Future economic damage from tropical cyclones: sensitivities to societal and climate changes

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This paper examines future economic damages from tropical cyclones under a range of assumptions about societal change, climate change and the relationship of climate change to damage in 2050. It finds in all cases that efforts to reduce vulnerability to losses, often called climate adaptation, have far greater potential effectiveness to reduce damage related to tropical cyclones than efforts to modulate the behaviour of storms through greenhouse gas emissions reduction policies, typically called climate mitigation and achieved through energy policies. The paper urges caution in using economic losses of tropical cyclones as justification for action on energy policies when far more potentially effective options are available.

Keywords: climate change; disasters; tropical cyclones

1. Introduction and background

Tropical cyclones have been the subject of considerable attention in the media, and among scientists and policy makers since the devastation wrought by Hurricane Katrina in late August, 2005. Particular attention has been paid by the media and political advocates to the possible role of human-caused climate change in patterns of tropical cyclone activity.[1] Such discussion has a scientific basis as well in a set of studies released in 2005 and 2006 that indicate a dramatic increase in tropical cyclone activity in recent decades (e.g. Emanuel 2005; Webster *et al.* 2005), stimulating a vigorous scientific debate (e.g. Landsea 2005; Chan 2006). A scientific consensus on the role of human-caused climate change on tropical cyclone activity is unlikely to materialize in the near term (Pielke *et al.* 2005, 2006; Anthes *et al.* 2006; WMO 2006).

Consequently, policy action in the face of tropical cyclone risks must occur in the face of some uncertainty about the future. This paper explores under a range of assumptions how possible societal and climate changes related to tropical cyclones might interact in the future, leading to increasing economic damage.

Such an assessment can be used to suggest to policy makers what actions have the greatest potential to mitigate future economic losses. This study updates and extends an analysis first presented by Pielke *et al.* (2000).

Not surprisingly, the issue of tropical cyclones has become caught up in the politics of global warming with images of human impacts of hurricanes and tropical cyclones often used in support of advocacy to reduce greenhouse gas emissions. For instance, in his movie *An inconvenient truth*, Al Gore uses images of Hurricane Katrina and its horrific aftermath to make the case for action on energy policies. But, the analysis in this paper, consistent with that in earlier studies, suggests that any practically or politically conceivable energy policies can have at best a very small and perhaps imperceptible effect on future tropical cyclone damage. Consequently, policy action should focus on reducing vulnerabilities, at least in the short term. This finding should not diminish the importance of mitigation policies in response to climate change, but can help to better align political advocacy with potential policy effectiveness.

2. Methodology of sensitivity analysis

The impacts of climate on society result from the interaction of a climate event with societal vulnerability to experiencing impacts. The goal of the sensitivity analysis methodology used in this paper is 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 neither to perform a cost–benefit analysis of policy options nor to predict future impacts or arbitrarily select among different scientific understandings. Rather, the goal is to explore the potential effectiveness of alternative approaches to address the future tropical cyclone losses in the context of a wide range of assumptions about the future.

3. Assumptions of the sensitivity analysis

In order to assess possible future damage to tropical cyclones relative to today requires a number of assumptions. This analysis uses a wide range of assumptions in order to characterize a broad set of possible outcomes. The sensitivity analysis focuses on tropical cyclone damage in 2050 as compared to 2006. Assumptions must be made about societal change, climate change and the relationship of climate change to damage.

(a) Changes in population and wealth

Increases in population growth and wealth are each related proportionately to an increase in damage. For example, if a storm destroys two identical beach houses, losses will be twice the amount had only one beach house been destroyed. Similarly, a storm destroying a beach house of twice the value of another and containing twice the material goods would result in twice the economic damage. Past research on normalized economic losses related to hurricanes provides

support for these common-sense assumptions (Pielke & Landsea 1998). Thus, to estimate future losses, some assumptions about the combined growth in population and wealth in the future are required.

For the rate of population growth and increases in wealth, as we did in Pielke *et al.* (2000), we rely on a range of wealth and population estimates.[2] Here we use two scenarios. One scenario assumes that in 2050 the combined global population and wealth in locations exposed to tropical cyclones will be 2.8 times greater than 2006 values. The second scenario assumes that the combined global population and wealth in locations exposed to tropical cyclones will be seven times greater than today. These values equate to a combined annual increase in wealth and population of approximately 2.5 and 4.9%, respectively.[3] Mid-range estimates have global population increasing by approximately 1% yr^{-1} and *per capita* GDP is, by some estimates, projected to increase by approximately 2.5% yr^{-1} in excess of population grown.[4] These values combine to a 3.5% annual increase which is in between the scenarios used here.

