

# The impact of socio-economics and climate change on tropical cyclone losses in the USA

Silvio Schmidt · Claudia Kemfert · Peter Höppe

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**Abstract** Tropical cyclones that make landfall on the coast of the USA are causing increasing economic losses. It is assumed that the increase in losses is largely due to socio-economic developments, i.e. growing wealth and greater settlement of exposed areas. However, it is also thought that the rise in losses is caused by increasing frequency of severe cyclones resulting from climate change, whether due to natural variability or as a result of human activity. The object of this paper is to investigate how sensitive the losses are to socio-economic changes and climate changes and how these factors have evolved over the last 50 years. We will then draw conclusions about the part the factors concerned play in the observed increase in losses. For analysis purposes, storm loss is depicted as a function of the value of material assets affected by the storm (the capital stock) and storm intensity. The findings show the increase in losses due to socio-economic changes to have been approximately three times greater than that due to climate-induced changes.

**Keywords** Tropical cyclones · Climate change · Socio-economic impact · Storm damage function

## Introduction

Economic losses caused by tropical cyclones on the Atlantic coast of the USA have risen considerably in the last ten years (see Fig. 1),<sup>1</sup> largely due to socio-economic and climate-related developments, the former being primarily population growth, greater per capita wealth, and increasing settlement of exposed areas. Since the USA is likely to experience similar population and wealth development in the future, the Intergovernmental Panel on Climate Change (IPCC) expects a further increase in storm losses in North America, particularly along the Gulf and Atlantic coasts. On the other hand, the extent to which the losses are or are expected to be affected by climate change has not been clearly established. However, the IPCC believes there is evidence of an increase in the average intensity of tropical cyclones in most tropical storm basins since the 1970s. No definite pronouncement is made as to the proportion of losses that is now, or will in future, be attributable to climate change (cf. IPCC 2007a, b).

This paper investigates how sensitive the losses are to socio-economic changes, in terms of increased material assets, and to climate changes, in terms of storm intensity, and how these factors have evolved over the last 50 years. It then draws an albeit approximative conclusion about the effect they may have had on historical losses. In this paper

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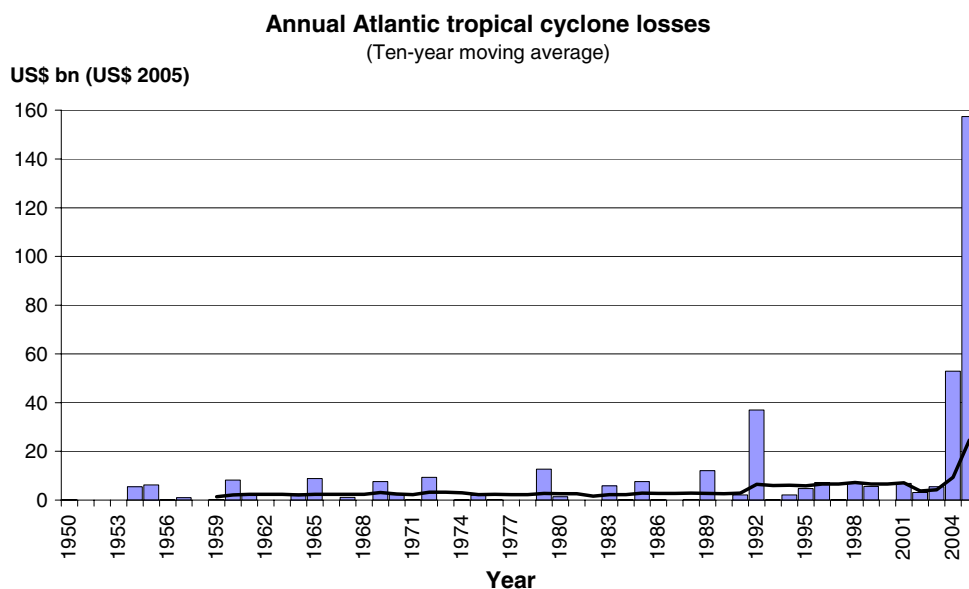
S. Schmidt (✉)  
Humboldt-Universität zu Berlin,  
c/o Munich Reinsurance Company,  
Königinstr. 107, 80802 Munich, Germany  
e-mail: sischmidt@munichre.com

C. Kemfert  
German Institute for Economic Research (DIW Berlin),  
Mohrenstr. 58, 10117 Berlin, Germany  
e-mail: ckemfert@diw.de

P. Höppe  
Munich Reinsurance Company, Königinstr. 107,  
80802 Munich, Germany  
e-mail: phoeppe@munichre.com

<sup>1</sup> The term “tropical cyclone” is used to designate storms with wind speeds of more than 63 km/h that form over the sea in the Tropics. Depending on the region, they may be referred to as typhoons in the northwest Pacific, cyclones in the Indian Ocean and Australia, and hurricanes in the Atlantic and northeast Pacific.

**Fig. 1** Annual losses recorded in NatCatSERVICE<sup>®</sup> caused by Atlantic tropical cyclones that made landfall in the USA in inflation-adjusted US\$ bn (2005 values). The figures only relate to windstorm and storm surge losses (source: authors)



we use the term “climate change” as defined by the IPCC in its Fourth Assessment Report, i.e. “Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity” (IPCC 2007b, p. 871). We do not see ourselves being in a position to make quantitative statements about the separate effects of natural climate variability and human activity. According to Höppe and Pielke (2006), this question is unlikely to be settled unequivocally in the near future. Nevertheless, the impact that climate change as a whole (due to both natural and anthropogenic forcings) has on loss trends is still worth looking at in more detail. Our interest focuses on distinguishing between the signal due to socio-economic changes and the signal due to climate-related storm intensity from storm losses. This will help to understand better what is behind the observed increase in economic losses due to tropical cyclones.

