EXTREME WEATHER & CLIMATE CHANGE: UNDERSTANDING THE LINK AND MANAGING THE RISK

CENTER FOR CLIMATE
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by

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Thousands of record-breaking weather events worldwide bolster long-term trends of increasing heat waves, heavy precipitation, droughts and wildfires. A combination of observed trends, theoretical understanding of the climate system, and numerical modeling demonstrates that global warming is increasing the risk of these types of events today. Debates about whether single events are "caused" by climate change are illogical, but individual events offer important lessons about society's vulnerabilities to climate change. Reducing the future risk of extreme weather requires reducing greenhouse gas emissions and adapting to changes that are already unavoidable.

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.[1] This fact is illustrated by a large number of costly weather disasters in 2010, which tied 2005 as the warmest year globally since 1880.[2] 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. 2011 continued in similar form, with "biblical" flooding in Australia, the second hottest summer in U.S. history, devastating drought and wildfires in Texas, New Mexico and Arizona as well as historic flooding in North Dakota, the Lower Mississippi and in the Northeast.[3]

Munich Re, the world's largest reinsurance company, has compiled global disaster for 1980-2010. In its analysis, 2010 had the second-largest (after 2007) number of recorded natural disasters and the fifth-greatest economic losses.[4] 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 in 2010.

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.[5] 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 1). 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.

Climate change is defined by changes in mean climate conditions—that is, the average of hundreds or thousands 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 illogical 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 illogic of attributing 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 what can be done to minimize future damages. 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.

Box 1: Why can't scientists say whether climate change "caused" a given weather event?

Climate is the average of many weather events over of 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.

RECENT EXTREME WEATHER

Since 2010 tied with 2005 as the warmest year on record globally, it should come as no surprise that 19 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.[6] 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).[7] Strikingly, no new national record low-temperatures occurred in 2010.[8] 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.[9] In China, extreme heat and the worst drought in 100 years struck Yunan province, causing crop failures and setting the stage for further devastation by locust swarms.[10] In the United States, the summer of 2010 featured record breaking heat on the east coast with temperatures reaching 106 degrees as far north as Maryland.[11] Records also were set for energy demand and the size of the area affected by extreme warmth.[12] 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.

Global precipitation was also far above normal, with 2010 ranking as the wettest year since 1900.[13] 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.[14] 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.[15]

Developed countries also suffered debilitating downpours. On the heels of Queensland, Australia's wettest spring since 1900, December rainfall broke records in 107 locations.[16] Widespread flooding shaved an estimated $30 billion off Australia's GDP.[17] The United States experienced several record breaking torrential downpours. In Tennessee, an estimated 1,000-year flooding event[18] brought more than a foot of rain in two days, resulting in record flooding and over two 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.[19] 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.

In 2011, there have already been three separate historic floods in the United States, the driest 12 months ever recorded in Texas, and a record breaking tornado outbreak (see Box 2).[20] Damages from Hurricane Irene, much of which is flood related, are estimated to be between $7 and $10 billion, making it one of the top ten most damaging hurricanes ever to hit the US.[21]

The historic weather extremes of 2010 and 2011 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.[22] 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 ferocity that they should be expected to occur only once in 300 years.[23] Other unprecedented disasters include the 2008 California wildfires that burned over a million acres,[24] and the decade-long Southwest drought, which continues in spite of an uncharacteristically wet winter.[25] Mumbai, India, recorded its highest ever daily rainfall with a deluge of 39 inches that flooded the city in July of 2005.[26] This neared the Indian daily record set the year before when 46 inches fell in Aminidivi, which more than doubled 30-year-old record of 22.6 inches.[27] Torrential downpours continued for the next week, killing hundreds of people and displacing as many as 1 million.[28]

Box 2: What about climate change and tornadoes?

Scientists are unsure if tornadoes will become stronger or more frequent, but with increased temperatures changing the weather in unexpected ways, the risk is real that tornado outbreaks will become more damaging in the future. The lack of certainty in the state of the science does not equate with a lack of risk, since risk is based on possibility. The lack of scientific consensus is a risk factor itself, and we must prepare for a future that could possibly include increased tornado damage.

