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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.

They do so for two main reasons. The first is uncertainty whether an apparent trend is real or is just a poorly understood cyclical phenomenon that will be reversed, or just a string of random events. The second is the dilemma in giving more weight to recent observations, which might better represent current conditions, but which would provide less data with which to estimate a probability distribution representative of extreme and unlikely events.[4]

Uncertainty about future climate conditions affecting particular localities and weather phenomenon is the main reason why weather risk assessments estimates are still based on historical data, despite strong scientific and empirical evidence that the future will not be like the past. Conservative agencies retain methodologies and estimates likely to be erroneous rather than make use of scientific projections of future conditions that are still quite uncertain, especially at a regional or local geographic scale. The question bedeviling weather risk assessment is "If the future will not be like the past, what will it be like?" Climate models are still unable to provide answers to this question with high reliability.

Nonetheless, weather risk assessments become increasingly outdated as time passes or when projected further into the future. They provide unreliable guidance for the design, placement and construction of infrastructure that will be in place for many decades and vulnerable to extreme weather throughout its useful life. By underestimating future risks, they also provide unreliable guidance for investment and program decisions to make existing infrastructure and communities more resistant to extreme weather. As a result, according to a new report by a National Research Council panel, "Government agencies, private organizations, and individuals whose futures will be affected by climate change are unprepared, both conceptually and practically, for meeting the challenges and opportunities it presents. Many of their usual practices and decision rules—for building bridges, implementing zoning rules, using private motor vehicles, and so on—assume a stationary climate—a continuation of past climatic conditions, including similar patterns of variation and the same probabilities of extreme events. That assumption, fundamental to the ways people and organizations make their choices, is no longer valid."[5]

This is a problem of broad and significant scope. Among the public and private sector organizations that are exposed to increasing but under-estimated risks are

- Local, state and federal disaster management agencies;
- Local, state and federal agencies that finance and build public infrastructure in vulnerable areas as well as those that own and operate vulnerable infrastructure;
- Private investors and owners of vulnerable buildings and other physical property;
- Property and casualty insurers;
- Creditors holding vulnerable infrastructure directly or indirectly as collateral;
- Vulnerable businesses and households.

Clearly, this listing encompasses a large proportion of the American economy, and an assessment of the vulnerable regions would also extend over a large part of the country, including coastal regions subject to hurricanes, storm surges, and erosion; river basins subject to flooding; and agricultural areas subject to wind, storm and drought damage.

These under-estimated risks should not be neglected in any program of adaptation to climate change. Efforts to improve climate change forecasts at regional and local scale should be intensified. In these efforts, more emphasis should be placed on forecasts of the likelihood of extreme weather events. While these efforts are underway, however, agencies responsible for weather risk assessment should update their estimates, incorporating the best available scientific climate projections that provide guidance regarding future conditions. Uncertainties in these projected weather risks should be frankly acknowledged and explained. In addition to their best estimates, agencies should also present plausible uncertainty bands around those probabilities. Finally, vulnerable agencies such as those listed above should be encouraged or directed to use these revised risk estimates in their program and investment planning as an important step toward anticipatory adaptation to climate change.

II. A Case Study: Hurricane Risk in the New York City Region

To further clarify and illustrate the issue, a case study is presented of the risks to the New York City metropolitan region from hurricane damage. Of course, the scope of the problem is much wider. Hurricane risks imperil the entire Atlantic seaboard, the Gulf of Mexico, the Caribbean, many Pacific coastal areas, and the Indian Ocean. Nor is the issue just that of hurricane risks: risks of floods, droughts, and severe storms may also be underestimated for the same underlying reasons.

The New York metropolitan region extends across three states and encompasses an extraordinarily dense concentration of infrastructure, physical assets, and business activity. In 2006, for example, the value of insured coastal property in the New York, Connecticut and New Jersey region was almost $3 trillion.[6] The metropolitan region's economy is vulnerable to the more extreme effects of climate change. Storm surges could reach 18-24 feet in a strong hurricane. Low-lying regions, including Kennedy Airport and lower Manhattan, would flood. Roads, subway and tunnel entrances would be submerged, along with ground level and underground infrastructure. High winds would do severe damage, partly by blowing dangerous debris through city streets. The New York City government has recognized such risks and in 2008 created the New York City Panel on Climate Change and the Climate Change Adaptation Task Force to develop an adaptation strategy. Studies toward this objective are underway.

