Case studies in disaster losses and climate change

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Abstract. This paper presents three case studies. Part I summarizes a 2006 workshop on floods and storms sponsored by Munich Re, U.S. NSF, the Tyndall Centre, and the GKSS Institute for Coastal Research. Part II examines the spatial distribution of increases in hurricane activity in the North Atlantic. And part III presents a sensitivity analysis of future economic losses related to tropical cyclones in the context of possible changes in storm intensity and societal development.

Introduction

This paper has three independent sections that together address important issues related to recent increasing losses related to extreme weather events. Part I relates a consensus perspective on this subject as developed at a 2006 workshop in Hohenkammer, Germany. Part II seeks to explain an important, and overlooked, aspect of trends in hurricane statistics in the North Atlantic, where a large fraction of increasing economic losses has occurred in recent decades. Part III looks to the future to explain why it is that regardless of climate change, societal factors will continue to be the most important factors driving loss trends.

Part I: Disasters and climate change (co-authored with Peter Hoeppe)

In summer 2006 we organized a workshop to bring together international experts in the fields of climatology and disaster research.[1] The general questions to be answered at this workshop were these:

- What factors account for increasing costs of weather-related disasters in recent decades?
- What are the implications of these understandings, for both research and policy?

In total, 32 participants from 13 countries attended the two day workshop.

We adopted the IPCC definitions of *climate change* and *climate variability*. According to the IPCC (2001) *climate change* "refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer)" and can be due to natural or human causes.[2] *Climate variability* refers to "variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events." Such variability also may be due to natural or human causes. We therefore use the phrase *anthropogenic climate change* to refer to human-caused effects on climate.

A wide range of datasets and analyses from around the world paint a consistent picture: Direct economic losses (adjusted for inflation, but not otherwise adjusted) have been increasing rapidly in recent decades around the world (Figure 1). Disaster losses have not increased in every region at a constant rate. Some regions, like Australia, have seen decreasing trends. Since the 1980s there has been a particularly large increase in the frequency and magnitude of disasters. The trend in the global numbers of great natural catastrophes since 1950 shows a steep increase in the largest weather-related disasters—from about 1 event in the 1950s to about 5 in recent decades while geophysically caused disasters (earthquakes, tsunamis, volcano eruptions) have increased from 1 to less than 2 in the same time (*Munich Re*, 2005). Weather-related disasters therefore are the major contributor to increasing losses due to natural disasters.

[1] The workshop was sponsored by Munich Re, the U.S. National Science Foundation, the Tyndall Center for Climate Change Research, and the GKSS Institute for Coastal Research. The full report can be found at: http://sciencepolicy.colorado.edu/sparc/research/projects/extreme_events/munich_workshop/

[2] http://www.grida.no/climate/ipcc_tar/wg1/518.htm

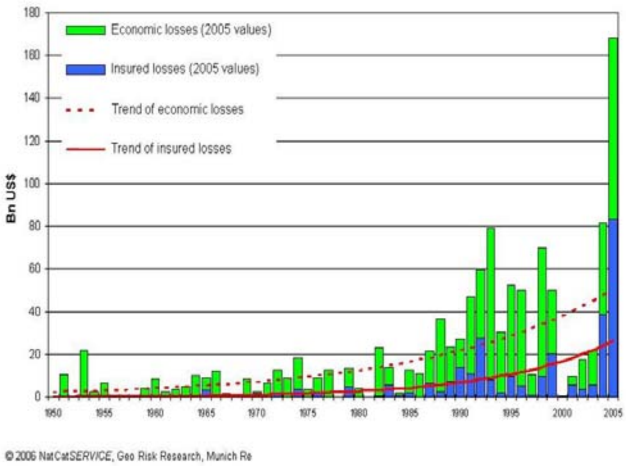

Figure 1. Global disaster losses, 1950-2005.

Climate change and variability are important factors which shape patterns and magnitudes of disaster losses. For example, even after adjusting for changes in inflation, wealth, and population in the 1970s and 1980s the United States experienced approximately $41 billion and $36 billion in hurricane losses, respectively. By contrast, the 1990s and 2000s (through 2005) saw $87 billion and $167 billion (updated data from *Pielke and Lande*a 1998). The 1970s and 1980s were characterized by below average hurricane activity and storm landfalls, whereas the period since 1995 has seen very active seasons and correspondingly more landfalls, particularly in 2004 and 2005. Similarly, in Australia 13 tropical cyclones made landfall along its east coast from 1966-1975 whereas 7 made landfall from 1996 to 2005 (and 1976-1985 had 7 landfalls and 1986-1995 had 6) (*Crompton*, 2005). Similar results have been found for floods and other weather events in different regions around the world.

