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Source: *Climate Change Economics*, Vol. 1, No. 1 (2010), pp. 1-20

Published by: World Scientific Publishing Co., Inc.

Stable URL: https://www.jstor.org/stable/10.2307/climchanecon.1.1.1

Climate Change Economics, Vol. 1, No. 1 (2010) 1–20

DOI: 10.1142/S2010007810000054

World Scientific
www.worldscientific.com

THE ECONOMICS OF HURRICANES AND IMPLICATIONS OF GLOBAL WARMING*

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This study examines the economic impacts of US hurricanes. The major conclusions are the following: First, there are substantial vulnerabilities to intense hurricanes in the Atlantic coastal United States. Damages appear to rise with the ninth power of maximum wind speed. Second, greenhouse warming is likely to lead to stronger hurricanes, but the evidence on hurricane frequency is unclear. We estimate that the average annual US hurricane damages will increase by $10 billion at 2005 incomes (0.08 percent of GDP) due to global warming. However, this number may be underestimated by current storm models. Third, 2005 appears to have been a quadruple hurricane outlier, involving a record 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.

Keywords: Hurricanes; global warming; climate impacts; Katrina.

1. Geophysical Background

Recent hurricane activity in the North Atlantic has been extremely destructive. Hurricanes in 2005 broke many records: 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 US history.[1]

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 rising seas and the 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.

*This study was presented at the Annual Meetings of the American Economic Association, Boston, Massachusetts, January, 2006; the Snowmass Workshop on Abrupt and Catastrophic Climate Change, Snowmass, Colorado, July–August, 2006; the Yale Workshop on Environmental Economics; and a Cowles Foundation Seminar.

[1]Details on the estimation can be found in: "Accompanying materials: The Economics of Hurricanes in the United States", available at http://www.worldscinet.com/cce/cce.html.

1.1. *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 maximum sustained surface winds of at least 17 meters per second (mps) — or, equivalently, 34 nautical miles per hour (kts) or 39 miles per hour (mph). If sustained winds reach 33 mps (64 kts or 74 mph), they are called "hurricanes" in the North Atlantic Ocean.

Tropical cyclones (TCs) are giant heat engines fueled by the 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 a sea-surface temperature (SST) of at least 26.5°C (80°F). Moreover, there are thermodynamic upper limits on the strength of hurricanes, determined primarily by ocean temperature.

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

On a global scale, the annual number of TCs over the 1970–2004 period averaged around 85 (Webster *et al.*, 2005). It is unclear whether there are long-term trends or cycles in global TC frequency, which is not surprising given that reliable data have only been available since the advent of satellite data in 1960.[2] Since the current study involves primarily the United States, we focus on TCs in the North Atlantic. Using "best track" or HURDAT data for North Atlantic storms, there has been a clear increase in the frequency of storms over the 1851–2005 period, particularly since 1980.[3] The increase in hurricane frequency is positively and significantly related to sea-surface temperatures in the cyclogenic North Atlantic.

Recent studies indicate that there has been an increase in the intensity of storms in the North Atlantic over the last three decades. Hurricane "power" is conventionally defined as a function of maximum wind speed squared or cubed. NOAA has constructed a power index called the accumulated cyclone energy (ACE) index, which is a function of maximum wind speed squared.[4] An examination of the global trend in ACE does not reveal an upward trend since 1985, but the shortness of the record and the variability of ACE indicate that this is not a powerful test. Emanuel (2005) defines a "power dissipation index" (PDI) as a function of the cube of maximum wind speed summed every six hours over the life of the cyclone. His calculations indicate that PDI has increased markedly since the mid-1970s. Other evidence is mixed. A long-term

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[2]Some of the difficulties of measuring long-term trends are described in Landsea *et al.* (2006).

[3]According to the US National Oceanic and Atmospheric Administration, "HURDAT is the official record of tropical storms and hurricanes for the Atlantic Ocean, Gulf of Mexico and Caribbean Sea, including those that have made landfall in the United States" (http://www.aoml.noaa.gov/hrd/hurdat/).

[4]"The ACE index is calculated by summing the squares of the 6-hourly maximum sustained wind speed for all named storms during their existence as a tropical storm or hurricane" (Bell *et al.*, 2000).

storm index for the British Isles, North Sea and Norwegian Sea over the period 1881–2004 shows no trend in storminess over the long term.[5]

In summary, the time-series data on storminess is inconclusive given the short span of reliable data and the variability of storms. We will rely primarily on basic physics and modeling results for our projections.

2. How Vulnerable Are Different Regions?

The vulnerability of the economy to hurricanes will depend in part on the frequency and intensity of storms. The other major factor is the location of economic activity. 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 lies in coastal areas and at low elevation. For this purpose, I have applied the "G-Econ data set" to estimate disaggregated regional economic vulnerability. This data set provides comprehensive global estimates of gross domestic product, average elevation, distance from coastline, and population for 1° latitude $\times 1^\circ$ longitude.[6] For the present study, I further divided the US 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 1 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 the large storm surges that might accompany intense hurricanes. The major concentrations of vulnerable economic activity and capital (with capital stock greater than $100 billion) are the Miami coast, New Orleans, Houston, and Tampa.

3. Economic Impacts of Hurricanes

The economic impacts of hurricanes in a year depend upon several factors: total output, the capital-intensity of output, the location of economic activity, the number of storms, the intensity of storms, and the geographical features of the affected areas.

