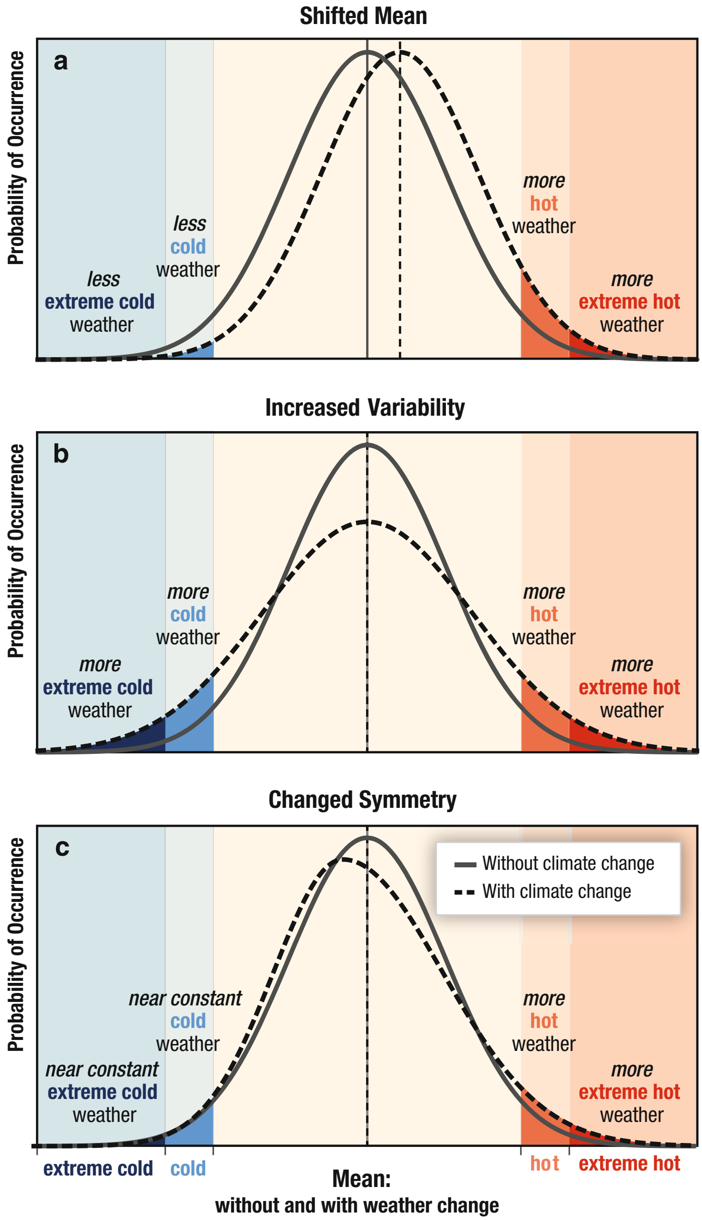

Fig. 2.5 The effect of changes in temperature distribution on extremes. Different changes in temperature distributions between present and future climate and their effects on extreme values of the distributions: (**a**) effects of a simple shift of the entire distribution toward a warmer climate; (**b**) effects of an increase in temperature variability with no shift in the mean; (**c**) effects of an altered shape of the distribution, in this example a change in asymmetry toward the hotter part of the distribution (Reproduced from IPCC 2012b)

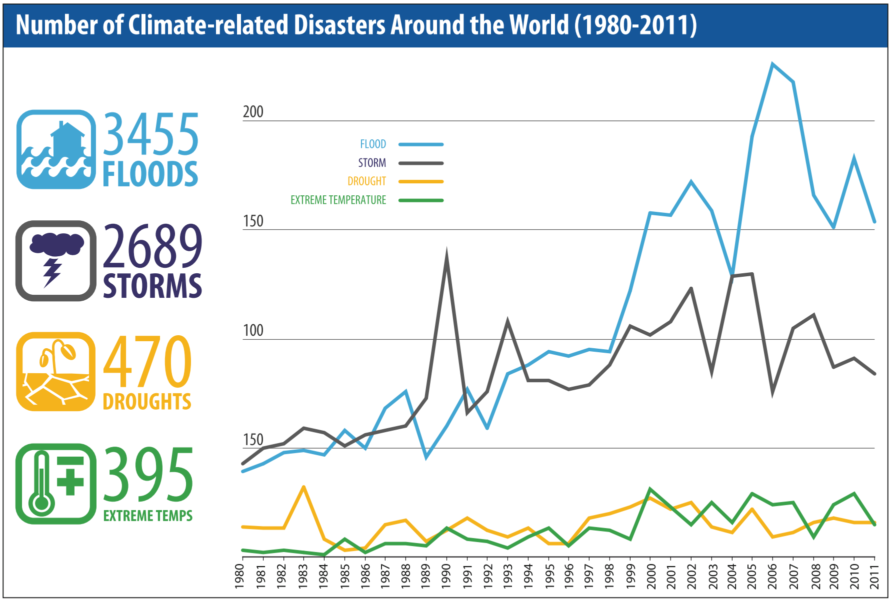

Fig. 2.6 Number of climate-related disasters around the world (1980–2011). Data from EM-DAT. EM-DAT records a natural hazard as a disaster if one of the following criteria is met: ten or more people are reported killed, hundred or more are reported affected, state of emergency is declared, or international assistance is called for (Reproduced from UNISDR 2012)

What role has climate change played in this observed increase of hazardous events? When interpreting the drivers of historical trends in hazardous events over the last few decades, it is important to remember that the data is based on observations of events. Parts of the historical increase in hazardous events can be credited to better reporting. The increased exposure to events, due to population growth, as well as the radically increased access to information, due to the progress in information technology (e.g., global media coverage, Internet), lead to better reporting of hazardous events (Peduzzi 2005).