Attribution of a trend to anthropogenic climate change is difficult (*IPCC*, 2001). With respect to climate events in some cases there are often insufficient record lengths, which consequently do not allow the exclusion of long-term natural variability as causes of observed trends. Other problems arise from inhomogeneous data sets. For instance hurricane wind speeds were measured by empirical observation of wave characteristics from ships, by using pressure-wind relationships, by measuring velocities of airborne sondes dropped from aircrafts or by Doppler radar techniques. Changing river discharges over time might depend on changing flow regimes accounted for by changing land use patterns or changing hydrodynamic characteristics of rivers brought about by hydro-engineering construction work over time. Since IPCC 2001, additional research results have been published on the changing nature of extremes and the IPCC will report again on this subject in 2007.

Regardless of what is found with respect to trends in extremes, societal change and economic development are the principal factors responsible for the documented increasing losses to date. Such results have been found looking at disasters globally and in specific regions and for specific phenomena, such as with respect to U.S. tornados, Australian weather-related hazards, floods in the United Kingdom, U.S. hurricane and floods, Indian tropical cyclones, Chinese floods and storms, Latin American floods and storms, and Caribbean hurricanes.[3]

Societal changes include population growth and migration to exposed locations, increasing wealth at risk to loss, policies which lead to increased (or in some cases, decreased) vulnerabilities, and development characteristics. Changes in various societal factors vary according to context. For instance, China's economy has grown as fast as 8.5% annually, and regions such as Florida in the United States have seen population growth at a rate far greater than the U.S. national average. Europe has seen little population growth overall, but significant increases in wealth. Different patterns of societal change result in correspondingly different effects on trends in disaster losses. There is evidence that, in some locations, disaster mitigation policies have reduced vulnerabilities, but the effect on losses and loss trends remains to be quantified.

The impact of extreme weather events varies between the developing and the developed world. While the developed world sees the highest absolute direct economic losses from weather extremes, the largest numbers of casualties and affected people occur in poor communities. Unsustainable exploitation of natural resources in many regions in the world may exacerbate the impacts of natural disasters, for instance by deforestation that may increase the frequency and intensity of floods. The relative role of disaster mitigation activities in addressing disaster losses remains poorly documented and understood.

[3] These are documented in our report: http://sciencepolicy.colorado.edu/sparc/research/projects/extreme_events/munich_workshop/workshop_report.html

Recent studies comparing relevant cost-benefit analysis conclude, in spite of the methodological challenges, that the benefit-to-cost ratio of investments in disaster mitigation are about 2-4 (e.g., *Mechler* 2005).

Because of issues related to data quality, the stochastic nature of extreme event impacts, length of time series, and various societal factors present in the disaster loss record, it is still not possible to determine the portion of the increase in damages that might be attributed to climate change due to greenhouse gas emissions. Long time-series disaster loss data for some regions are either unavailable or of poor quality for various phenomena, particularly before the 1980s (e.g., for China) and the 1970s (Australia, Canada, Caribbean, Central America, China, Europe, India, Japan, Korea, United States). The historical loss record is strongly influenced by a small number of very large events such as hurricane Katrina, which accounted for about 50% of global storm and flood losses in 2005. Thus there is a strong element of chance in short-term records.

The quantitative attribution of trends in storm and flood losses to climate changes related to GHG emissions is unlikely to be answered unequivocally in the near future because the problems described above are expected to persist. As a consequence we urge decision makers not to expect a definitive solution of questions about the linkage of growing disaster losses and anthropogenic climate change, as this area will remain an important area of study for years to come. Such uncertainty need not preclude proactive decision making. Adaptation to extreme weather events should play a central role in reducing societal vulnerabilities to climate and climate change. There are three main reasons for this conclusion.

Adaptation to climate variability and extremes has always been necessary and future adaptation can be most effectively designed if it continues and builds upon experience. Declining global and U.S. trends over the long term in mortality and morbidity (or injury) rates due to various extreme weather events suggest that adaptation might successfully help contain economic losses.

Mitigation of greenhouse gas emissions will take substantial time to become effective and in the meantime adaptation will become increasingly necessary.

There is a current adaptation deficit, and practices of maladaptation and unsustainable development are serving to increase vulnerability in many places. In particular, the insufficient pricing of adaptation and its benefits in terms of goods and services preserved in the face of changes and extreme events' impacts leads to inappropriate valuation of risk reducing measures in investment and financial calculations both at the public and private sector level, particularly in developing countries.

In all socio-economic sectors impacts of climate variability and extremes occur now and adaptation policies and measures are used to help to reduce exposure and impacts. Climate change, regardless of cause, may require a broader perspective in adaptive capacity than has been the case in the past. Generally these activities are in the domain of specialized professionals such as agronomists for agriculture, engineers and hydro-meteorologists for water management, irrigation, flood control etc., structural and design engineers for infrastructure, buildings, etc., public health officials for infectious and vector borne diseases. The work of these professionals is not referred to as adaptation but may be described as plant breeding and selection, flood control or flood damage reduction, and so forth. Current adaptation as now practiced is not sufficient to prevent the growth of losses from climate change, variability, and extremes.