The following case study builds on several relevant investigations, incorporating them as components in an overall design that shows to what extent hurricane probabilities may be under-estimated, how economic damage risks may consequently also be underestimated, how these risks assessments can be updated and projected into the future based on relevant scientific information, and how these updated risk assessments might be used to improve decisions on investments in adaptation. The technical details of the analysis are contained in the mathematical appendix.

The starting point is the probability assessment carried out by the National Hurricane Center (NHC), an office within the National Oceanic and Atmospheric Administration. The methodology used for NYC and other coastal regions counts the occurrence of hurricanes of specific intensities (defined in terms of maximum sustained wind speeds) striking within a 75-mile radius during the historical record of approximately one hundred years. NHC scientists fitted a particular probability distribution, the Weibull distribution, to these observed frequencies and the probabilities of hurricanes of various intensities were then read off the fitted probability distribution. There were no actual observations of the most severe hurricanes in the historical record for the New York region, so those probabilities were extrapolations based on the fitted distribution. The results, expressed as the 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.

Table 2
Estimated Hurricane Return Periods, 2000-2030

Hurricane Category	**2000**	**2010**	**2020**	**2030**
1	14.4	13.9-14.1	13.5-13.9	13.1-13.7
2	44	41.8-42.7	39.9-41.6	38.1-40.6
3	68	63.9-65.8	60.1-63.6	56.6-61.5
4	150	136.7-142.2	125.9-135.8	116.2-129.9
5	370	327.2-346.1	290.7-324.2	259.2-304.1

The effects of climate change will increase the probability of hurricanes striking New York but especially the more severe hurricanes. By 2030, the probabilities of category 4 and category 5 hurricanes striking the New York metropolitan region are likely to have increased by as much as 25 and 30 percent, respectively. For category 3 storms, what was a one-in-sixty-eight chance of a Category 3 hurricane may have become a one-in-fifty-eight year event. These changing probabilities have dramatic economic implications.

IV. The Economic Implications of Increasing Weather Risk

A professional risk management consultancy recently estimated that a Category 3 hurricane with a landfall in the New York metropolitan region would probably result in losses of approximately $200 billion in property damage, business losses, and other impacts.[15] According to the National Hurricane Center's 2000 estimates, there is only a 1.5 percent chance of that happening in any year. However, this may be a very misleading portrayal of the economic risk.