Empirical data on the combined growth of wealth and population in US coastal counties suggest that the scenarios used here are conservative, if such rates of growth occur in the future and around the world. The average combined wealth and population increase in 177 US coastal counties from 1950 to 2005 was 4.1%, with a minimum of 1.2% and a maximum of 11.7%.[5] A recent insurance industry study concluded that increasing population and wealth means that loss potentials related to hurricanes should be expected to double every 10 years.[6] Such a rate of increase would result in losses in 2050 to be approximately 15 times more than in 2006, far higher than either of the scenarios used in this analysis. The analysis below uses a growth scenario of 180 and 600% more people and wealth above the current values for the combined effects of societal changes to wealth and population to 2050 (2100 is discussed below). Note that no adjustment is made for changes in future characteristics of vulnerability, such as building codes and practices. Such changes, if successfully implemented, could have the effect of reducing future damages and will be discussed in §4.

4. Effects of climatic change on tropical cyclone frequency and intensity

For future changes in tropical cyclone frequency and intensity, Pielke *et al.* (2000) relied on the consensus perspective of Henderson-Sellers *et al.* (1998), which projected an increase in global tropical cyclone intensity of 10–15% by 2050 resulting from human-caused climate change and no expected changes in frequency. Since that time, a number of studies have been published that suggest a greater role for human-caused climate change in the behaviour of tropical

[2] Our 2000 paper replied on the IPCC SRES estimates. The IPCC has since that time released an update (Nakicenovic *et al.* 2000).

[3] These assumptions do not include the effects of inflation. All dollars presented in this paper are expressed in 2006 values.

[4] The IPCC SRES exercise estimates increases in *per capita* GDP to 2050 range from about 0.5% yr^{-1} to close to 4% yr^{-1}, see fig. 3.10 at http://www.grida.no/climate/ipcc/emission/058. htm. The value of 2.5% is chosen so as to be within this range. On projected population growth see: http://www.census.gov/ipc/www/worldpop.html.

[5] Thanks to Joel Gratz for these calculations.

[6] http://www.insurancejournal.com/news/national/2006/04/18/67389.htm.

cyclones (e.g. Hoyos *et al.* 2006; Mann & Emanuel 2006). Thus, to assess current expectations of leading scientists for future changes in tropical cyclone activity, I conducted a simple informal expert elicitation.

In the spring of 2006, I contacted 10 of the leading scholars on tropical cyclones and climate change and asked them what values they would like me to use in this project for changes in global tropical cyclone frequency and intensity between today (spring 2006) and 2050 and 2100. Of the 10 scientists, seven can be characterized as supporting the hypothesis that human-caused global warming has had a discernible influence on tropical cyclone activity over the past 30 years. The other three scientists remain unconvinced. I guaranteed the scientists that their individual responses would be held in confidence.[7]

I received responses from nine out of the 10 scientists. Of the nine who responded, three chose not to engage in predictions of the future. Of the remaining six scientists, one provided only a qualitative response, expressing a lack of sufficient knowledge to provide more precise estimates. The remaining five, which included scientists with a diversity of perspectives, provided quantitative estimates. For present purposes, what matters from this exercise are the endpoints of the range of values from the entire set of responses.

For 2050, the range was as follows.
  Intensity: increase of 0–18%.
  Frequency: decrease of 20% to increase of 20%.
For 2100, the range was as follows.
  Intensity: increase of 0–36%.
  Frequency: decrease of 40% to increase of 40%.

In the sensitivity analysis, I focus on the maximum increase in intensity for 2050 and 2100 for losses in 2050. Since the estimates of frequency are symmetrical and centred on no change, I do not include the frequency changes in the analysis below.[8] In addition, one scientist suggested a probable increase in rainfall related to tropical cyclones in the future. Analysis of rainfall-caused flood damage related to tropical cyclones goes beyond the present focus.