The analysis here considers three primary factors: the number of storms, maximum wind speed at landfall, and GDP. The impact of the number of storms is obvious, and we take damages to be linear in frequency. For the analysis, we assume that damages per storm over time conditional on wind speed are proportional to nominal GDP. This is an appropriate normalization to correct for economic growth, assuming no adaptation and neutral changes in technology and the location and structure of economic activity. However, several factors might lead the damage function to shift over time. These "drift factors" include coastal migration, rising housing values, sea-level rise,

[5]See Intergovernmental Panel on Climate Change (2007), p. 313 and Figure 3.41 (hereafter cited as "IPCC 2007").
[6]The methodology and data as well as selected relationships are contained in Nordhaus (2006). The complete data set is on the web at *http://gecon.yale.edu.*

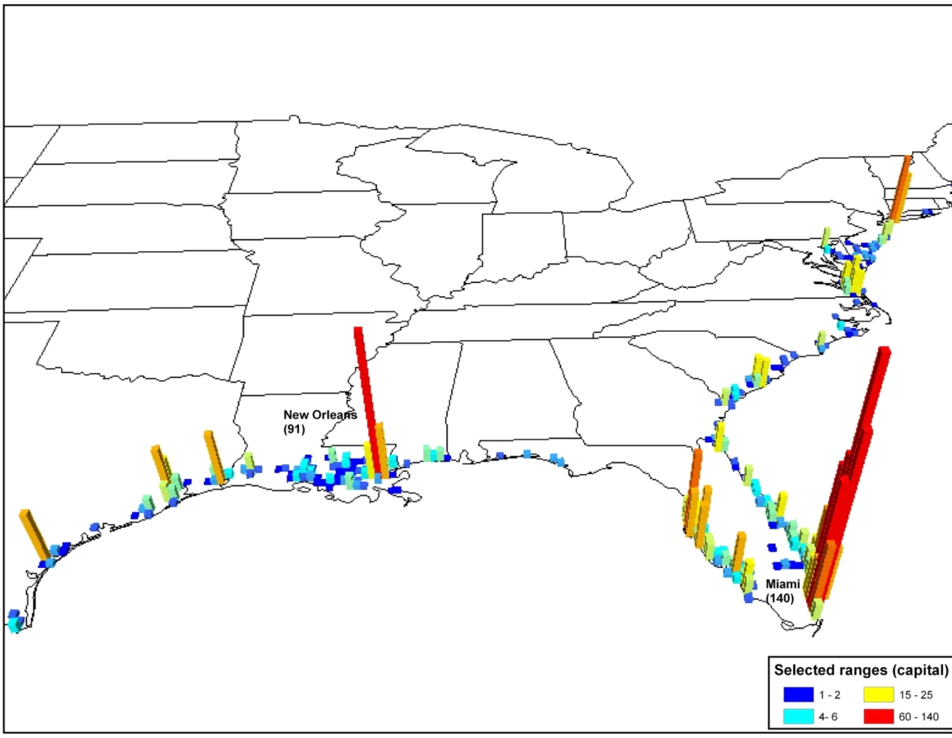

Figure 1. Low-lying areas at risk of sea-level rise and storm surges
This map shows the location of areas with mean altitude per sub-grid cell less than 8 meters above sea level grouped by estimated capital stock. Each sub-grid cell is approximately 15 km × 15 km. The legend shows selected densities of different regions. The numbers in parentheses are the capital stock of the largest sub-grid cell in the region.
Source: 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. The author thanks Kyle Hood for his help in preparing the sub-grid cell data and David Corderi for preparation of the map.

measurement errors, building codes, and adaptation to storms. An assessment suggests that drift factors may have raised the ratio of hurricane damages to GDP in the order of 1.5% per year in the last half-century.[7] However, many of these trends are likely to abate, and we project no further drift for the future.

[7]There has been no significant change in the nominal national capital–output ratio in recent decades (based on BEA data). However, the market value of household real estate has risen at 0.20% per year over the 1952–2006 period (based on Federal Reserve Flow of Funds data). Moreover, there has been rapid population migration to coastal communities, which raises vulnerability. Approximately half of hurricane power over land has intersected Florida, and Florida's share of GDP or personal income has risen on average around 2% annually over the last half-century (based on BEA and Census data). An additional factor affecting estimates over time is the convention of estimating total damages as a multiple (two times) of insured damages, which might bias estimates if coverage ratios or deductibles have changed. There has been some upward trend in the ratio of casualty premiums to the total capital stock, but data on hurricane insurance coverage are not readily available. Our discussion below suggests that sea-level rise might account for a rise of 0.25% per year in vulnerable capital. Totaling these factors would yield an upward trend in the damage–GDP relationship of around 1.5% per year. For a discussion of drift factors, see the Accompanying Materials.

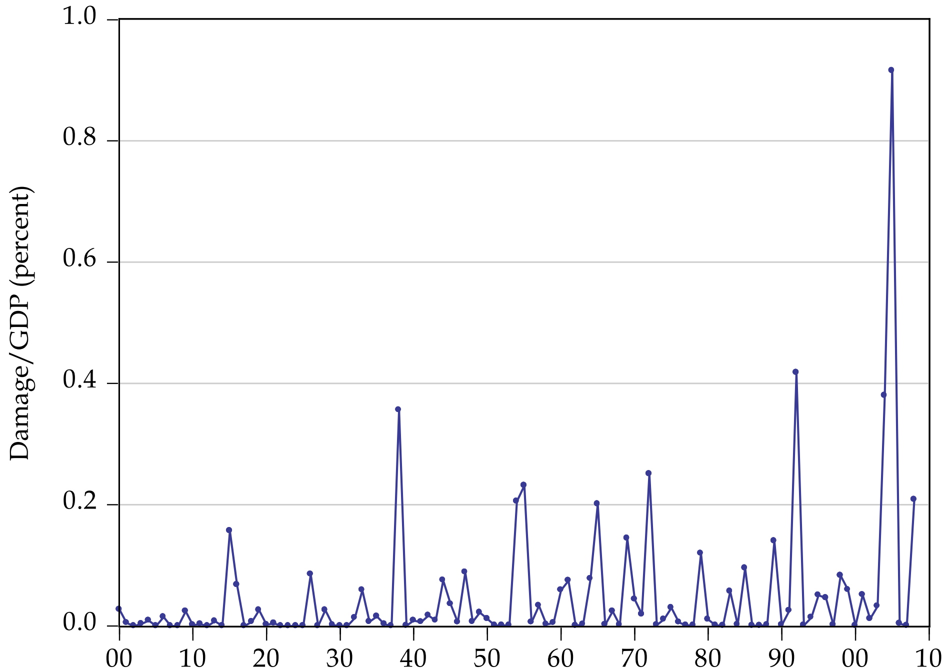

Figure 2. Normalized costs of hurricanes, 1900–2008
This figure shows the ratio of damages to GDP for all hurricanes for the given year.
Source: See text for discussion of damages. GDP from US Bureau of Economic Analysis.