Reporting of non-climate events can be used to separate the role of climate change from that of improvement in observations. Earthquakes, for example, are not climate events and can hence be used as a basis to judge the influence on improved access to information versus the influence on climate change (Peduzzi 2005). Both the number of reported earthquakes as well as of reported climatic disasters has increased since 1970, which is in line with better access to information, as media coverage was global by the end of 1970s. However, since this initial increase, the number of earthquakes remained steady, whereas the numbers of floods, for example, continued to increase (Peduzzi 2005). The fact that tectonic events remain steady and climatic events are increasing raises concern about the impact of climate change on the frequency of natural hazards (Peduzzi 2005).

There is evidence from observational data that weather and climate extremes have changed since 1950 due to the human impact on the climate system (IPCC 2012a). The latest IPCC Working group I report confirms these findings (IPCC 2013).

Cold days and nights have decreased, whereas warm days and nights have increased. This is based on a global scale and on land data only (IPCC 2013). Heat waves frequency has increased in most areas of Europe, Asia, and Australia (IPCC 2013). Further, a statistically significant increase in heavy precipitation events (e.g., 95th percentile) has been detected in many regions. This is consistent with the increase in temperature and the observed rise in atmospheric water vapor (IPCC 2007a). Europe and North America experienced increased frequency and intensity of heavy precipitation events (IPCC 2013). However, there remains great variation within the precipitation trends depending on the region (IPCC 2012a).

The trends are less consistent for droughts, floods, and cyclone activity (IPCC 2012a) (see Sect. 2.2.4 for a targeted section about tropical cyclone activity). Some regions, for example, have shown more intense and longer drought periods (e.g., southern Europe, West Africa) others have shown a decline (e.g., Central North America) (IPCC 2012a).

2.2.3 Future Trends

Confidence of future projections of climate and weather extremes depends on a variety of factors, including the uncertainty inherent to future climate simulations (e.g., uncertainty related to climate sensitivity and choice of scenarios), the type of extreme events, the temporal and spatial scale of events, and the ability of models to describe the key underlying processes. Historical data availability plays a critical role as well (IPCC 2012a).

A portion of the uncertainty in future predictions is epistemic ("knowable unknowns") and may be reduced through further model development and data availability. There is some level of stochastic uncertainty ("unknowable unknowns"), however, which may be insensitive to further scientific efforts.

Despite the uncertainty, there is scientific consensus on the overall future trajectory of some weather and climate extremes. Extreme temperatures and precipitation events are anticipated to increase under a warming climate (Peterson et al. 2012). Model projections assess that the returning period of extreme hot days and heat waves will increase. A hottest day that used to occur once every 20 years is likely to occur once every other year by the end of the twenty-first century in most areas around the globe (IPCC 2012a). Also projected to increase are the length, frequency, and/or intensity of heat waves (IPCC 2013). It is important to note that cold extreme events will continue to happen (IPCC 2013). Extreme hot and cold days can, for example, influence the mortality rate in cities. A recent study by Li et al. (2013) forecasts an increase in net temperature (heat- and cold-) related deaths for Manhattan, New York, by 2080 of more than 15 %.

Likewise, the frequency of extreme precipitation events and coastal high waters are projected to increase in many regions across the globe (IPCC 2013). Heavy precipitation events are projected to increase particularly in higher latitudes, tropical regions, as well as in the Northern Hemispheric mid-latitudes during winter (IPCC 2012a). A recent study by Kunkel et al. (2013a) confirms this projection. They found that many regions of the Northern Hemisphere are expected to see a 20–30 % increase in the maximum precipitation by the end of this century if greenhouse gas emissions continue to rise (Kunkel et al. 2013a). They analyzed moisture in the atmosphere, upward motion of air in the atmosphere, and horizontal winds, all factors that contribute to extreme precipitation events. Following the Clausius–Clapeyron equation, a warmer atmosphere as a result of increased greenhouse gas concentration can hold more water. This increased moisture content dominates the other factors (upward motion and horizontal winds) and hence fuels more intense extreme precipitation events (Kunkel et al. 2013a).

The confidence remains medium or low regarding projections of droughts, floods, and cyclones. However, the projected precipitation and temperature patterns are most likely impacting natural hazards. Increasing extreme precipitation events, for example, can influence the occurrence of floods and landslides (IPCC 2012a). Drought events, likewise, can be intensified by reduced overall precipitation and increased temperatures which affect evapotranspiration (IPCC 2012a). Increased drought events, for example, are projected with medium confidence in southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa (IPCC 2012a). Sea-level rise is projected to continue to increase during the twenty-first century. All of the Representative Concentration Pathways scenarios predict an even higher rate of increase than the rate observed during 1971–2000, which will be mainly caused by increased thermal expansion of the oceans and melting of glaciers and ice sheets (IPCC 2013). Regarding cyclone projections, precipitation rates and average wind speed are expected to increase in the coming century (IPCC 2012a; Seneviratne et al. 2012) (see next section for more details).