The literature on the current role of climate change and of socio-economic development in US cyclone losses adopts a variety of approaches, but one problem common to all of them is the difficulty in obtaining valid quantitative results. According to Höppe and Pielke (2006), this is primarily due to the stochastic nature of weather extremes, the relative shortness and, in some cases, inferior data-quality of the available time series, and the parallel impact of socio-economic and climate-related factors on the loss data. These are the issues that have resulted in this paper, which adopts a new approach and compares the resulting findings with those of other studies. In this way, it provides further insight into the effects of climate change on US storm losses.

Pielke et al. (2008) adopts a landmark approach in which the losses are adjusted to remove the effects of inflation, population growth and increased wealth. The approach utilises the concept of “normalised hurricane

damages” first presented in Pielke and Landsea (1998). The authors conclude that there are no long-term trends in normalised losses. We expanded on the Pielke et al. (2008) approach in Schmidt et al. (2008), and noted a positive short-term trend for the period 1971–2005 that can at least be interpreted as a climate variability impact.<sup>2</sup> Based on this, we advanced the premise that, if the losses are affected by natural climate fluctuations, they are also likely to be affected by additional global warming due to anthropogenic climate change.

This paper uses another relevant approach in the literature, presented in Nordhaus (2006), to devise a method (as mentioned above) for investigating how sensitive the losses are to socio-economic and climate changes. Nordhaus depicts cyclone losses in function of intensity and society’s vulnerability to cyclones. Accordingly, the more intense the destructive force of the storm and the greater society’s vulnerability to disasters, the higher the losses. In his analysis, Nordhaus adjusts the loss data to remove the increase in exposed values due to economic growth, by depicting nominal storm losses in relation to US nominal gross domestic product (GDP) in the year of windstorm occurrence.<sup>3</sup> Nordhaus uses an econometric model to investigate the extent to which the adjusted losses are affected by maximum wind speed and time, wind speed representing storm intensity and time, vulnerability. The findings indicate that adjusted windstorm losses are highly responsive to changes in maximum wind speed.

<sup>2</sup> This short-term trend for the period 1971–2005 is confirmed by applying the dataset in Pielke et al. (2008).

<sup>3</sup> The dataset in Nordhaus (2006) is statistically identical to that produced by Pielke et al. (2008) for the time period the two datasets overlap.

The approach in this paper is to express storm loss as a function of the value of material assets (capital stock) in the region affected, and the intensity with which those assets are impacted by the storm. Unlike Nordhaus (2006), we incorporate the socio-economic factor directly in the loss function in the form of increased wealth based on material assets. This avoids the need to exclude socio-economic factors from the loss data. A comparable approach is described in Sachs (2007), which applies a loss function comprising wind speed, population, and per capita wealth.<sup>4</sup>

The section “**Method**” first derives the loss function representing the assumed link, storm losses being a function of the capital stock affected and the intensity with which that stock is impacted. The section “**Data**” describes the necessary data and the data sources. The results of the loss function estimate are presented in section Results. They are subsequently discussed, and the past evolution of socio-economics and climate-related factors considered. Conclusions are then drawn as to the degree to which socio-economic and climate-related developments have contributed to the increase in losses. The paper also discusses various approaches to the role of climate change in tropical cyclone losses, and concludes with an appraisal of the results from an insurance industry perspective.

## Method

Our basic premise is that a storm loss can be expressed as a function of socio-economic and climate-related factors. Specifically, we assume that the economic loss can be calculated from the value of the material assets (capital stock) in the region affected by the storm and the intensity with which the storm impacts those assets. The capital stock variable represents the socio-economic components. The wind speed at landfall variable represents the intensity or climate-induced components.<sup>5</sup>

<sup>4</sup> Sachs also analyses US tropical cyclone losses. However, the paper does not clearly indicate on what loss data it was based and from what source they were taken.

<sup>5</sup> There are indications that the intensity of tropical cyclones is affected by climate change. The destructive force of tropical cyclones has been increasing globally since the mid-1970s. This correlates very closely with the sea surface temperature (SST) (cf. IPCC 2007a; Emanuel 2005; Webster et al. 2005). According to Barnett et al. (2005) there is also a correlation between SST and anthropogenic greenhouse gas emissions. The SST is not the only factor that influences intensity, however. It is possible that other factors are even more important, e.g. wind shear (cf. Knutson and Tuleya 2004; Bengtsson et al. 2007; Emanuel et al. 2008). Climate change has an impact on various parameters like ocean temperature, atmosphere, circulation, and water vapour, and hence influences tropical storms. The processes involved are complex and not yet completely understood (cf. Wang and Lee 2008).

We do not include population since it has only an indirect effect on economic losses caused by storm. Generally, the higher the population, the greater the quantity of material assets and thus, indirectly, the higher the losses. This factor is reflected in the loss function in the form of capital stock. On the other hand, loss of life, labour shortages, lower earnings and other factors directly linked to population, are not normally included in economic losses (refer to the section on data and data sources).

In fact, a number of other factors are involved such as vulnerability of assets to storm damage, surface topography, wind profile and effectiveness of disaster-prevention measures. However, in the absence of sufficient data to quantify them, we have taken the simplified view that total asset value and wind speed only are relevant (see also Sachs 2007).

This fundamental premise can be expressed by the following mathematical formula:

$$\text{Loss}_j = f(\text{Capital\_stock}_j, \text{Wind\_speed}_j),$$

$j$  being the windstorm event. (1)

The normal loss function in which storm loss is a power function of wind speed [loss =  $xW^n$ ;  $W$  = wind speed (cf. Howard et al. 1972)] is thus extended to include a capital stock index. Thus, the loss function to be estimated is:

$$\text{Loss}_j = \beta_1 * \text{Capital\_stock\_index}_j^{\beta_2} * \text{Wind\_speed}_j^{\beta_3} \quad (2)$$

We use the Levenberg–Marquardt algorithm to estimate this non-linear loss function.<sup>6</sup>

## Data<sup>7</sup>

The data required for the loss function are: capital stock affected, wind speed at landfall and resulting loss. To determine the capital stock affected, we first have to define the region concerned. By our definition, the region affected by the storm comprises all US counties where the storm caused substantial losses. This can be ascertained from the wind field, which defines the areal extent of the storm, i.e. the area in which a specific wind speed has been exceeded. For our purposes, the wind field includes all counties in which the storm was still classified as a tropical storm, i.e., where wind speeds were at least 63 km/h. Heavy losses can occur above this limit. The wind fields are based on the storm track dataset provided by the National Oceanic and Atmospheric Administration (cf. NOAA Coastal Services Center, <http://maps.csc.noaa.gov/hurricanes/download.html>, download 12.01.2007).