Decision processes that are dependent upon unequivocal quantitative linkages of disaster losses to anthropogenic climate change might be reconsidered in the context of this expected continuing uncertainty. Decision makers might embrace more fully an alternative approach to decision making, e.g.one based on no-regrets vulnerability reduction or proactive risk management.

Mitigation of greenhouse gas emissions should also play a central role in response to anthropogenic climate change, though it cannot decrease the hazard risk for several (or more) decades. Carbon dioxide contributes most to the anthropogenic greenhouse effect and primarily is released when burning fossil fuels like coal, oil or natural gas.[4] Once released into the atmosphere, carbon dioxide has an average residence time in the atmosphere of up to 200 years. This means that emission reductions of carbon dioxide cannot reduce its concentration on a short term and therefore cannot result in immediate changes to the climate system. Emission reductions, however, influence the future levels of carbon dioxide in the atmosphere and thus the further increase in global temperatures and the potential for more frequent and

[4] Other relevant green house gases are methane, N_2O and CFCs and water vapor.

intense extreme events. Emission reductions reduce the risk of abrupt climate changes and climate processes that could become irreversible.

With respect to disaster losses, we recommend the creation of an open-source disaster database according to agreed-upon standards. Currently, only a few global databases exist, the most comprehensive being the NatCatSERVICE® database of Munich Re, the Sigma reports by Swiss Re, and the EM-DAT database of CRED at Leuven University. The most comprehensive disaster databases are currently not publicly available. An open-source database would enable the scientific community to study worldwide disaster characteristics and trends as well as contribute to assessing and improving its quality.

But improved policies with respect to disasters and anthropogenic climate change need not await the creation of such a database. The major factors underlying increasing disaster losses are manifestly apparent. Greater detail may be useful, but it will not change the conclusion that effective policies must focus on both adaptation as well as mitigation.

Part II: Deconvolving trends in North Atlantic power dissipation (co-authored with Steve McIntyre)

In 2005, *Emanuel* (2005a) published a paper arguing that an index of power dissipation (PDI, defined as the time integral of the cubed wind speed) has doubled in the Atlantic basin over the period 1949-2004. In replies to this paper, *Landsea* (2005) noted that a time series of trends in PDI at landfall in the United States showed no such increases, and *Pielke* (2005) presented similar results looking at normalized economic losses. In reply, *Emanuel* (2005b) accepted these findings and argued that the difference between trends at landfall and those found in the basin as a whole could likely be explained by simple randomness, suggesting that the dataset that he used contained “about 100 times more data” than the landfall data set and that his results accordingly had “a signal-to-noise ratio that is ten times that of an index based on landfalling wind speeds.” In other words, the landfall data might simply reflect the randomness of a small subset of the overall Atlantic basin hurricane dataset.

We utilize the identical dataset used in *Emanuel* (2005a) and find that the trend reported in Atlantic PDI is confined exclusively to the eastern portion of the Atlantic basin. In the western portion, where all U.S. landfalls occur, there is in fact symmetry between trends in the overall basin PDI and that observed at landfall. Our analysis presents several new empirical results:

- a trend to the east in median annual longitude of NATL tropical cyclone tracks;
- a lack of trend in the western 60% of the NATL basin in all relevant integrals (storm-days, hurricane-days, power dissipation index); the entire NATL increase in relevant integrals is derived from the eastern 40% (and especially eastern 20%) of the NATL basin.
- A corresponding decrease in the proportion of storms that make landfall in the United States.

We discuss the significance of these findings for the ongoing debate over trends in metrics of NATL tropical cyclone activity.

Analysis

The North Atlantic track dataset used here is the HURDAT data, (http://www.nhc.noaa.gov/tracks 1851to2006_atl.txt) as archived on Feb 1, 2007, and is the same dataset used in *Emanuel* (2005a). Wind speeds were adjusted according to the Emanuel (2007) implementation of the adjustment proposed in *Landsea* (1993), reflecting the exchange between *Landsea* (2005) and *Emanuel* (2005b). “Storms” denote cyclones with adjusted wind speeds exceeding 35 knots (hurricanes – 65 knots). Landfall data are from http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist 18512005-gt.txt, as downloaded on Jan 17, 2007.

The first panel of Figure 2 shows total North Atlantic and U.S hurricane counts. from 1851 to 2006. Researchers differ on when the dataset becomes reliable for trends analysis, but most agree that data since 1970 are of the highest quality (*WMO* 2006). The second panel of Figure 1 shows the NATL power dissipation index (following *Emanuel* 2005a) with a bold smoothed trace covering 1950-2004. The bottom panel of Figure 1 shows the median annual longitude of storm tracks in the HURDAT data base. The median longitude has moved nearly 16 degrees - from 76W in the decade preceding World War I to 60W in the 1997-2006 decade.

