

The Economics of Hurricanes in the United States¹

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Abstract

Hurricanes were an important scientific, economic, and political factor in the U.S. in 2005. Was 2005 a harbinger of new era of increasingly destructive hurricanes? This study examines the economic impacts of tropical cyclones in the United States. The major conclusions are the following: First, there is no clear long-term change in the number or intensity of hurricanes worldwide, in the North Atlantic, or landfalling in the United States, but there is an apparent increase in storms in most regions since 1970. Second, there are substantial vulnerabilities to intense hurricanes in the southern coast of the United States. Damages appear to rise with the ninth power of maximum wind speed. The major concentrations of vulnerable capital are Miami, New Orleans, Houston, and Tampa. Third, greenhouse warming is likely to lead to greater intensity of intense hurricanes, but the evidence on the frequency is unclear. We estimate that the average annual U.S. hurricane damages will increase by \$10 billion at 2005 incomes (0.08 percent of GDP) as a result of hurricane intensification due to global warming. Fourth, the experience of 2005 appears to have been a quadruple outlier of nature, involving a large number of North Atlantic tropical cyclones, a large fraction of intense storms, a large fraction of the intense storms making landfall in the United States, and an intense storm hitting the most vulnerable high-value region in the country.

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Hurricanes in the North Atlantic were an important scientific, economic, and political factor in 2005. That year broke a number of records for the North Atlantic: most hurricanes (fifteen), most major hurricanes hitting the United States (four), the strongest recorded hurricane, and the most category 5 hurricanes (four). On the economic front, hurricane Katrina was (in inflation corrected prices) the costliest hurricane in U.S. history. On the political front, the slow response of the federal government led to widespread criticism of President G.W. Bush.

Was 2005 a harbinger of a new era of increasingly destructive hurricanes? Does it reflect global warming? What kinds of policies should be undertaken to cope with the rising seas and possibility of more intense hurricanes? Should cities like New Orleans be abandoned to return to salt marshes or ocean? There can be no definitive answers to these questions, but this study provides an analysis of the economic issues involved.

Geophysical background

What are hurricanes?

Hurricanes are the name given to the North Atlantic versions of a spectacular natural phenomenon known as “tropical cyclones.” Such storms are known as “tropical storms” when they reach a maximum sustained surface winds of at least 17 meters per second, mps (34 nautical miles per hour, kts, or 39 miles per hour, mph). If sustained winds reach 33 mps (64 kts or 74 mph), then they are called “hurricanes” in the North Atlantic Ocean.

Tropical cyclones (TCs) are giant heat engines fueled by condensation of warm water, with a positive feedback loop whereby stronger winds lead to lower pressure, increased evaporation and condensation, and yet stronger winds. The genesis of hurricanes is incompletely understood, but one important necessary condition is sea-surface water temperature of at least 26.5 °C (80 °F). Moreover, there are thermodynamic upper limits on the strength of hurricanes, determined primarily by ocean temperature.

Are there trends in the frequency or intensity of tropical cyclones?

There is no apparent trend in the global frequency of TCs. The global number of TCs over the 1970-2004 period has averaged around 85, with no statistically significant trend.² Whether there are longer term trends or cycles in TC frequency either globally or in the North Atlantic is controversial, which is not surprising given that reliable data are only available since the advent of satellite data in 1960.³

Since this paper involves primarily the United States, we focus on TCs in the North Atlantic. A regression analysis of number of storms on time for 1950-2005 yields coefficients on time equal to $-0.063 (\pm 0.017)$ for tropical storms, $0.027 (\pm 0.014)$ for minor hurricanes (SSS or Saffir-Simpson scale = 1 or 2), and $-0.0089 (\pm 0.016)$ for major hurricanes (SSS = 3 to 5). We can also examine the trend in intensity in the North Atlantic basin using an index known as Accumulated cyclone energy (ACE), shown in Figure 1. These data suggest a long cycle at which 1950 and 2005 are the peaks but no significant change in intensity over the period. A regression of the natural logarithm of ACE on time yields a coefficient of $-0.00073 (\pm 0.0056)$, indicating no trend.

Recent data, on the other hand, indicate an increase in intensity along with sea surface temperature since around 1970. The ACE index shows a positive significant time coefficient after 1970. Emanuel defines a more complete hurricane power index over the lifetime of the cyclone and shows that this index has increased markedly since the mid-1970s.⁴ The growth in both indexes is much larger than would be attributed to the impact of global warming.

² P. J. Webster, G. J. Holland, J. A. Curry, H.-R. Chang, "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment," *Science*, 16 September 2005, Vol. 309. no. 5742, pp. 1844 - 1846.

³ Some of the difficulties of measuring long-term trends are described in Christopher W. Landsea, Bruce A. Harper, Karl Hoarau, and John A. Knaff, "Can We Detect Trends in Extreme Tropical Cyclones?" *Science*, 28 July 2006, vol. 313. no. 5786, pp. 452 - 454.

⁴ This is similar to the "power dissipation index" constructed in Kerry Emanuel, "Increasing destructiveness of tropical cyclones over the past 30 years," *Nature*, 436, 4 August 2005, pp. 686 - 688.

The time series is longer for TCs making landfall in the United States, with estimates going back to 1851.⁵ While these data are probably less accurate in earlier years, they provide an order-of-magnitude estimate of hurricane frequency and intensity. We convert these data into a “hurricane power” index by taking the cube of the maximum sustained wind speed at landfall in the United States. We then add the power of all recorded hurricanes each year to construct a time series, which is shown in Figure 2 along with a smoothed kernel fit.

A time series analysis of the annual hurricane power for the landfalling hurricanes, shown in Figure 2, indicates no trend in the power of hurricanes over the 1851-2005 period. The regression is the ln of power on a constant and a year variables, with the coefficient on time being $-0.00050 (\pm 0.0016)$. This coefficient, which is consistent with the estimates for the North Atlantic, is essentially zero. However, if the time series considers only the 1970-2005 period, then the time trend becomes positive and marginally significant.

All these results indicate that there is little firm evidence of a long-term increase in the frequency or severity of TCs either globally or in the North Atlantic region, but there is some evidence of a recent increase in hurricane intensity. However, these conclusions are of limited statistical power because of the short duration of satellite observations and the difficulties of classifying intensities.

Was 2005 an unusual year for the United States?

The answer to this question is that 2005 was unusual but not unique. This point was illustrated by all the records broken for 2005 cited at the beginning of this study. A more satisfactory approach is to look at the distribution of hurricane power across years. Looking at the power index shown in Figure 2, we see that 2005 was the third highest year in terms of total

⁵ Hurricane data are from Eric S. Blake, Jerry D. Jarrell, Edward N. Rappaport, and Christopher W. Landsea, “The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2005,” NOAA Technical Memorandum NWS TPC-4, NOAA/AOML/Hurricane Research Division, Miami, Florida, Updated July 2006 (Appendix A), http://www.nhc.noaa.gov/Deadliest_Costliest.shtml, downloaded on July 11, 2006. This has been adjusted where appropriate. See background document for details on adjustments.

intensity, with 2004 and 1886 being slightly larger. Calculating the appropriate frequency distribution is complex because hurricane power is skewed with truncated observations, but if we look at the logarithm of power by year, 2005 was about 2.2 standard deviations from the mean for the 1851-2005 period. 2005 was high not because the power of individual hurricanes at landfall was large, however, but because the number of powerful hurricanes was so large.