5. Relationship of intensity change to damage

In order to project the effect of changes in tropical cyclone intensity on future damage, an assumption about the relationship of the two is required. Pielke *et al.* (2000) followed the practice of the IPCC's Second Assessment which assumed a linear, or linear plus, damage function relating a change in intensity to a change in economic losses. A linear function clearly underestimates the relationship. Conventional wisdom among experts in the community holds that damage is

[7] The scientists that I contacted for the informal elicitation were: Chris Landsea, Tom Knutson, Kerry Emanuel, Peter Webster, Johnny Chan, Greg Holland, Judy Curry, Kevin Trenberth, Gerry Bell, and Robert Tuleya. I also shared an early draft of this analysis with these scientists providing a chance to comment in advance of submission.

[8] Note that the effect of a 20% increase in frequency will have about the same effect as about a 1.7% increase in intensity (using damage function proportional to the 6th power of the change in windspeed) or about a 2.7% increase in intensity (using a cubic damage function). So the independent effects of frequency changes at the 20% level on damages fall within the bounds of the analysis below for 2050 focused on intensity change in any case.

proportional to the square or cube of the intensity (cf. Iman *et al.* 2005; Nordhaus 2006); but this also apparently underestimates the relationship. Part of the uncertainty in estimating this relationship no doubt stems from different definitions of damage, different approaches to adjusting historical losses to present-day values and different representations of the relationship of intensity to damage.

Our empirical analysis of the relationship of intensity to damages follows Howard *et al.* (1972) who proposed the following relationship:

$$D = xW^y, \tag{5.1}$$

where D is damage; W is wind speed; and x and y are empirical constants derived from the historical record of tropical cyclone damage. Using per-storm normalized US hurricane losses from 1900 to 2005 and maximum wind speed at landfall reported by the National Hurricane Center, we find y to be approximately 3.9.[9] On the contrary, using normalized US data aggregated by Saffir–Simpson Category results in y equal to 4.2 for the mean damage and 7 for the median. Howard *et al.* (1972) reported a value of 4.36, calculated on a per-storm basis, and cited research showing the value to be as high as 6.7 (in their footnote 18). Nordhaus (2006) cited values for y proposed by the insurance industry as being between 4 and 6. Nordhaus (2006) suggested from his own analysis that damage may even be proportional to the 9th power of the wind speed.[10]

Clearly, there is some uncertainty about how changes in wind speed are related to corresponding changes in damage. Without resolving this question here, which is unnecessary for present purposes, in the analysis below results are presented for damage being proportional to the 3rd, 6th and 9th power of wind speed in order to bound the set of probable possibilities.

6. Analysis of future sensitivities

With the assumptions described, we are now in a position to integrate them to assess the integrated effects of societal and climate changes on future global tropical cyclone damage. In the analysis, we begin with $1.00 in damages today and ask how this will increase by 2050. Table 1 and figure 1 illustrate the analysis step by step by assuming that all tropical cyclones increase in intensity by 18% by 2050, population/wealth increases by 180% above today's levels and damage is proportional to the cube of the intensity.

From table 1, of total costs of tropical cyclone damage in 2050, the fraction that can be addressed, in principle, by intentionally modulating the intensity of tropical cyclones by stabilizing the climate such that intensities remain at their current levels is $1.80 (B + D), and the part that can be addressed, in principle, by reducing vulnerability is $4.60 (F). Assuming (unrealistically) (i) an instantaneous reduction of greenhouse gases to 2006 levels and (ii) no commitment to climate change due to past emissions, at the theoretical limit climate stabilization policies could reduce the increase in future damages from $3.60 to $1.80 or a 50% reduction.

A more realistic exercise would focus on the potential effectiveness of more realistic policy proposals. Here, we illustrate the potential effectiveness of efforts to reduce greenhouse gas emissions with a hypothetical emissions reduction

[9] Thanks to Joel Gratz for this calculation.