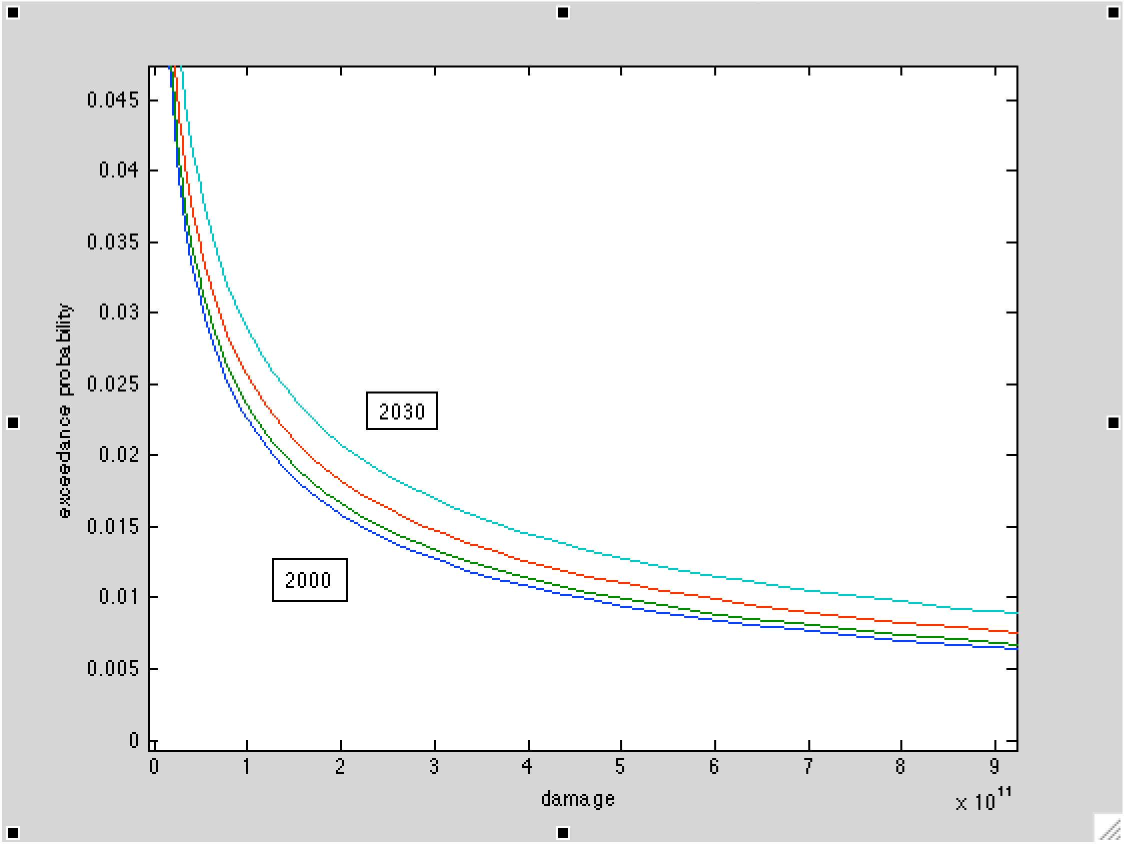
A more complete assessment makes use of a tool common in the insurance industry: the loss exceedance curve. This curve represents the annual probability of a loss *equal to or greater than* specified amounts. It summarizes the probabilities of hurricanes of various intensities and estimates of the damages they would create. A loss exceedance probability of $200 billion represents the chance that a hurricane loss of that amount or more, into the trillions of dollars, might occur. To construct such a loss exceedance function for the New York region, one needs not only the probabilities of Category 1-5 hurricanes but also the damages that they respectively would inflict.

A recent study by Yale economics professor William Nordhaus, based on hurricanes recorded throughout the United States, investigated the relationship between maximum wind speeds and resulting damages.[16] Shockingly, this study found that damages increase as the 8^{th} power of the wind speed: if a hurricane with wind speeds of 50 miles per hour would cause $10 billion in damages, then one with maximum winds of 100 miles per hour would cause not twice the damages, $20 billion, but more than $2,500 billion. The reasons for this dramatic escalation are three-fold. First, higher winds will obviously do more damage to everything in their path; second, more intense hurricanes are likely to have impacts over wider areas; and third, their winds are likely to persist at damaging speeds, although not at the maximum, for longer periods of time.

The loss exceedance curve implied by this relationship is plotted in Figure 1 for the year 2000 and for subsequent decades, using the higher estimate of sea surface temperature increase. On the horizontal axis, damages are marked in hundreds of billions of dollars. On the vertical axis are the probabilities of hurricane losses of those amounts *or more.* One striking feature that is immediately apparent is that the exceedance curve is "fat-tailed": probabilities decline slowly as heavy losses mount. As maximum wind speeds increase, damages mount very rapidly, offsetting the declining probability of the more intense storms. The probability of losses exceeding a trillion dollars is not half the probability of losses exceeding $500 billion, but substantially more than that. This illustrates how vulnerable to catastrophic hurricane damage the New York metropolitan region is now.

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 cities. In the absence of effective adaptation measures, risks of catastrophic losses will very likely continue to rise over coming decades.