How vulnerable are different regions?

One factor determining economic vulnerability to hurricanes is the variability of storm intensity just discussed. The other major factor is the vast difference in vulnerability of different regions. As an example, of the 41 hurricanes with maximum winds between 95 and 110 kts, the maximum damages were \$81 billion and the smallest damage was \$220 thousand.

How vulnerable are different regions? We can get a rough estimate of the “intrinsic vulnerability” by examining the magnitude of the nation’s capital stock that is in coastal areas and at low elevation. For this purpose, I have applied the “G-Econ data set” to estimate disaggregated region economic vulnerability. This data set provides comprehensive global estimates of gross domestic product, average elevation, distance from coastline, and population for 1° latitude x 1° longitude.⁶ For the present study, I further divided the country into sub-grid-cells of 10’ by 10’ (approximately 15 by 15 kilometers) for the vulnerable Atlantic coast of the United States, and then estimated the capital stocks for each sub-grid-cell.

Figure 3 gives a picture of the vulnerable areas of the coastal Atlantic. For this figure, we select all coastal sub-grid-cells with elevation less than 8 meters and with 2005 capital stocks of more than \$1 billion. These areas are vulnerable to large storm surges that might accompany major hurricanes. The major concentrations of vulnerable economic activity and capital (with capital stock greater than \$100 billion) are in the Miami coast, New Orleans, Houston, and Tampa.

⁶ The methodology and data as well as selected relationships are contained in William Nordhaus, “Geography and Macroeconomics: New Data and New Findings,” *Proceedings of the National Academy of Sciences (US)*, March 7, 2006, vol. 103, no. 10, pp. 3510-3517. The complete data set is on the web at www.gecon.yale.edu .

Economic Impacts of Hurricanes

Before looking at the economic impact of hurricanes, it will be useful to put the impacts of hurricanes in the context of the costs of all “disasters.” Table 1 shows a tabulation of disasters other than war on a global scale, with estimates of insured losses and total losses for 2005. Storms were more than half the total losses, and contributed 94 percent of insured losses. Of the total \$78 billion of global insured losses, \$45 billion was estimated to arise from Hurricane Katrina and \$65 billion were from the three largest U.S. hurricanes. Earthquakes were the other large contributor, producing 90 percent of fatalities. 2005 was typical of the distribution of costs of disasters. To put these in a broader context, by far the largest “disaster” is war, which has produced on average 180,000 fatalities per year since 1946.⁷ Fatalities from terrorism have averaged around 200 per year since 1946 and pale by comparison with war and other disasters.

Turn next to hurricanes. The total impact of hurricanes has risen over time because of inflation and a larger economy. The most natural normalization for hurricane damages is to divide them by GDP. This would be an appropriate correction for inflation and for balanced changes in the location and structure of economic activity, and assuming no changes in technology or adaptation. Additionally, there has been migration to coastal communities, which raises vulnerability. Approximately half of hurricane power has intersected Florida, and Florida’s share of GDP or personal income has risen on average around 2 percent annually over the last half century.

An additional factor affecting estimates over time is the convention of estimating total damages as a multiple of (two times) insured damages. There has been some upward trend in the ratio of casualty premiums to the total capital stock, but data on hurricane coverage is not readily available. Overall, these data suggest that – holding other things such as hurricane intensity and building codes constant – the ratio of hurricane damages to GDP would rise in the order of 1 to 1½ percent per year.

⁷ Bethany Lacina and Nils Petter Gleditsch, “Monitoring Trends in Global Combat: A New Dataset of Battle Deaths,” *European Journal of Population*, Vol. 21, N. 2-3, June 2005, pp. 145 – 166.

We have collected data on the damages from 140 hurricanes that have made landfall in the United States.⁸ These include all storms since 1933 and 13 storms before 1933. Figure 4 shows the trend in normalized hurricane damages since 1950. 2005 stands out from the crowd, primarily because of Katrina (\$81 billion). Comparing Figures 2 and 4, we see that 2005 was an economic outlier primarily because the cost per unit power was high, not because power was extraordinarily high. The reason is that Hurricane Katrina hit what is probably the most vulnerable high-value spot in the United States, as we saw in Figure 3.

Figure 5 shows a scatter plot of hurricane power and normalized damages for the 140 hurricanes with complete data. We can also estimate the relationship between normalized damages and maximum wind speed. The basic equation is:

$$(1) \quad \ln(cost/GDP) = \alpha_0 + \alpha_1 \ln(maxwind) + \alpha_2 year .$$

In equation (1), *cost* is estimated total damages and *maxwind* is estimated maximum sustained wind speed at landfall. The results are shown in the following table:

Specification Period	Coefficient on ln(maxwind)		Coefficient on year	
	Coefficient	t-statistic	Coefficient	t-statistic
OLS				
All	8.03	10.24	0.022	3.21
Since 1975	9.87	9.15	0.037	1.40
TOLS				
All	10.14	8.69	0.036	10.94
Since 1975	9.82	10.94	0.026	3.67

The table shows four different estimation procedures. The first two lines are ordinary least squares for all hurricanes and for hurricanes since 1975. The

⁸ The major early study in this area is R. A. Pielke, Jr. and C. W. Landsea, "Normalized Hurricane Damages in the United States: 1925-1995," *Weather and Forecasting*, 1998, vol. 13, pp. 621-631, available online at <http://www.aoml.noaa.gov/hrd/Landsea/USdmg/data.html>. We have verified the data from the original sources, with revisions where appropriate.

second two lines use instrumental variables (two-stage least squares, or TSLS), again for the entire sample and for the period since 1975. TSLS is useful if we suspect that the estimates are contaminated by errors in measurement of maximum wind speed. For the TSLS estimates, we use as instruments SS scale and minimum pressure.

This regression contains one of the major surprises of this paper. The regression indicates that the elasticity⁹ of damages with respect to maximum wind speed is in the range of 8 to 10. This is at first blush a substantial puzzle. Current presumptions appear to be that damages rise with the energy of hurricanes, or as the cube of maximum wind speed.¹⁰ The estimates indicate that economic damages rise much more rapidly than with hurricane energy.

The table indicates a range of values depending upon the specification. The standard all-sample OLS has the lowest estimate of 8.0. The estimated coefficient for the post-1975 period is consistent between TSLS and OLS, with a coefficient of 9.9. The TSLS estimates yield a higher elasticity for the early period –as would be expected if the wind speed is measured with error –with 10.1 for the longer period instead of 8.0. The table indicates that the super-

⁹ Note for non-economists: Elasticities are commonly used to show the scale-free proportional relationships between variables. In this context, the elasticity of y with respect to $x = \partial[\ln(y)]/\partial[\ln(x)]$. Later, we use the semi-elasticity, which is equal to $\partial y/\partial[\ln(x)]$.