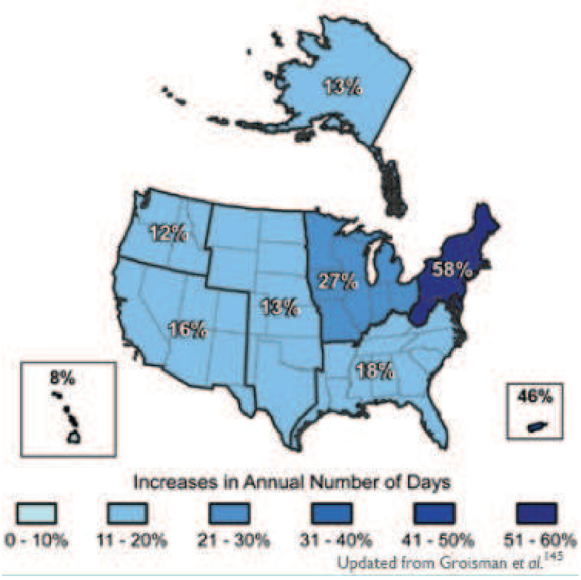
CLIMATE TRENDS

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 heavy downpours is an expected consequence of a warming climate, and this trend has been observed. Some areas will see more droughts as overall rainfall decreases and other areas will experience heavy precipitation more frequently. Still other regions may not experience a change in total rainfall amounts but might see rain come in rarer, more intense bursts, potentially leading to flash floods punctuating periods of chronic drought. Therefore, observed trends in heat, heavy precipitation, and drought in different places are consistent with global warming.[29]

Over the past 50 years, total rainfall has increased by 7 percent 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 percent of rain events has increased by nearly 20 percent overall, while the frequency of light and moderate events has been steady or decreasing (Fig. 1).[30] 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.[31] In the western United States, drought is more frequent and more persistent, while the Midwest experiences less frequent drought but more frequent heavy precipitation.[32]

Record daytime and nighttime high temperatures have been increasing on a global scale.[33] In the United States today, a record high temperature is twice as likely to be broken as a record low, and nighttime temperature records show a strong upward trend (Fig. 2). By contrast, record highs and lows were about equally likely in the 1950s (Fig. 3).[34] 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.[35] Indeed, the observed heat wave intensities in the early 21st century already exceed the worst-case projections of climate models.[36] Moreover, the distribution of observed temperatures is wider than the temperature range produced by climate models, suggesting that models may underestimate the rising risk extreme heat as warming proceeds.

FIGURE 1: Increases in the Number of Days with Very Heavy Precipitation (1958 to 2007).



Percentage increase in heavy downpours in the regions of the United States since the late 1950s. The map shows the percentage increases in the average number of days with very heavy precipitation (defined as the heaviest 1 percent of all events) from 1958 to 2007 for each region. There are clear trends toward more days with very heavy precipitation for the nation as a whole, and particularly in the Northeast and Midwest.

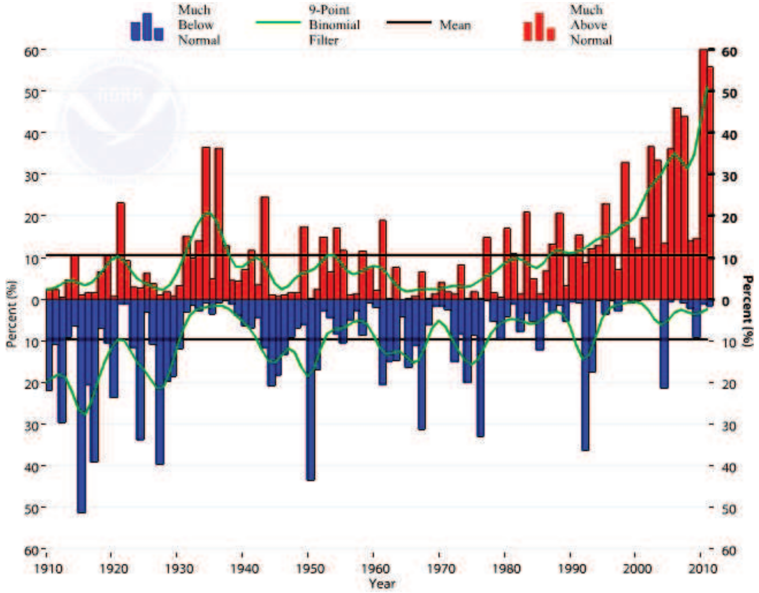
SOURCE: USGCRP (2009) (Ref. 32).

