Climate Change and Damage from Extreme Weather Events

by
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ABSTRACT

The risks of extreme weather events are typically being estimated, by federal agencies and others, with historical frequency data assumed to reflect future probabilities. These estimates may not yet have adequately factored in the effects of past and future climate change, despite strong evidence of a changing climate. They have relied on historical data stretching back as far as fifty or a hundred years that may be increasingly unrepresentative of future conditions.

Government and private organizations that use these risk assessments in designing programs and projects with long expected lifetimes may therefore be investing too little to make existing and newly constructed infrastructure resistant to the effects of changing climate. New investments designed to these historical risk standards may suffer excess damages and poor returns. This paper illustrates the issue with an economic analysis of the risks of relatively intense hurricanes striking the New York City region.

I. How and Why Climate Risks may be Under-estimated

Over the past half-century, temperatures and precipitation in the United States have gradually increased, more of the precipitation has fallen in heavy storms, sea level and sea surface temperatures have risen, and other aspects of climate have also changed. A scientific consensus agrees that such changes will continue for many decades, whatever reductions of greenhouse gas emissions are achieved. It is not these gradual changes that are most threatening, however. Organisms and ecosystems can tolerate a range of weather conditions and man-made structures and systems are designed to do so as well. Within this range of tolerance, weather variability causes little damage and if change is sufficiently gradual, many systems can adapt or be adapted.

When weather varies outside this range of tolerance, however, damages increase very disproportionately. As floodwaters rise, damages are minimal so long as the levees hold, but when levees are overtopped, damages can be catastrophic. If roofs are constructed to withstand eighty mile an hour winds, a storm bringing seventy mph winds might only damage a few shingles, but if winds rose to one hundred mph, roofs might come off and entire structures be destroyed. Plants can withstand a dry spell with little loss of yield, but a prolonged drought will destroy the entire crop. The very damaging risks from climate change arise from an increasing likelihood of such extreme weather events, not from a gradual change in average conditions.

Unfortunately, even if weather conditions do not become more volatile as climate changes, which might happen, a shift in average conditions will also bring about a changing probability of weather events far removed from average conditions[2]. For example, as more rain falls in heavy storms, the probability rises that deluges will occasionally occur that bring about extreme flooding and disastrous damages. As average temperatures rise, the likelihood of an extreme heat wave rises too.

Weather risk assessments have not come to grips with the changing probabilities of extreme weather. The methodologies in use typically are backward-looking and conservative. The frequencies with which specific weather events occur are estimated from measurements in the historical record going back decades. These frequencies, calculated from past records, are then used to “fit” to the data a probability distribution with a similar mean, variance, and skewness. The probability distribution can then be used to estimate the likelihood of extreme weather, even though there are few, if any, such events in the historical record.

Estimating the probability of extreme, and therefore very infrequent, weather events in this way is inherently difficult, because there are so few such events in the measured record. Extrapolating from the occurrence of rarely observed events to the probability of even more extreme events beyond the historical record is unavoidably uncertain.

When climate is changing, an even more serious problem lies in assuming that the future will be like the past, and projecting probabilities estimated from historical data into the future[3]. Not only are agencies charged with assessing weather risks making this assumption, that the estimated probability distributions are stationary, they are also ignoring measured trends in historical weather patterns.

expected return periods, which are the reciprocals of the annual probabilities, are shown in Table I for various categories of hurricanes.[7]

Table I
Estimated Hurricane Probabilities for the New York Metropolitan Region By the National Hurricane Center

Hurricane Category	Maximum Wind Speed (mph)	Expected Return Period	Annual Probability
Cat 1	74-95	17 years	.059
Cat 2	96-110	39 years	.026
Cat 3	111-130	68 years	.015
Cat 4	131-155	150 years	.007
Cat 5	>155	370 years	.0027

These probability estimates were constructed in 1999. It is questionable whether these estimates were valid in that year, because there has apparently been an upward trend in intense hurricanes in the North Atlantic over at least the past 35 years. The number of Category 4 and 5 hurricanes in the North Atlantic increased from 16 during the period 1975-89 to 25 from 1990-2004[8]. Consequently, the earlier years in the historical record used to compute frequencies might not have been representative of the final years.

There is good reason to believe that this increasing frequency of stronger hurricanes in the North Atlantic is linked to climate change through the gradual rise in sea surface temperatures[9]. Warming ocean waters provide the energy from which more intense hurricanes are developed and sustained.[10] According to a recent study, a 3 degree centigrade increase in sea surface temperature would raise maximum hurricane wind speeds by 15 to 20 percent.[11]

Measurements throughout the oceans have found a rising trend in sea surface temperatures at a rate of approximately 0.14 degrees centigrade per decade.[12] The rate of warming is apparently increasing, however, and the North Atlantic warming has been faster than the global average. According to a recent examination, in the 28-year period from 1981 to 2009, warming in the North Atlantic has averaged 0.264 degrees centigrade per decade, roughly twice the global average.[13] Rising sea surface temperatures in the North Atlantic, the driving force behind the increasing frequency of intense hurricanes, explain why backward-looking historical probability estimates, such as those generated using the National Hurricane Center's approach, probably do not provide adequate guidance with respect to current and future risks.