Another way of understanding the increasing economic risks is to ask how much the region should be willing to pay to insure against all hurricane damages, if such comprehensive insurance were available. Even without an aversion toward catastrophic risks, the region should be willing to pay an annual insurance premium up to the expected value of losses in the absence of insurance. The expected value of losses is the sum of all possible hurricane losses, weighted by their probabilities of occurring. Because the 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 and increasing stocks of buildings and other infrastructure in the coastal zone, and the erosion of barrier beaches and other protection, among other factors. Were vulnerabilities to increase over coming decades at the same pace as in the past, a rate that Nordhaus estimated at 2.9 percent per year for constant hurricane intensities, the region’s vulnerabilities and expected losses would obviously become much higher still. By 2010 the expected value of annual damages would have risen to $45-47 billion, by 2020 they would be $65-75 billion, and by 2030 they would range from $100-130 billion per year.

Moreover, no one should expect businesses, individuals or their representatives in government to be indifferent to the risks of catastrophic damage. In many contexts, all manifest a significant aversion to risks of major losses. Individuals and businesses often buy insurance against catastrophic losses with a premium greatly exceeding the actuarial fair value (reflecting the insurance companies’ administrative costs and profit margins). Attempts by financial economists to explain the large and persistent equity risk premium evident in securities markets, the higher long-term returns to stocks over less risky bonds, have concluded that the coefficient of relative risk aversion must be as high as 4. With this degree of risk aversion, society would be willing to give up significant fractions of annual income, well in excess of the expected value of losses, if it were possible to eliminate or reduce significantly the threat of rare disasters.[17]

III. Risks to Investors

Investors in infra-structure projects vulnerable to hurricane damage, whether buildings, roads, or other structures, face greater risks than they realize and are likely to experience rates of return from their investments that are dramatically below those that they anticipate. Infrastructure projects are designed and engineered to withstand extreme weather, so that it would take an extremely unlikely event to cause major damage. There is a trade-off between an extra margin of safety and the additional cost required to achieve it. Civil engineers and planners are trained to estimate and base decisions on such trade-offs, often going beyond what is strictly required by building codes and other regulations.

Unfortunately, in assessing these trade-offs civil engineers and planners are still relying on historical frequency estimates and are making the same assumptions that the future will be like the past, despite climate change. Thought leaders in the engineering profession have only recently begun weighing alternative approaches to climate change issues.[18] Practicing engineers are predominantly still adhering to "best practice", a term implying a continuation with assumptions validated by past experience, not innovative approaches aimed at new challenges.

For example, consider an infrastructure project anticipated to have a 40-year lifetime, which is designed to meet the hurricane risks calculated in 2000 (and still promulgated by the National Hurricane Center). The investor might require an expected income stream that would provide a discounted present value return of 12 percent on his investment, taking into account possible income losses from hurricane damage. Unfortunately, as the years pass over the 40-year project lifetime, the probabilities of more intense hurricanes striking the region increase. The initial estimates of risk are no longer valid. The expected returns on the project are dramatically affected, as Table 3 illustrates. These results are based on three alternative real (inflation-free) discount rates: 3, 5, and 8 percent. Three percent represents a discount rate appropriate for public sector investments; five percent is an inflation-free return indicative of private returns on capital; eight percent is a still higher alternative. Higher discount rates give less weight to future years and to the higher risks of future hurricane damage.

As before, hurricane damages are estimated as a function of maximum wind speed, but the more conservative Carvill index is used, which relates 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] Moreover, it is assumed that hurricane damages sustained in any year are limited to that year. Despite these conservative assumptions, Table 3 shows the dramatic impact of increasing risk on expected returns. The project is not likely to earn the planned 12 percent return. At a 3 percent discount rate, expected investment returns would be reduced by almost 90 percent, with a significant probability that the project would not repay the capital investment. With a 5 percent discount rate, the expected project rate of return is reduced by more than two-thirds. With an 8 percent discount rate, the expected return is reduced by almost one-half. The message is clear: designing vulnerable infra-structure projects without adequately estimating future weather risks will lead to significant investment losses.