[10] I am grateful to William Nordhaus for a useful exchange on the issue of damage functions.
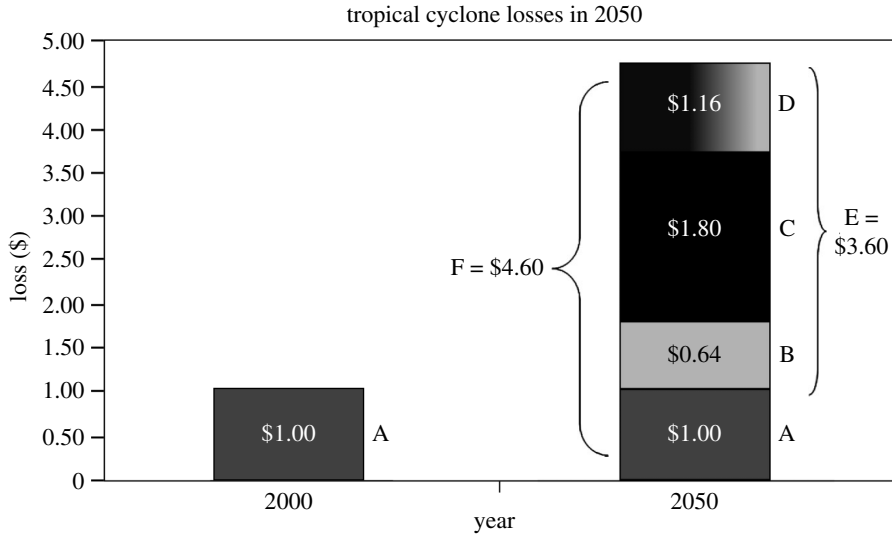
Figure 1. Display of values presented in table 1. A, baseline loss in 2000; B, climate change effect on baseline; C, additional loss due to greater population and wealth; D, climate change effect on additional loss.

Table 1. An initial overview of the approach.

assumptions for 2050
change in tropical cyclone intensity $=18\%$
change in population and wealth above present baseline $=180\%$
damage function $=$ cubic (using equation (5.1))
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 $=$ $\$1.00 \times 1.80 = \$1.80$
D $=$ combined effect of B and C $= \$1.80 \times 0.64 = \$1.16$[a]
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 $= \$4.60$

[a]Pielke *et al.* (2000) did not include this interactive effect.

policy that leads to a 10% reduction in the projected increase in atmospheric greenhouse gas concentrations in 2050. Carbon dioxide concentrations are approximately 380 ppm 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. $10\% = 12/(500-380)$). By contrast, under the Kyoto Protocol, if fully and successfully implemented by 2012 (including participation of the USA and Australia), the corresponding carbon dioxide reduction would be 2 ppm by 2012 and, other policies absent, approximately 2.5 ppm by 2050 (cf. Höhne 2005). If we assume 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,[11] 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 as described in table 1 would be therefore approximately $0.21 (i.e. the increase in intensity would be reduced from 18 to 16.2%; see table 3 for details) reducing losses in 2050 from $4.60 to $4.39, a reduction of approximately 4.5%. Under these assumptions, 100% success in implementation of a policy about five times more ambitious than Kyoto is equivalent in its effect of approximately a 4.5% success rate in addressing ever increasing vulnerability through efforts to build societal resilience.

It is crucial to emphasize that nothing has been presented in this analysis on the costs associated with emissions or vulnerability reductions. The point of this analysis is to explore the potential policy effectiveness of greenhouse gas mitigation policies as compared to vulnerability reduction. The concept of policy effectiveness is important because it can provide a perspective on the maximum potential reductions possible, independent of costs.

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 (and the literature suggests that it is, e.g. Pielke & Sarewitz 2005), then even if greenhouse gas mitigation polices were cost-free the 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 behaviour. Using larger societal changes and more realistic assumptions about climate science would result in a larger potential effectiveness ratio in favour 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. For example, conducting the same analysis assuming an increase in tropical cyclone intensity of 36% by 2050—twice the largest value found in the expert elicitation—underscores the robustness of the conclusion of the much greater effectiveness of reducing disaster vulnerability over to efforts to modulate storm behaviour through energy policies.

Tables 2 and 3 illustrate the results under a range of different assumptions. The column headings refer to the assumptions used in the calculations about increase in tropical cyclone intensity and growth in combined population and wealth. The first column of table 2 provides the values presented in table 1 and figure 1. Within the table, the values presented reflect three different damage functions (i.e. calculated using equation (5.1)).

Under these various assumptions, the largest *maximum potential effectiveness* of a 10% reduction in the projected increase in greenhouse gas concentrations by 2050 for reducing future global tropical cyclone damage is far less than the

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

Table 2. 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 wind speed. (The first column shows the values from table 1.)

societal change (%)	180	180	180	600	600	600
damage function	cubic	6th power	9th power	cubic	6th power	9th power
(a) 18% increase in intensity by 2050						
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 CO_2 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
(b) 36% increase in intensity by 2050						
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

maximum potential effectiveness of adaptation (i.e. reducing the vulnerability of people and property) by a ratio of approximately 8 : 1 under the maximum change in intensity resulting from the expert elicitation and approximately 5 : 1 when arbitrarily doubling the maximum change in intensity. Alternatively, under the assumptions most favourable to vulnerability reduction, the ratios are 22 : 1 and 13 : 1 under the assumptions of the expert elicitation and an arbitrary doubling of those values, respectively.