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 larger areas of sinking, dry air, thus expanding the area of land that is subject to drought.[37] The expansion of this sub-tropical circulation pattern also is 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

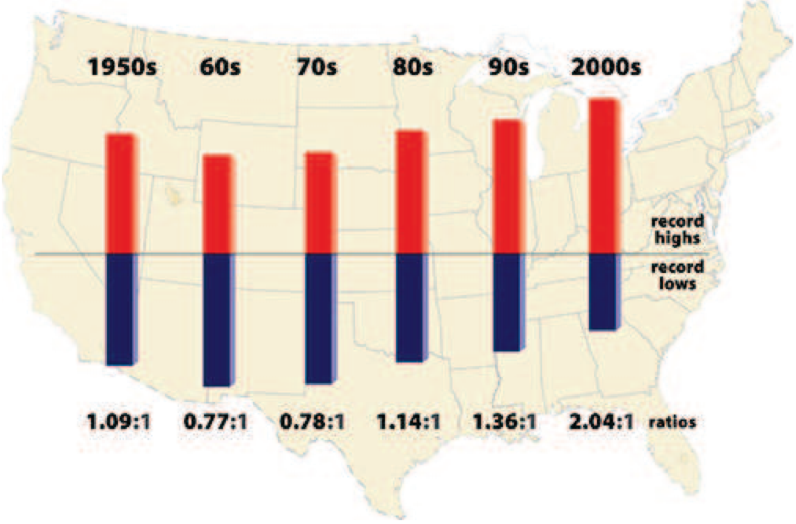
Figure 2: Contiguous U.S. Extremes in Minimum Temperature (Step 2) Summer (June-August) 1910-2011.



Changes in land area (as percent of total) in the contiguous 48 U.S. states experiencing extreme nightly low temperatures during summer. Extreme is defined as temperatures falling in the upper (red bars) or lower (blue bars) 10th percentile of the local period of record. Green lines represent decade-long averages. The area of land experiencing unusually cold temperatures has decreased over the past century, while the area of land experiencing unusually hot temperatures (red bars) reached record levels during the past decade. During the Dust Bowl period of the 1930s, far less land area experienced unusually hot temperatures.

SOURCE: NOAA NCDC Climate Extremes Index (2011) (Ref. 38).

Figure 3: Ratios of record highs to record lows for successive decades in the United States.



A non-changing climate would have approximately equal numbers of record highs and lows, as observed in the 1950s-1980s. The last decade (2000s) had twice as many record highs as it did record lows.

SOURCE: Meehl et al., 2009 (Ref 33); figure ©UCAR, graphic by Mike Shibao 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.

It is also important to disentangle natural cycles from climate change, both of which are risk factors for extreme weather. Consider an analogy: An unhealthy diet, smoking, and lack of exercise are all risk factors for heart disease, and not one of these factors can or should be singled out as *the* cause of a particular heart attack. Similarly, a particular weather event is not directly caused by a single risk factor but has a higher probability of occurrence depending on the presence of various risk factors. The influence on risk from different sources of climate variability is additive, so global warming presents a new risk factor added on top of the natural ones that have always been with us. Over time, natural cycles will come and go, but global warming will continue in one direction such that its contribution to risk will reliably increase over time. Global warming has simply added an additional and ever rising risk factor into an already risky system (see Box 3).

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 it 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 we expect to 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.

Box 3: The 2011 Texas drought: A case study in multiple risk factors

Over the past year, Texas has experienced its most intense single-year drought in recorded history. Texas State Climatologist John Nielsen-Gammon estimated the three sources of climate variability – two natural cycles plus global warming – that contributed to the drought's unprecedented intensity:

- La Nina, 79%
- Atlantic Multidecadal Oscilation, 4%
- Global Warming, 17%

Although information about uncertainty is lacking in this analysis, it clearly identifies global warming as one of the risk factors.