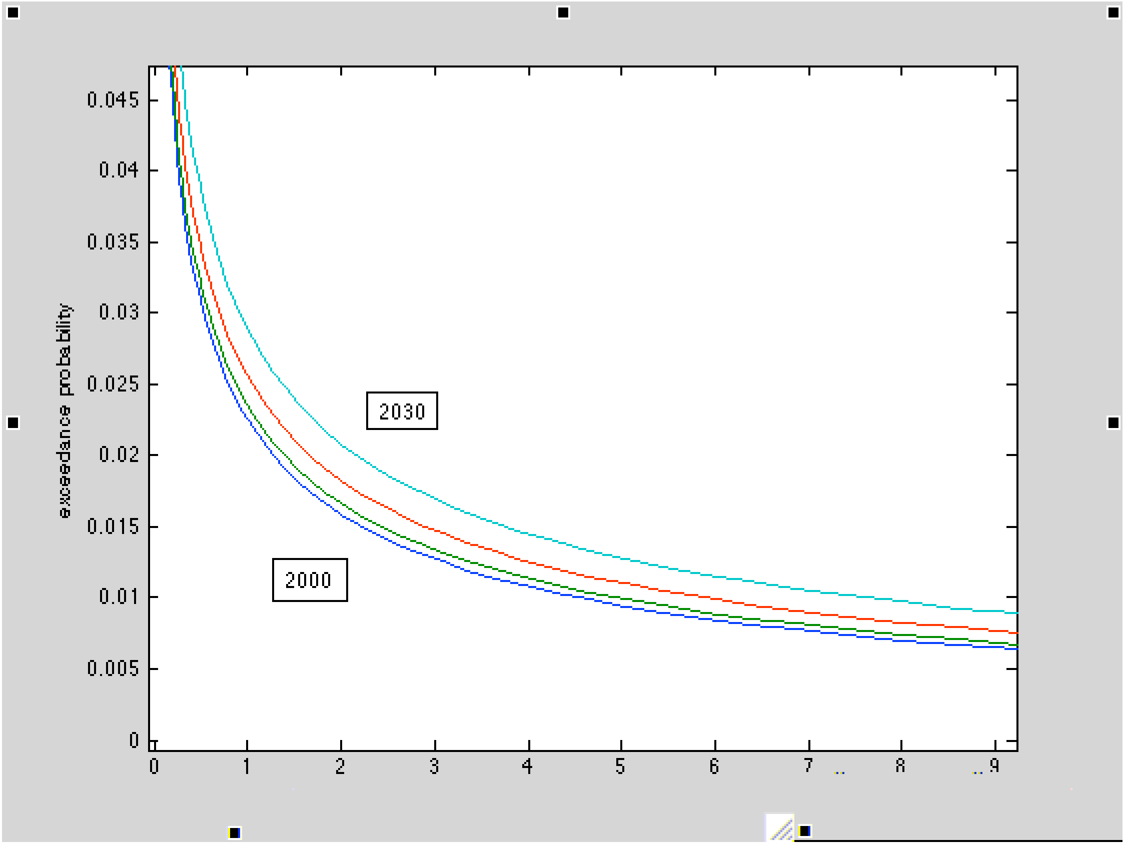
This problem is compounded by the rising trend in sea level, itself partly the result of increasing ocean temperatures. Higher sea levels and tides raise the probability of flooding driven by hurricane-force winds. In the North Atlantic between New York and North Carolina, sea level has also risen more rapidly than the global average, at rates between .24 and .44 centimeters per decade.[14]

These scientific findings and measurements can be used to project hurricane risk estimates into the future. The trend in sea surface temperature, linked to the relationship between sea surface temperature and maximum wind speed, provides a way to forecast changes in the intensity of future hurricanes. High and low estimates can define a range of future probabilities. Though there are considerable uncertainties inherent in forecasts based on this approach, the results are arguably more useful than static estimates based on historical data that fail to incorporate any relevant information about the effects of climate change. At a minimum, this approach can provide a quantitative sensitivity analysis indicating by how much existing estimates may be under-estimating future risks.

Table 2 displays some results, based on both the higher and lower estimates of sea surface temperature trends and the relationship between sea surface temperature and maximum wind speeds. The table shows the estimated return periods for hurricanes striking the region, based on the 1999 Weibull distribution estimated by the National Hurricane Center return periods for the New York metropolitan region. (Figures differ slightly from those in Table 1 for less intense storms because of curve-fitting variances.) In addition, it presents return periods for 2010, 2020, and 2030 estimated by indexing the scale parameter of the probability distribution to a time trend based on the rate of temperature change and its effect on maximum wind speeds. The ranges shown for the decades 2010-2030 are based on the high and low estimates of the rate of sea surface temperature increase.