<sup>6</sup> A detailed explanation of the variables and parameters can be found in Table 1.

<sup>7</sup> This chapter largely corresponds to our comments on the Schmidt et al. (2008) data and data sources.

**Table 1** Estimation results of the storm loss function (source: authors)

Dependent variable: losses due to wind	Model 1	Model 2
Constant	9.36E−09 (0.000)	2.32E−05 (0.000)
Capital stock index	0.515 (0.205)	0.441 (0.097)
Wind speed	4.394 (1.126)	2.797 (0.559)
<i>N</i>	130 <sup>a</sup>	127 <sup>a,b</sup>
<i>R</i> <sup>2</sup>	0.188	0.307

Standard error in brackets

Model 2, applied to the storm events of the dataset, produces an average estimated loss per windstorm of US\$ 1,455.7 m (2005 values). The average observed loss was US\$ 1,424.4 m (2005 values). The outliers Andrew 1992, Charley 2004 and Katrina 2005 have not been included. These outliers have been included in model 1. The coefficient of determination ( $R^2$ ) however is lower and model 1 produces an average estimated loss per windstorm of US\$ 2,583 m (2005 values), higher than the average observed loss

The Levenberg–Marquardt algorithm estimates are based on the following loss function:  $Loss_j = \beta_1 * Capital\_stock\_index_j^{\beta_2} * Wind\_speed_j^{\beta_3}$ .  $Loss_j$  being material damage directly caused by Storm  $j$  as a result of storm surge and/or wind. Flood losses are not included. Losses to offshore facilities and major installations have also been subtracted from the loss. The loss is shown in inflation-adjusted US\$ (2005 values).  $Capital\_stock\_index_j$  is a proxy for the inflation-adjusted value of all material assets (2005 values) in the region affected by the storm.  $Wind\_speed_j$  is the maximum wind speed of Storm  $j$  at landfall in knots. Parameter  $\beta_1$  is a constant. Parameters  $\beta_2$  and  $\beta_3$  indicate how much the loss changes if the capital stock index or wind speed change by one unit (elasticity)

<sup>a</sup> Excluding Chantal 1989 (loss due to wind = 0, flood losses only)

<sup>b</sup> Excluding outliers Andrew 1992; Charley 2004; Katrina 2005 (losses more than 1.5 times SD from mean)

To ascertain the capital stock of the relevant counties, we use a geographic information system (GIS), combining the wind field with a map of the counties. The map indicates the amount of capital stock in the individual counties in the year of storm occurrence. The amount of capital stock is given in inflation-adjusted US\$ (at 2005 values).

Annual estimates of US capital stock are presented in the form of national figures for fixed assets and consumer durable goods. However, details of fixed assets and consumer durables are not available for individual states and counties (according to a written reply from the Bureau of Economic Analysis dated 23 August 2006). We have accordingly estimated capital stock time series for the individual counties and entered them in a database comprising all the counties located in the area affected by North Atlantic cyclones. Capital stock details for the 1,756 counties are available for the period 1950–2005. It has been estimated by taking the number of housing units and the median home inflation-adjusted value in US\$ (at 2005 values).

Accordingly, the capital stock affected by storm  $j$  in year  $y$  is determined as follows:

$$Capital\_stock\_index_j = \sum_{i=1}^I \left( (residential\_units\_in\_counties\_beneath\_wind\_field_j)_{y,i} \cdot median\_value_{y,i} \right) \quad (3)$$

Index  $i$  represents the states affected by storm  $j$ .

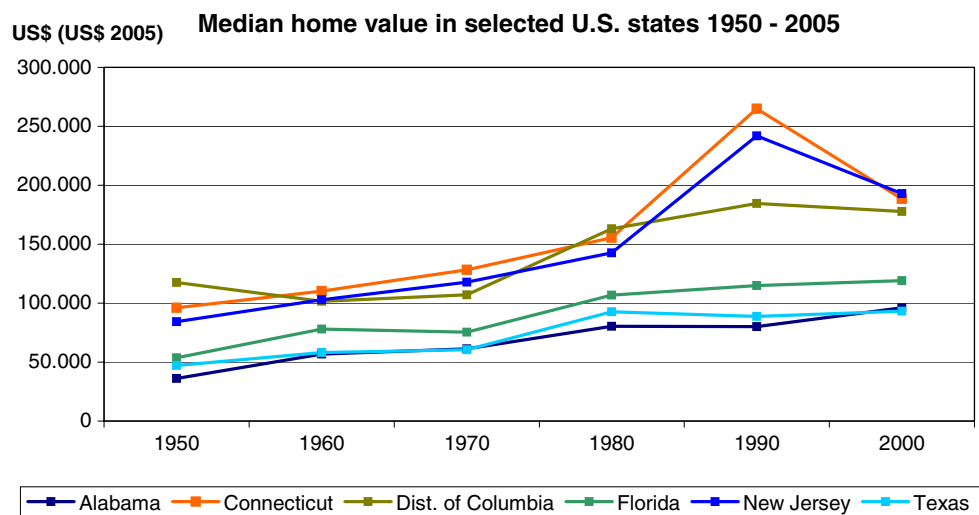
The concept of “residential unit” as a statistical factor comprises houses, apartments, mobile homes, groups of and

individual rooms used as accommodation. Relevant county data are available from the US Census (cf. Bureau of the Census 1993, and US Census, Census 2000 Summary File 3, download 27.07.2007). No data are available on average residential unit value, which has therefore been calculated from median home value data available for each US state from US Census (cf. US Census, Historical Census of Housing Tables, <http://www.census.gov/hhes/www/housing/census/historic/values.html>, download 27.07.2007). Both factors, residential unit and median home value, are surveyed every 10 years in the US Census. Data for the intervening years have been generated by linear interpolation. The figures for the period 2001–2005 we have extrapolated.