2.2.4 Influence of Climate Change on Past and Future Tropical Cyclones

Formal detection of past trends in measures of tropical cyclone activity is constrained by the length and quality of the historical data records and uncertain understanding of natural variability in these measures, particularly on decadal time-scales (Knutson et al. 2010; Lee et al. 2012; Seneviratne et al. 2012; Kunkel et al. 2013a, b; Zwiers et al. 2013). When designing Early Warning Systems (EWS), it is useful to consider past and projected trends on the spatial scale of a particular ocean basin, but trends focused on more targeted regions such as those defined by islands or sections of coastline are most relevant. Unfortunately, this narrowing of the spatial scales of interest introduces further uncertainty into both detection of past trends and projections of future trends (Seneviratne et al. 2012). In addition to the reduced sample size that accompanies the narrowing of scale, a substantial amount of noise is introduced by tropical cyclone track variability (e.g., Kossin and Camargo 2009).

Track variability is largely driven by random day-to-day variability in atmospheric wind currents, but there are also linkages operating on a broad range of time-scales in response to known modes of climate variability such as the El Niño – Southern Oscillation (ENSO), among many others (Ho et al. 2004; Wu et al. 2005; Camargo et al. 2007, 2008; Kossin and Vimont 2007; Wang et al. 2007, 2010; Chand and Walsh 2009; Tu et al. 2009; Kossin et al. 2010; Chu et al. 2012). Even relatively small changes in tropical cyclone tracks can lead to large differences in associated impacts at any given location. For example, a group of islands can be impacted by multiple tropical cyclones in a single season (e.g., the Philippines in 2009) and then remain largely unaffected for many subsequent years, even while the total number of storms in the larger basin exhibits normal variability. This type of clustering occurs randomly, but it can also occur through more systematic and persistent modulation by climate variability.

Of particular relevance to longer-range disaster planning and risk mitigation strategies aimed at specific intra-ocean-basin regions is how tropical cyclone tracks may change in a warming world (Wang et al. 2011; Murakami and Wang 2010). This needs to be considered in addition to questions about how basin-wide changes in tropical cyclone frequency and intensity may change. For example, conditions that lead to increased basin-wide activity can also shift tracks such that landfall frequency may increase proportionally more or less, thus compounding or offsetting the impacts. Presently, there has been more research toward understanding linkages between climate change and tropical cyclone frequency and intensity than toward understanding linkages between climate and track variability. These are both active areas of study of great relevance to designing EWS.

Increasing trends in land-falling tropical cyclones have not yet been detected in any of the regions that have been studied (Wang and Lee 2008; Chan and Xu 2009; Kubota and Chan 2009; Lee et al. 2012; Weinkle et al. 2012). A statistically significant decreasing trend in the number of severe tropical cyclones making landfall over northeastern Australia since the late nineteenth century has been identified by Callaghan and Power (2010). Contrarily, a significant positive trend has been identified in the frequency of extreme sea-level anomaly events along the United States East and Gulf Coast in the period 1923–2008, and this trend is argued to represent a trend in storm surge associated with land-falling hurricanes (Grinsted et al. 2012). As stated above, these trends likely represent some combination of basin-wide frequency changes and track shifts (e.g., Bromirski and Kossin 2008). The difference between Callaghan and Power (2010), who show a long-term decreasing trend in Australian landfall events and Grinsted et al. (2012), who suggest a long-term increasing trend in storm surge associated with US landfall events, emphasizes the challenge of understanding and projecting changes in tropical cyclones that are most relevant to coastal impacts.

Human-caused increases in greenhouse gases have very likely contributed to the observed increase in tropical ocean temperatures over the past century (Santer et al.

2006; Kunkel et al. 2008). Shorter-term decadal variability in regions where tropical cyclones form and track is generally dominated by natural variability (e.g., Ting et al. 2009; Camargo et al. 2013; Zhang et al. 2013) and factors such as volcanic eruptions (e.g., Thompson and Solomon 2009; Evan 2012), changes in natural particulates such as African dust (e.g., Evan et al. 2009, 2011a, 2012), and changes in human-caused particulate pollution (e.g., Mann and Emanuel 2006; Baines and Folland 2007; Chang et al. 2011; Booth et al. 2012; Evan et al. 2011b). There is presently some debate about the effect that globally increasing greenhouse gases has on tropical cyclones versus the effect of regional changes in particulate concentrations (e.g., Emanuel and Sobel 2013). Increases in globally well-mixed greenhouse gases are argued to be less effective at making the tropical environment more conducive to tropical cyclone formation and intensification compared to the more local effects caused by changes in particulate pollution (Vecchi and Soden 2007; Ramsay and Sobel 2011; Camargo et al. 2013), but both factors need to be considered for short- and long-range planning.

While there is currently debate about the relative contributions of natural versus human-caused changes in tropical climate on 10–40-year time-scales, there is mounting evidence that human-caused particulate pollution has played a substantial role in some of the recent marked increases in tropical cyclone activity. In the tropical North Atlantic Ocean, the reduction of pollution aerosols since the United States Clean Air Act and Amendments during and after the 1970s (with further contribution from the European Commission's Air Quality Framework Directive) has been linked to tropical sea surface temperature increases and associated increases in tropical cyclone activity. This linkage has been related to the direct effect of reduced atmospheric dimming allowing more sunlight to reach the ocean surface (e.g., Mann and Emanuel 2006), and to the indirect effects of reduced cloud albedo (Baines and Folland 2007; Booth et al. 2012; Dunstone et al. 2013). In the Northern Indian Ocean, black carbon particulate pollution has been linked to changes in sea surface temperature gradients (Chung and Ramanathan 2006; Meehl et al. 2008), which has weakened the mean vertical wind shear in the region. Evan et al. (2011b) linked the reduced wind shear to the observed increase in the number of very intense storms in the Arabian Sea, including five very severe cyclones that have occurred since 1998, killing over 3,500 people and causing over $6.5 billion in damages (in 2011 US dollars).