Table 3
Expected Return on a Project Investment with Increasing Climate Risk

Discount Factor	Expected Rate of Return
.03	1.3%
.05	3.9%
.08	6.7%

IV. Investments in Adaptation and Prevention

Not surprisingly, if past frequencies of extreme weather events are projected into the future without taking into account the effects of climate change, the economic value of investments in adaptation and prevention are dramatically under-estimated. Using the previous investment analysis as a starting point, imagine that at an additional investment cost, it is possible to strengthen the structure to withstand an additional 10 mph of maximum wind speed without any additional damage. The pay-off to this adaptation investment would be a lower risk of hurricane damage and a higher expected income return. Suppose further that such an investment in adaptation would just break even if the historical hurricane frequencies were projected into the future, over the project's anticipated lifetime. Under these assumptions, adaptation would be considered uneconomic, since it would yield no positive return on investment.

If the effects of climate change were taken into account by anticipating the increasing probabilities of more extreme storms striking the region, then the economic advantage of investing in adaptation and prevention would appear much more attractive. Table 4 shows the expected returns on such an investment that would have been considered only a break-even proposition if historical probabilities were projected into the future. The differences are dramatic: at a 3 percent time discount rate, the zero return on adaptation rises to a 68 percent return; at 5 percent, it becomes a 56 percent rate of return; and, at 8 percent time discount, it becomes a 43 percent investment return.

Table 4
Returns to an Adaptation Investment with Increasing Risk

Time Discount Rate	Return Assuming Historical Risk	Returns Assuming Changing Risks
.03	0%	68%
.05	0%	56%
.08	0%	43%

Since, with few exceptions, private investors and public agencies at local, state and federal levels are still relying on static, historically-based probability estimates of extreme weather events and have not yet incorporated the effects of climate change into these risk estimates when evaluating the economics of adaptation investments, these agencies are grossly under-estimating the economic case for investments in adaptation. This is one of the reasons why adaptation has lagged and is proceeding so slowly.[20]

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.

Ignoring the effects of climate change on future probabilities of extreme weather events could lead to significant under-estimates of future risks to vulnerable communities, infrastructure, and investments. Deriving such probabilities from historical records going back many decades, with no adjustment for changes in climate extending inevitably into future decades, is likely to produce faulty estimates for planning and investment decisions. Climate change is very likely to be affecting the frequency with which many forms of extreme weather will occur.

The effects of climate change on weather and storm patterns are still uncertain, particularly at local and regional geographical scales. Uncertainty is not a justification for paralysis. It should be incorporated into estimates of future risks by establishing plausible ranges for key variables and parameters, as has been done in this study. Adhering to estimates almost certain to be wrong, waiting for uncertainties to be resolved, provides misleading information for current decisions. The resulting decision errors can be very costly.

Public and private sector agencies responsible for providing estimates of weather risks are now grappling with the problems of incorporating the effects of climate change, but progress is slow and the bias is toward conservatism: sticking to the historical record until an alternative is clearly established. Leadership in such agencies is needed ensure that their risk estimates, to the extent now possible, reflect current and future probabilities, not past historical conditions, and that their estimates are frequently updated to incorporate new information about climate change effects.

Mathematical Appendix

The National Hurricane Center based its estimates of the hurricane risks in the New York City region on historical records, consisting of approximately 42 such storms of various intensities in the area over the period 1851-2000. [7] To these records, the NHC fitted a Weibull probability distribution of maximum wind speeds. The Weibull probability distribution is used to interpolate and extrapolate the wind speed and return probability data in the historical record, and is then used to calculate the probability of maximum wind speed x exceeding a given value. Return periods of hurricanes in various categories, the inverse of annual probabilities, were estimated from the fitted probability function.

The Weibull probability density function with parameters *a*, and *b* is:

$$\rho(x;a,b) = (a/b)(x/b)^{a-1}\exp(-[x/b]^{a}).$$

The probability that the variable x exceeds a value *z* is

$$prob(x > z) = \exp(-[z/b]^{a}).$$

In this case study, without access to the exact NHC distribution, we approximated its values by choosing the parameters to replicate the probabilities of category 3 and category 5 hurricanes, resulting in parameter values of $a = 1.3568 \quad b = 42.0967$.