One drawback encountered when using capital stock as a loss function factor is that storm losses are largely made up of building repair costs. Whilst buildings may be completely destroyed in some cases, most losses involve repairs, the loss amount depending more on the cost of materials and labour than on property prices. Capital stock is used because of a lack of data and to reduce complexity in the loss function.

A further drawback when using the capital stock factor is that the calculations are based only on price and number of residential units, neither asset values within those units nor infrastructure and industrial and office premises being taken into account. In addition, median home value also includes the land value, which can represent a large fraction of the total selling value. As a result, the capital stock figures used are just a proxy for total capital stock. Actual figures of total capital stock in the USA would be higher. Therefore, we call this proxy a capital stock index.

**Fig. 2** The level of wealth varies from one US state to another. This can be seen from the example of the median home value in inflation-adjusted US\$ (2005 values). (Data source of nominal average values: US Census, <http://www.census.gov/hhes/www/housing/census/historic/values.html>, download 27.7.07; chart: authors)



Pielke et al. (2008) uses an alternative method for estimating affected capital stock. Affected capital stock is ascertained from the population of the most affected coastal counties and national per capita capital stock. National per capita capital stock can be determined from the national estimates of fixed assets and consumer durables referred to above. However, since this parameter is based on national figures, it assumes that wealth is evenly distributed throughout the USA, which is debatable given the different prosperity levels of the individual states. This point is illustrated, for example, by variations observed between the median home value in the different states (see Fig. 2). Pielke et al. (2008) also use housing units in affected coastal counties instead of population and find no significant differences between using housing units and population.

Another approach could be to use only the losses to residential units instead of total economic losses. This would correspond more with the capital stock approximation used here. Unfortunately, no data are available on losses to housing units only.

Despite these shortcomings, we believe the total residential unit value used is a reasonable approximation of regional capital stock, particularly since data is in limited supply and this method allows regional wealth differences to be taken into account.

The second loss function factor is the intensity with which the storm impacts the capital stock, and for this we use wind speed recorded at landfall. Over land areas, tropical cyclones generally reach peak intensity at landfall, after which, cut off from their energy source, they gradually weaken as they move inland.

The storm therefore impacts the capital stock of different counties with varying intensities, those further inland normally being exposed to lower wind speeds. For

simplification purposes, we apply wind speed at landfall to the affected region as a whole. This simplification is to be criticised. Although regional wind speed data are available, there is no information on regional losses. This makes it impossible to break losses down by wind speed and is the reason for our assumption of a uniform wind speed. The wind speed data are taken from the Historical Hurricane Tracks supplied by the National Oceanic and Atmospheric Administration (cf. NOAA Coastal Services Center, <http://hurricane.csc.noaa.gov/hurricanes/>, various searches).

The third loss function factor is the economic loss caused by the storm. Natural catastrophe loss estimates are undertaken by a wide variety of institutions, such as the UN, national authorities, aid agencies like the Red Cross, and of course insurance companies. Each has its own method of evaluating losses and there is no standard procedure. Loss assessments therefore vary according to source and are not entirely comparable. Downton and Pielke (2005) note that the accuracy of loss assessments increases proportional to the scale of the event (for reliability of loss estimates, see Downton and Pielke 2005; Pielke et al. 2006).

Economic losses are understood here to be losses to material assets as an immediate consequence of the storm. Intangible losses and indirect consequences are not included. Losses thus relate to residential, industrial and office buildings, infrastructure, building contents and moveable property in the open, e.g. vehicles are included but indirect losses are not. The latter would include, for instance, higher oil prices caused by the suspension of drilling activities in the Gulf of Mexico or more long-term effects such as increased insurance premiums. On the other hand, since prices tend to be driven up after natural catastrophes by a surge in demand for construction and repair services, these are included in the loss data. This is because the loss

estimates are largely based on the cost of reinstating destroyed items.<sup>8</sup> Our economic loss calculations are based on the figures obtained from Munich Re's NatCatSERVICE<sup>®</sup> database.

Founded in 1974, NatCatSERVICE<sup>®</sup> is now one of the most comprehensive databases of global natural catastrophe losses in existence. Every year, some 800 events are entered into the database, which now contains more than 25,000 entries, including all great natural catastrophes of the past 2,000 years and all loss events since 1980.<sup>9</sup> Direct material losses and corresponding insured losses are recorded for each catastrophe. Loss assessments are based, according to availability, on well-documented official estimates, insurance claim payments, comparable catastrophe events and other parameters. The data are obtained from more than 200 different sources. They are observed over a period of time, documented, compared and subjected to plausibility checks. Individual loss data, estimates for the event as a whole, long-term experience and site inspections are used to produce well-documented, clearly substantiated loss figures, which are then entered in the NatCatSERVICE<sup>®</sup> database (cf. Faust et al. 2006; Munich Re Company 2001, 2006). Information provided by the Property Claims Service (PCS) is a key element of the NatCatSERVICE<sup>®</sup> estimates of insured tropical cyclone losses in the USA.

The NatCatSERVICE<sup>®</sup> loss estimates also include losses at big industrial plants and offshore installations, examples being large factories, airports and oil rigs. However, the capital stock figures used in this paper relate only to the total value of the residential units in the counties affected, and exclude large industrial plants and offshore installations. Therefore, as far as possible, losses at large and offshore installations have been deducted from the estimated loss. NatCatSERVICE<sup>®</sup> provides this loss information for many cases of large industrial plants and offshore installations. Unfortunately, the database does not provide this loss information for smaller factories and installations. Therefore, these losses can not be deducted from the estimated loss because they are not taken into account in our capital stock index.