As with observational analyses, confidence is compromised when numerical projections of tropical cyclone activity are reduced from global to regional scale (IPCC SREX Box 3–2; Seneviratne et al. 2012). When assessing the results of all available model simulations, it is likely that global tropical cyclone frequency will decrease slightly in the twenty-first century, but there is little confidence in this on regional scales (e.g., Ying et al. 2012). Mean tropical cyclone intensity and rainfall rates are projected to increase with continued warming, and the models tend to agree better when projecting these measures of activity (Knutson et al. 2013). Models that are capable of producing very strong cyclones usually project increases in the frequency of the most intense cyclones (Emanuel et al. 2008; Bender et al. 2010; Knutson et al. 2010; Yamada et al. 2010; Murakami et al. 2012; Knutson et al. 2013). This measure is highly relevant to physical and societal impacts, compared with measures of overall storm frequency or mean intensity, which can be dominated by weaker storms. Long-term planning under projected warming scenarios should then account for these potential increases in severe tropical cyclones, as well as a likely increase in rainfall rates and associated coastal and inland fresh-water flooding.

Based on idealized numerical simulations, Knutson and Tuleya (2004) suggested that increases in tropical cyclone intensity forced by CO_2-induced tropical warming would not be clearly detectable for multiple decades. However, as discussed above, regional forcing by particulate pollution can bring about more rapid changes. Thus, numerical projections based on future scenarios are highly dependent on projections of both CO_2 concentrations and particulate concentrations, particularly on decadal time-scales. But there is greater uncertainty in projections of particulate pollution than CO_2 (e.g., Forster et al. 2007; Haerter et al. 2009). At present, regional projections of tropical cyclone activity on time-scales relevant to EWS design remain somewhat uncertain, but this is an area of active research.

2.3 Event Attribution

The SREX (IPCC 2012a, b) confirms that extreme events have been and are projected to be on the rise. Major extreme event databases and insurance companies' numbers corroborate this (EM-DAT 2011; Munich 2012). There is also increasing scientific evidence that the changing likelihood of extreme events is linked to human-induced climate change (IPCC 2012a). The working group I of the IPCC fifth Assessment Report (2013) concludes that the probability of heat waves in some areas has more than doubled due to human influence.

In the aftermath of major disasters, scientists are usually confronted with the question of whether individual extreme events (i.e., floods and hurricanes) can be attributed to climate change. There is disagreement among climate scientists about the proper response to such inquiries. In the past, climate scientists were generally cautious linking a single extreme event to climate change because of the statistical difference between weather and the long-term averaged climate and would only conclude that climate change increases the possibility for extreme events to occur. Recently, however, the idea of event attribution has become more realistic, although the possible outcomes of event attribution studies are still limited to statistical probabilities. This section explains the science of event attribution and its challenges. It also raises the question of liability in general: Does event attribution bolster the case of lawsuits and damage claims?

2.3.1 What Is Event Attribution?

Event attribution tries to understand and quantify the human and natural influences on individual extreme events (such as a drought or flood events) (Stott et al. 2011). In general, it tries to answer the following question:

Is a particular extreme event more or less likely with or without human influence on the climate?

Event attribution often uses a method called fractional attribution. This method tries to assess what fraction can be attributed to natural cycles and what can be attributed to human influence on climate. This approach is based on the physical understanding of the climate system and the individual hazard itself, on data comparison, as well as on climate models. Pall et al. (2011) and Min et al. (2011) applied this method in their studies (see Sect. 2.3.3).

The Interpreting Climate Conditions group at the Earth System Research Laboratory's Physical Science Division from NOAA and the Attribution of Climate-related Events group (ACE) as part of the Met Office/Hadley Centre in collaboration with NOAA have been established to forward this research arm.

Whereas the Interpreting Climate Conditions group is mainly focused on the climate attribution of the United States, the ultimate goal of ACE is to establish an international system that could provide timely, scientifically robust, and reliable assessments of recent extreme events and the influence climate change has had on them (Schiermeier 2011).

2.3.2 Potential Issues

Event attribution cannot relate a specific event with absolute confidence to human causes. Extreme events are part of the natural climate system and have always occurred, even when humans have not been present. Event attribution statements therefore remain in the realm of possibilities and cannot deliver finite answers (Nature 2011; Allen 2003). This means that only the influence of factors on the probability and intensity of an extreme event can be assessed (Stott et al. 2011).

Event attribution is dependent on how well we understand the physics behind extreme events (Stott et al. 2011). Hence, some events like heat events are easier to attribute than others (Schiermeier 2011). Further, "[a]ttribution is only as good as the models and statistics that power it" (Nature 2011). The results depend on the model and the data availability, reliability, resolution, and length of historic records.

The results of event attribution also depend on the exact research question and what the research tries to attribute: If it is the magnitude of an individual event or the likelihood that a certain threshold is exceeded (Peterson et al. 2012) (see Sect. 2.3.3).

Lastly, a very important question is: what drives event attribution research? Is it the goal to create a liability case for climate change extremes and their related costly damage? Who do you sue in the aftermath of a flooding when the house prices fall? (Allen 2003).

Event attribution up until now can only produce probabilities; will that be enough to make legal cases? This is not only a scientific question but also a legal one (Allen 2003).

> The big question is whether current greenhouse-gas emitters could ever be held liable for the actual impacts of their emissions. (Allen 2003)

Trenberth (2012) suggests that the attribution approach should be changed; instead of having a null hypothesis that states that the human influence has no effect on climate to a null hypothesis that recognizes the anthropogenic influence. As a consequence he then argues that all weather events are impacted by climate change, because climate change altered the background environment in which they occur (Trenberth 2012). So the task then would be to prove that an extreme event is not influenced by climate change.

