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# **Extreme Weather and Climate Change**

## **Understanding the Link, Managing the Risk**

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# Extreme weather and climate change: Understanding the link, managing the risk

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## Introduction

Typically, climate change is described in terms of average changes in temperature or precipitation, but most of the social and economic costs associated with climate change will result from shifts in the frequency and severity of extreme events.<sup>1</sup> This fact is illustrated by a large number of costly weather disasters in 2010, which tied 2005 as the warmest year globally since 1880.<sup>2</sup> Incidentally, both years were noted for exceptionally damaging weather events, such as Hurricane Katrina in 2005 and the deadly Russian heat wave in 2010. Other remarkable events of 2010 include Pakistan's biggest flood, Canada's warmest year, and Southwest Australia's driest year. The early months of 2011 continued in similar form, with "biblical" flooding in Australia, devastating drought and wildfires in Texas, New Mexico and Arizona, and unprecedented flooding in North Dakota.<sup>3</sup>

Munich Re, the world's largest reinsurance company, began compiling global disaster data in 1980. In that data set, 2010 had the second-largest (after 2007) number of recorded natural disasters and the fifth-greatest economic losses.<sup>4</sup> Although there were far more deaths from geological disasters—almost entirely from the Haiti earthquake—more than 90 percent of all disasters and 65 percent of associated economic damages were weather and climate related (i.e. high winds, flooding, heavy snowfall, heat waves, droughts, wildfires). In all, 874 weather and climate-related disasters resulted in 68,000 deaths and \$99 billion in damages worldwide.

The fact that 2010 was one of the warmest years on record as well as one of the most disastrous, begs the question: Is global warming causing more extreme weather? The short and simple answer is yes, at least for heat waves and heavy precipitation.<sup>5</sup> But much of the public discussion of this relationship obscures the link behind a misplaced focus on causation of individual weather events. The questions we ask of science are critical: When we ask whether climate change "caused" a particular event, we pose a fundamentally unanswerable question (see box). This fallacy assures that we will often fail to draw connections between individual weather events and climate change, leading us to disregard the real risks of more extreme weather due to global warming.

**Why can't scientists say whether climate change "caused" a given weather event?**

*Climate* is the average of many weather events over a span of years. By definition, therefore, an isolated event lacks useful information about climate trends. Consider a hypothetical example: Prior to any change in the climate, there was one category 5 hurricane per year, but after the climate warmed for some decades, there were two category 5 hurricanes per year. In a given year, which of the two hurricanes was caused by climate change? Since the two events are indistinguishable, this question is nonsense. It is not the occurrence of either of the two events that matters. The two events together – or more accurately, the average of two events per year – define the change in the climate.

Climate change is defined by changes in mean climate conditions—that is, the average of hundreds or thousands of events over the span of decades. Over the past 30 years, for example, any single weather event could be omitted or added to the record without altering the long-term trend in weather extremes and the statistical relationship between that trend and the rise in global temperatures. Hence, it is nonsense to debate the direct climatological link between a single event and the long-term rise in the global average surface temperature.

Nonetheless, individual weather events offer important lessons about social and economic vulnerabilities to climate change. Dismissing an individual event as happenstance because scientists did not link it individually to climate change fosters a dangerously passive attitude toward rising climate risk. The uncertainty about future weather conditions and the inability to attribute single events to global warming need not stand in the way of action to manage the rising

risks associated with extreme weather. Indeed, such uncertainty is why risk managers exist – insurance companies, for example – and risk management is the correct framework for examining the link between global climate change and extreme weather.

An effective risk management framework accommodates uncertainty, takes advantage of learning opportunities to update understanding of risk, and probes today's rare extreme events for useful information about how we should respond to rising risk. Risk management eschews futile attempts to forecast individual chaotic events and focuses on establishing long-term risk certainty; that is, an understanding of what types of risks are increasing and should be managed to minimize future costs. An understanding of the meaning of risk and how it relates to changes in the climate system is crucial to assessing vulnerability and planning for a future characterized by rising risk.