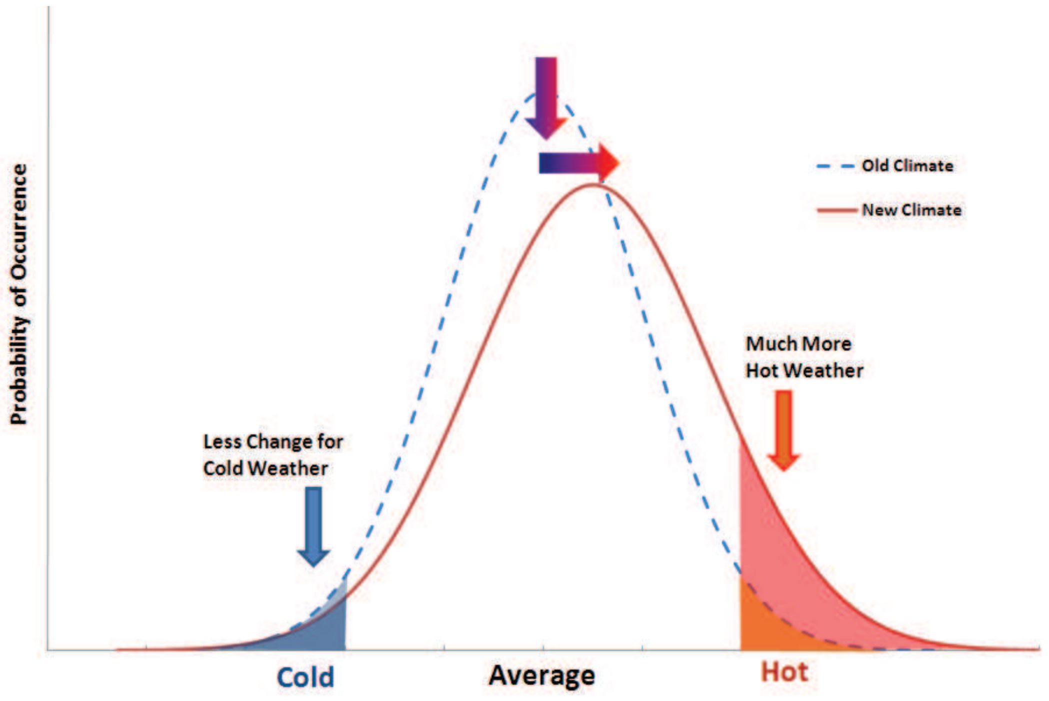
UNDERSTANDING CLIMATE RISK

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 (Fig. 4).

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 4. 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 more likely than before.

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 toward warmer events. Cold extremes become less frequent but do not disappear (Fig. 4). Moreover, like heavy downpours, heavy snowfall is also consistent with global warming (see Box 4).

Figure 4: Increase in Mean Temperature and Variance.



Conceptual representation of the shift in the probability distribution for average and extreme temperatures as a result of global warming. The frequency of extreme high temperatures increases non-linearly, while extreme lows show a more muted response.

SOURCE: Adapted from IPCC (2001) (Ref. 39).

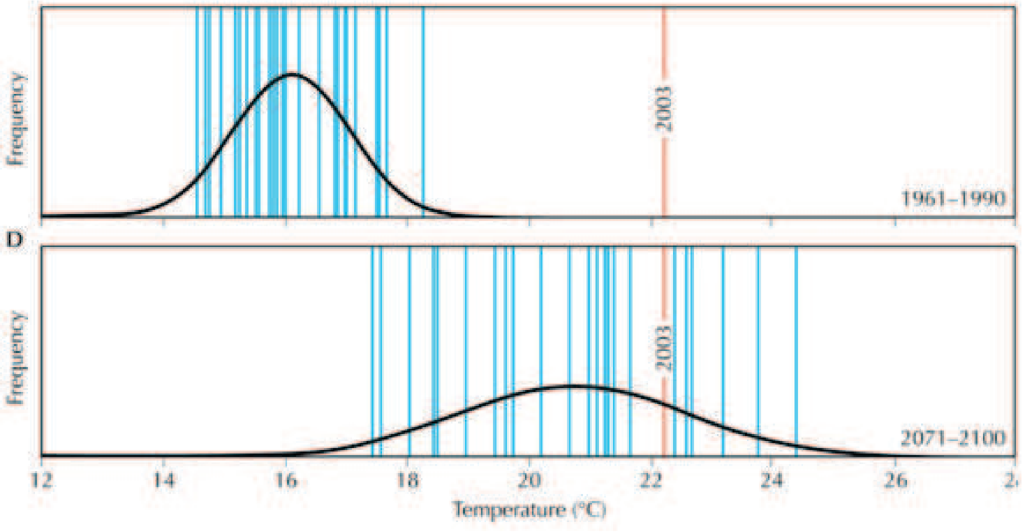
Box 4: Can global warming cause heavy snow?