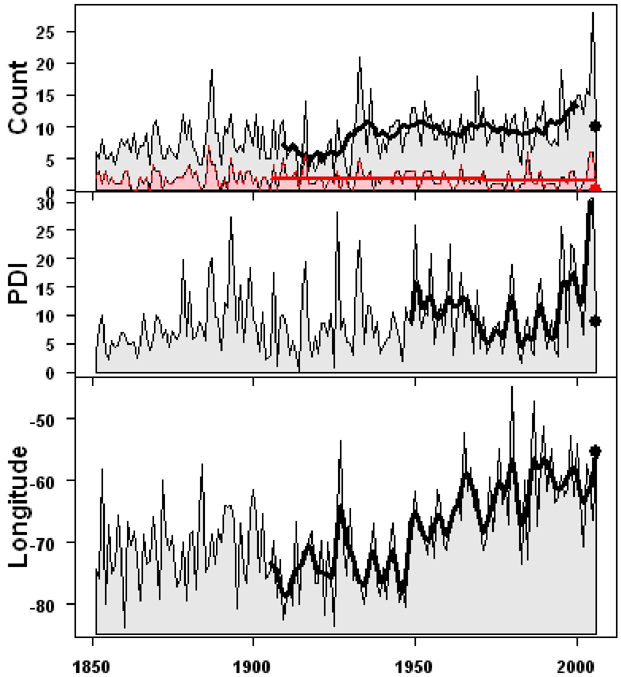

Figure 2. Top: Black – Total North Atlantic cyclone count; red – U.S. landfall hurricane count; 2006 values also highlighted. Middle: PDI smoothed as in *Emanuel* 2005a. Bottom : Mean longitude of North Atlantic storm tracks (>= 35 knots) smoothed as in *Emanuel* 2005a.

In order to analyze the impact of the eastward trend of track measurements on storm and hurricane day counts, we classified the *Emanuel* (2005a) data (>= 35 knots) for the 1851-2006 period into five longitude quintiles (quintiles at 51W, 63W, 73W and 83W, see Figure 3). Most U.S. landfalls occur in the two western quintiles (west of 73W), while the two eastern quintiles (east of 63W) – especially the southern portions – are relatively remote from land.

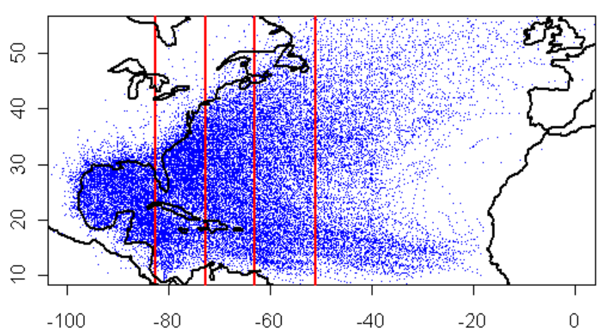

Figure 3. Longitude quintiles. Each track measurement in the HURDAT database indicated by a dot.

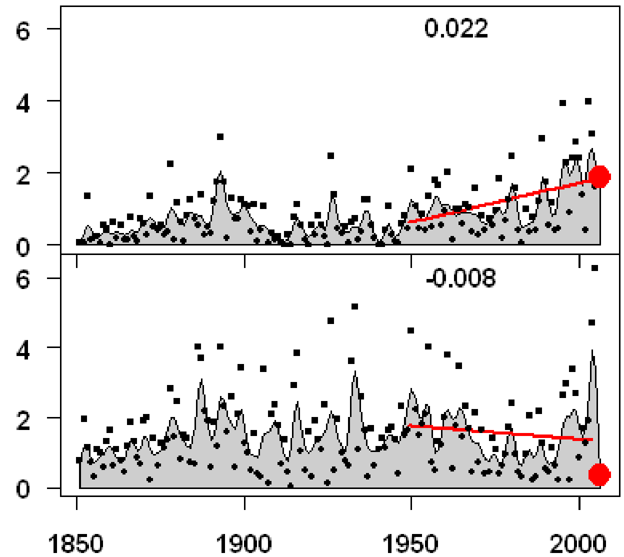

Figure 4. North Atlantic PDI. Top – two eastern quintiles; bottom – three western quintiles, together with linear trend and as smoothed in *Emanuel* (2005). Slope of 1949-2004 (as in *Emanuel*,(2005) trend shown at top of each panel.

Figure 4 shows the NATL PDI for 1851-2006, with the two eastern quintiles in the top panel and for the three western quintiles in the bottom panel. Also shown is the smoothing (a 1-2-1 filter applied twice) used in *Emanuel* (2005a as corrected by *Emanuel* 2005b) and the 1949-2004 trend (the period used in *Emanuel* 2005a). There is a trend in the two eastern quintiles, but not in the three western quintiles. In the western quintiles, 2004 and 2005 were extremely active years, but 2006 was one of the most inactive years.