**Recent Extreme Weather**

Since 2010 tied with 2005 as the warmest year on record globally, it should come as no surprise that nineteen countries set new national high-temperature records; this is the largest number of national high temperature records in a single year, besting 2007 by two.<sup>6</sup> One of the countries was Pakistan, which registered "the hottest reliably measured temperature ever recorded on the continent of Asia" (128.3 °F on May 26 in Mohenjo-daro).<sup>7</sup> Strikingly, no new national low-temperature records were recorded in 2010.<sup>8</sup> Several historic heat waves occurred across the globe, as well. Unprecedented summer heat in western Russia caused wildfires and destroyed one-third of Russia's wheat crop; the combination of extreme heat, smog, and smoke killed 56,000 people.<sup>9</sup> In China, extreme heat and the worst drought in 100 years struck Yunnan province, causing

crop failures and setting the stage for further devastation by locust swarms.<sup>10</sup> In the United States, the summer of 2010 featured record breaking heat on the east coast with temperatures reaching 106 °F as far north as Maryland.<sup>11</sup> Records were also set for energy demand and the size of the area affected by extreme warmth.<sup>12</sup> Even in California where the average temperatures were below normal, Los Angeles set its all time high temperature record of 113 degrees on September 27<sup>th</sup>.

Global precipitation was also far above normal, with 2010 ranking as the wettest year since 1900.<sup>13</sup> Many areas received record heavy rainfall and flooding. Westward shifts of the monsoon dropped 12 inches of rain across wide areas of Pakistan, flooding the Indus River valley, displacing millions of people, and destabilizing an already precariously balanced nation.<sup>14</sup> Rio de Janeiro received the heaviest rainfall in 30 years—almost 12 inches in 24 hours, causing nearly 300 mudslides and killing at least 900 people.<sup>15</sup>

Developed countries also suffered debilitating downpours. On the heels of Queensland, Australia's wettest spring since 1900, December rainfall broke records in 107 locations.<sup>16</sup> Widespread flooding shaved an estimated \$30 billion off Australia's GDP.<sup>17</sup> The United States experienced several record breaking torrential downpours. In Tennessee, an estimated 1000-year flooding event<sup>18</sup> brought over a foot of rain in two days, resulting in record flooding and over a billion dollars in damages in Nashville alone, equivalent to a full year of economic output for that city. In Arkansas, an unprecedented 7 inches of rain fell in a few hours, causing flash flooding as rivers swelled up to 20 feet.<sup>19</sup> Wisconsin had its wettest summer on record, which is remarkable given the series of historic floods that have impacted the upper Midwest over the last two decades.

The historic weather extremes of 2010 fit into a larger narrative of damaging extreme weather events in recent decades. Recent heat waves in Russia and the United States have evoked memories of the 1995 heat wave that killed hundreds of Chicagoans, and the 2003 European heat wave that killed at least 35,000 people.<sup>20</sup> In the United States, the number of storms costing more than \$100 million has increased dramatically since 1990. Although the 2010 flooding in the American Midwest was highly damaging, it was not on the scale of the 1993 and 2008 events, each costing billions of dollars and of such severity that they should be expected to occur only once in 500 years.<sup>21</sup> In 2011, there has already been another historic flood on the Mississippi River and a record breaking tornado outbreak (see box). Other unprecedented disasters include the 2008 California wildfires that burned over a million acres,<sup>22</sup> and the decade-long Southwest drought, which continues in spite of an uncharacteristically wet winter.<sup>23</sup> Mumbai, India recorded their highest ever daily rainfall with a deluge of 39 inches that flooded the city in July of 2005.<sup>24</sup> This neared the Indian daily record set the year before when 46 inches fell in Aminidivi,

#### **Will climate change affect tornadoes?**

In contrast to extreme heat, flooding, and drought, Scientists are unsure how tornadoes will respond to global warming, but rising temperatures introduce the risk that tornado-producing thunderstorms could become more violent. The lack of scientific certainty does not equate to a lack of risk. Indeed, the lack of scientific understanding is a risk factor itself. In a world where tornadoes already cause significant damage and could change because of climate change, taking steps to become more resilient is a win-win risk management strategy.