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 "apocalyptic" snowstorms.

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 (Fig. 5). 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 percent 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.[40] 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.[41]

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

Figure 5: Warmth of the 2003 European heat wave relative to historical summer temperatures (1961-1990) and future (2071-2100) summer temperatures as projected by a climate model.



Historically 2003 is exceptionally warm but in the future scenario it has become relatively common.

SOURCE: Schar et al., 2004 (Ref. 38) as redrawn by Barton et al., 2010 (Ref. 42).

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.[43] 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.

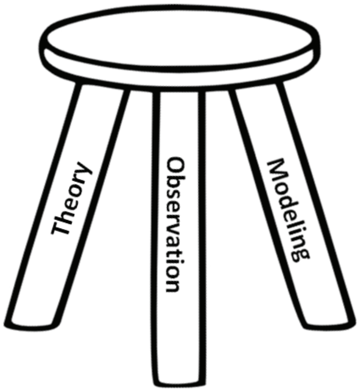
ATTRIBUTING RISK AND ASSESSING VULNERABILITY

It should be clear that while one cannot attribute a particular weather event to climate change, it is possible to attribute and project changes in risk of some categories of extreme weather. In order to have confidence in any climate-related risk assessment, the connection between climate change and a particular type of weather event needs to be established by multiple lines of evidence. This connection relies on three supporting avenues of evidence: theory, modeling and observation, which can be viewed as the legs of a stool (Fig. 6). First, scientists must understand the physical basis of why a type of weather event ought to respond to climate change. To assess whether such a response has already begun, observational data should show an increase in frequency, duration, or intensity that is commensurate with the physical understanding. Finally, computational models forced by elevated greenhouse gas concentrations should show an increase in risk that is consistent with theory and observation.

There is supporting evidence in all three areas (theory, modeling, and observation) pointing to a global-warming induced increase in risk for four important categories of weather-related extreme events: extreme heat, heavy downpours, drought and drought-associated wildfires. For some other types of weather events, there is not sufficient evidence to conclude that global warming has increased risk. For example, evidence relating hurricane risk to climate change is "two-legged": There is a physical basis for expecting hurricanes to have stronger winds and produce more rainfall due to global warming, and models with enhanced greenhouse gas levels show an increase in the number of such storms. With two legs of the stool, hurricanes are a type of event that we should consider a potential future threat for increased risk, but more research is needed to confirm. However, observational evidence is insufficient to confirm that such a response has already begun. For tornadoes, the evidence is "zero-legged," meaning that neither theory, modeling, nor observation offer any indication of how tornado risk has changed or might change in the future due to global warming, although that does not mean there is no risk (see Box 2).

In addition to aggregate trend analysis, 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 similar events 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.[44] Prior to the 2003 European heat wave, the possibility that such a deadly heat wave could strike

Figure 6: Three-legged stool paradigm for assessing the changing risk of extreme weather due to global warming.



Physical understanding (theory) should provide a reason to expect a change in risk. Observations are needed to confirm that a change is taking place and computational modeling can be used to determine whether the observations reconcile with the theory and, if so, to project future changes in risk.

Europe had not been considered. Now that European society is aware of this possibility, preparations have been made to decrease future suffering and economic damage. Similarly, Hurricane Katrina demonstrated that a major American city can be paralyzed for weeks, without effective emergency response, communications, security, sanitation, or health care. Other recent examples of flooding and extreme rainfall should provide lessons on where flood control and emergency response systems are most needed and how much the investments in preparation are worth. Additionally, extreme events represent data points that can improve trends and estimates of future risk, as it is critically important to update trends for estimating existing risk as well as future risk.

RESPONDING TO RISING 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_2 in the atmosphere limits the magnitude of climate change in general, reducing CO_2 emissions is effective at preventing both linear increases in risks and the more difficult to predict, nonlinear changes in extremes. Due to this property, mitigation action can be thought of as a benefit multiplier, as 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 actions beyond what would be expected by looking at changes in average climate conditions. Moreover, many adaptation options are likely to be infeasible if the climate changes too much; adequate mitigation is therefore required to facilitate successful adaptation.

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 rise 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 mechanism for investigating 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.