¹⁰ “But the amount of damage increases roughly as the cube of the maximum wind speed in storms...” (Kerry Emanuel, “Increasing destructiveness of tropical cyclones over the past 30 years,” *Nature*, 436, 4 August 2005, pp. 686-688, citing Southern, R.L., “The global socio-economic impact of tropical cyclones,” *Australian meteorological magazine*, vol. 27, no. 4, December 1979, pp. 175-195). Insurance industry estimates put the power between four and six. (“The average increase in the loss ratio is approx. the fourth to fifth power of the increase in wind speed,” based on loss ratios in Europe from Münchener Rück, Munich Re Group, Analysis of 1999 Losses and Loss Potentials: the 1999 Winter Storms, available online at www.munichre.com/publications.) A sixth power law appears to apply to damage to buoys (“So roughly a factor of the sixth power applies to wind speed on the oceans and potential for damage to buoys,” Report on Autonomous Systems in Extreme Environments Workshop, August 31 – September 2, 1999, Jet Propulsion Laboratory, available at geodynamics.jpl.nasa.gov/antarctica/ASEE_Report_Final.pdf).

high elasticity finding survives the obvious sensitivity analyses. In the global warming estimates below, I use an elasticity of 9.??0 as the central case.

What are the reasons for the super-high elasticity? To begin with, there is no presumption that a damage function should be proportional to power or energy. The damage dose-response curve will depend upon the material and the stress. It seems likely that the impact to wind or water will be highly non-linear, where small stresses cause little damage, but past a certain stress the damage increases non-linearly or even catastrophically. The best example would be threshold effects in responses, such as those due to catastrophic failures when water or wind overwhelm structures designed up to a given tolerance. The threshold effects were dramatically illustrated by the levees of New Orleans. If we estimate equation (1) with non-linear effects of wind speed, the results suggest that the elasticity is extremely high (>10) for low wind speed and declines as wind speed increases, suggesting sharp non-linear impacts.

A second reason for the super-high elasticity is that stronger storms lead to higher storm surges, a larger area exposed to hurricane winds, and therefore to a larger exposure of the capital stock. To estimate this effect, we calculate the capital vulnerability index (CVI), which is an extension of Emanuel's power dispersion index.¹¹ The CVI estimates the weighted amount of capital that is in the path of the hurricane, where the weights are proportional to the cube of wind speed. Details of the calculation are provided in the Appendix.

The empirical question is the shape of the relationship between vulnerable capital and wind speed. An estimated equation finds that the elasticity of CVI with respect to maximum wind speed is 5.3 (± 0.49) for the central specification, with alternative specifications have elasticities between 4.5 to 6.7. This shows that the vulnerable capital stock does indeed rise more rapidly than the cubic power law suggests.

At this point, we can only make tentative suggestions about the reasons for the super-high elasticity of damages with respect to maximum wind speed. It seems unlikely that it comes from measurement errors, but the sample size is modest and more digging would be fruitful. Second, the

¹¹ Kerry Emanuel, "Increasing destructiveness of tropical cyclones over the past 30 years," *Nature*, 436, 4 August 2005, pp. 686-688.

economic vulnerability increases very sharply with maximum winds. This arises both because of a non-linear relationship between wind speed and damage and because the “cone” of high winds increases sharply with maximum wind speed. Third, it seems likely that the damage function lies in that part of the “dose-response curve” at which sharp threshold effects begin to emerge.

Finally, note that the time trend in the OLS full-sample equation indicates that normalized damages have risen by 2.2 percent per year, indicating increased vulnerability to storms of a given size.¹² The coefficient is slightly above the presumption given the growth in coastal population and insurance ratios, discussed above. This increase is contrary to the standard “lessening hypothesis,” whereby societies have become less vulnerable to weather shocks.¹³

Global warming and hurricanes: inconvenient truth?

Hurricanes have featured prominently in the national media partly because 2005 was so unusual and partly because of fears that global warming may bring a string of hurricanes like Katrina to our shores. Should we thereby expect terrible and costly events like Katrina and the inundation of New Orleans to recur frequently in the future? The answer here is probably not frequently, but much here is murky.

The basic physics of the link between global warming and tropical cyclones is clear if complex. Global warming might affect hurricanes in several dimensions, including the frequency, size, intensity, and geographic

¹² This is contrary to Roger A. Pielke, Jr., “Are There Trends in Hurricane Destruction?” *Nature*, Vol. 438, December 2005, E11, who reports no statistically significant trend. Similar negative results were found in Roger A. Pielke, Jr. and Christopher W. Landsea, “La Niña, El Niño, and Atlantic Hurricane Damages in the United States,” *Bull. Amer. Meteor. Soc.*, vol. 80, 2027-2033. The equations and data were not provided so no comparison can be made with the current results. Additionally, issues of comparability over time are non-trivial, as is discussed in Christopher W. Landsea, “Hurricanes and Global Warming,” *Nature*, Vol. 438, December 2005, E11-E12.

¹³ Warrick, R. A. “Climatic Constraints and Human Activities,” eds. Ausubel, J. and Biswas, A. K., Pergamon, Oxford, 1980, pp. 93-123.

distribution of tropical cyclones. Of the four, the only clear link from basic physics is between global warming and cyclonic intensity. As sea-surface temperature rises, the “potential intensity” or upper limit of cyclonic wind speed increases (holding other factors constant).

Early calculations by Emanuel indicated that each degree C of warming of sea-surface temperature (SST) would lead to an increase in potential intensity (maximum wind speed) of 5.5 percent; that is, the semi-elasticity of maximum wind speed with respect to SST is estimated to be 5.5.¹⁴ Using several global circulation models (GCMs), Knutson and Tuleya estimated the distribution of hurricane intensity with the current (pre-global-warming) climate and with a climate of doubled CO₂ concentrations. Their study indicated that the maximum wind speed would increase by 5.8 percent in the high-CO₂ world. More precisely, the experiment increased CO₂ concentrations 1 percent per year for 80 years, which produced a 1.7 °C increase in tropical sea-surface temperatures.¹⁵ These experiments indicate a semi-elasticity of 3.5 of maximum wind speed with respect to SST. To move from potential intensity to the actual distribution, statistical work of Emanuel found that there is a uniform distribution of the ratio of actual maximum wind speed to potential maximum wind speed.¹⁶ If this relationship holds in the warmer world, it would imply that the distribution of actual hurricane intensity would increase with the increase in potential intensity.

To estimate the impact of climate change on hurricanes further requires an estimate of changes in SST in the tropical Atlantic. General circulation models suggest that the equilibrium impact of doubling of atmospheric CO₂ concentrations would be an increase in tropical Atlantic SST of around 2.5 °C.

¹⁴ Kerry A. Emanuel, “The Dependence of Hurricane Intensity on Climate,” *Nature*, 326, April 8, 1987, pp. 483 – 485.

¹⁵ A discussion and report on simulations is contained in Thomas R. Knutson and Robert E. Tuleya, “Impact Of CO₂-Induced Warming On Simulated Hurricane Intensity And Precipitation: Sensitivity To The Choice Of Climate Model And Convective Parameterization,” *Journal of Climate*, Vol. 17, No. 18, September 15, 2004, p. 3477-95. A useful summary of the state of the science is by Kerry Emanuel at <http://wind.mit.edu/~emanuel/anthro2.htm>.