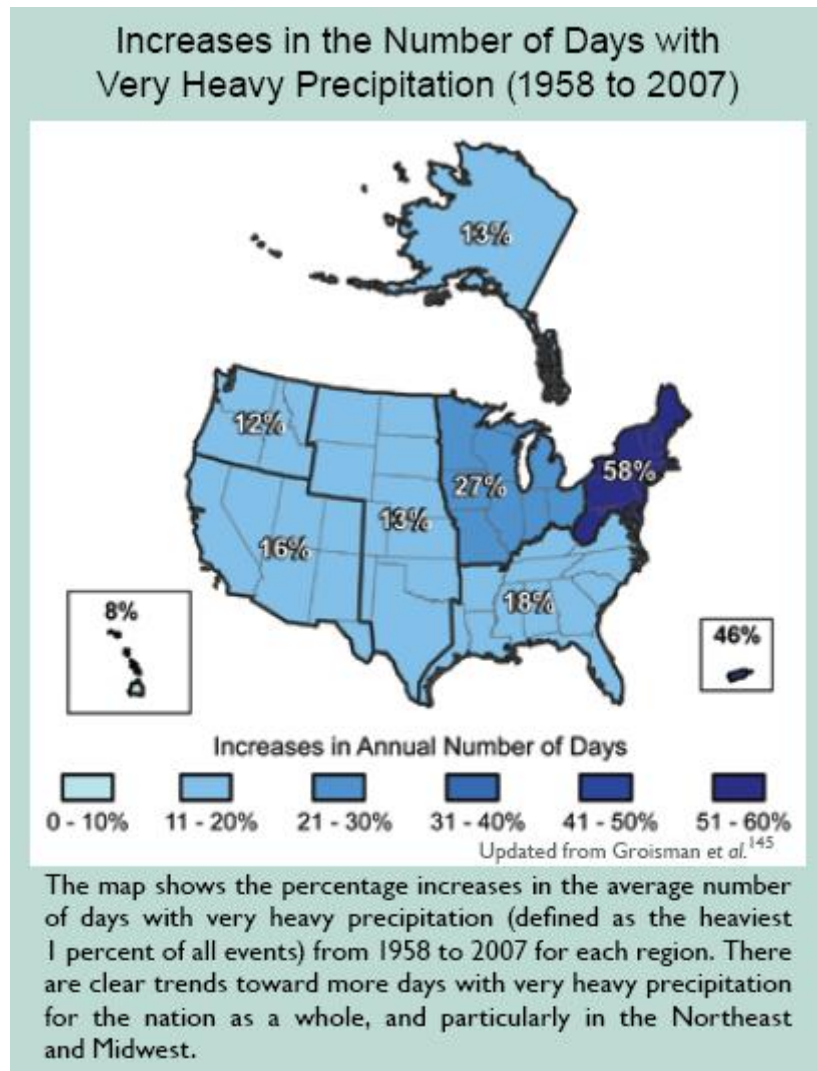
which more than doubled 30-year-old record of 22.6 inches.<sup>25</sup> Torrential downpours continued for the next week, killing hundreds of people and displacing as many as 1 million.<sup>26</sup>

### Climate Trends

Taken in aggregate, this narrative of extreme events over recent decades provides a few snapshots of a larger statistical trend toward more frequent and intense extreme weather events. Rising frequency of both droughts and floods is an expected consequence of a warming climate, and both trends have been observed. Some areas will see more droughts as overall rainfall decreases and other areas will flood more regularly. Still other regions may not experience a change in total rainfall amounts, but might see rain come in rarer, more intense bursts, resulting in periodic flash flooding punctuating periods of chronic drought. Therefore, observed trends in heat, flooding, and drought in different places are consistent with global warming.<sup>27</sup>

Over the past 50 years, total rainfall has increased by 7% globally, much of which is due to increased frequency of heavy downpours. In the United States, the amount of precipitation falling in the heaviest 1% of rain events has increased by nearly 20 percent overall, while the frequency of light and moderate events has been steady or decreasing (Figure 1).<sup>28</sup> Meanwhile, heat waves have become more humid, thereby increasing biological heat stress, and are increasingly characterized by extremely high nighttime temperatures, which are responsible for most heat-related deaths.<sup>29</sup> In the western United States, drought is more frequent and more persistent, while the Midwest experiences less frequent drought but more frequent flooding.<sup>30</sup>