Emanuel (2005b) argued that lack of a trend in U.S. landfall PDI (identified by *Landsea* 2005) corresponding to the overall increase in NATL PDI was likely a random fluctuation. However, our analysis shows that there is no inconsistency between the lack of landfall trend and the lack of trend in the western quintiles using the same HURDAT data employed by Emanuel.

Figure 2 indicates a declining proportion of landfalls throughout much of the twentieth century. Thus, it necessarily must be true that either the historical data are flawed or there are real changes in the characteristics of NATL tropical cyclone climatology, or perhaps both. In addition, there is no simple relationship between the percentage of landfalling storms and Atlantic June-October sea surface temperature anomalies with a correlation of less than 0.006 (http://www.cpc.noaa.gov/data/indices/sstoi.atl.indices)

Discussion

In the 1990s, tropical cyclone research generally indicated that there was no statistically significant upward trend in North Atlantic hurricane activity (e.g., *Landsea et al*. 1996, *Solow and Moore* 2000; *Landsea* 2001). This view has been challenged in several recent studies that claimed to observe "statistically significant" upward trends in indices related to North Atlantic (NATL) tropical cyclones (power dissipation index: *Emanuel*, 2005a, *Mann and Emanuel*, 2006; number of storms: *Holland and Webster*, 2007; proportion of intense Category 4+ hurricanes: *Webster et al.* 2005). In contrast, other analyses have reported a lack of trend in indices related to landfalling NATL cyclones (number: *Landsea* 2005; normalized damage: *Pielke* 2005) and a lack of trend in global storm and hurricane counts and days (*Webster et al* 2005). These discrepancies have not been resolved (*WMO*, 2007, *IPCC* 2007).

Some have argued that offshore storm data are under-measured in earlier parts of the historical record, noting potential biases through changing detection and measurement methodologies and technologies, which include not just the introduction and improvement of aircraft and satellite reconnaissance, but changes from sail to steam and diesel vessels and the introduction of the telegraph (e.g., *Solow and Moore*, 2000, 2002; *Landsea et al.* 2006; *Kossin et al*. 2007). In contrast, those claiming to have identified significant trends argue that the record is adequate for climate research. For example, *Mann and Emanuel* (2006) stated:

A reasonably reliable record of annual North Atlantic tropical cyclone counts is thus available back into the late nineteenth century.

Holland and Webster (2007) made a similar claim

… we consider that the veracity of the NATL tropical storm data base is sufficient to enable the broad brush analysis that we undertake in this study. Prior to 1945 we concentrate on the total number of tropical cyclones, irrespective of intensity.

The analysis presented here shows that the lack of trend in U.S. landfall data accurately reflects a corresponding lack of trend in power dissipation, storm and hurricane-days west in the western 60% of the NATL basin, i.e., west of 63W. The combination of no trend in the western NATL and a strong trend in the eastern NATL means that the *entire* NATL increase is contributed by events in the eastern NATL. These trends have coincided with many changes in observational technology and techniques that could easily have had a stronger impact on measurements in the east Atlantic, ranging from the introduction of aircraft reconnaissance and satellite surveillance in the more recent period to earlier changes such as the change from sail to steam and then diesel vessels at sea and the introduction of telegraph reporting (*Landsea et al*. 2006). Given that the increase in activity only exists in the portion of the Atlantic that was relatively more remote from U.S. surveillance, it is possible that this trend in the eastern Atlantic (and thus the count for the entire basin) is due to differential impact of technical advances on detection in more remote locations.

Of course, it is also possible that the changing mean longitude and decreasing proportion of U.S. landfalls is at least in part a reflection of the actual behavior of the climate system. However, if one is to argue that the trend in east Atlantic quintiles is due to climatic, rather than methodological or technological changes, then a climatic explanation of the differences between eastern and western quintiles is required. Candidate explanations might include an expansion of the parts of the NATL basin favorable to tropical cyclone development and tracks, or a change in track patterns. If, indeed, climatic changes and not changes in observing systems are responsible for the decreasing proportion of U.S. landfalling storms, then these changes have had the fortuitous result of causing no increase in the activity level of the storms that cause the most damage and casualties.

Conclusion

This short analysis has revisited trends in North Atlantic tropical cyclone activity showing a marked easterly trend in median annual longitude through the 20th century. The entire increase in Atlantic cyclone took place east of 63W, while there was no trend in the western part of the NATL basin. This lack of trend is completely consistent with a previously observed lack of trend in U.S. landfall hurricanes, all of which occur in the western part of the basin. It is possible to rule out a hypothesis of randomness as the basis for the discrepancy between lack of trend in landfall data and the seemingly significant trends in other overall basin indices of hurricane activity.