¹⁶ K. Emanuel, “A Statistical Analysis of Tropical Cyclone Intensity,” *Monthly Weather Review*, 128, April 2000, pp. 1139-1152.

Using the estimated impact from the Knutson and Tuleya study, this would lead to an increase in maximum wind speed of 8.7 percent. The scientific jury is still out as to whether there will be an increase in hurricane frequency. I assume unchanged frequency, but the adjustment to changing frequency is linear and therefore trivial.

In considering the impact of global warming on hurricane damages, we would want to consider both the effect on the mean impact and the effect on the tails of the distribution. Estimating the mean impact of global warming is conceptually straightforward in the present model. The ratio of the mean impact with to that without global warming is equal to the product of the elasticity of damages with respect to wind speed, the semi-elasticity of increased wind speed with respect to mean temperature, and the increase in mean temperature. More precisely, the increase in the impact of hurricanes from global warming is equal to:¹⁷

$$(2) \quad \ln(V_1 / V_0) = \{\partial[\ln(D)]/d[\ln(W)]\} \times \{\partial[\ln(W)]/dT\} \times (T_1 - T_0)$$

where V_1 = mean damages with global warming, V_0 = mean damages without global warming, $\partial[\ln(D)]/d[\ln(W)]$ = elasticity of damages with respect to maximum wind speed, $\{\partial[\ln(W)]/dT\}$ = semi - elasticity of wind speed with respect to mean temperature of the surface waters, and $(T_1 - T_0)$ = change in the mean temperature of the surface waters.

Table 2 shows numerical estimates of the percentage increase in hurricane damages using estimates of the three parameters in equation (2) from this study and from the scientific literature as discussed above. The central estimate is that the impact of a doubling of CO₂-equivalent atmospheric concentrations would lead to an increase in the mean damages of 128 percent. Additionally, the table shows three estimates with alternative values of the parameters, with the increase ranging from 28 percent to 286 percent.

To put actual numbers on these relationships, we assume the appropriate sample is the number, intensity, and damages of hurricanes making landfall in the United States for the 1851-2005 period. More

¹⁷ The mathematical structure implies that the relationship holds even with a distribution of wind speeds.

specifically, I assume that the frequency is given by a Poisson distribution with a frequency of $1.8 = (281/155)$ per year. I further assume that the distribution of intensities of TCs making landfall in the Atlantic U.S. (before global-warming adjustments) is given by the historical distribution of intensities. The distribution of maximum wind speeds with global warming is given by shifting the distribution of maxima upward 8.7 percent. We also note that these findings do not include any adjustment for adaptation, improved siting requirements, or sea-level rise.

To obtain the distribution of outcomes, I use equation (1) above with three modifications. I first remove the time trend, assuming that the historical shift in vulnerability has come to an end. I use an elasticity of 9.0, as explained above. Finally, I assume that there are unexplained log-normal random errors with a standard deviation of 0.94. The distribution of total annual economic impacts is determined as follows.

$$(3) \quad V_t = \sum_{nt=0}^{mnt} f[Maxw(nt)] h[(Maxw(nt))]$$

where V_t = economic impact of all tropical cyclones in simulation year t ($t = 1, \dots, 10,000$); nt = tropical cyclone number n for year t , mnt = maximum number of tropical cyclones in year t (from the Poisson distribution); $Maxw(nt)$ = maximum wind per tropical cyclone for storm nt ; $f[(Maxw(nt))]$ = distribution of tropical cyclone intensity from the 1851 - 2005 distribution; and $v = h[Maxw(nt)]$ is the normalized impact (impact divided by GDP). The distribution of costs is given by $\ln(v) = const + 9.0 \ln(Maxw) + N(0,0.94)$, where $N(0,0.94)$ is a normal distribution with mean 0 and standard deviation 0.094, and $const$ is a constant that adjusts the mean to equal the mean cost for the period 1950 - 2005. For the "no global warming" simulation, we calculate the distribution according to equation (3). For the "global warming" simulation, we substitute the global warming distribution of intensities in (3), where the cumulative distribution function of $f(Maxw)$, which is $F(Maxw)$, shifts by 8.7 percent. That is, $F(Maxw)$ with global warming = $F(Maxw \times 1.087)$. We use the same realizations of the random numbers for the two simulations.

The results are shown in Table 3. We show the results both as a percent of GDP and as scaled to 2005 GDP levels. The mean for the period 1950-2005 is 0.065 percent of GDP (\$8.2 billion scaled to 2005 GDP). The impact of global

warming is shown in the last column of Table 3. According to the calculations described above, the mean expected impact would be to increase the impacts by 0.084 percent of GDP (\$10.5 billion), which amounts to slightly more than doubling. This number is exactly the estimate described above.

Table 3 also shows the tails of the distribution of impacts. Because of the ninth-power relationship, the distribution of extremely costly storms is expected to increase sharply.

Was 2005 the signal of global warming or a huge outlier?

One of the standard critiques of scientific studies projecting global warming or its impacts is that time series estimates do not show either that the warming is statistically significant or that there is a significant coefficient of the anthropogenic variables on warming or impacts. This debate has been paralleled in the discussion about the impact of global warming on hurricanes. The calculations provided above show why it will be extremely difficult to sort out the climate signal from the weather noise in the hurricane data. The projections underlying the impacts estimates are that the annual power of hurricanes will increase about $1/3$ percent per year over the next century or so (roughly 28 percent over the equilibrium CO₂ doubling period). For the 1950-2005 period, a time series regression of the natural logarithm of annual power on year has a standard error of around 0.80 on the time trend – far above the level that would be required to identify an annual increase that is estimated to be less than one-third of that.

While we cannot detect the climatic signal at this stage, we can make a preliminary judgment as to whether 2005 is likely to be a typical year in a warmer world. In terms of hurricane power, 2005 was 3.5 times the mean power for the historical period and 2.7 times the estimated mean power for the global warming scenario. In terms of cost, 2005 was 12.3 times the mean hurricane damage for years with data, and 5.8 the estimated mean annual hurricane damage with global warming.

We can also examine the distributions shown in Table 2 along with two major recent hurricanes. The normalized cost (percent of GDP) of the 1:100 year hurricanes is estimated to increase from 0.84 to 1.91 percent of GDP. According to the estimates in Table 2, the impact of Hurricane Andrew was a 3.1 percentile event without global warming but will increase to a 7.6 percentile event with global warming. Hurricane Katrina is estimated to be a

1.5 percentile impact event without global warming but increasing to a 4.9 percentile event with global warming. In non-technical terms, we would expect hurricanes with impact as high as Katrina once every 67 years without global warming but once every 20 years with global warming.

Another way of viewing 2005 in historical perspective is to examine the frequency distribution of the power of landfalling hurricanes. Figure 6 shows the frequency distribution by annual hurricane power with and without global warming; the global warming distribution assumes no change in frequency and scales up power by 28 percent, as described above. This estimate suggests that the annual frequency of years with power as great as the highest three years would increase from 3/150 to 6/150. Therefore, while we can take comfort that we are unlikely to have year after year of Katrina/Rita/Wilma type experiences, these would recur occasionally on a century scale.