2.3.3 Examples of Event Attribution Studies

To date, only a few studies have attempted extreme events attribution; for example, the heat wave in Europe in 2003 (Stott et al. 2004; Christidis et al. 2010) or in Moscow in 2010 (Dole et al. 2010), the flood in the United Kingdom in 2000 (Pall et al. 2011), the increased extreme precipitation events over the Northern Hemisphere (Min et al. 2011), and recently the drought in Somalia in 2011 (Lott et al. 2013) have been subject to event attribution research. Some studies found that a certain fraction of the cause of climate extreme events could be attributed to human influence on climate, others could not.

In the case of the European heat wave in 2003, Stott et al. (2004) concluded that "human influence has at least doubled the risk of a heatwave […]" with mean summer temperatures as high as those recorded in Europe in 2003. Pall et al. (2011) examined the flood event that occurred in the United Kingdom in the year 2000 during the wettest summer since records started in 1766. They found that "[…] in nine out of ten cases their model results indicated that twentieth-century anthropogenic greenhouse gas emissions increased the risk of floods occurring in England and Wales in autumn 2000 by more than 20 %, and in two out of three cases by more than 90 %." Similarly, Min et al. (2011) examined the increased intensity of extreme precipitation events in the Northern Hemisphere and found that human influenced greenhouse warming played a role in the pattern of extreme precipitation events.

Studies that assessed the human impact on the 2010 Russian heat wave published controversial results. Dole et al. (2011) concluded that the heat wave was most likely from natural origin, Rahmstorf and Camou (2011) concluded that it was affected by anthropogenic influence. Otto et al. (2012) demonstrated that the discrepancy between the Dole et al. (2011) and Camou (2011) results stems from the different attribution questions asked: magnitude (Dole et al. 2011) versus the probability of the heat wave (Rahmstorf and Camou 2011). This showcases the importance of the focus of the attribution question as mentioned in Sect. 2.3.2.

The most recent publication by Lott et al. (2013) assessed whether or not the unusual rainy season preceding the drought in Somalia in 2011 can be attributed to human-induced climate change. They found that the rainy season in 2010 was mostly affected by the teleconnections of the ongoing La Niña event. However, human influence most likely played a role in the unusual dry rainy season in the following year in 2011. Between 24 % and 99 % of the causes of the dry rainy season in 2011 could be attributed to human influence on the climate (Lott et al. 2013).

It is important to note that not all climate extreme events are attributable to human impacts on climate. Perlwitz et al. (2009) showed that the cold snap in North

America in 2008 was mostly due to cooling sea surface temperatures in the tropical Pacific, which is part of natural ocean variability. They, however, also found that the cooling was partially offset by the ongoing human warming impact on the climate.

2.3.4 Outlook

Extreme events can be destructive and knowing what causes them is a major public interest (Schiermeier 2011).

As past studies have shown, some extreme weather events are not wholly or even partly attributable to human-induced climate change, as many other factors are playing roles as well (i.e., Lott et al. 2013; Perlwitz et al. 2009).

Being able to attribute extreme events to climate change is valuable from litigation, insurance, and adaptation points of view. The risk of misattribution of events, however, looms large. Incorrectly attributing events to climate change can lead to public confusion about climate change and limit public and political support for investment in disaster risk reduction and climate change adaptation (Stott et al. 2011; Donner 2012). Even in a case where it can be shown that human influence leads to a higher probability of occurrence of a certain type of event, the probability of that event is not necessarily the same every year (Peterson et al. 2012).

Despite these limitations, there remains great potential for future advancement in event attribution research. Rather than examining only temperature or precipitation anomalies, attribution researchers may find higher statistical confidence by focusing on other climate variables or on atmosphere and ocean dynamics.

For example, most of the research on Atlantic hurricanes has focused on forcing from ocean temperatures and storm intensity. Estimating the role of anthropogenic climate change in the formation of an individual Atlantic hurricane like Sandy, or the frequency of hurricanes like Sandy, is limited by the complex array of factors that influence hurricane development. Alternatively, looking beyond ocean temperatures, and examining the unique path of Hurricane Sandy and record storm surge in New York City may present additional opportunities for attribution research. First, Hurricane Sandy made landfall in the United States because a strong high pressure system forced the oceanic storm to make an unusually sharp westward turn – and anti-Coriolis left turn. Attribution research could build upon recent findings that prolonged "blocking" high pressure systems are expected to be more common (Trenberth and Fasullo 2012), especially in North America due to the climate-driven decline in Arctic sea ice cover (Francis and Vavrus 2012). Second, Sandy created a record storm surge at New York City's Battery Park gauge, for which sea levels have increased on average by 40 cm since the late 1880s due to climate change and land subsidence (NPCC 2010). Attribution research could examine the relative contribution of sea-level rise to the storm surge and wave run-up at individual locations using climate and hydrodynamic models.

Different perspectives that try to connect the influence of teleconnections and the relationship between events as well as to understand the environment in which the extreme events are happening may prove relevant for future event attribution research (Trenberth and Fasullo 2012).

2.4 Global Distribution and Impact of Natural Hazards

Natural hazards are occurring all over the world in developing to developed countries: from the floods in Nigeria to the drought in the United States in 2012. As mentioned in Sect. 2.1, not all hazards turn into disasters and not all of them have negative and wide reaching impacts and/or monetary damage. The impact of natural hazards and, in particular, the disaster risk, when compared on a global level are unevenly distributed across the globe (UNISDR 2009b). In general, it can be said that disaster risk is related to economic development pathways and low-income countries are most at risk (UNISDR 2011a). This section illustrates the global distribution of disaster impacts and risks with numbers and statistics.