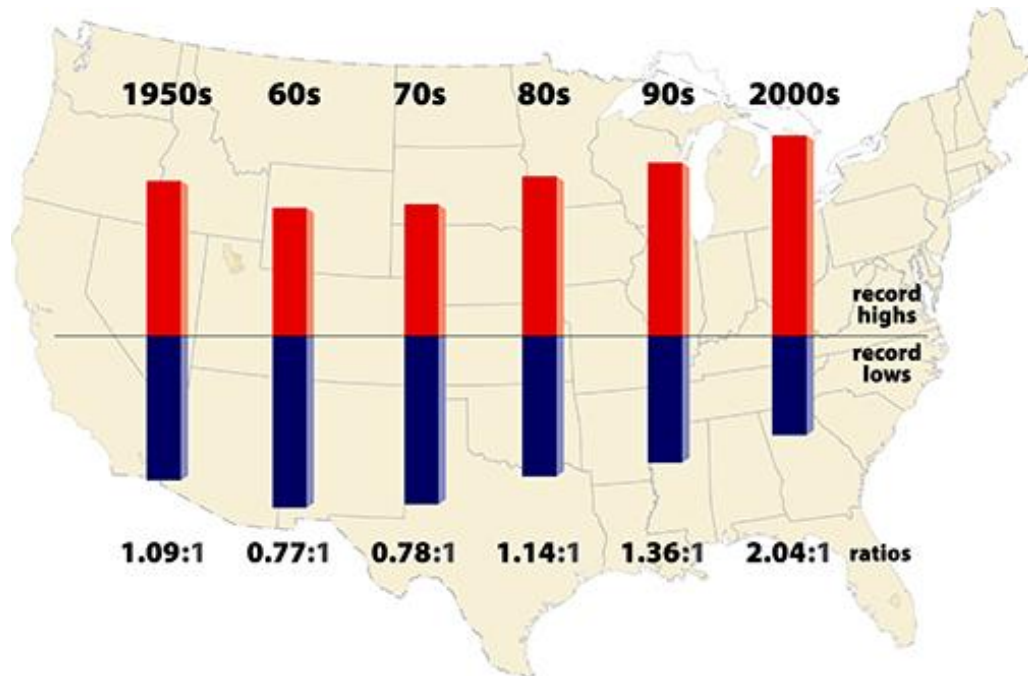
Record daytime and nighttime high temperatures have been increasing on a global scale.<sup>31</sup>



**Figure 1.** The increase in heavy downpours in the United States. SOURCE: USGCRP (2009)



In the United States today, a record high temperature is twice as likely to be broken as a record low. By contrast, record highs and lows were about equally likely in the 1950s (Figure 2).<sup>32</sup> This trend shows that the risk of heat waves is increasing over time, consistent with the results of global climate models that are forced by rising atmospheric greenhouse gas concentrations.<sup>33</sup> Indeed, the observed heat wave intensities in the early 21<sup>st</sup> century already exceed the worst-case projections of climate models.<sup>34</sup> Moreover, the distribution of observed temperatures is wider than the temperature range produced by climate models, suggesting that current models may underestimate the rising risk of extreme heat as warming proceeds.



**Figure 2.** Ratios of Record Highs to Record Lows for successive decades in the United States. SOURCE: ©UCAR, graphic by Mike Shibao (2009)

### Climate Change and the Rising Risk of Extreme Weather

When averaged together, changing climate extremes can be traced to rising global temperatures, increases in the amount of water vapor in the atmosphere, and changes in atmospheric circulation. Warmer temperatures directly influence heat waves and increase the moisture available in the atmosphere to supply extreme precipitation events. Expanding sub-tropical deserts swelling out from the equator are creating ever larger areas of sinking, dry air, thus expanding the area of land that is subject to drought.<sup>35</sup> The expansion of this sub-tropical circulation pattern is also increasing heat transport from the tropics to the Arctic and pushing mid-latitude storm tracks, along with their rainfall, to higher latitudes.

As discussed above, no particular short-term event can be conclusively attributed to climate change. The historical record provides plenty of examples of extreme events occurring in the distant past and such events obviously occur without requiring a change in the climate. What matters is that there is a statistical record of these events occurring with increasing frequency and/or intensity over time, that this trend is consistent with expectations from global warming, and that our understanding of climate physics indicates that this trend should continue into the future as the world continues to warm. Hence, a probability-based risk management framework is the correct way to consider the link between climate change and extreme weather. Just as speeding increases the risk of a deadly auto accident, but cannot be conclusively assigned as the cause of an accident, a particular heat wave is not directly caused by global warming, but has a higher risk of occurrence and of being intense because of global warming.