Table 2 also shows the potential effectiveness of 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.

This idealized exercise indicates that a small percentage reduction in vulnerability leads to about the same effect on future damages as 100% success of a significant change in greenhouse gas emissions. These conclusions are qualitatively insensitive to the magnitude of the projected increase in tropical

Table 3. The effects of a 10% reduction in greenhouse gas emissions by 2050, assuming that the effect on tropical cyclone intensity is directly proportional. (Thus, intensities are 90% of those used in table 2. The differences between the total damage in this table from the corresponding values in table 2 are the values used in the row titled 'maximum effect of 10% reduction in 2050 CO_2 concentrations'.)

societal change (%)	180	180	180	600	600	600
damage function	cubic	6th power	9th power	cubic	6th power	9th power
(a) 10% reduction in intensity by 2050 to 16.2%						
climate	0.57	1.46	2.86	0.57	1.46	2.86
society	1.80	1.80	1.80	6.00	6.00	6.00
climate/society	1.02	2.63	5.15	3.41	8.77	17.17
total damage	4.39	6.89	10.81	10.98	17.23	27.04
(b) 10% reduction in intensity by 2050 to 32.4%						
climate	1.32	4.39	11.50	1.32	4.39	11.50
society	1.80	1.80	1.80	6.00	6.00	6.00
climate/society	2.38	7.90	20.70	7.93	26.32	69.01
total damage	6.50	15.08	35.01	16.25	37.71	87.52

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.

To emphasize, the analysis presented 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 favourable 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 centre of climate policy discussions and viewed as a complement to mitigation policies. It also helps to explain why mitigation policies in the short term necessarily must be focused on their non-climate benefits.

Most importantly, these results show how misleading it is to use tropical cyclone damage as a reason 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 tropical cyclone damages that exceed the societal factors is to hold societal change constant and focus only on the climate component, which is in fact what some studies have done in the past.[12] Climate change is an important issue and policy action on mitigation makes sense, but when compared with available alternatives for addressing the escalating costs of

[12] For example, a 2005 study by the Association of British Insurers (http://www.abi.org.uk/Display/File/Child/552/Financial_Risks_of_Climate_Change.pdf) reported that an increase in future losses from tropical cyclones could be mitigated via energy policies, but their analysis did not factor in societal changes. When such changes are considered, reducing vulnerability is up to 52 times more effective than energy policies, qualitatively identical to the results reported here. For discussion see: Pielke (in press).

tropical cyclones, ameliorating damage from tropical cyclones should not be conflated with other justifications for changing energy policies. Those interested in honest advocacy and effective policy should keep these issues separate.

7. Discussion

If reducing vulnerability is potentially far more effective that efforts to reduce greenhouse gas concentrations for efforts to address future losses from tropical cyclones, then what are the specific costs and benefits of vulnerability reduction policies?

Formal evaluation of specific options for reducing disaster vulnerability remains difficult because 'natural hazards and related vulnerability are rarely considered in the design and appraisal of development projects. Similarly, monitoring and evaluation are still relatively neglected in disaster reduction, especially where impact evaluation is concerned' (Benson & Twigg 2004). There are a number of benefit–cost estimates that circulate in the disaster community that suggest that 'disaster mitigations pays', typically by a ratio of 3 : 1 or higher. Of such estimates, Benson & Twigg (2004, pp. 13–14) wrote,

> However, there is surprisingly little evidence in support of many broad-brush statements. Detailed underlying calculations are not available, suggesting that they may, in fact, be no more than 'back-of the-envelope'—if informed—estimates. Even if they are based on more extensive calculations, the fact that the workings underlying them are not readily available can cast doubts on their legitimacy, particularly if figures involve some valuation of non-tangibles. Of course, financial analysis of loss and the cost of investments needed to avoid loss may not be sufficient to ensure greater attention to natural hazard risk, as demonstrated from experience elsewhere (for instance, in relation to disease, water pollution and illiteracy). But proof of net financial benefits is almost undoubtedly a first, very necessary step in making a case for the importance of analysing hazard-related risks.