2.4.1 Disaster Impact in Numbers

The second biennial Global Assessment Report (GAR) of disaster risk reduction summarizes the state of the art of disaster risk in the context of the UNISDR and the Hyogo Framework for Action (HFA), an international initiative to improve risk reduction strategies (UNISDR 2011a). The main findings are that the overall economic costs related with natural hazards are rising, whereas the number of people killed by these hazards is decreasing (UNISDR 2011a). This relationship of increasing cost and decreasing number of deaths is however not true for low-income countries with weak risk governance capacity (UNISDR 2011a). Over the last few decades, the majority of fatalities (more than 95 %) related with extreme events have been recorded in developing countries (UNEP 2012b). The IPCC (2012a, b) SREX report confirms this by stating that climate extremes cause developing countries higher death rates and greater impact measured as portion of their gross domestic product (GDP) but higher total economic loss for developed countries.

When considering continents instead of developing and developed countries as a baseline the distribution again is uneven. Between 2000 and 2008, Asia recorded the highest number of weather- and climate-related disasters (floods and storms being the most frequent (CRED 2013)), whereas the Americas recorded the highest economic loss (54.6 % of the total loss). Africa's proportion of economic loss was less than 1 % (IPCC 2012a). However, these statistics generally do not include estimates of the cost of lives, cultural damage, or ecological damage, and thus may underestimate losses from disasters, especially in the developing world (IPCC 2012a).

The year 2012 was overall the third costliest year for the insurance companies according to data collected by Munich RE (Fig. 2.7). Hurricane Sandy and the drought in the United States were the costliest natural catastrophes in 2012, both by overall losses as well as insured losses (Munich 2013). Figure 2.8 summarizes the wide reaching impacts of disasters from 2000 to 2012: 1.2 million people killed, 2.9 billion affected, and a total of 1.7 trillion US dollar damage (UNISDR 2013b). The numbers are slightly different than the results from Munich RE as they are based on a different database. New numbers from the GAR 2013 add that disasters during the

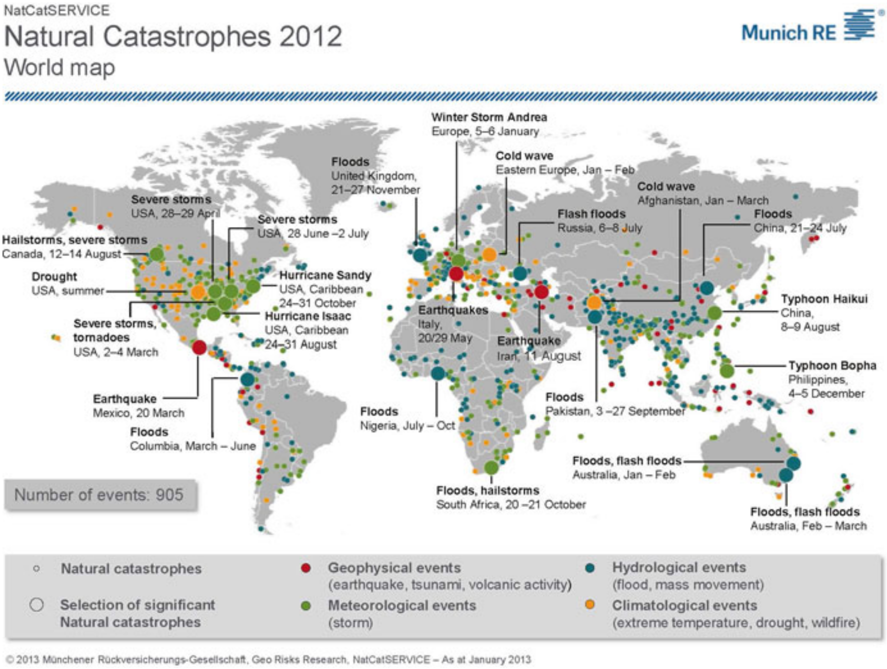

Fig. 2.7 Natural catastrophes that occurred across the globe in the year 2012 as recorded by Munich RE (Reproduced from Munich 2013)

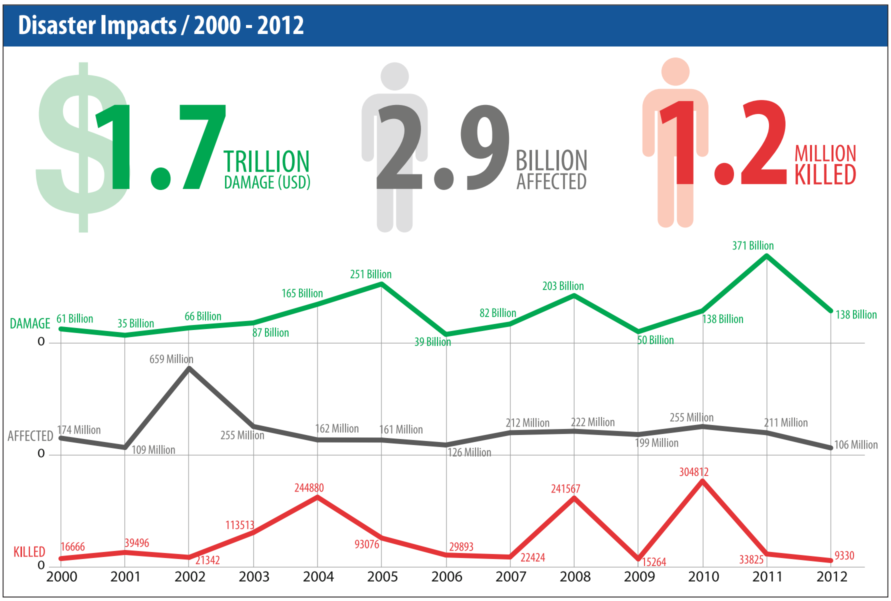

Fig. 2.8 Impacts of disasters from 2000 until 2012 expressed by damage in USD, people affected and people killed. Disasters include drought, earthquake, epidemic, extreme temperature, flood, insect infestation, mass movement, storm, volcano, and wildfire. Data from EM-DAT (Reproduced from UNISDR 2013b)