Concluding thoughts

The basic story here is the following: There has been no clear long-term change in the number or intensity of hurricanes worldwide, although there has been an uptrend in intensity in the last two or three decades. The trend and cycles for tropical cyclones in the North Atlantic or landfalling in the United States is ambiguous, with some evidence of a recent upturn but no evidence of a long-term upward trend or regular cycle. Only a small fraction of global storms make landfall in the U.S. Although 2005 was the third largest year in terms of power of landfalling hurricanes, it was not a record.

Second, there are substantial vulnerabilities to hurricanes in the southern coast of the United States. Damages are extremely sensitive to hurricane intensity, with the suggestion of a ninth-power law relating damages to maximum wind speed. The source of this super-high elasticity is unclear, but two likely suspects are threshold effects and impact of more intense storms on capital vulnerability.

Third, greenhouse warming is likely to lead to greater intensity of intense hurricanes but the evidence on the frequency is unclear. Our simulation model indicates that the average annual hurricane damages will increase by 0.08 percent of GDP due to the intensity effect of a CO₂-equivalent doubling.

Fourth, the experience of 2005 appears to have been a quadruple outlier of nature. The number of North Atlantic storms was among the highest in a half-century; the fraction of intense storms in 2005 was above average; the fraction of the intense storms making landfall in the United States was unusually high; and one of the intense storms hit what is the most vulnerable high-value region in the country. New Orleans was to the gods of natural destruction what the World Trade Towers were to the gods of human destruction.

Fifth, all this does not address the issues of whether and how the nation should rebuild New Orleans. Perhaps this analysis might relieve those who worry that the precedent of rebuilding New Orleans is a dangerous one fraught with moral hazard. People may worry that New Orleans will inevitably be followed by a string of costly post-hurricane rebuilding projects, but that seems an unlikely prospect given the analysis here.

Finally, we should emphasize that the economic analysis of capital stocks and densities cannot capture the fact that New Orleans is a unique corner of American culture and history. We should recall that our first bellicose Republican President, Thomas Jefferson, threatened to go to war with France and Spain over New Orleans. He thought it the most important spot outside of Virginia, writing, "There is on the globe one single spot, the possessor of which is our natural and habitual enemy. It is New Orleans." If the entire city returns to marshland, the losses will not be huge in our economic accounts, but they will be surely be grave in our cultural accounts.

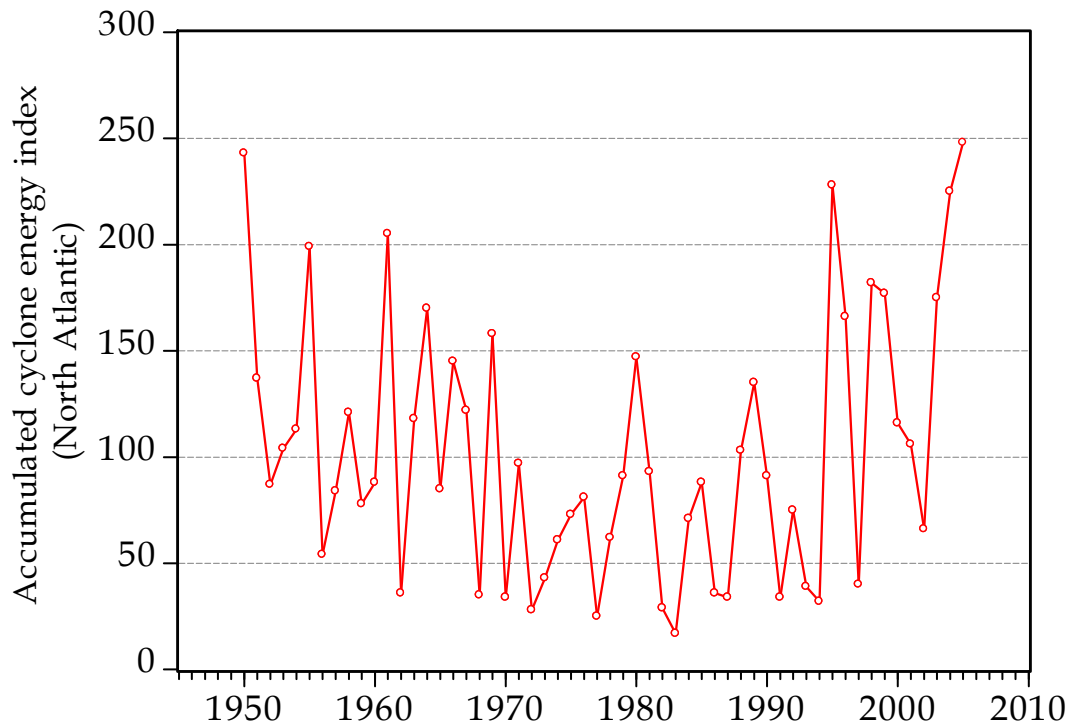


Figure 1. Index of accumulated cyclone energy (ACE) of tropical storms in the North Atlantic, 1950-2005

The ACE index is calculated by summing the squares of the estimated sustained velocity of every active tropical storm (wind speed 35 kts or higher), at six-hourly intervals.

Source: NOAA at

<http://www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html> .

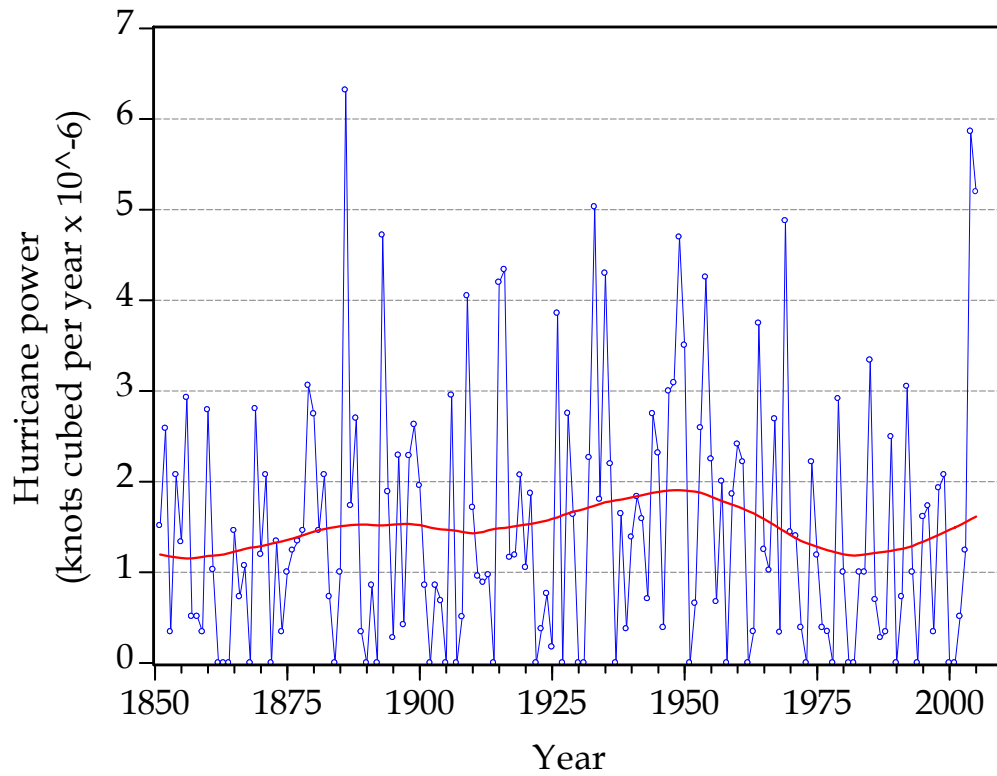


Figure 2. Hurricane Power, 1851-2005

“Hurricane power” is an index that takes the cube of the maximum sustained wind speed at landfall in the United States and then sums all storms for the year. The smooth line is the kernel fit to the data.