The NatCatSERVICE<sup>®</sup> estimates also include windstorm and storm surge losses, and flood caused by rainfall accompanying the storm. However, since Eq. (1) assumes the loss to be a function of wind speed and affected capital

stock only, flood losses have, as far as possible, been subtracted from the estimated losses. Information on flood losses is also taken from NatCatSERVICE<sup>®</sup> if available or from the National Flood Insurance Program (NFIP).<sup>10</sup>

Our dataset comprises 113 North Atlantic storms that made landfall in the USA during the period 1950–2005. Storms that made landfall several times, i.e. where the storm returned to the open sea after initial landfall, and subsequently made two or three landfalls, have been divided into their constituent events. This reflects the fact that their condition changes as they draw fresh energy from the warm sea surface. Consequently, the dataset comprises 131 storm events in all, the overall loss in the case of multiple-landfall storms being divided among the individual occurrences.<sup>11</sup> Capital stock index in the counties affected, wind speed at landfall and windstorm and storm surge losses are available for each storm event.

## Results

The following equation appears in the section describing the method:

$$\text{Loss}_j = \beta_1 * \text{Capital\_stock\_index}_j^{\beta_2} * \text{Wind\_speed}_j^{\beta_3} \quad (4)$$

The regression parameter values estimated for this equation are:

$$\beta_1 = 0.0000232$$

$$\beta_2 = 0.441$$

$$\beta_3 = 2.797$$

Regression parameter  $\beta_1$  gives the value of the constants. Parameters  $\beta_2$  and  $\beta_3$  indicate by how much the loss changes if *capital stock index* or *wind speed* increase or decrease by one unit,  $\beta_2$  showing loss elasticity relative to changes in capital stock index and  $\beta_3$  loss elasticity relative to changes in intensity (in this case, wind speed). According to coefficient of determination  $R^2$ , the estimated

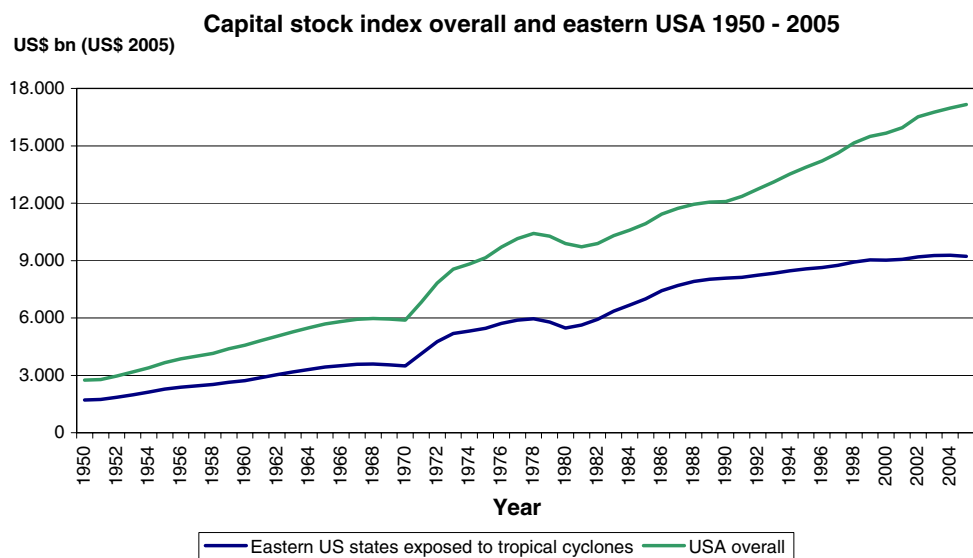
<sup>8</sup> Examples illustrating estimation of aggregate direct and indirect economic losses can be found in Hallegatte (2008) and Kemfert (2007).

<sup>9</sup> A natural catastrophe is considered “great” if fatalities are in the thousands, numbers of homeless in the hundreds of thousands or material losses on an exceptional scale given the economic circumstances of the economy concerned (cf. Munich Re Company 2007, p. 46).

<sup>10</sup> The NFIP provides data about insured losses due to flood. For the purpose of considering flooding losses in the estimated overall losses, we first subtracted the insured losses according to NFIP from the insured losses in NatCatSERVICE<sup>®</sup>. Then we reduced the estimated overall losses by the same proportion.

<sup>11</sup> The breakdown was carried out by determining the region affected by each landfall. The proportion of overall losses for each region affected was based on the aggregate and regional losses reported by the Property Claims Service (cf. PCS, <https://www4.iso.com/pcs>, download 14.03.2007). The overall loss figures from NatCatSERVICE<sup>®</sup> were split in the same proportions. NatCatSERVICE<sup>®</sup> itself only has aggregate storm loss details. We were not able to apportion the figures for some storms, for instance if storms that made landfall twice in the same state or if the loss was below the threshold at which storms are recorded in PCS catastrophe history.

**Fig. 3** Capital stock evolution in the US states exposed to Atlantic tropical cyclones and overall US capital stock during the period 1950–2005, in inflation-adjusted US\$ bn (2005 values). Estimated capital stock index is based on the US Census of the number of housing units in the counties and the median home value in the relevant state (source: authors)



function can account for 31% of the variance in the dependable variable *loss*.<sup>12</sup>

The regression results can be interpreted as follows: whereas a 1% increase in capital stock index in the region affected by the storm produces a 0.44% increase in loss, a 1% increase in wind speed produces a 2.8% increase. In other words, storm loss is far more elastic in respect of changes in wind speed than changes in capital stock index. To determine the historical impact of climate-related changes and socio-economics, we need to consider the extent of climate-related and socio-economic changes in the past.