The third factor affecting damage is wind speed. It was conventional in the past to assume that damages are a function of wind speed to either the second or third power.[8] However, as we see below, this presumption is based on an energy–wind speed relationship, which is probably not applicable to the impact of wind and water on designed structures. Hence, we treat this power as an important parameter to be estimated.

We have gathered data on the storm characteristics and economic damages for 233 hurricanes that have made landfall in the United States between 1900 and 2008. These include all storms since 1933 and 30 storms before 1933.[9] Figure 2 shows the trend in normalized hurricane damages since 1900. 2005 stands out from the crowd. 2005 was an economic outlier primarily because Katrina was by a wide margin the most costly hurricane in recent history. In turn, Katrina was so costly not because of its intensity

[8]Some examples are the following: (i) The widely used ACE index described above assumes that storm intensity is measured by the square of wind speed. (ii) "But the amount of damage increases roughly as the square of the intensity of the storms, as measured by their maximum wind speed …" (Emanuel, undated). (iii) "But the amount of damage increases roughly as the cube of the maximum wind speed in storms…" (Emanuel, 2005). (iv) "Because damage increases with at least the square of wind speed…" (Pielke and Landsea, 2002). (v) "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, 2002).

[9]The major early study in this area is (Pielke and Landsea, 1998). For a discussion of data problems, see the Accompanying Materials.

but because it hit the most vulnerable high-value spot in the United States, as we saw in Fig. 1.

3.1. *The damage-intensity function and empirical estimates*

We next investigate the relationship between normalized damages and maximum wind speed, which we call the *damage-intensity function*. The general presumption in the geophysics literature is that economic damage is a function of either the square or the cube of wind speed. Figure 3 shows a double-logarithmic scatter plot of hurricane power and normalized damages for the 185 hurricanes with complete data. The line is the kernel fit. It is evident that the relationship has a slope well above 3 from the scatter plot. Using these data, we estimate a double-log relationship between normalized

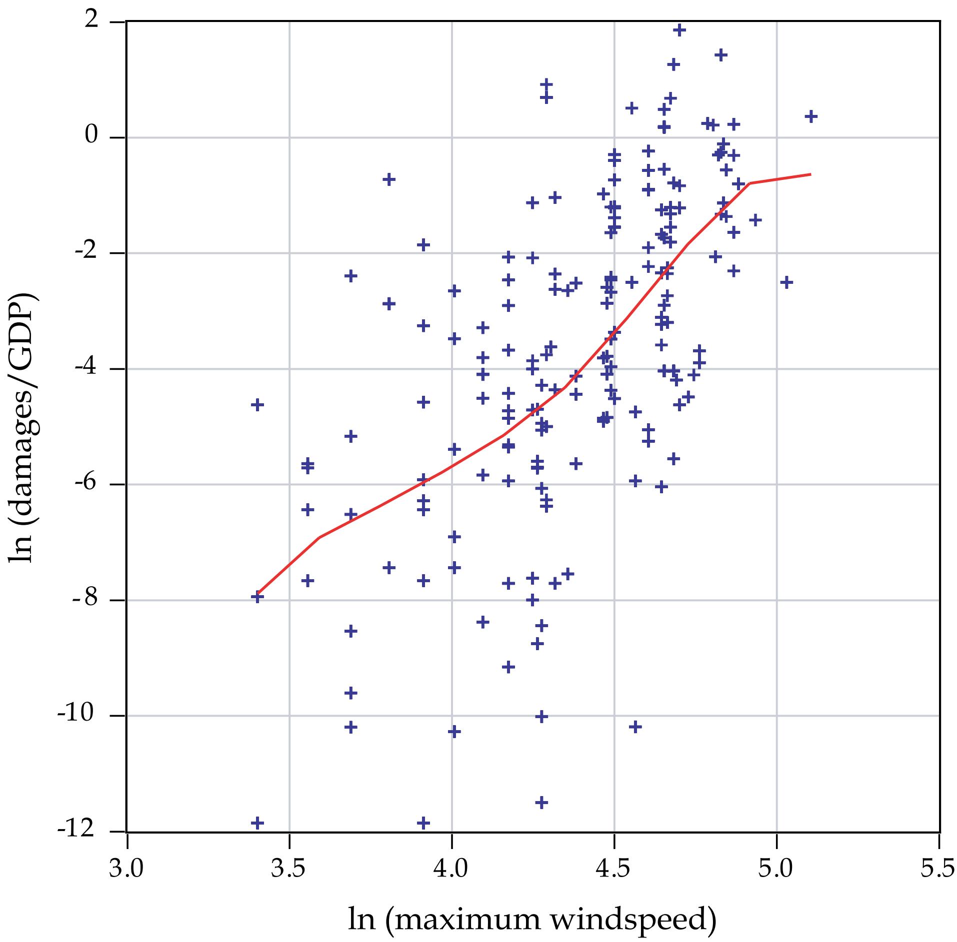

Figure 3. Wind speed and normalized damages for major hurricanes
Figure shows data and a kernel fit.
Source: See text for definitions and data sources ($N = 233$).

damage and maximum wind speed, including time to control for drift factors. The basic damage-intensity function is:

$$\ln(\text{cost}_{it}/\text{GDP}_t) = \alpha + \beta \ln(\text{maxwind}_{it}) + \delta\ \text{year}_t + \varepsilon_{it}. \tag{1}$$

In Eq. (1), cost_{it} is the estimated total damages for hurricane i in year t in current prices, maxwind_{it} is the estimated maximum sustained wind speed at landfall, GDP_t is US gross domestic product in current prices, and ε_{it} is a residual error. Greek letters are estimated coefficients.