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 greenhouse gas concentrations compared to preindustrial concentrations.[45] Conversely, modeling 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 a similar magnitude later this century.[46] 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 current events are supercharged by climate change. It does make sense, however, to take lessons from them about our current vulnerabilities and the risks inherent 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.

Box 5: **Suggested Citation**

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ENDNOTES

1 Karl, T. R., Meehl, G. A., Miller, C. D., Hassol, S. J., Waple, A. M., & Murray, W. L. (2008). Weather and Cliamte Extremes in a Changing Climate; Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, D.C., USA: Department of Commerce, NOAA's National Climatic Data Center.

2 National Climatic Data Center. (2010, December). State of the Climate Global Analysis: Annual 2010. Retrieved May 19, 2011, from http://1.usa.gov/fxdFai

3 BBC News. (2011, January 1). Australia's Queensland faces 'biblical' flood. Retrieved May 19, 2011, from http://bbc.in/fNzGgK; Associated Press. (2011, May 1). Federal fire crews bring expertist to huge TX fire. Retrieved May 19, 2011, from http://bit.ly/iz6JRs; Associated Press. (2011, June 16). Concern over human-caused blazes grows as wind-driven wildfires promp more evacuations. Retrieved June 22, 2011, from Washington Post: http://wapo.st/iWxirz; Sulzberger, A.G. (2011, June 26). In Minot, N.D., Flood Waters Stop Rising. Retrieved November 22, 2011, from New York Times: http://nyti.ms/ufT9jY; Doyle, R. (2011, September 8). U.S. sweltered through hottest summer in 75 years. Retrieved November 22, 2011, from USA Today: http://usat.ly/o73h4o; Robertson, C. (2011, May 15). Record Water for a Mississippi River City. Retrieved November 22, 2011, from New York Times: http://nyti.ms/lp0cTA; Freedman, A. (2011, September 12). Historic Flooding Recedes in Pennsylvania, New York; at least 15 dead. Retrieved November 22, 2011, from Washington Post: http://wapo.st/qvywOo

4 Munich Re. (2011, February). Topics Geo Natural catastrophes 2010: Analyses, assessments, positions. Retrieved May 19, 2011, from http://bit.ly/i5zbut

5 Karl et al., Weather and Climate Extremes in a Changing Climate, Op. cit.

6 Masters, J. (2010, August 7). Dr. Jeff Masters' WunderBlog. Retrieved May 20, 2011, from Weather Underground: http://bit.ly/dxKthO

7 Masters, J. (2010, June 2). Dr. Jeff Masters' WunderBlog. Retrieved May 20, 2011, from Weather Underground: http://bit.ly/bDAvx2

8 Herrera, M. (n.d.). Extreme temperatures around the world. Retrieved May 20, 2011, from http://bit.ly/crTJ2a

9 Munich Re, Topics Geo Natural Catastrophes 2010, Op. cit.

10 National Climatic Data Center. State of the Climate Global Analysis: Annual 2010, Op.cit.

11 National Climatic Data Center. Top 10 US Weather/Climate Events of 2011. Retrieved May 19, 2011, from http://1.usa.gov/lGpdnE

12 Ibid.

13 National Climatic Data Center (2011, January 12). 2010 Global Climate Highlights. Retrieved May 20, 2011, from http://1.usa.gov/eCwQmd

14 National Climatic Data Center, State of the Climate Global Analysis: Annual 2010, Op.cit.

15 Biles, P. (2010, April 7). Flooding in Rio de Janeiro state kills scores. Retrieved May 19, 2011, from BBC News: http://bit.ly/kKe20D. O Globo. (2011, February 16). Número de mortos na Região Serrana já passa de 900 após chuvas de janeiro. Retrieved May 19, 2011, from O Globo: http://glo.bo/lMkp7G

16 Australian Government Bureau of Meteorology. (2010, December 1). Queensland in spring 2010: The wettest spring. Retrieved May 19, 2011, from http://bit.ly/l0FVKs; Australian Government Bureau of Meteorology Queensland Climate Services Centre. (2010). Monthly Weather Review: Queensland December 2010. Brisbane: Commonwealth of Australia. Available at http://bit.ly/jcdZLt