last 3 years have all caused more than US$ 100 billion annually in direct economic losses, uninsured losses are not even included (UNISDR 2013a).

Linking monetary disaster loss to climate change can be misleading, Crompton et al. (2011) suggest caution when linking normalized damage losses of weather-related natural hazards, in particular tropical cyclone losses, to human-caused climate change, stating that it might be better to focus on climate data than loss data in order to detect a climate signal. However, it should be noted that normalizing for damages may ignore the improvement in design and protective measures that reduce the risk of damages during a disaster in general.

2.4.2 Disaster Risk Distribution

The risk of disaster and the possible damages depend heavily on socioeconomic factors, as well as the frequency and intensity of extreme events. The GAR as well as the SREX report concludes that the rising risk of economic loss due to weather events is related to the increasing number of people and economic assets exposed to events (UNISDR 2011a; IPCC 2012a). Risk therefore broadly follows urban and regional development, meaning that the economic risk increases with growing population and exposed assets (UNISDR 2011a). A 2012 study released found that around 60 % of people living in urban areas, with more than one million inhabitants (in 2011), are living in regions at risk from natural hazards (UNDESA 2012). In other words, approximately 1.4 billion people are living in risk exposed regions (UNDESA 2012).

Disaster risk also increases where GDP and assets are not high. The SREX report states that socioeconomic factors will impact the future distribution and increases in weather-related losses (IPCC 2012a). The poorest communities are generally considered most at risk, as they tend to live in risk-prone areas, such as floodplains and unstable slopes. Their limited assets increase the chances that they live in poorly built houses, are dependent on climate-related sectors for income (e.g., agriculture), and have limited capacity to cope with the impacts of natural hazards or have inadequate access to relevant emergency services (UNISDR 2008, 2009b). As an example, 44 % of the global population already lives near coastal areas (UN Atlas of Oceans). These areas, however, are at risk of floods, cyclones, and rising sea levels (UNISDR 2009b). The IPCC SREX report showed that the amount of people at risk to future sea-level rise is tremendous, in particular in highly populated mega-deltas in Asia, such as the Mekong or Ganges delta (IPCC 2007b).

Small island developing states as well as land locked developing countries are at elevated risk due to their limited economic strength and resilience (UNISDR 2009b). The GAR 2011 declared drought as the hidden risk due to its complexity and many different drivers (UNISDR 2012). Further complicating is the disconnectedness between the early warning and the adequate early action (Chatham House 2013). Figure 2.9 represents the multi-risk associated with tropical cyclones, floods,