Extreme events are often described by their expected frequency of recurrence. A “25-year event” has a statistical expectation of occurring once in 25 years, on average. It may occur more than once in any 25 year span or not at all for a full century, but over many centuries it is expected to occur **on average** once every 25 years. Events with a longer recurrence time tend to be more severe, so that a 100-year flood is a more dreaded event than a 25-year flood. A 500-year flood would be even more damaging, but is considered to be so rare that people generally do not worry about events of such a magnitude. The problem with climate change, however, is that what used to be a 500-year event may become a 100-year or 10-year event, so that most people will experience such events within their lifetimes.

Risk cannot be thought of in a discontinuous way, with singular events having predictive power about specific future events. Risk is the accumulation of all future possibilities weighted by their probabilities of occurrence. Therefore, an increase in either disaster frequency or severity increases the risk. Events can be ordered on a future timeline and ranked by expectations about their frequency, but this only describes what will happen on average over a long period of time; it does not predict individual events. Consequently, impacts are uncertain in the short term, but the risk of impacts will rise in a predictable fashion. Risk therefore tells us what future climate conditions we should plan for in order to minimize the expected costs of weather-related disasters over the lifetime of long-lived investments, such as houses, levees, pipelines, and emergency management infrastructure.

Risk management is used extensively almost anywhere decision-makers are faced with incomplete information or unpredictable outcomes that may have negative impacts. Classic examples include the military, financial services, the insurance industry, and countless actions taken by ordinary people every day. Homeowners insurance, bicycle helmets, and car seatbelts are risk-management devices that billions of people employ daily, even though most people will never need them.