Figure 1

Hurricane Loss Exceedance Curves, 2000-2030



The second feature that Figure 1 illustrates is that the probabilities of large losses shift upward over time, as climate change makes intense hurricanes more likely. By 2030, the probability of hurricane damages exceeding amounts in the range of $100 to $500 billion could be 30-50 percent greater than current estimates assume. Warming sea surface temperatures and rising sea levels increase the economic risks to coastal loss exceedance curve is so “fat-tailed”, with significant probabilities of huge losses, that rational insurance premium, calculated using the outdated 2000 return periods estimated by the National Hurricane Center, is about $33 billion dollars per year. To put that amount in context, the entire 2009 expenditure budget of the City of New York is just over $60 billion. However, as the likelihood of hurricane damage rises, that insurance premium increases to $35-37 billion in 2010, $40-46 billion in 2020, and $47-62 billion in 2030. The ranges reflect the high and low estimates of the pace of sea surface temperature increase. In other words, the expected value of losses could nearly double over three decades, just on account of the increasing likelihood of intense hurricanes.

Unfortunately, the reality is even more disturbing. William Nordhaus’s investigation and others have found an increasing trend of damages over time for the same maximum wind speeds. The rising trend reflects population increases Thett. 7 bccktimatbuildt. sgation and trend

damages to the third power of wind speed rather than to the eighth power, as Nordhaus estimated. The Carvill index is used in this illustration because it underlies some recent financial derivative instruments available to hedge hurricane risk.[19]

V. Conclusions

Every year the United States is hit with hurricanes, floods, droughts, and other weather-related disasters such as wildfires and pest outbreaks. These cause many billions of dollars in damages, loss of life, and disruption or displacement of entire communities. Some of these losses can be avoided if preventive and anticipatory actions are taken. If the risks of extreme weather events are under-estimated, however, the pace and extent of preventive activities will lag.

Mathematical Appendix

$v = 0.014 \quad v = 0.026$ [12, 13]. These high and low estimates were used to establish a range of probabilities.

In combination, these two relationships imply that maximum hurricane wind speed responds to rising sea surface temperatures according to the equation

$$x(t) = [1 + kvt]x(0).$$

In the Weibull distribution, the parameter *b* is a scale factor that stretches the maximum wind speed variable x. Therefore, we set

$$b(t) = [1 + kvt]b(0),$$

with $b(0) = 42.0967$, keeping $a = 1.3568$ unchanged. These estimates and relationships determine our forecast change in the Weibull distribution over time. The loss exceedance curves pictured in figure 1 were plotted using the exceedance probability from the forecast Weibull distribution for the years 2000, 2010, 2020, and 2030.

Hurricane damage has been estimated as a function of maximum wind speed in an empirical study by William Nordhaus, based on the record of more than 140 storms [16]. The least squares logarithmic regression of economic damage on maximum wind speed produces an estimate that damages increase as the eighth power of wind speed.

We assume that winds below 30 miles per hour cause no damage and make use of a recent estimate that the damage caused by a category 3 hurricane hitting the area would be two hundred billion dollars. [15] This calibrates the damage function to be

$$d(y) = Ay^8, \quad y = x - 30, \quad A = 4.6461 \# 10^{-5}.$$

An alternate calibration that assumes no damage occurs at wind speeds less than 60 miles per hour would give a much higher damage estimate at high wind speeds.

Expected annual damage was calculated according to the relationship

$$ExpectedDamage = \int_{74}^{200} d(x)\rho(x;a,b(t))dx,$$

integrating probable damages over all hurricane-force wind speeds. A range of expected damages was obtained by using low and high estimates of the rate of change of the parameter $b(t)$, based on the low and high values of the parameter ν obtained from sea surface temperature rise.

The Nordhaus study also found a time trend of 2.5 – 3.0 percent per year in damages from a storm of given intensity, reflecting the increase over time in value at risk. Assuming a yearly increase $\quad = 1.025$ (a 2.5% yearly increase in assets at risk), the time dependent damage function is

$$(\;,\;) = \qquad (\quad - 30)^8.$$

Replacing the static damage function $d(x)$ with $D(x,t)$ in the expected damage calculation we obtain much higher estimates of expected annual damages over the period 2000-2030.

To model investment risks we consider an investment in an asset that yields a constant yearly return of amount y. The asset is subject to hurricane damage. The damage depends on a random environmental variable x, represent0 40th8nximumithnTj ET Q q 0.2000000

[8] P.J. Webster et al., 2005, "Changes in Tropical Cyclone Number, Duration and Intensity in a Warming Environment", *Science*, 309:1844-1846; September 16.
[9] Union of Concerned Scientists, 2006, "Hurricanes in a Warmer World", Cambridge, MA.