To forecast how the probabilities of more intense hurricanes might shift over time in response to climate change, we made use of the linkage to sea surface temperatures reported in scientific literature by first relating the maximum wind speeds of hurricanes to sea surface temperatures, and making use of trend data of the change in sea surface temperature in the North Atlantic.

We assume that the maximum hurricane wind speeds are proportional to temperature according to the formula

$$x(T_0 + \Delta T) = (1 + k\Delta T)x(T_0).$$

The parameter T_0 denotes year 2000 sea surface temperature. Kerry Emmanuel [10] has estimated that a 3 degree centigrade increase in sea surface temperature produces a 15 to 20 percent increase in maximum wind speed. This produces an estimate that the parameter $k = 0.06$.

Studies of sea surface temperature suggest that the temperature T has been rising in recent decades a linear trend rate $T = T_0 + vt$. The variable t denotes time in years beyond 2000. Low and high estimates of the parameter v, from various studies, are

$v = 0.014$ $v = 0.026$ [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

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

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 v 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 $r = 1.025$ (a 2.5% yearly increase in assets at risk), the time dependent damage function is

$$D(x,t) = Ar^t(x - 30)^8.$$

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, representing maximum wind speed, which has a non-stationary probability density function $\rho(x,t)$. The fraction of the asset that is damaged is a function $d(x)$ of x. We assume that damage is limited to the year in which the storm occurs. Thus the net return in year t is equal to the constant return less the damage that occurs in the previous year. The net return is $y[1-d(x(t-1))]$. The expected damage in year t is

$ED(t) = \int d(x)\rho(x,t)dx$. The expected return is $y(t) = y[1-ED(t-1)]$.

The present value of the expected returns for $1 \le t \le T$ with time discount factor β is

$$PV = \sum_{t=1}^{T} \beta^t y(t).$$

If the expected damage is forecast using the static probability density function $\rho(x,0)$, then the expected return is constant and the estimate of the asset's present value is

$$PV^0 = \sum_{t=1}^{T} \beta^t y(1).$$

In the reported calculations we assume that the fraction of damage is zero for wind speeds x<30 and one for x>130. The fractional damage function has the form

$$d(x) = (x-30)^3/(100)^3,$$

for values of x in the range 30 < x < 130. Instead of adopting the Nordhaus damage estimates, we use the power $k = 3$. This is derived from the Carvill index, which is used by investors to hedge hurricane risk in weather markets.

In the reported calculations, the initial investment was assumed to be 100 and the value y^0 of the undamaged constant stream of returns was set to yield a discounted return of 12 percent over the investment cost of 100, under the assumption that hurricane risks remain constant over time and the economic lifetime of the asset is 40 years.

$$\sum_{t=1}^{40} \beta^t y^0[1-ED(0)] = (1.12)(100)$$

Maintaining the same assumed investment costs and undamaged return stream, we then use the time dependent Weibull distribution derived from the high forecast of sea surface temperature rise to calculate expected returns in a changing climate. The expected net return $y(t)$ in year t is the probability-weighted damaged return. The discounted expected return r on investment over its economic life, assumed to be 40 years, was calculated according to the formulas below, using various time discount rates.

$$\sum_{t=1}^{40} \beta^t y(t) = (1+r)(100) \qquad y(t) = y^0[1 - \int_{30}^{130} d(x)\rho(x,t-1)dx].$$

The results are tabulated in table 3.

To estimate the returns on investments in adaptation, we assume that an initial investment could shift the damage function in such a way that the investment will withstand an additional 10 mph of wind speed with no additional damage. Then the shifted damage function is

$$D(x) = (x-40)^3/(100)^3 \ .$$

The expected net return in year t with the shifted damage function is

$$Y(t) = y^0[1 - \int_{40}^{140} D(x)\rho(x,t-1)dx].$$

For static hurricane risks the expected net return is $Y(1)$.