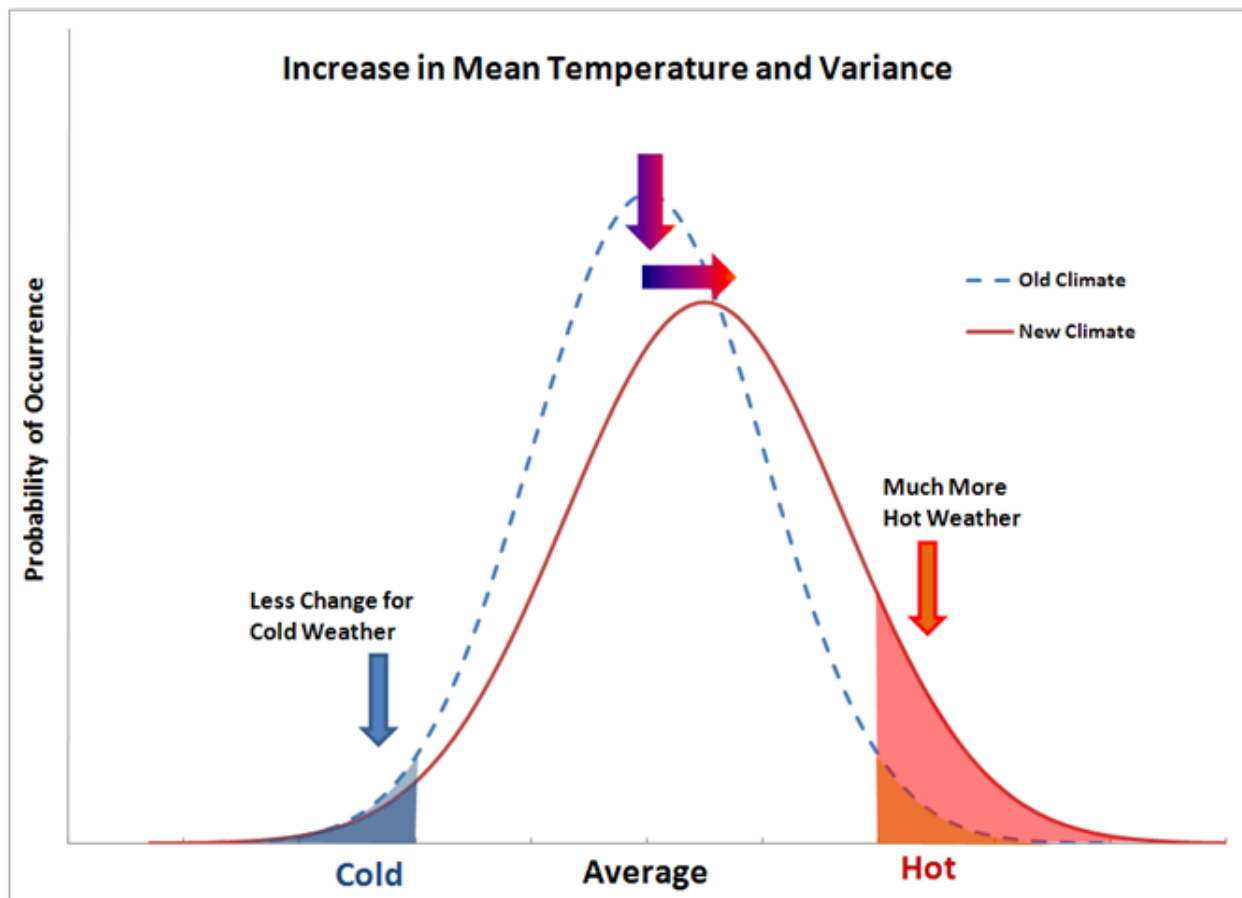
### **Understanding Climate Risk**

The extreme events cataloged above and the trends they reflect provide a proxy for the types of events society will face with greater risk in the future. With a clear record of trends and reasonable projections for the future, the level of risk can be assessed and prepared for. Risk can be thought of



as a continuous range of possibilities, each with a different likelihood of occurring; extreme outcomes reside on the low-probability tails of the range or distribution. For example, climate change is widening the probability distribution for temperature extremes and shifting the mean and the low-probability tails toward more frequent and intense heat events (Figure 3).

The rising risk of extreme events has much in common with playing with loaded dice, where the dice are weighted to roll high numbers more frequently. Moreover, one of the dice has numbers from two to seven instead of one to six. It is therefore possible to roll a 13 (i.e. the maximum possible temperature is higher than before) and would be more likely (because the dice are loaded) than rolling a 12 with two normal dice. The probability distribution of the loaded dice compared to normal dice is translated into changing climate risk in Figure 3. With normal dice, one can expect to roll snake eyes (cold extremes) about equally as often as double sixes (hot extremes). But with climate change, the dice are loaded so that cold extremes (as defined in the previous climate) are a bit less likely than they used to be and hot extremes are hotter and much more likely than before.



**Figure 3.** Conceptual representation of the shift in the probability distribution for average and extreme temperatures as a result of global warming. SOURCE: Adapted from IPCC (2001)

### Can global warming cause heavy snow?

In December 2009 and February 2010, several American East Coast cities experienced back-to-back record-breaking snowfalls. These events were popularly dubbed “Snowmageddon” and “Snowpocalypse.” Such events are consistent with the effects of global warming, which is expected to cause more heavy precipitation because of a greater amount of water vapor in the atmosphere. Freezing temperatures are normal during the winter for cities like Washington, D.C., Philadelphia, and New York. Storms called Nor’easters are also normal occurrences. As global warming evaporates more water from the Gulf of Mexico and the Atlantic Ocean, the amount of atmospheric moisture available to fuel these storms has been increasing, thus elevating the risk of events like “Snowpocalypse.”

The new risk profile presents a nonlinear increase in the number of extremes on one tail (i.e. heat waves). In light of recent cold winters in the United States and Europe, it is important to recognize that this new curve does not dispense with cold extremes, as the widening of the distribution (i.e. increase in variability) partially offsets the shift in the toward warmer events. Cold extremes become less frequent, but do not disappear (Figure 3). Moreover, like heavy downpours, heavy snowfall is also consistent global warming (see box).

Under this new risk profile, the probability of record heat increases dramatically. The deadly 2003 European heat wave offers an example of a real world event that conforms to this new expectation. An event of that magnitude has a very small probability under the unchanged climate regime, but has a much higher probability under a new climate profile that is both hotter and more variable. Since this event actually happened, we know that an event of that intensity is possible, and model projections tell us that the risk of such an event should be expected to rise dramatically in the coming decades due to global warming. Indeed,

a 50% increase in variance alone, without even shifting the average temperature, could make the 2003 heat wave a 60-year event rather than a 500-year event under the old regime.<sup>36</sup> Other research has indicated that the risk of a 2003-type heat wave in Europe is already twice as large because of warming over recent decades. With continued warming, the frequency of such an event could rise to multiple occurrences per decade by the middle of this century.<sup>37</sup>