Source of hurricane data: See source in footnote 5.

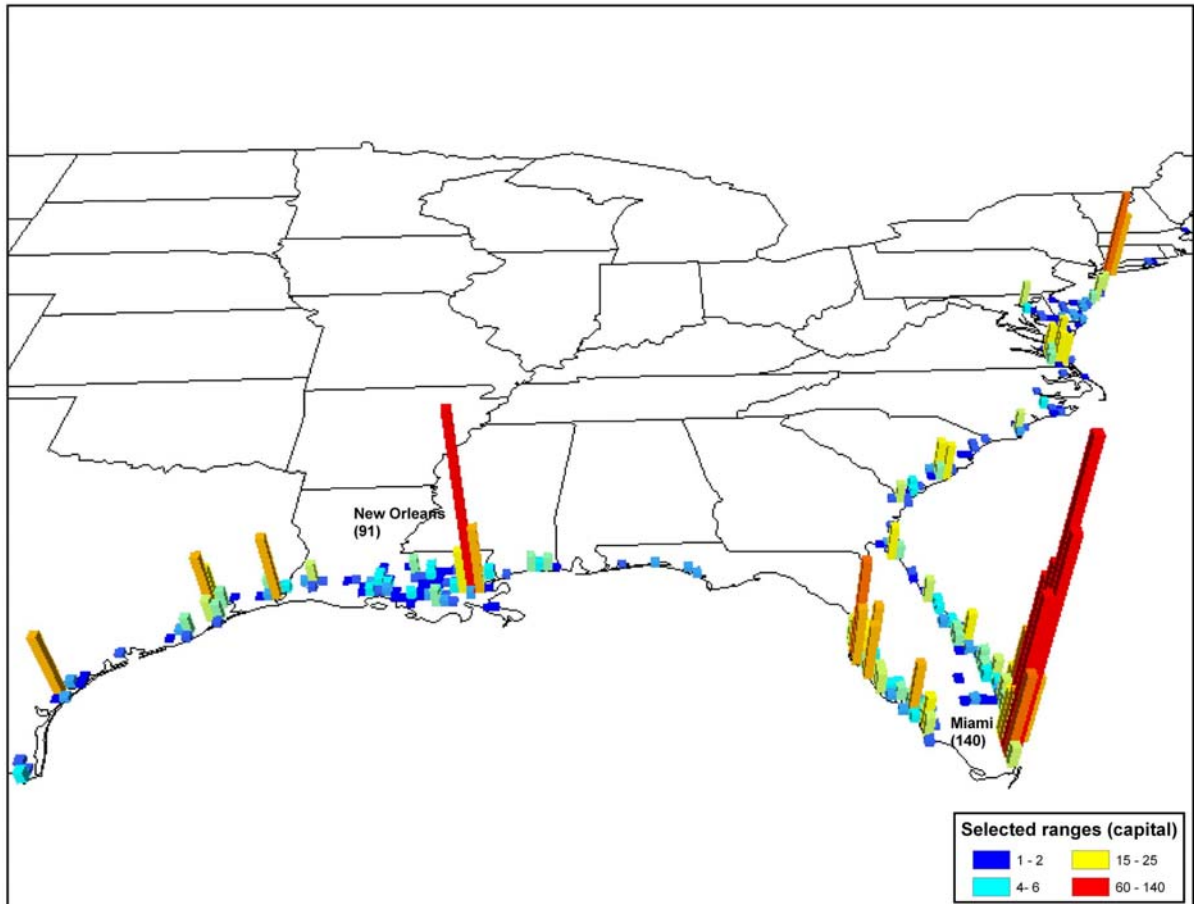


Figure 3. Low-lying areas at risk of sea-level rise and storm surges

This map shows the location of areas with mean altitude per sub-grid-cell less than 8 meters above sea level grouped by estimated capital stock. Each sub-grid-cell is approximately 15 km x 15 km. The legend shows selected colors. The numbers in parentheses are the capital stock of the largest sub-grid-cell.

Data on economic activity by grid cell are from Yale G-Econ project (see gecon.yale.edu). The data on economic activity are extrapolated to 2005 using the ratio of national capital stock in current prices in 2005 to 1990 GDP in 1995 prices. Thanks for Kyle Hood and David Corderi for helping prepare the sub-grid-cell data and to David Corderi for preparation of the map.