17 ABC News AU. (2011, January 18). Flood costs tipped to top $30b. Retrieved May 19, 2011, from http://bit.ly/gD7FyR

18 US Army Corps of Engineers. (n.d.). Fact Sheet: Nashville Flood After Action Report (AAR). Retrieved May 19, 2011, from http://bit.ly/lUtgrR

19 National Climatic Data Center, Top 10 US Weather/Climate Events of 2010, Op. cit.

20 Associated Press. (2011, November 16). Texas wildfire season roars on, with no end in sight. Retrieved November 22, 2011, from USA Today: http://usat.ly/rKqiWq

21 Cooper, M. (2011, August 30). Hurricane Cost Seen as Ranking Among Top Ten. Retrieved November 22, 2011, from New York Times: http://nyti.ms/q0KDYG

22 Schär, C., & Jendritzky, G. (2004). Climate change: Hot news from summer 2003. Nature , 432, 559-560.

23 Larson, L. W. (1996, June). The Great USA Flood of 1993. Retrieved May 19, 2011, from Destructive Water: Water-Caused Natural Disasters- Their Abatement and Control: http://1.usa.gov/4qyQbo; National Climatic Data Center. (2008, July 9). 2008 Midwestern U.S. Floods. Retrieved May 19, 2011, from http://1.usa.gov/iUW1MM

24 Higgs, K. (2008, August 11). California Wildfires~FEMA EM-3287-CA Total Incidents from 6/22/08-8/11/08. Retrieved May 19, 2011, from http://1.usa.gov/knDLpr

25 Carlton, J. (2011, March 31). Wet Winter Can't Slake West's Thirst. Retrieved May 19, 2011, from Wall Street Journal: http://on.wsj.com/gmPD3t

26 Government of Maharashtra Department of Relief and Rehabilitation. (n.d.). Maharashtra Floods 2005. Retrieved May 19, 2011, from http://mdmu.maharashtra.gov.in/pdf/Flood/statusreport.pdf

27 Ibid.

28 Ibid.

29 Karl et al. (2008), Op. cit.

30 Ibid.

31 Ibid; Ebi, K.L. & Meehl, G.A. (2007). The Heat is On: Climate Change & Heatwaves in the Midwest. In [Gulledge, J. & Smith, J., Eds.] Regional Impacts of Climate Change: Four Case Studies in the United States. Pew Center on Global Climate Change, Arlington, Virginia USA.

32 Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). Global Climate Change Impacts in the United States. Cambridge University Press. Available at http://1.usa.gov/7Mcd7Q

33 Meehl, G. A., Tebaldi, C., Walton, G., Easterling, D., & McDaniel, L. (2009). The relative increase of record high maximum temperatuers compared to record low minimum temperatures in the U.S. Geophysical Research Letters , 36 (23), L23701.

34 Ibid.

35 Ebi & Meehl (2007),Op. cit.

36 Ganguly, A. R., Steinhaeuser, K., Erickson III, D. J., Branstetter, M., Parish, E. S., Singh, N., et al. (2009). Higher trends but larger uncertianty and geographic variability in 21st century temperature and heat waves. PNAS , 106 (37), 15555-15559.

37 Seidel, D. J., Fu, Q., Randel, W. J., & Reichler, T. J. (2007). Widening of the tropical belt in a changing climate. Nature Geoscience , 1, 21-24.

38 National Climatic Data Center, (2011). U.S. Climate Extremes Index, National Oceanic and Atmospheric Administration. Retrieved November 22, 2011, from: http://1.usa.gov/vAH4Qx

39 IPCC, (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, & C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

40 Schar, C., Vidale, P.L., Luthi, D., Frei, C., Haberli, C., Liniger, M.A. & Appenzeller, C. (2004). The Role of Increasing Temperature Variability in European Summer Heatwaves. Nature 427, 332-336.

41 Stott, P. A., Stone, D., & Allen, M. (2004). Human contribution to the European heatwave of 2003. Nature , 432, 610-614.

42 Barton, N.H., Briggs, D.E.G., Eisen, J.A., Goldstein, D.B. & Patel, N.H. (2010). Evolution. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY.

43 Lenderink, G., & van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. Nature Geoscience, 1, 511-514.

44 Ebi & Meehl (2007), Op. cit.

45 Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Hilberts, A. G., et al. (2011). Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature , 470, 382-385.

46 Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., et al. (2011). Was there a basis for anticipating the 2010 Russian heat wave? Geophysical Research Letters , 38, L06702.

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