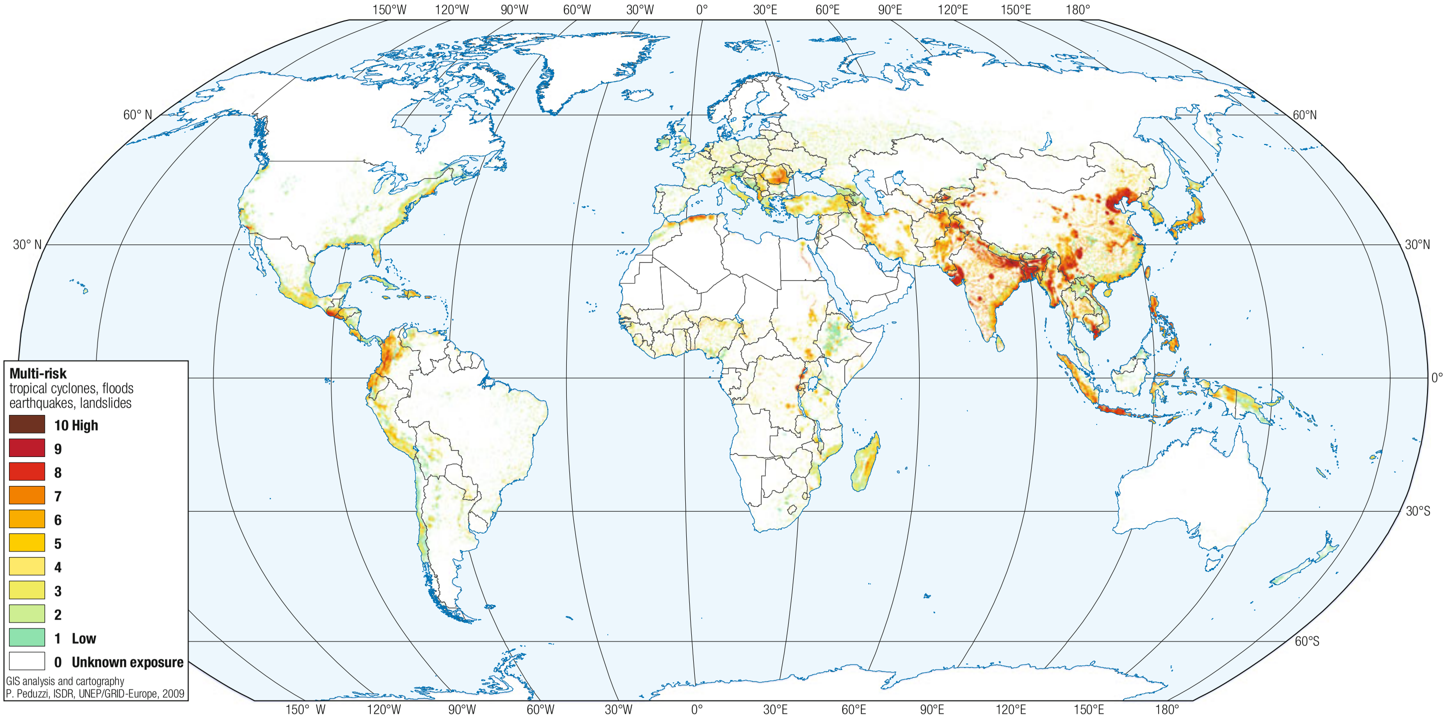

Fig. 2.9 Global distribution of multiple hazards mortality risk from tropical cyclones, floods, earthquakes, and landslides in 2009 (Image provided by P. Peduzzi, ISDR, UNEP/GRID-Europe, reproduced from 2009 Global Assessment Report on Disaster Risk Reduction (UNISDR 2009b))

earthquakes, and landslides combined as analyzed in the GAR 2009. This figure shows high multiple hazard mortality risk across Asia.

To summarize, regions at risk vary depending on how the risk is defined. For example, the countries with the highest tropical cyclone mortality rates are Bangladesh and the Philippines. When risk to tropical cyclones, however, is defined by absolute economic loss, OECD (Organisation for Economic Cooperation and Development) countries such as Japan and the United States are more at risk. Conversely, when relative economic risk is considered African countries such as Madagascar suffer the highest risk (UNISDR 2009b).

2.4.3 Outlook

Natural hazards already place an enormous burden on economies, societies, and the environment worldwide. With projected increases in intensity and frequency of extreme events due to climate change as well as increasing exposure and vulnerability of populations, impacts of natural hazards are most likely worsening (UNISDR 2012).

The IPCC SREX report (2012a) concludes that knowledge about future changes of extreme events should be combined with knowledge of vulnerability and exposure to inform adaptation, mitigation, and disaster risk management as well as sustainable development efforts. Combining these efforts can be beneficial (IPCC 2012a). The most recent GAR (UNISDR 2013a) further strengthens the importance of considering disaster risk management into business decisions. Including disaster risk can increase business resilience, competitiveness, and sustainability (UNISDR 2013a). The report further points out the importance of the business case for disaster risk reduction. Focusing on managing risks as compared to managing disasters opens up opportunities and markets for businesses (UNISDR 2013a).

Regarding adaptation efforts, there exists a variety of estimated adaptation costs that would climate-proof predicted increasing disaster risks. The World Bank (2010) recently estimated a total cost of US$ 75–100 billion (in 2005 US$) annually for adaptation for developing countries. The GAR of 2013 states that the cost estimate for corrective disaster risk management ranges in the same numbers (UNISDR 2013a). Adaptation cost estimates are however based on low confidence, as there are only a limited amount of global studies and a variety of factors and assumptions that complicate these estimates (IPCC 2012a). In recent UNFCC negotiations in Cancun the developing world has then agreed to establish a Green Climate Fund, with the goal to raise $100 billion per year by the year 2020 to help the developing world to respond to climate change (UNFCC 2010). However, donor countries have yet to make specific funding commitments, and the funds are anticipated to go toward both adaptation and mitigation efforts (Donner et al. 2011). Nevertheless, the GAR 2013 further points out that disaster risk management is a potential market with great opportunities for development (UNISDR 2013a).

The IPCC SREX report also points out the importance and potential of EWS as they can reduce the amount of lost lives and mitigate the economic impact and damage from extreme events (IPCC 2012a). EWS inform populations at risk and provide timely warnings to allow for preparation (UNEP 2012a). An EWS consists, however, of much more than just a forecasting system (IPCC 2012a). The HFA points out that EWS must include "guidance on how to act upon warnings" and they should be "understandable to those at risk" (UNISDR 2010). In a changing future with a predicted increase in extreme events, there is a growing need to strengthen disaster risk management and adequate response strategies. A particular focus should lie on multi-hazard EWS, as these are still very rare and not available on a global scale. More about EWS can be found in Chap. 5.

2.5 Conclusion

Extreme weather events are going to happen, they have happened in the past and the will happen in the future. Most likely, however, the frequency and intensity of extreme events is going to be changed as the environment in which they occur has altered due to climate change. The GAR (UNISDR 2013a) even warns that "the worst is yet to come." The human impact on the climate system is clear (IPCC 2013). Whether or not individual events can be attributed to human impacts, a focus has to lie on reducing the disastrous outcome of natural hazards. This can be done in a variety of ways, EWS as well as reducing underlying vulnerability and exposure of people and assets are among them.

Chris Field, Co-Chair of the IPCC Working Group II who together with Working Group I produced the IPCC SREX report, gets to the point:

> The main message from the report is that we know enough to make good decisions about managing the risks of climate-related disasters. Sometimes we take advantage of this knowledge, but many times we do not, […] [t]he challenge for the future has one dimension focused on improving the knowledge base and one on empowering good decisions, even for those situations where there is lots of uncertainty. (IPCC 2012a)

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