Hot extremes are not the only sort of weather event to have increased beyond expectations. Observed increases in extreme hourly precipitation are beyond projections, even while daily precipitation changes remain within expectations. This indicates that the scaling of precipitation with increases in atmospheric moisture is not consistent between short bursts and total amounts over longer periods. In the Netherlands, a study shows that one-hour precipitation extremes have increased at twice the rate with rising temperatures as expected when temperatures exceed 12°C.<sup>38</sup> This is another example of the type of rapid increase in extreme events that is possible when the risk distribution is not only shifted, but also exhibits increased variance.

### Assessing Risk and Vulnerability

Planners and policymakers can and do use individual extreme weather events as laboratories for assessing social and economic vulnerabilities and crafting appropriate actions to minimize the suffering and costs expected from the rising risk in the future. For example, in 1995 a prolonged heat wave killed hundreds in Chicago, after which the city took effective steps to prepare for future

heat waves.<sup>39</sup> Prior to the 2003 European heat wave, the notion that such a deadly heat wave could strike Europe was unknown. Now that European society is aware of this possibility, preparations have been made to decrease future suffering and economic damage. Hurricane Katrina showed that a major American city could be paralyzed for weeks without adequate communications, security, sanitation, or health care. One adaptation response was to close the Mississippi River-Gulf Outlet Canal, which channelled Katrina's storm surge directly into New Orleans.<sup>40</sup> Other recent examples of flooding and extreme rainfall should provide lessons on where flood control and emergency response systems are most needed and the value of the required investments. Additionally, extreme events represent data points for updating trends and improving estimates of future risk, as it is critically important to update estimates of current risk as well as future risk.

Both adapting to unavoidable climate change and mitigating future greenhouse gas emissions are required to manage the risks of extreme weather in a warmer climate. Since limiting the amount of CO<sub>2</sub> in the atmosphere limits the magnitude of climate change in general, reducing CO<sub>2</sub> emissions is effective at minimizing nonlinear changes in extremes. Due to this property, mitigation action is a benefit multiplier, since linear decreases in emissions can result in nonlinear decreases in extreme risk. Conversely, since climate change is already underway, some impacts are unavoidable and society must adapt to them. In order to be effective, adaptation actions must be commensurate with the magnitude of the risk. Nonlinear increases in risk associated with weather extremes require adaptation measures beyond what would be expected from changes in average climate conditions. Moreover, many adaptation options will become infeasible if the climate changes too much. Hence, mitigation should be commensurate with the level of adaptation that is feasible.

Science is not a crystal ball, but it offers powerful tools for evaluating the risks of climate change. Scientists can investigate whether the risk of certain types of events is rising by examining recent trends, and also whether the risks are likely to increase in the future using projections from climate models. When these two indicators converge, we should look to reduce vulnerability to such events. Indeed, a growing body of research is using climate models as a tool for assessing future increases in risk. Models cannot predict specific events but for some types of extremes they can indicate how risk profiles are likely to change in the future. This approach is particularly powerful when benchmarked against actual events that society agrees should be guarded against.

For example, in 2000 the United Kingdom experienced devastating autumn floods associated with meteorological conditions that are realistically mimicked in climate models. In a climate model, the risk of severe autumn flooding increased by 20 to 90 percent under present-day climate conditions compared to preindustrial conditions.<sup>41</sup> Conversely, model simulations of the deadly 2010 Russian heat wave found no evidence that climate change has so far increased the risk of such an event, but did find that continued warming is very likely to produce frequent heat waves of similar magnitude later this century.<sup>42</sup> Hence, regardless of the cause of that particular heat wave, the risk of similar events in the future can be expected to rise with continued warming of the global climate. Because the event was so deadly and economically harmful, the rising risk of similar events should prompt serious consideration of appropriate actions to limit and adapt to this risk.

Given the uncertainties and risks, it does not make sense to focus on whether individual events are supercharged by climate change. It does make sense, however, to take lessons from actual events about our current vulnerabilities and the risks to society caused in unabated greenhouse gas emissions that drive extreme weather risks ever higher as time passes. Climate science can provide risk-based information that decision makers can use to understand how the risk is changing so that they can prioritize and value investments in prevention and adaptation.

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