We have estimated Eq. (1) using several different approaches, as shown in Table 1. The major estimators are ordinary least squares (OLS), two-stage least squares (TSLS), and median (least absolute deviation) regressions. These are shown for the full period since 1900 and for the period since 1979; with and without trends; and for different minimum wind speeds. The first two lines are ordinary least squares estimates for all hurricanes (those with landfall maximum winds > 64 kts, $N = 149$) and for hurricanes since 1980. We focus on the period since 1980 because the wind-speed data are more reliable for the later period. We next show the estimates without a trend. The third pair

Table 1. Alternative estimates of damage-intensity function. For a discussion of different estimates, see text.

Specification	Coefficient on ln(maxwind)		Coefficient on year		Observations
Period	Coefficient	*t*-statistic	Coefficient	*t*-statistic	
OLS					
All	7.27	8.13	0.031	4.27	149
Since 1980	8.21	5.78	0.081	2.45	50
OLS without trend					
All	6.23	7.19	[0]	—	149
Since 1980	8.08	5.38	[0]	—	50
TSLS					
All	9.53	9.17	0.035	6.41	149
Since 1980	10.69	6.41	0.077	2.26	50
TSLS without trend					
All	8.21	8.14	[0]	—	149
Since 1980	10.91	6.07	[0]	—	50
Quantile regression					
All	7.25	8.75	0.035	4.80	149
Since 1980	8.24	3.94	0.080	1.68	50
TSLS					
Wind $>$ 30 kts	7.55	10.65	0.036	4.59	185
Wind $>$ 50 kts	9.30	10.16	0.038	5.18	162
Wind $>$ 70 kts	10.43	8.22	0.035	4.51	130
Wind $>$ 90 kts	13.35	4.34	0.030	3.45	71
Wind $>$ 110 kts	8.04	1.56	0.010	0.85	24

of estimates uses instrumental variables (IV) for the same two sample periods. IV is useful if we suspect that the estimates are contaminated by errors in measurement of maximum wind speed. For the IV estimates, we use as instruments the level and logarithm of minimum pressure, which is generally assumed to have less measurement error than the estimated maximum wind speed.

The quantile regressions estimate the parameters for the median estimator using least absolute deviations. This approach is useful to determine if outliers or asymmetries are affecting the results. Since the results of the quantile regression are virtually identical to the OLS results, we conclude that outliers are not a central factor.

The last set of results uses different minimum threshold wind speeds. As can be seen, the results do not disappear if only the powerful storms are included. Indeed, the elasticity increases as wind speed increases up to 90 kts.

This regression contains one of the major surprises of this paper. The regression indicates that the elasticity of damages with respect to maximum wind speed is extremely high. Moreover, the *t*-statistics are high, indicating that the result is highly significant. To take the TSLS for the entire sample, the estimate is 9.5 with a standard error of 1.0.

These results are at first blush a substantial puzzle. This elasticity is vastly larger than the standard presumption cited above of an elasticity of 2 or 3. The estimates indicate that economic damages rise much more rapidly than with the square or cube of wind speed. For the purposes of this study, we take a coefficient of 9 as the central estimate. We denote this relationship as the *ninth-power law of damages*.

3.2. *Why the super-high elasticity of damages?*

What are the reasons for the super-high elasticity in the ninth-power law? There are three possible reasons. These concern (i) statistical bias, (ii) the increasing extent of damaging winds for large hurricanes and (iii) the engineering relationship between stress and damage. We discuss each of these in turn.

(i) The first question is the reliability of the estimates. The results in Table 1 indicate that the elasticity depends upon the exact specification (OLS vs. TSLS, sample period, and so forth), but is super-high in all estimates. It seems extremely unlikely that the elasticity is less than 5 on the basis of these estimates.

The main statistical concerns with the super-high damage elasticity are errors in measurement of wind speed and correlation of wind speed with omitted variables [as represented by ε_{it} in Eq. (1)]. To deal with measurement errors in wind speed, we use an IV estimator or examine estimates for the post-1980 period, which has more reliable data. The estimated OLS coefficient for the post-1980 period is 8.2. The IV estimates yield a higher elasticity than the OLS for the entire period — as would be expected if the wind speed in early years is measured with substantial error — with 10.7 for the longer period instead of 8.2. We cannot choose between these different estimates with current information and use 9 as a reasonable synthesis.

The issue of omitted variables is more complicated. One important omitted variable is the value of the vulnerable capital stock at hurricane landfall. If that variable is orthogonal to wind speed, which seems likely on both theoretical and empirical grounds, then the estimated coefficient on wind speed will be unbiased. Another important set of omitted variables is associated storm characteristics, such as rainfall, storm size, storm surge, and storm lifetime. These are likely to be positively correlated with wind speed and therefore will increase the estimated damage coefficient above a "true" wind-speed-only coefficient (as we discuss explicitly in the next point). To the extent that these associated storm characteristics are determined by minimum pressure and wind speed, the higher coefficient correctly captures the economic impacts of higher intensity and is the appropriate coefficient for estimating the economic impacts of intensification. This discussion indicates that the estimate of a super-high elasticity survives an examination of the obvious statistical issues.