Taking inflation into account, capital stock index in the states exposed to Atlantic tropical cyclones increased by an average of 3.1% per annum in the period 1950–2005. The increase for the period as a whole is 438% (see Fig. 3). Concerning equation (2), the climate-related changes in the past should be measured by average annual maximum wind speed at landfall. Our dataset contains data on wind speed at landfall for just 131 storm events. That is not enough to obtain a valid average annual maximum wind speed at landfall. For many years there are records of just one or two storm events and for a few years the dataset does not contain a single event. For this reason, the development of storm intensity is calculated from the accumulated cyclone energy (ACE) of all Atlantic basin storms for a given year. The ACE is an index of storm lifetime and intensity combined. It is derived from the sum of the squares of estimated maximum sustained velocity at six-hourly intervals and shown in units of  $10^4 \text{ kt}^2$  (cf. Atlantic Oceanographic and Meteorological Laboratory (AOML), <http://www.aoml.noaa.gov/hrd/tcfaq/E11.html>, download 10.10.2008).<sup>13</sup> To be consistent with Eq. (2), we used the

square root of ACE.<sup>14</sup> During the period 1950–2005, storm intensity increased by 27% in absolute terms (see Fig. 4).

Unlike the absolute growth in the capital stock index, however, restrictions are to be made regarding the robustness of the increase in storm intensity. There are two reasons for this: the high variability of the ACE and the high sensitivity of the growth rate in terms of the selected start and end points. In order to keep these influences low, we have used the average per phase of the Atlantic Multidecadal Oscillation.<sup>15</sup> The 27% is therefore to be seen as the increase from the average intensity of the last “warm phase” (1926–1970) to the average intensity of the current “warm phase” (since 1995).<sup>16</sup> Figure 4 shows that since 1870 windstorm intensity has increased from each “warm phase” to the next with the exception of the two phases between 1886 and 1897. The increase in storm intensity is 0.4–5% in each case. The 27% increase in the current “warm phase” is therefore well above the long-term average. Whether this is a sign of a change in the long-term trend is uncertain because the increase will be influenced by the further development of the on-going “warm phase”.

<sup>13</sup> 1 kt = 1.852 km/h.

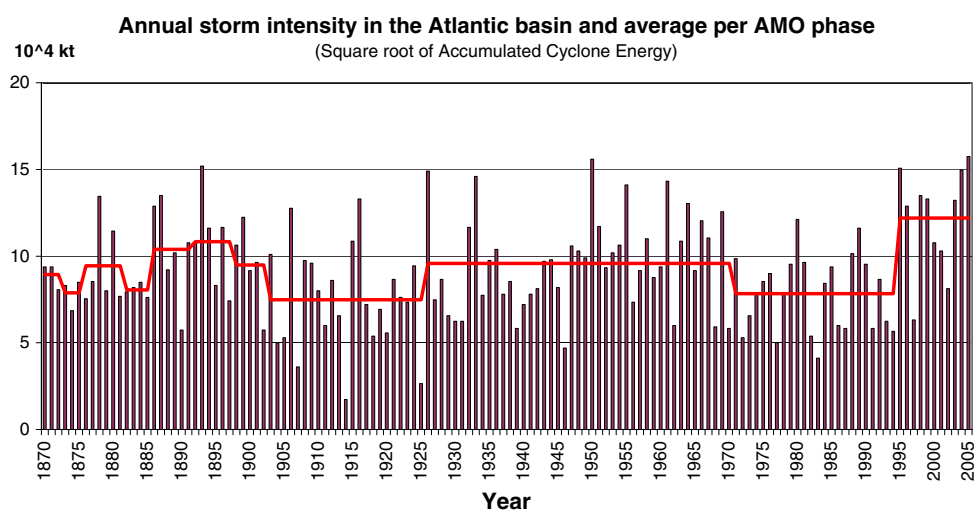
<sup>14</sup> Thanks to an anonymous reviewer for the recommendation to use the square root of ACE instead of ACE.

<sup>15</sup> Sea surface temperatures in the North Atlantic fluctuate due to the Atlantic Multidecadal Oscillation (AMO), referred to either as a “cold phase” or a “warm phase”, depending on the deviation from the long-term average. Warmer phases cause greater tropical storm activity (cf. Emanuel 2005; Webster et al. 2005). The terms “cold phase” and “warm phase” are contested among tropical cyclone experts (cf. Goldenberg et al. 2001; Zhang and Delworth 2006; Kossin and Vimont 2007; Mann and Emanuel 2006). Among those positing an AMO influence the beginning of the last “cold phase” is under discussion. We refer to Goldenberg et al. 2001 taking 1971 as the beginning.

<sup>16</sup> Allocation of phases according to Goldenberg et al. (2001).

<sup>12</sup> Regression analysis details are shown in Table 1.

**Fig. 4** Evolution of annual tropical cyclone intensity in the period 1950–2005. The chart features all storm systems in the Atlantic basin, i.e. including those which did not make landfall (data source of ACE: Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA), <http://www.aoml.noaa.gov/hrd/tcfaq/E11.html>, download 10.10.08; allocation of phases according to Goldenberg et al. 2001; chart: authors)



**Table 2** Growth of Atlantic tropical cyclone intensity (measured in square root of Accumulated Cyclone Energy) (source: authors)

From	To	Growth (%)
1870–1872	1995–2005	36.4
<b>1926–1970</b>	<b>1995–2005</b>	<b>27.5</b>
1870–1872	1876–1881	5.6
1876–1881	1886–1891	9.9
1896–1891	1898–1902	−8.7
1876–1881	1898–1902	0.4
1898–1902	1926–1970	0.9
1870–1872	1926–1970	7.0
1870–1872	1995–2007	30.4
1926–1970	1995–2007	21.8

The growth is calculated on the basis of the square root of average ACE during the AMO phase. The table includes only so-called “warm phases” (data source of Accumulated Cyclone Energy: Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA), <http://www.aoml.noaa.gov/hrd/tcfaq/E11.html>, download 10.10.08; allocation of phases according to Goldenberg et al. 2001)

This becomes apparent if the 2 years 2006 and 2007 are also taken into consideration. The average level of storm intensity of the current “warm phase” drops. Accordingly, the increase in storm intensity between the average of the last “warm phase” and the current “warm phase” drops to 22% (see Table 2).