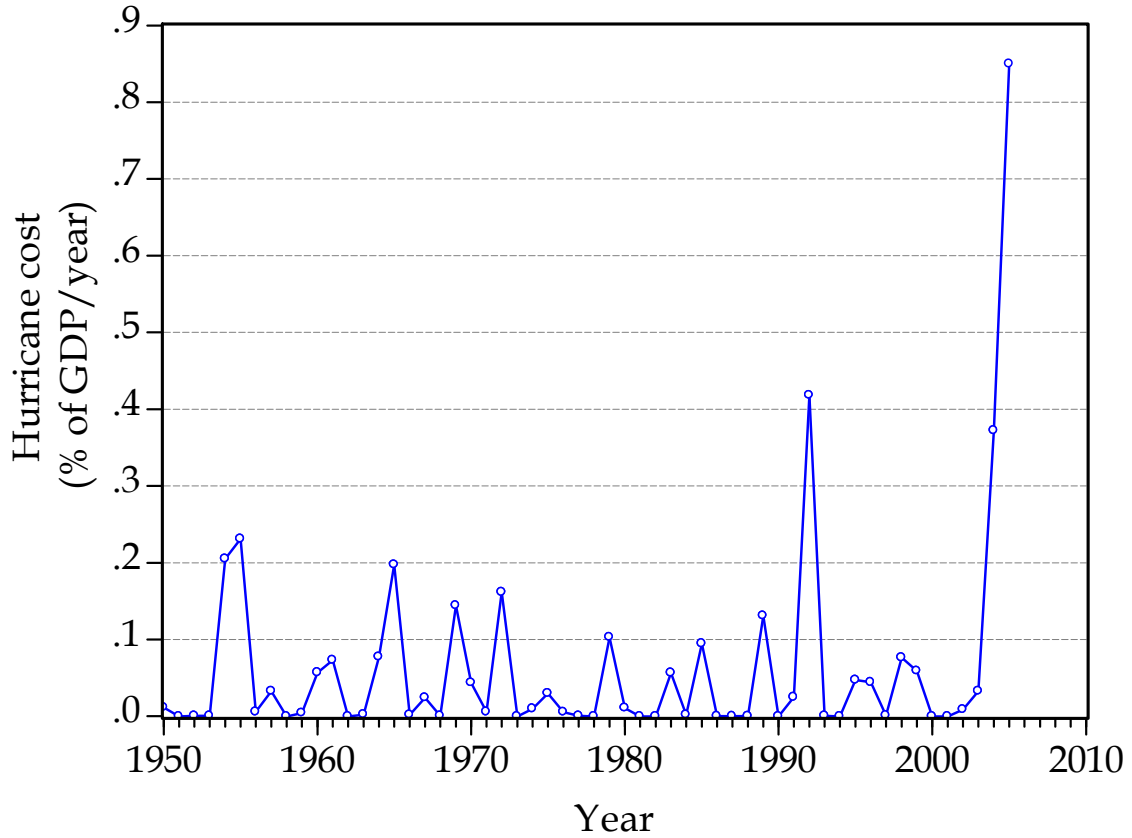


Figure 4. Normalized costs of hurricanes, 1950-2005

This series takes the ratio of estimated damages to GDP of all hurricanes for the given year.

Source: See footnote 8 for damages. GDP from U.S. Bureau of Economic Analysis.

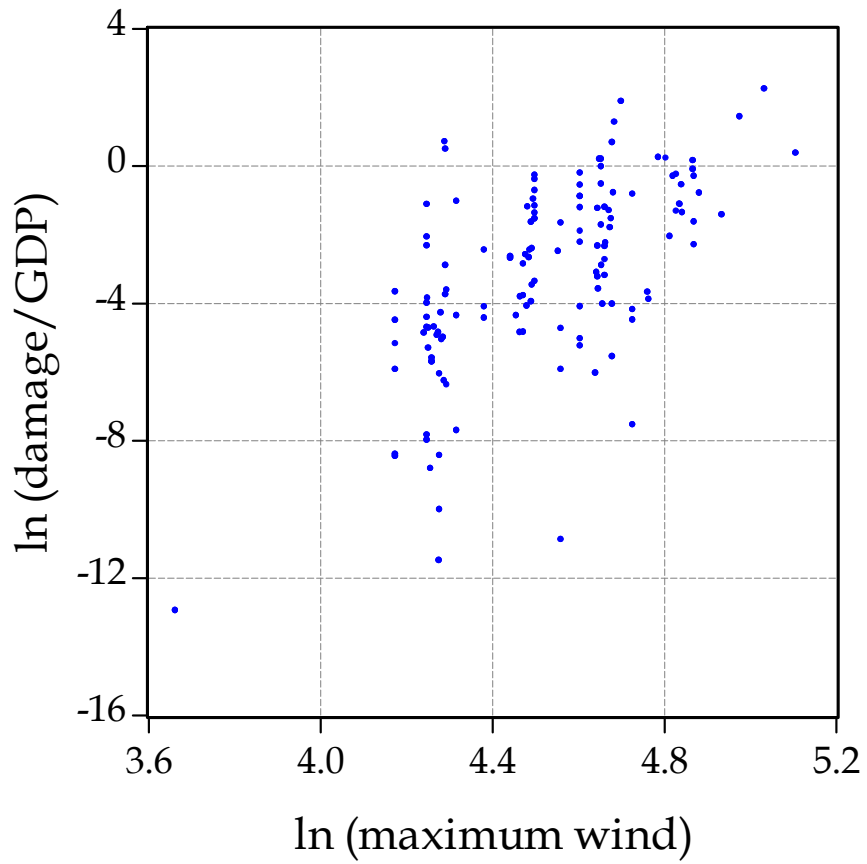


Figure 5. Wind speed and normalized damages for major hurricanes

Source: See footnote 8 for damages and footnote 5 for damages.

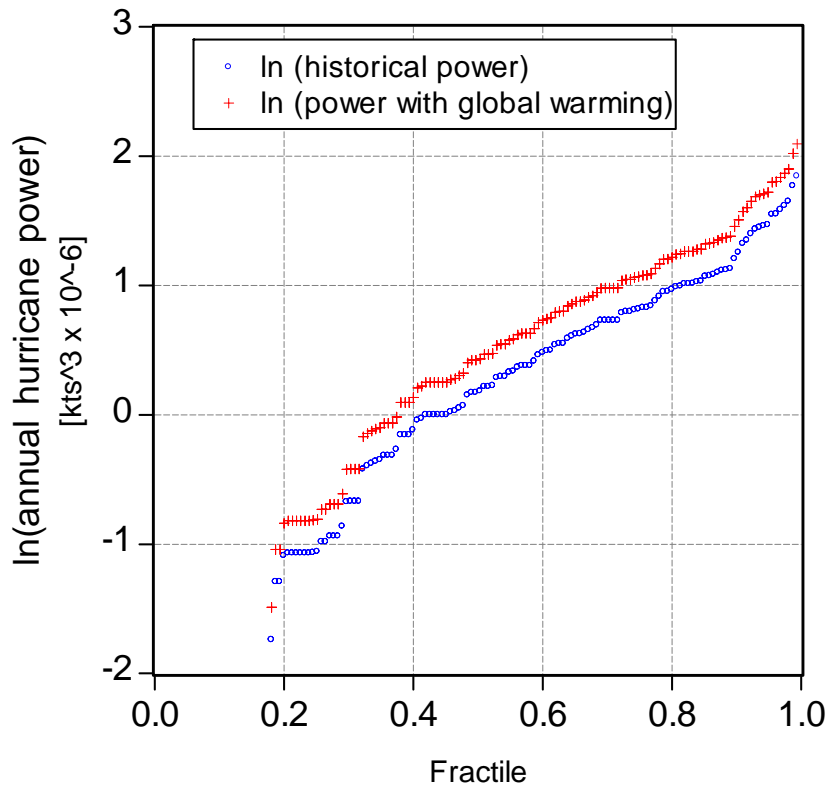


Figure 6. Cumulative distribution of hurricane power, historical and simulated with global warming

Lower curve shows the distribution of power of hurricanes with landfall in U.S. over the 1851-2005 period. Upper red curve shows the distribution assuming no change in frequency but with the simulated increase due to global warming in equilibrium CO₂ doubling scenario. Highest three points are (from top) 1886, 2004, and 2005.