(ii) As noted in the last paragraph, more intense storms have many associated characteristics that would increase economic damages. To what extent would this raise the estimated damage elasticity? We cannot answer this question directly, but we can measure the extent to which more intense storms lead to a larger quantity of vulnerable capital. For this purpose, we calculate a capital vulnerability index (CVI), which is an analog of Emanuel's power dispersion index (Emanuel, 2005). The CVI estimates the weighted amount of capital that is in the path of the hurricane, observed at each six-hour period. The weights are proportional to estimated power, equal to the cube of wind speed, and the estimate is summed over the lifetime of the hurricane. Details of the calculation are provided in the Accompanying Materials.

To the extent that associated characteristics such as storm surge are positively associated with maximum wind speed, this would increase the vulnerable capital stock and presumably increase economic damages. The empirical question is the shape of the relationship between vulnerable capital and maximum wind speed. An estimated equation finds that the elasticity of CVI with respect to maximum wind speed is 5.3 ($\pm$ 0.49) for the central specification of a cubic wind-speed damage function; alternative specifications have elasticities between 4.5 and 6.7. These calculations indicate that the vulnerable capital stock does indeed rise more rapidly than the cube power law suggests because of associated storm characteristics. However, even taking into account the value of vulnerable capital, the vulnerability does not come close to the ninth-power law of damages.

(iii) The most likely reason for the super-high elasticity is that economic damages are related to storm characteristics through engineering stress and rupture relationships rather than through simple energy or power relationships. In other words, the damages from storms have little direct relationship with the energy exerted by winds. The precise relationship between storm intensity and damage will differ for different materials (brittle vs. flexible), for different objects (windows vs. levees), and for different design tolerances. One example of the relationship is the classical strain–stress–fracture relationships used in mechanical engineering and building design. For many materials, catastrophic failure occurs when the stress exceeds a given level. If we were to estimate the elasticity of damage with respect to a stress (such as wind), it would be very small up to the fracture level and then extremely high as the material fractured. A simple example is damage to trees, which bend up to a certain point after which there is a catastrophic fracture. Yet another example is the rupture or overtopping of levees, which shows extreme non-linearities.

Going from engineering to actual damages involves aggregation over different structures, materials, building codes, ages of structures, compliance, and other factors. The threshold effects were illustrated by the rupture of the levees of New Orleans. The role of catastrophic non-linear damages was shown even more dramatically by the collapse of the World Trade Towers on September 11, 2001.

If structures are designed to withstand up to a 50-year storm, and suffer catastrophic damage when that occurs, then intense hurricanes (which are low-probability events) will cause large damages where they hit, and the wind-damage elasticity will be much higher than the physics power curve in the vicinity of the fracture point.

To summarize: given the number and complexity of relationships entering the wind speed–damage relationship, it is unlikely that the actual functional parameters can be derived from first principles. 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. First, it seems unlikely that it comes from measurement errors, but the sample size is modest and it would be fruitful to examine other regions' experiences. Second, the economic vulnerability increases very sharply with maximum wind speeds. This arises because of a non-linear relationship between wind speed and damage, because the "cone" of high winds increases sharply with maximum wind speed, and because storm lifetime is positively associated with maximum wind speed. Third, because hurricanes are rare events, we are likely to observe the wind speed–damage relationship at exactly the point where sharply non-linear and even catastrophic failures arise. Taking all these together, we should not be surprised if the empirical wind speed–damage relationship has a completely different structure from the physical wind-power function.

3.3. ***Time trends and the lessening hypothesis***

A standard presumption in the literature on environmental vulnerability is the "lessening hypothesis," whereby societies have become less vulnerable over time to environmental shocks. Examples of declining sensitivity include the impacts of draughts on agriculture or nutrition and the impacts of weather extremes on human health.[10] Note that the time trend in the OLS full-sample equation found that normalized damages have risen by 3.1 ($\pm$0.72)% per year, indicating *increased*

[10] Warrick (1980); Ausubel (1991). In economic affairs, there has been a trend toward substantially lower variability in output growth (the "Great Moderation") in the last half-century, although the period since 2007 may put that trend in doubt.

vulnerability to storms of a given size.[11] The coefficient is higher than the presumption, discussed above, that related damages to coastal population, housing values, and sea-level rise. The finding of a "worsening" trend has troubling implications for damages in a warmer world. There is a suggestion of out-migration from Florida in recent years, but this appears to be linked more to the US housing bubble bursting than to hurricane experience.

4. Global Warming and Hurricanes

Hurricanes have featured prominently partly because 2005 was so unusual and partly because of fears that global warming may bring a string of hurricanes like Katrina. Are terrible and costly events such as Katrina and the inundation of New Orleans likely to recur frequently in the future? The answer here is probably not, but much in this area is murky. In this section, we estimate the impact on hurricane damages of an equilibrium doubling of atmospheric CO_2 concentrations. For reference purposes, this is the middle of the range of projections for the year 2100 from current economic and climate models.

4.1. *Functional forms for economics and global warming*

The relationship between hurricane damages and global warming is a complex function of economics, geography, and geophysics. We can write the general relationship for storm i at time t:

$$V_{it} = f\{Q_t, KQ_t, Kdens_{it}, Kvul_{it}, storm[STT_t(T_t)]\} \tag{2}$$

where V_{it} = damage, Q_t = GDP, KQ_t = nominal capital–output ratio, $Kdens_{it}$ = spatial density of capital, $Kvul_{it}$ = vulnerability of capital as function of geography, $storm_{it}$ = wind speed and other storm characteristics, SST_t = sea-surface temperature in the cyclogenic region, and T_t = global mean surface temperature. Note that storm characteristics are a function of SST_t, which is in turn a function of T_t.

In our central estimates below, we consider only the number of hurricanes, the size of the economy, and the impact of warming on hurricane intensity. For estimation purposes, I simplify the damage estimate in (2) and use the following functional form for damage per hurricane:

$$\ln(V_{it}) = \ln(Q_t) + \beta \ \ln[(1 + \gamma\Delta SST_t)\mathrm{wind}_{it}] + \varepsilon_{it} \tag{3}$$

In this simplification, the diverse unmeasured locational and storm factors as well as stochastic factors are collected in ε_{it}, while wind_{it} is maximum wind speed. The wind term contains the wind speed-damage elasticity β (discussed above) and the impact of

[11]This is contrary to Pilke (2005), who reports no statistically significant trend. Similar negative results were found in Pielke and Landsea (2002). Additionally, issues of comparability over time are non-trivial, as is discussed in Landsea (2005).

increased SST on maximum wind speed given by the coefficient γ (discussed next). We later consider some further refinements.