Given an inflation-adjusted increase in capital stock index of 438% in the region investigated, and loss elasticity of 0.44 in response to a 1% change in capital stock index, it can be inferred that the loss increase due to the rise in capital stock index since 1950 was approx. 190%. Although storm intensity increased by only 27%, loss elasticity in response to a 1% change in intensity is as much as 2.8. It can therefore be concluded that the increase in

losses due to greater annual storm intensity was 75%. This result depends very heavily, however, on how the intensity of the current “warm phase” develops. If the long-term increase in storm intensity of 0.4–5% in the observation period 1950–2005 is taken as a basis, it is found that losses have increased by only 1.4–14% as a result of the change in storm intensity. That is to say, the change in socio-economic conditions has a lower specific impact on the losses than the change in storm intensity. However, the loss trend is dominated by socio-economic conditions insofar as they changed much more than (climate-change induced) storm intensity during the investigation period.

## Discussion

Socio-economic developments and the impact of climate change are considered to be the primary causes of the higher tropical cyclone losses observed in the USA. Socio-economic changes largely account for the loss evolution of both tropical cyclones in the USA and weather-related natural catastrophes in general, the main reasons for this being increased wealth and greater settlement of exposed areas (cf. IPCC 2007b), as confirmed by our results. On the other hand, the conclusions about the role of natural and anthropogenic climate change are less clear-cut. Our aim is therefore to develop our own approaches based on relevant papers taken from the literature and then compare the results with those in the literature and with each another. In this way, we will provide an additional component for determining the effects of climate change on US storm losses. The approach presented in this paper is based on Nordhaus (2006). To begin with, therefore, we will compare the results obtained using our method with the Nordhaus (2006) results.



Nordhaus depicts cyclone losses as a function of wind speed and society's vulnerability to cyclones, the analysis being based on loss data from which the increase in wealth has been subtracted. Instead of deducting increases in wealth from the losses, as is the case with Nordhaus, with our approach the impact such increases have on storm losses is included in the function. Thus, we can draw conclusions about the extent to which the historical loss development is due to increased wealth. Like Schmidt et al. (2008), we base changes in wealth on changes in the material assets exposed to storm (affected capital stock).

According to Nordhaus (2006), wind speed loss elasticity is 7.3, i.e. much higher than that indicated by our study and others. However, Nordhaus believes this also underestimates the true position, and suggests that 8 is more realistic.<sup>17</sup> Pielke (2007) states that elasticity is 3–9, a range based on the results of a number of studies. According to our calculations, elasticity is no more than 2.8 if capital stock is also included in the loss function and losses due to flood are not taken into account. This does not, however, apply to the papers cited in Pielke (2007) and Nordhaus (2006).

It is therefore not possible to draw a direct comparison between our conclusions on elasticity and those of Nordhaus (2006). We therefore applied the Nordhaus (2006) method once more to our data in order to establish the reasons for the differences in elasticity. Whilst Nordhaus uses 142 storms from the period 1851–2005,<sup>18</sup> our data are available only from 1950. To be able to work with a comparable investigation period, we use Nordhaus' data from the period 1950–2005 only, leaving a total of 90 storms. The wind speed regression parameter obtained from these 90 windstorms is 7.2, an elasticity result very close to that of 7.3 obtained in Nordhaus (2006) using the complete dataset of 142 storms.<sup>19</sup> The number of 90 storms recorded in the Nordhaus dataset for the period 1950–2005 is considerably lower than the number of 113 storms recorded in NatCatSERVICE<sup>®</sup> over the same period, one reason for this being that Nordhaus (2006) does not include less severe storms but only those with wind speeds at or above hurricane force.

To apply the Nordhaus method to our data, we first had to base the individual storm losses on nominal GDP in the US in the year of the storm in order to remove the effects of economic growth and inflation. When we adjust our loss

data in this way, the result obtained for loss elasticity to wind speed change is 4.6.<sup>20</sup> This is still far lower than the Nordhaus (2006) result.

The datasets are not consistent. There are differences in the storms recorded and, to some extent, in the individual storm data.<sup>21</sup> A comparison of the loss data and wind speeds for the 78 storms recorded in both datasets reveals no major deviations. The mean loss in million US\$ is 4,094.8 applying the Nordhaus dataset and 4,825.1 applying the data from NatCatSERVICE<sup>®</sup>. Mean wind speed recorded is 173.3 and 169.5 km/h, respectively. If we include only the 78 storms recorded in both datasets, the loss elasticity to wind speed change is 6.1 for the Nordhaus dataset and 5.0 for the NatCatSERVICE<sup>®</sup> dataset.<sup>22</sup>

Although the differences in the averages of the two datasets are only minor, they appear to have a distinct impact on the regression result. The sometimes large differences in the case of individual storms are likely to be significant. In line with the mean values, the dataset in Nordhaus (2006) reveals on average lower losses at higher wind speeds. Consequently, loss elasticity to wind speed is affected by the structure of the underlying dataset.

Despite the fact that Nordhaus (2006) does not analyse the role of capital stock loss elasticity, it is necessary to discuss our result in terms of this elasticity. The fact that loss elasticity relative to changes in the capital stock index is lower than one can be interpreted to mean that housing quality is correlated with capital stock. New capital (new housing units) seems to be of better quality and is more resilient to storms.

Nevertheless, the elasticity seems to be quite low. One reason for this could be that as a rule the capital stock index increases along with the size of the region affected. A justified objection is that we assume the same wind speed, i.e. the same loss intensity, for the entire region affected. This may have influenced our estimate in the following way: One windstorm that rapidly lost intensity after landfall only affected a small region. The same year, another storm that reached far inland because its intensity

<sup>17</sup> Nordhaus bases this on the following: wind speed is not the only factor involved; possible statistical errors in measuring wind speed, correlation of wind speed and omitted variables and the different extent to which the losses depend on building structure (cf. Nordhaus 2006).