There are several possibilities that can explain these findings:

- Data from earlier time periods may be relatively more deficient in the more remote eastern NATL, and the lack of trend in the western Atlantic may have also existed in the eastern Atlantic. If so, the trend in eastern NATL cyclone activity and PDI may simply be an artifact of changing measurement and detection methods. Since the overall Atlantic trend is a result of the eastern NATL trend, then this implies that the overall Atlantic trend would also be an artifact of changing methodologies.
- Alternatively, trends in the total number of storms may reflect increasing activity that occurs only in the eastern NATL. The decreasing proportion of activity in the western part of the basin and related decrease in landfall proportion would then result from some yet unknown climate process that may or may not have a relationship to human activity.
- There is no obvious relationship between SSTs and landfall proportions.

Hurricane activity in the western NATL basin was historically low in the 1970-1994 period and decision makers should take care not to overlook that these levels are likely to be frequently exceeded in the future whether due to global warming, randomness, natural causes, or some combination. Given the importance of landfalling storms to society, the research community should place even greater attention on the challenging and important scientific questions of tropical cyclone landfall climatology

Part III: Projecting global tropical cyclone losses on the basis of range of assumptions

The impacts of climate on society result from the interaction of a climate event and societal vulnerability to experiencing impacts. *Pielke* (in press) employs a sensitivity analysis to examine various combinations of climate change and societal conditions (and the relationship of the two) to assess future economic impacts of tropical cyclones and the relative potential for different approaches to their mitigation. The goal is not to perform a cost-benefit analysis of policy options. Nor is the goal to predict future impacts or to arbitrarily select among different scientific understandings. Rather the goal is to explore the potential effectiveness of alternative approaches to addressing future tropical cyclone losses in the context of a wide range of assumptions about the future.

In order to assess possible future damage to tropical cyclones relative to today requires a number of assumptions. *Pielke* (in press) uses assumptions about societal changes (two different changes in per capita wealth and population), climate change (two different scenarios for changes in intensity), and the relationship of climate change to damage (three different relationships). These various combinations give 2 * 2 * 3 = 12 possible outcomes which are meant to bound the space of possible outcomes under plausible ranges of assumptions for each of the key factors. Table 1 summarizes these assumptions, which are documented in detail in *Pielke* (in press).[5]

Table 1. Assumptions of the sensitivity analysis in Pielke (in press) to 2050

Societal change
Annual combined increase in wealth and population (based on expert projections): 2.5% and 4.7%

Climate change
Total increase in tropical cyclone intensity (based on an informal expert elicitation): 8% and 36%

Relationship of climate change to damage
Damage varies as (based on a literature review)**:** 3rd , 6th, and 9th power of the storm intensity

The analysis begins with $1.00 in damages today and asks how that value will increase by 2050. Table 2 and Figure 5 illustrate the analysis step-by-step assuming that all tropical cyclones increase in intensity by 18% by 2050, population/wealth increases by 180% above today's levels (i.e., 2.5% annual growth), and damage is proportional to the cube of the intensity. Under these assumptions the total costs of tropical cyclone damage in 2050 is $4.60. Table 3 shows the results for the full range of assumptions.

[5] Note that the assumptions used in *Nordhaus* (2006), cited by *Stern*, are within the bounds of the assumptions used by *Pielke* (in press).

Table 2. An overview of the approach in *Pielke* (in press)

Assumptions for 2050:

1. Change in tropical cyclone intensity = 18%
2. Change in population and wealth above present baseline = 180%
3. Damage function = cubic

A = tropical cyclone damages today = $1.00
B = increase in tropical cyclone damages in 2050 = 64%, i.e., damage increase = (($1.00 * 0.18))^3-$1.00 = $0.64
C = increase in tropical cyclone damage in 2050 = Today's damage + 180% increase = $1.00 * 1.80= $1.80
D = combined effect of B and C = $1.80 * 0.64 = $1.16
E = Total increase in costs = B + C + D = $0.64 + $1.80 + $1.16 = $3.60
F = Total tropical cyclone economic damage in 2050 = A + E = $4.60

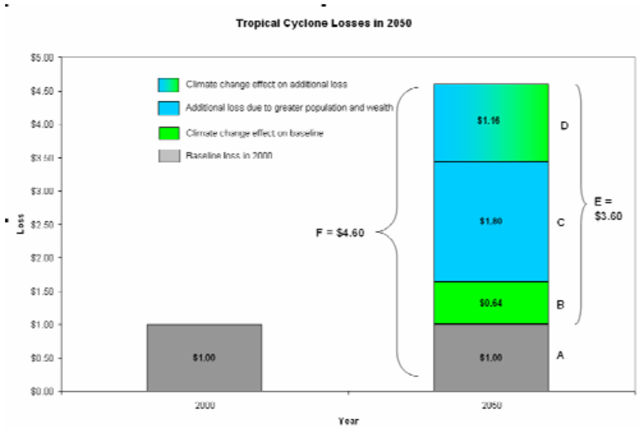

Figure 5. Display of values presented in Table 2. Colors refer to the effects of societal change (blue), climate change (green), and the combined effects of climate and societal change (green-blue).