4.2. *Parameter estimates from geophysics*

The basic physics linking global warming and tropical cyclones is clear if complex. Global warming might affect hurricanes in several dimensions, including the frequency, size, intensity, lifetime, and geographic distribution of tropical cyclones. Of the five, 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 rise in the sea-surface temperature (SST) would lead to an increase in potential intensity (maximum wind speed) of 5.5%. That is, the semi-elasticity of maximum wind speed with respect to SST, denoted in Eq. (3) as γ, is estimated to be 0.055 (Emanual, 2005). 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 CO_2 concentrations. Their study indicated that the maximum wind speed would increase by 5.8% in the high-CO_2 world with a 1.7°C increase in tropical sea-surface temperatures.[12] These experiments indicate a semi-elasticity of maximum wind speed with respect to SST, $\gamma = 0.035$. To move from potential intensity to the actual distribution, the statistical work of Emanuel (2000) found that there is a uniform distribution of the ratio of actual maximum wind speed to potential maximum wind speed. 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 atmospheric CO_2 concentrations would be an increase in tropical Atlantic SST of around 2.5°C. Using the estimated impact from the Knutson and Tuleya study, global warming would therefore increase maximum wind speed by 8.7%.[13]

The theoretical presumption and GCM modeling results indicate no increase in cyclonic frequency. These results are contrary to recent observational data on the tropical North Atlantic, which indicate that the frequency of hurricanes has in fact increased with rising SST. However, we have retained the theoretical presumption of no increase in frequency in our estimates.

[12] A discussion and report on simulations is contained in Knutson and Tuleya (2004).

[13] One further study is Oouchi *et al.* (2006). These authors conclude that the frequency of storms will decrease while intensity will increase. The estimated increase in maximum wind speed is approximately 14% globally and 20% for the North Atlantic. The experiment was for a 2.5°C global warming. These estimates are substantially higher than those in the Knutson and Tuleya study used in Tables 2 and 3, but the reasons have not been explained.

4.3. *Estimates of mean impacts*

In considering the impact of global warming on hurricane damages, we consider the effect on both the mean impact and the tails of the distribution. Estimating the mean impact of global warming is conceptually straightforward under the logarithmic specification in Eq. (3). The ratio of the mean impact with warming to that without global warming is equal to the product of the elasticity of damages with respect to wind speed (β), the semi-elasticity of increased wind speed with respect to mean temperature (γ), and the increase in mean temperature (ΔSST).

Table 2 shows numerical estimates of the percentage increase in hurricane damages using estimates of the three parameters in Eq. (3) from this study and from the scientific literature as discussed above. For these estimates, I use an elasticity of $\beta = 9.0$ and remove the time trend from the damage function. The central estimate is that the impact of an equilibrium doubling of CO_2–equivalent atmospheric concentrations would lead to an increase in the mean hurricane damages of 113%. Additionally, the table shows three estimates with alternative values of the parameters, with the increase ranging from 29%–219%. The low end would reflect a conventional wind speed–damage elasticity of 3. The high end uses the central elasticity of 9 with Emanuel's estimate of the semi-elasticity.

Table 2. Estimated mean damages from global warming: Central case and alternative estimates.This table shows the parameters underlying the estimates and the estimated increase in mean damages from an equilibrium doubling of CO_2-equivalent greenhouse gases. The estimate is from Eq. (3) in the text. The best estimate is an increase of 113% in the first row. Other estimates range from 29 to 219% with alternative parameters. The fifth row shows the estimated increase since 1950, assuming a 0.4°C increase in SST (based on results from Hadley and IPCC, 2007, Fig. 3.33).

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	9.00	0.035	2.5	112.7%	[a]
OLS elasticity	7.27	0.035	2.5	84.1%	[b]
Semi-elasticity	9.00	0.055	2.5	218.8%	[c]
Conventional damage impact	3.00	0.035	2.5	28.6%	[d]
Warming in 20th C	9.00	0.035	0.54	18.4%	[e]

[a] col (1) uses central estimate of semi-elasticity of 9; col (2) from Knutson and Tuleya (2004); col (3) as discussed in text.
[b] same as [a] except it uses OLS full period elasticity for col (1).
[c] same as [a] except it uses semi-elasticity in col (2) from Emanuel (2005) as discussed in text.
[d] same as [a] except it uses conventional estimate of cubic damage function.
[e] uses estimated rise of tropical SST in Atlantic cyclogenesis region from Santer (2006).

Table 3. Economic impacts of intensification of tropical cyclones in the United States due to global warming. This table collates historical data as well as central estimates of the impact of global warming on the economic damages from hurricanes for the eastern US. It shows the mean impact from the historical data for 1933–2005 and the estimates from earlier studies as reported in Pielke *et al.* (2001). Note that these estimates do not include the effect of sea-level rise or adaptation.

	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						
Historical data	0.071	8.9	0.150	19.0	0.080	10.0
Earlier studies						
Cline					0.013	
Fankhauser					0.003	
Tol					0.005	

To translate these estimates into actual dollars, I assume the appropriate sample to be the number, intensity, and damages of hurricanes making landfall in the United States for the 1933–2005 period. Table 3 shows the estimates from Table 2 normalized by the history. We show the results both as a percent of GDP and as scaled to 2005 GDP levels. The mean damages for the period 1950–2008 is 0.071% of GDP ($8.9 billion scaled to 2005 GDP). The impact of global warming is shown in the last two columns of Table 3. According to the calculations described above, the mean expected impact would be to increase the impacts by 0.08% of GDP ($10 billion), which amounts to slightly more than doubling.