We choose the investment cost C such that the adaptation investment would provide a discounted return equal to C if hurricane risks remain constant over time; in other words, a break-even proposition.

$$\sum_{t=1}^{40} \beta^t [Y(1) - y(1)] = C = \sum_{t=1}^{40} \beta^t y^0 [\int_{30}^{130} d(x)\rho(x,0)dx - \int_{40}^{140} D(x)\rho(x,0)dx]$$

Using the same assumed cost, we then compute the return r on the break even investment in adaptation using various time discount rates under the assumption of changing risks, as reported in table 4. The return is calculated using the formula

$$\sum_{t=1}^{40} \beta^t [Y(t) - y(t)] = (1+r)C \ .$$

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[2] " In the non-stationary case, a trend in the mean affecting the entire data set must imply a trend in extreme events.", M. Nogaj, S. Parey, D. Dacunha-Castelle, 2007, "Non-Stationary Extreme Models and a Climatic Application", *Nonlinear Processes in Geophysics*; 14:305-316; June 25.p. 306.

[3] P.C.D. Milly, J. Betancourt, M. Falkenmark, R. M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, R. J. Stouffer, 2008, "Stationarity is Dead: Whither Water Management?", 2008, Science;319:573-574. February 1.

[4] R. E.Livezey, K.Y. Vinnikov, M.M. Timofeyeva, 2007, "Estimation and Extrapolation of Climate Normals and Climatic Trends", *Journal of Applied Meteorology and Climatology*; 46:1759-1776; November.

[5] National Research Council, Panel on Strategies and Methods for Climate-Related Decision Support, 2009, "Informing Decisions in a Changing Climate", Washington DC, 2009. p.S-1.

[6] D.L. James Valverde, Jr., 2006, "Hurricane Risk in New York City and Long Island", Insurance Information Institute, February 24.

[7] Data accessed at http://www.nhc.noaa.gov/HAW2/english/basics/return/shtml

[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.

[10] Kerry A. Emanuel, 1987, "The Dependence of Hurricane Intensity on Climate", *Nature*, vol.326, no.6112, pp483-485; April 2.; Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, 436:686–688.

[11] Sriver, R., and M. Huber. 2006. Low frequency variability in globally integrated tropical cyclone power dissipation. *Geophysical Research Letters* 33. doi:10.1029/2006GL026167.

[12] Kenneth S. Casey & Peter Cornillon, 2001, "Global and Regional Sea Surface Temperatures", Journal of Climate, vol.14: 3801-3818; September

[13] Robert Tisdale, 2009, "The Impact of the North Atlantic and Volcanic Aerosols on Short-term Global Sea-Surface Temperature Trends", accessed at http://bobtisdale.blogspot.com/2009/02

[14] US Climate Change Science Program, 2009, Synthesis and Assessment Product 4.1, "Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region", Washington, DC, January 15.

[15] Karen M. Clark, CEO AIR Worldwide Corporation, 2006, "Major Hurricane Strikes the Northeast: How Large Will the Losses Be?", presentation to the Hortheast Hurricane Conference, July 19,2006.

[16] William Nordhaus, "The Economics of Hurricanes in the United States", Dec. 21.2006; accessed at http://nordhaus.yale.edu/hurr_122106.pdf

[17] Robert J. Barro, 2009, "Rare Disasters, Asset Prices and Welfare Costs", *American Economic Review*; vol. 99;no.1;243-264.

[18] See, for example, United States Geological Survey, "Climate Change and Water Resources: A Federal Perspective", Washington, DC, 2008.

[19] It is assumed that at wind speeds of 30 mph or below, there are no damages, and at wind speeds above 130 mph, there would be a total loss of project income, and between those limits damages would be proportional to the Carvill index.

[20] Robert Repetto, "The Climate Crisis and the Adaptation Myth", Yale School of Forestry and Environmental Studies, on line at http://environment.research.yale.edu/documents/downloads/v-z/WorkingPaper13.pdf