	Number of incidents	Victims (1)	Insured loss [millions of US \$] (2)	Estimated total losses (3)	Percent of total
Natural catastrophes	149	88,083	78,330	244,743	92.77
Floods	61	5,017	3,464	11,945	4.53
Storms	48	4,354	73,512	151,378	57.38
Earthquakes, tsunamis	12	75,267	234	75,735	28.71
Drought, bush fires, heat waves	10	783	20	823	0.31
Cold, frost	12	2,549	623	3,795	1.44
Hail	3		477	954	0.36
Other natural catastrophes	3	113		113	0.04
Man-made disasters	248	8,935	5,066	19,067	7.23
Major fires, explosions	60	692	4,095	8,882	3.37
Industry, warehouses	31	162	2,346	4,854	1.84
Oil, gas	5	110	1,450	3,010	1.14
Hotels	3	54	45	144	0.05
Department stores	5	26	118	262	0.10
Other buildings	13	267	136	539	0.20
Other fires, explosions	3	73		73	0.03
Aviation and space disasters	18	1,097	385	1,867	0.71
Crashes	16	1,097	232	1,561	0.59
Explosions, fires					
Damage on ground					
Air collisions					
Space	2		153	306	0.12
Other aviation accidents					
Shipping disasters	45	1,956	90	2,136	0.81
Freighters	6	81	66	213	0.08
Passenger ships	38	1,840	25	1,890	0.72
Tankers	1	35		35	0.01
Drilling platforms					0.00
Other shipping accidents					0.00
Rail disasters (incl. cableways)	18	563	167	897	0.34
Minor accidents	22	1,244		1,244	0.47
Collapse of buildings/bridges	3	195		195	0.07
Miscellaneous	82	3,188	328	3,844	1.46
Social unrest	12	550	236	1,022	0.39
Terrorism	22	614	52	718	0.27
Other miscellaneous losses	48	2,024	41	2,106	0.80
Total	397	97,018	83,396	263,810	100.00

(1) Dead and missing

(2) Property and business interruption, excluding liability and life insurance losses

(3) Estimates cost of fatality as \$1 million and estimates that total damages are twice the insured damages.

Table 1. Estimated Losses from “Disasters” in 2005

Source: Number of incidents, insured losses, and victims from Swiss Re, *Sigma*, 2006.2, Table 3. Estimated total damages as explained in footnote.

Case	(1) Elasticity of damages w.r.t. wind speed	(2) Semi- elasticity of maximum wind speed w.r.t. T	(3) Change in tropical sea- surface temperature (SST , °C)	(4) Estimated increase in mean damages	Source
Central case	9.85	0.035	2.5	128.5%	[a]
OLS elasticity	8.03	0.035	2.5	96.1%	[b]
Emanuel semi-elasticity	9.85	0.055	2.5	255.7%	[c]
Conventional damage impact	3.00	0.035	2.5	28.6%	[d]
Warming in 20th C	9.85	0.035	0.54	20.3%	[e]

[a] col (1) from estimates in text relying on IV estimates and sample since 1975; col (2) from $\kappa(T)$ as discussed in text.

[b] same as [a] except use OLS full period elasticity for col (1).

[c] same as [a] except use semi-elasticity in col (2) from Emanuel as discussed in text.

[d] same as [a] except use conventional estimate of cubic damage function.

[e] Use estimated rise of tropical SST in Atlantic cyclogenesis region from Santer 2006.

Table 2. Estimated mean damages from global warming, central case and alternative estimates

Table shows the parameters underlying the estimates and the estimated increase in mean damages from equilibrium doubling of CO2 equivalent greenhouse gases. Estimate is from equation (2) in text. Best estimate is an increase of 128 percent in first row. Other estimates range from 29 to 256 percent with alternative parameters. The last row shows the estimated increase over the 20th century assuming a 0.54 °C increase in SST.

		Annual cost of hurricane damage					
		Without global warming or historical data		With global warming		Difference	
		[% of GDP]	[billions, 2005 levels]	[% of GDP]	[billions, 2005 levels]	[% of GDP]	[billions, 2005 levels]
Mean							
a	Historical data	0.065	\$ 8.2				
b	Simulations	0.065	8.2	0.149	\$ 18.6	0.084	\$ 10.5
Earlier studies							
c	Cline					0.013	
c	Fankhauser					0.003	
c	Tol					0.005	
Distribution of impacts							
d	0.1 percentile	2.797	349.3	6.390	798.0	3.593	448.7
d	1 percentile	0.835	104.3	1.909	238.4	1.073	134.0
d	10 percentile	0.143	17.9	0.327	40.8	0.184	23.0
d	median	0.011	1.4	0.025	3.1	0.014	1.8
Item: Impacts of historical hurricanes							
e	Andrew (1992)	0.42	(pn, pg =	0.031	, 0.076)	
f	Katrina (2005)	0.65	(pn, pg =	0.015	, 0.049)	

Table 3. Economic Impacts of Intensification of Tropical Cyclones in the Eastern United States Due to Global Warming

This table collates historical data as well as estimates of the impact of global warming on the economic impacts of tropical cyclones for the eastern U.S. (a) is the mean impact from the historical data for 1950-2005. (b) are estimated impacts with global warming as described in the text. (c) are estimates from earlier studies as reported in Roger A. Pielke, Jr., Roberta Klein, and Daniel Sarewitz, "Turning the Big Knob: An Evaluation of the Use of Energy Policy to Modulate Future Climate Impacts," *Energy and Environment*, May 2001, vol. 11, no. 3, pp. 255-275. (d) are elements of the distribution of years from the simulations. (e) and (f) are cost estimates as percent of GDP. The p values from the simulations represent estimates of the percentile that these hurricanes lie in the distribution of impacts for both the no-global-warming and the global-warming distributions, with pn = percentile without global warming and pg = percentile with global warming. Note that these estimates do not include the effect of sea-level rise.

Appendix. Calculation of the Capital Vulnerability Index (CVI)

This appendix describes the calculation of the capital vulnerability index. The basic assumption is that the quantity of vulnerable capital is proportional to the density of the capital stock and to the time exposed to damaging winds. Additionally, damages are a function of wind speed (usually a polynomial function, such as cubic). The general formula for the CVI is:

$$(A1) \quad CVI = \iiint_{m,n,t} [K(m,n)]f[w(m,n,t)]dm \, dn \, dt$$

In this formula, the location is specified by coordinates (m,n) , the vulnerable capital is $K(m,n)$, wind speed at a particular time and location is $w(m,n,t)$, and the damage function is $f[w(m,n,t)]$. We might start with the presumption that $f[\cdot]$ is cubic in wind speed, but the results above raise the possibility of a higher exponent.

We do not have complete data on all the elements in equation (A1), so we calculate only the vulnerable capital in the vicinity of the point of landfall, which is designated as $(m,n) = (\bar{m}, \bar{n})$. We estimate the wind velocity as $v(m,n) = v(\bar{m}, \bar{n}) - \alpha d(m - \bar{m}, n - \bar{n})$, where $d(m - \bar{m}, n - \bar{n})$ is the distance between the landfall point and the reference point, and α is the parameter in the velocity decline equation. In the simplest case, the damage function varies as the cube of wind speed, in which case we substitute $\{v(\bar{m}, \bar{n}) - \alpha d(m - \bar{m}, n - \bar{n})\}^3$ for $f[w(m,n,t)]$ in (A1).

I estimate the discrete version of the CVI using the G-Econ data on capital stock (described above) along with estimates of wind speed and location of hurricane landfall. I calculate a central estimate and five variants. The estimates differ primarily by the parameterization of hurricane location and the wind speed function. For the central estimate, we assume that the damage function is cubic in wind speed. For details, see the background document.