Table 3 also compares the estimates with those of earlier studies. It concludes that the impact will be higher than was projected in the studies of Cline and Tol. The reason for the higher number here is that earlier studies generally used a lower elasticity of damages with respect to wind speed.[14]

4.4. *Frequency distribution of outcomes*

One important characteristic of hurricanes is the skewed distribution of outcomes. To illustrate the extreme outcomes, I estimate the frequency distribution of annual hurricane damages with and without global warming. For these estimates, I took the distribution of landfalling hurricanes over the 1900–2008 period. The distribution

[14]See Pielke *et al.* (2005). These authors conclude that “claims of linkages between global warming and hurricane impacts are premature…” The basic argument is that the evidence is mixed and the time-series evidence does not support the modeling.

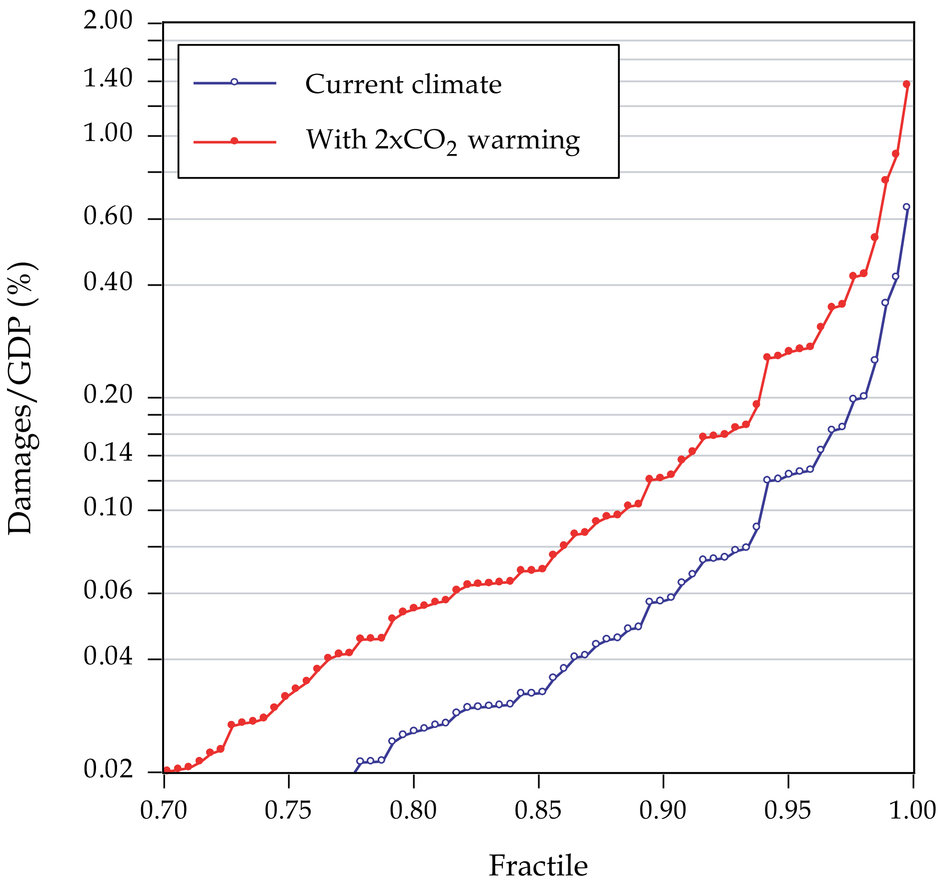

Figure 4. Distribution of hurricane damages with and without global warming
The lower curve shows the distribution of the damages of all 233 hurricanes with estimated damages that had landfall in US over the 1900–2008 period. The upper curve shows the distribution with the simulated increase due to global warming in equilibrium CO_2-doubling scenario. The highest three points are (from the top) 2005 (Katrina), 1992 (Andrew), and 1938 (New England).
Source: Global warming is central estimate as described in text.

of maximum wind speeds with global warming is given by shifting the distribution of maxima upward 8.7%. Note that this experiment does not include any time trend or adjustment for frequency, adaptation, improved siting, or sea-level rise.

Figure 4 shows the results of the distribution analysis. Because of the ninth-power relationship, the distribution shifts upwards sharply. During the historical period, there were 14 storms that cost more than 0.1% of GDP ($12.4 billion at the 2005 level of GDP). With global warming, that number would increase to 27. The maximum damage ratio was 0.64% of GDP ($81 billion in 2005) without warming, and that would be 1.36% of GDP ($172 billion in 2005) with warming. Note that these numbers are likely to overstate the top end of the distribution because they do not account for adaptation, for the "saturation" effect of having wiped out the most vulnerable regions, or for the possibility that the estimated impacts might exceed the capital stock in the affected areas. We turn to these next.

5. Damages with Sea-Level Rise, Adaptation, and Retreat

Two further complications are the impacts of potential sea-level rise (SLR) accompanying global warming and the potential for adaptation to the threat of more intense hurricanes. The methodology used to estimate the impacts of global warming assumes the historical damage function estimated in Eq. (1) without the time trend or SLR and further assumes that no future steps are taken to reduce vulnerability. We address these issues now.

5.1. *Sea-level rise*

While there has been much research on the economic impacts of SLR (Yohe *et al.*, 1996; Yohe and Schlesinger, 1998), relatively little of this research has examined the interaction of SLR with hurricanes. The nub of the issue is the following: as sea level rises, a larger fraction of the capital stock becomes vulnerable to storm surges and water damage. However, depending upon the speed of the SLR, the vulnerability can be reduced if capital migrates to higher and safer locations. The vulnerability to SLR depends on capital mobility, which in turn depends on the type of capital (for example, airplanes vs. ports), the deprecation rate (houses vs. computers), as well as coordination factors and political boundaries (such as the location of cities, building codes, and national boundaries). Additionally, adaptation will depend upon risk awareness and risk aversion, the availability and markup on insurance, and the reliability of estimates of hurricane vulnerability — each of which raises the possibility of seriously distorted decision making.