This analysis allows for a comparison of the potential effectiveness of mitigation policies and adaptation policies. For example, consider a hypothetical emissions reduction policy that leads to a 10% reduction in the projected increase atmospheric greenhouse gas concentrations in 2050. Carbon dioxide concentrations are about 380 parts per million in 2006, and assuming that carbon dioxide concentrations will be 500 ppm in 2050 under business as usual, a 10% reduction equates to a 12 ppm decrease (i.e., 10% = 12/[500 – 380])[6] Assuming that greenhouse gas reductions have an instantaneous (i.e., contemporaneous with the reductions) and proportional (i.e., a 50% decrease in emissions decreases the projected increase in tropical cyclone intensity by 50%) effect on tropical cyclone intensity,[7] then policies that lead to a 10% decrease in atmospheric carbon dioxide concentrations in 2050 would (under the assumptions here) decrease the projected increase in hurricane intensities by 10% in 2050. The corresponding reduction in projected damages would be therefore about $0.21 (i.e., the increase in intensity would be reduced from 18% to 16.2%, see *Pielke*, in press, for details of the calculation) reducing losses in 2050 from $4.60 to $4.39, a reduction of about 4.5%. Under these assumptions, 100% success in implementation of a policy about five times more ambitious than Kyoto is the equivalent in its effect of about a 4.5% success rate in addressing ever-increasing vulnerability through efforts to build societal resilience.

Greenhouse gas mitigation may certainly be justified for other reasons, such as its cost-effectiveness, but if the case of tropical cyclones is representative of other disaster-related phenomena, then even if greenhouse gas mitigation polices were cost-free, then vulnerability reduction would still have far greater potential to address the mounting toll of disaster losses because emissions reduction policies can only address a subset of the multiple causes of increasing losses. It should be underscored that this exercise was conducted using conservative projected societal changes (i.e., wealth, population) as well as unrealistic assumptions about climate behavior. Using larger societal changes and more realistic assumptions about climate science would result in a larger potential effectiveness ratio in favor of vulnerability reduction. Thus, the effectiveness of mitigation is certainly overstated in this analysis. These results are robust even under the full range of assumptions about changes in tropical cyclone intensities.

Table 3 also shows the potential effectiveness of

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[6] By contrast under the Kyoto Protocol if fully and successfully implemented by 2012 (including participation of the U.S. and Australia) the corresponding carbon dioxide reduction would be 2 ppm by 2012 and, absent other policies, about 2.5 ppm by 2050.

[7] Of course, the real climate system does not work this way, and the effects of mitigation on hurricane behavior remain poorly understood, but it is certainly less direct than the oversimplification offered here.

instantaneous climate stabilization at 2006 values. Under no scenario does this form of mitigation result in a greater potential effectiveness than vulnerability reduction. It is therefore appropriate to conclude that vulnerability reduction is potentially more effective under any theoretically possible mitigation scenario. Under any plausible mitigation scenario, vulnerability reduction vastly exceeds mitigation in terms of its potential effectiveness. These conclusions are qualitatively insensitive to the magnitude of the projected increase in tropical cyclone intensity or population scenarios. The longer the time scale, the greater the role of the societal factors assuming continued growth in wealth and/or population.

Table 3. For a range of assumptions about intensity change and changes in population/wealth, the growth of $1.00 in global tropical cyclone damage today into damage in 2050 using damage functions that assume damage as being proportional to the 3rd, 6th, and 9th powers of windspeed. The first column of Table 2.1 shows the values from the example shown in Table 3. Values expressed in constant 2007 dollars.

3a. 18% increase in intensity by 2050

Societal Change	180%	180%	180%	600%	600%	600%
Damage Function	Cubic	6th Power	9th Power	Cubic	6th Power	9th Power
Climate	0.64	1.70	3.44	0.64	1.70	3.44
Society	1.80	1.80	1.80	6.00	6.00	6.00
Climate/Society	1.16	3.06	6.18	3.86	10.20	20.61
Total Damage	4.60	7.56	12.42	11.50	18.90	31.05
Maximum effect of 10% Reduction in 2050 CO2 Concentrations	0.21	0.67	1.60	0.52	1.66	4.01
Maximum Mitigation	1.80	4.76	9.62	4.50	11.90	24.05
Maximum Vulnerability Reduction	4.60	7.56	12.42	11.50	18.90	31.05

3b. 36% increase in intensity by 2050

Societal Change	180%	180%	180%	600%	600%	600%
Damage Function	Cubic	6th Power	9th Power	Cubic	6th Power	9th Power
Climate	1.52	5.33	14.92	1.52	5.33	14.92
Society	1.80	1.80	1.80	6.00	6.00	6.00
Climate/Society	2.73	9.59	26.85	9.09	31.97	89.50
Total Damage	7.04	17.72	44.57	17.61	44.29	111.42
Maximum effect of 10% Reduction in 2050 CO_2 concentrations	0.54	2.63	9.56	1.36	6.59	23.90
Maximum Mitigation	4.24	14.92	41.77	10.61	37.29	104.42
Maximum Vulnerability Reduction	7.04	17.72	44.57	17.61	44.29	111.42