The lack of a well-developed body of cost–benefit analyses of the value of disaster mitigation sets the stage for a chicken-and-egg problem. Since such studies do not exist, it can be difficult to compare projects or policies focused on disaster mitigation/climate adaptation to other sorts of development policies; hence disaster mitigation policies are at risk of being overlooked in any systematic comparison of costs and benefits across different policy alternatives. But, if such projects are overlooked, then there is less incentive to call for and support rigorous cost–benefit studies. One consequence of this dynamic is that funds for disaster relief in the aftermath of a horrific disaster are, in many cases, easier to secure than funds for long-term reduction of vulnerability to disasters, which may have supported efforts that would have reduced the need for post-disaster relief. This vicious cycle is well appreciated by observers of disaster policy, but remains entrenched (Wisner *et al.* 2004).

Thus, one recommendation is for increasing attention to the need for rigorous cost–benefit analyses of disaster mitigation policy alternatives and practices. To put this another way, irrespective of how such studies turn out (in terms of relative costs and benefits) there is a substantial benefit to decision making related to disasters to be gained from a more rigorous understanding of the value of climate adaptation. More fundamentally, there is also a pressing need for more rigorous information on the impacts of disasters (Benson & Clay 2004) as well as

indicators of relative vulnerability (UNDRO 1990) in order to help prioritize disaster mitigation investments. Even in the USA and Europe, where response to disasters is generally quite successful as measured by lives lost and community recovery from disasters, there is exceeding little information available on the costs and benefits of vulnerability reduction, as well as the role of government investments in disasters on outcomes (Meade & Abbott 2003).

Even in the absence of well-developed studies of the costs and benefits of vulnerability reduction, there are many proven and promising options for cost-effective actions that increase resilience to disasters. Actions to reduce the impacts of natural disasters are many and varied around the world. Some of these actions are developed in the longer term, such as building codes, evacuation plans and emergency response plans. Some of these longer-term plans require additional action in the short term in the face of an impending threat, such as an order of evacuation.

In some instances not only has a cost–benefit analysis not been attempted, but neither has a more general risk assessment. Hurricane evacuation in the USA is an example of such a situation. Hurricane forecasts of storm tracks have improved steadily over the past three decades or so, yet at the same time the area of coastline warned per storm has increased over the same time period. This suggests that decisions makers (including forecasters and emergency managers) have possibly become more risk averse over time and have used advances in the science of forecasting to reduce the chances of a leaving part of the population unwarned. Of course, such strategies have costs in the form of a greater number of people warned unnecessarily. But to date, there has been little demand for the quantification of the costs, benefits and risks associated with different approaches to the challenge of hurricane evacuation in the face of uncertainty (Pielke 1999). Arguably, the case of hurricane evacuation is representative of the broader challenges of evaluating existing disaster mitigation policies in terms of their costs, benefits and risks.

There are new and innovative policy options that have been proposed for disaster mitigation that will probably stimulate demand for greater attention to costs and benefits. Among these are the securitization of risk through financial products such as catastrophe bonds and derivatives,[13] and the provision of micro-finance[14] in developing countries as a tool of disaster recovery in ways that reduce long-term vulnerabilities. Such policies are not widespread, however, and have not been subject to rigorous evaluation of costs and benefits, but nonetheless have strong support among many disaster experts. The good news from the analysis presented here is that despite the expected increase in economic damage related to tropical cyclones, there are many opportunities to address those potential increases through deliberate action.

8. Conclusion

This paper finds that under a wide range of assumptions about future growth in wealth and population, and about the effects of human-caused climate change, in every case there is far greater potential to affect future losses by focusing

[13] http://www.axa.com/lib/axa/uploads/cpsocietes/2006/United_nations_PR_20060306.pdf.
[14] http://www.proventionconsortium.org/themes/default/pdfs/microfin_guidebook.pdf.

attention on the societal conditions that generate vulnerability to losses. Efforts to modulate tropical cyclone intensities through climate stabilization policies have extremely limited potential to reduce future losses. This conclusion is robust across assumptions, even across unrealistic assumptions about the timing and magnitude of emissions reductions policies on tropical cyclone behaviour. The importance of the societal factors increases with the time horizon.

This does not mean that climate stabilization policies do not make sense or that policy makers should ignore influences of human-caused climate change on tropical cyclone behaviour. It does mean that efforts to justify emissions reductions based on future tropical cyclone damages are misleading at best, given that available alternatives have far greater potential to achieve reductions in damage. The most effective policies in the face of tropical cyclones have been and will continue to be adaptive in nature, and thus should play a prominent role in any comprehensive approach to climate policy.

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