I have estimated the potential effect of SLR on hurricane damages by examining the fraction of the capital stock that is vulnerable to flooding and storm surges for hurricanes of different intensity. The calculations are as follows (see Accompanying Materials for a full description). Using the G-Econ data described above, I estimate the distribution of the capital stock as a function of elevation. I then use standard estimates of the relationship between storm surges and elevation, along with estimates of hurricane frequency, to estimate the expected value of capital that is vulnerable to flooding.

Using this methodology, I estimate that, to a first approximation, the vulnerability of the capital stock to hurricanes doubles with a meter of SLR. Recent central estimates are that sea level has risen about $2\frac{1}{2}$ mm per year in the last two decades and is projected to rise about 5 mm per year over the next century. Assuming that damages are proportional to vulnerable capital, this indicates that sea-level rise would have increased damages by about 1/4% per year recently and would contribute about 1/2% per year over the next century under the assumption of no adaptation. (Recall from an earlier section that the estimated trend in vulnerability per unit GDP was 3.1% per year over the last century.) These estimates suggest that SLR will produce an upward tilt over time to the damage-intensity function.

5.2. *Adaptation*

Estimating the cost of climate change requires the consideration of adaptations to changing conditions. "Adaptations, which can be autonomous or policy-driven, are adjustments in practices, processes, or structures to take account of changing climate conditions" Intergovernmental Panel on Climate Change (2000), Sec. 1.4.1. Adaptation to more intense hurricanes or SLR would include such factors as greater setbacks from shoreline, retreat from vulnerable areas, abandonment of damaged areas after storms, and higher or improved coastal protection.

The potential role of adaptation can be seen in considering the super-high elasticity of damages with respect to wind speed. One interpretation of the super-high elasticity discussed above is that damages occur at that point where stresses exceed the design threshold. If building codes and designs are modified in anticipation of changing hurricane intensity and sea-level rise, then the design threshold would rise along with storm intensity. The result would be that the damage-intensity function would shift out over time. This would lead to a negative time trend in the damage-intensity function shown in Eq. (1). Up to now, however, the trend has been positive, as the estimates above show.

Adaptation to offset SLR would involve many of the same measures as general adaptation to more intense hurricanes. A concrete example of SLR adaptation would be the relocation of structures to higher or safer elevations. Using the calculations above, offsetting SLR would require upward migration of about 1/2% per year of the capital in the most vulnerable locations. This seems a manageable task for all but the most immobile capital, but again there seems to be no indication of upward migration in behavior to date.

5.3. *Adaptation and the envelope theorem*

Including potential adaptation is beyond the scope of the current study. However, if changes in the means and higher moments of environmental parameters are small or gradual, and if agents make decisions on the basis of appropriate expectations, then omitting adaptation will have, to a first approximation, no effect on correctly measured damages. The reason is due to the "envelope theorem" of decision making.[15] Under this result, the first-order cost of changing environmental conditions is equal to the first-order cost of adapting to those conditions. Of course, if environmental conditions change very rapidly, expectations are wildly inaccurate, or the cost of adapting is very non-linear, then second-order effects come into play. We would then need to consider adaptation costs explicitly.

[15] For a description of the invention of the envelope curve in economics, see Samuelson (1998).

6. Was 2005 the Signal of Global Warming or a Huge Outlier?

Standard critiques of scientific studies projecting global warming or its impacts are 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. Similarly, it will be extremely difficult to sort out the climate signal from the weather noise in the next few years.

One way to examine this question is to ask how frequent hurricanes as damaging as Katrina are likely to be in the current climate and a warmer one. This question is illustrated by the distributions shown in Fig. 4. The frequency of very damaging hurricanes (over 0.1% of GDP) is estimated to increase by a factor of approximately two. Assuming the historical distribution, the frequency of these would be approximately 1 per 7.9 years, while it would be approximately 1 per 4.1 years with global warming. Hurricane Katrina was a 1 in 110 year event with the current climate but is expected to be a 1 in 40 year event with warming. Therefore, while we can take comfort that we are unlikely to have year after year of Katrina-type experiences, these would recur occasionally on a century scale.

7. Concluding Thoughts

The basic story here is the following: First, 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 thresholds effects and the impact of more intense storms on capital vulnerability.

Second, greenhouse warming is likely to lead to a greater intensity of intense hurricanes, but the evidence on the frequency is mixed. Our simulation model indicates that the average annual hurricane damages will increase by 0.08% of GDP due to the intensification effect of a CO_2-equivalent doubling.

Third, the extremely high damages of 2005 appear to have been a quadruple outlier of nature. The number of North Atlantic storms was the highest on record; 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.

Fourth, it must be emphasized that the calculations of damages presented here ignore risk aversion and the fact that concentrated damages may have a significant effect on social capital. Risk aversion may enter because the damages from hurricanes are very concentrated on particular individuals and regions and are unlikely to be fully insured (recall the rule of thumb that only half of the damages are insured).

Additionally, we must recognize that when entire communities are destroyed, the social impacts are likely to extend beyond the sum of physical damages. New Orleans, for example, is a unique *quartier* of American culture and history. The nation's 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 entire communities return to marshland, the losses may be relatively minor in the economic accounts, but grave in the cultural accounts.

Acknowledgments

The author is grateful for research assistance and mapping help from David Corderi, Kyle Hood, Justin Lo, and Gokay Saher. The author is grateful for comments of participants at many seminars at which the paper was presended.

Supporting Information

Accompanying materials on "The Economics of Hurricanes in the United States" is available free of charge *via* the internet at http://www.worldscinet.com/cce/cce.html.

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