To emphasize, the analysis summarized here should not be interpreted as an argument against mitigation of greenhouse gases. And there is no suggestion here that human-caused climate change is not real or should not be of concern. Instead, this simple analysis under the most favorable assumptions for mitigation indicates that in the coming decades any realistically achievable mitigation policies can have at best only a very small and perhaps imperceptible effect on global tropical cyclone damage, whatever the costs of those policies might happen to be. This reality explains why adaptation necessarily must be at the center of climate policy discussions and must be viewed as a complement to mitigation policies, rather than being viewed simply as the costs of failed mitigation, as suggested by the Stern Review. It also helps to explain why mitigation policies in the short-term necessarily must be focused on their non-climate benefits. These are decidedly different conclusions than were presented in the Stern Review.

Most importantly these results show how misleading it is to use tropical cyclone damage – and disaster losses more generally – as a justification for greenhouse gas mitigation when other actions have far more potential effectiveness. The images of storm-spawned death and destruction are no doubt compelling, but it is misleading or disingenuous to suggest that energy policies can have an appreciable effect on future damages. The only way to arrive at effects on damages from human-caused climate change that exceed the effects of societal change is to hold society constant and focus only on the climate component, which is what was done in the ABI reports and subsequently done (apparently unknowingly) in the Stern Review. Climate change deserves serious attention, and policy action on mitigation makes sense, but when compared with available alternatives for addressing the escalating costs of disasters, adaptive policies deserve to be in the fore.

Bibliography

Crompton, R.P. 2005. Indexing the Insurance Council of Australia Natural Disaster Event List. Report prepared for the Insurance Council of Australia, Risk Frontiers.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, 436, 686-688.

Emanuel, K. 2005b. Emanuel Replies. *Nature* 438, E13.

Emanuel 2007 (submitted). Environmental Factors Affecting Tropical Cyclone Power Dissipation, 6 January.

Holland, G.J. and P.J. Webster 2007 (in press). Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend?, *Philos.Trans. Roy. Soc. A*.

http://www.mmm.ucar.edu/people/holland/files/NaturalVariabilityOrClimateTrend.pdf (Accessed 13 Feb 2007)

IPCC. 2001. Climate Change 2001. The Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu). Cambridge University Press, United Kingdom, 881 pp.

Intergovernmental Panel on Climate Change, 2007. Climate Change 2007: The Physical Science Basis. Summary for Policymakers http://ipcc-wg1.ucar.edu/wg1/docs/WG1ARA_SPM_approved_05_Feb_pdf.

Kossin, J., P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper, 2007 (in review). A globally consistent reanalysis of hurricane variability and trends. *Geophys. Res. Lett.*

Landsea, C.W. 1993. A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, 121, 1703–1713.

Landsea, C.W. 2001; Comment on "Changes in the rates of North Atlantic major hurricane activity during the 20th Century", *Geophys. Res. Lett.* 28, 2871-2872 http://www.aoml.noaa.gov/hrd/Landsea/20thCenturyHurricanes.html

Landsea , C.W., 2005. Hurricanes and global warming, *Nature* 438, E12-13.

Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila, 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophys. Res. Lett.*, 23, 1697-1700.

Mann, M.E. and K. Emanuel 2006 Atlantic hurricane trends linked to climate change. *EOS, 87*, 233-244.

Mechler, R., 2005. Cost-benefit Analysis of Natural Disaster Risk Management in Developing and Emerging Countries. Long Study. Interim report for GTZ.

Munich Re, 2005. Annual Review: Natural Catastrophes 2004, http://www.munichre.com/publications/302-04321_en.pdf?rdm=71234%20.

Pielke, R.A. 2005. Are there trends in hurricane destruction? *Nature* 438, E11.

Pielke, Jr., R. A. and C. W. Landsea, 1998. Normalized Hurricane Damages in the United States: 1925-95. *Weather Forecast*., 13, pp. 621-631.

Solow, Andrew R. and Laura Moore, 2000. Testing for a Trend in a Partially Incomplete Hurricane Record, *J. Climate* 13, 3696–3699.

Solow, Andrew R. and Laura Moore, 2002. Testing for Trend in North Atlantic Hurricane Activity, 1900–98, *J. Climate* 15, 3111–3114.

Stern, N., 2007, *The Economics of Climate Change: The Stern Review*, Cambridge University Press.

Webster, P.J., G. J. Holland, J. A. Curry and H.-R. Chang 2005 Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science*, 309, 1844-1846.

WMO International Workshop on Tropical Cyclones, IWTC-6, San Jose, Costa Rica, November 2006. Statement on Tropical Cyclones and Climate Change.