<sup>18</sup> Nordhaus' dataset for the period 1851–2005 comprises 281 storms, but includes 139 storms without any information on damage.

<sup>19</sup> Table 3 shows the regression results in detail.

<sup>20</sup> Details of the regression analysis are shown in Table 4. In our data, we divided storms that made landfall more than once into separate storm events. As Nordhaus does not make this distinction, for comparison purposes, we have not divided the storms into separate events, when we apply the Nordhaus method to our data.

<sup>21</sup> Twelve of the Nordhaus (2006) storms for the period 1950–2005 are not registered in NatCatSERVICE<sup>®</sup>, whilst NatCatSERVICE<sup>®</sup> includes 35 storms not recorded in Nordhaus (2006).

<sup>22</sup> If Hurricane Katrina is excluded, because there is a large difference in estimated loss between the datasets (81 bn US\$ and 125 bn US\$), the mean estimated loss is 3,096.0 million US\$ and 3,264.4 million US\$, respectively. Mean wind speed is 173.0 km/h, respectively, 168.5 km/h. Loss elasticity to wind speed change is 5.9 (data from Nordhaus' dataset) and 4.8 (data from NatCatSERVICE<sup>®</sup>). Table 5 show the regression results in detail.

**Table 3** Reproducing the Nordhaus (2006) results (source: authors)

Dependent variable: $\ln(\text{loss}/\text{GDP})$	Model 1	Model 2
Constant	-100.7*** (15.58)	-107.9*** (25.22)
$\ln(\text{wind speed})$	7.300*** (0.8605)	7.214*** (0.9877)
Year	0.02933*** (0.007249)	0.03317*** (0.01226)
$N$	142	90
$R^2$	0.3557	0.3941

Model 1 includes all data for the period 1851–2005 (as in Nordhaus, 2006)

Model 2 is confined to data for the period 1950–2005

Standard error in brackets

Model 1 reproduces the Nordhaus (2006) results. Model 2 is confined to storms during the period 1950–2005 to allow comparison with the NatCatSERVICE® data. The estimates using the ordinary least squares method are based on the loss intensity function and data from Nordhaus (2006):  $\ln(\text{Loss}_{jy}/\text{GDP}_y) = \alpha + \beta \ln(\text{Wind\_speed}_{jy}) + \delta \text{Year}_y + \varepsilon_{jy}$

$\text{Loss}_{jy}$  being the loss caused by Storm  $j$  in year  $y$  at actual prices.  $\text{Wind\_speed}_{jy}$  is maximum wind speed at landfall.  $\text{GDP}_y$  is US gross domestic product in year  $y$  at actual prices.  $\text{Year}_y$  is the year in which the storm occurred.  $\varepsilon_{jy}$  is the disturbance term

\* Significance with a significance level of 10%

\*\* Significance with a significance level of 5%

\*\*\* Significance with a significance level of 1%

**Table 4** Regression analysis results applying the loss intensity function from Nordhaus (2006) to the data from NatCatSERVICE® (source: authors)

Dependent variable: $\ln(\text{loss}/\text{GDP})$	Model 3
Constant	-24.94 (26.72)
$\ln(\text{wind speed})$	4.608*** (0.5943)
Year	-0.002578 (0.01306)
$N$	113
$R^2$	0.3738

Model 3 includes all storms for the period 1950–2005

Standard error in brackets

Model 3 estimates the Nordhaus (2006) intensity function using the ordinary least squares method. Losses are based on NatCatSERVICE® data for 113 storms during the period 1950–2005

\* Significance with a significance level of 10%

\*\* Significance with a significance level of 5%

\*\*\* Significance with a significance level of 1%

decreased slowly affected a much larger region. In both cases, the main losses occurred in the coastal counties. The second storm also caused further losses inland. With a much larger capital stock index, however, it goes down as the no. 1 Storm in the regression analysis. If the second storm had hit a capital stock that was 50% larger, it would have caused a loss that was larger 50%, too, based on our assumption of a constant wind speed throughout the region. In fact, however, the loss is less than 50% larger because in reality the wind speed decreases inland. This would probably lead to the loss elasticity relative to the capital stock index being lower in our calculation than it actually is. One

possible way of achieving a more accurate calculation of the elasticity would be to divide the individual storms by regions with different wind speeds and to apply the losses incurred in these regions. This would require loss data at county level, but these are not available. Another option would be to include only the coastal counties in the observation. As a rule, these are the counties where the maximum wind speed is in fact likely to be recorded at landfall. This approach means that all losses are attributed to the coastal counties, however. And here, too, there are no loss data available for extracting the actual losses in the coastal counties. As this means that the capital stock index is too small compared to the losses, the estimated elasticity would be too high.

Another approach compared here is described in Schmidt et al. (2008). Although the findings reported in this paper on the role of socio-economics and climate-related factors in the loss increase of recent decades differ somewhat from Schmidt et al. (2008), the assumption that climate-related changes positively influence losses is confirmed. In Schmidt et al. (2008) we used a method based on the “normalised hurricane damages” approach put forward by Pielke et al. (2008), and Pielke and Landsea (1998). Pielke et al. (2008) adjust the losses to remove the effects of inflation, population changes and per capita wealth. Normalisation is based on changes at the coast only. The authors conclude that there is no long-term trend in normalised losses. In Schmidt et al. (2008) we took this method a stage further and adjusted the losses to subtract increased wealth in terms of material assets. At the same time, changes in material assets (capital stock index) were based on all the counties affected by the storm, so that the

**Table 5** Regression analysis results applying the loss intensity function from Nordhaus (2006) to the 78 identical storms in the Nordhaus and the NatCatSERVICE® dataset (source: authors)

Dependent variable: ln (loss/GDP)	Model 4	Model 5
Constant	−36.76** (4.341)	−36.11** (4.306)
ln (wind speed)	6.082** (0.9605)	5.930** (0.9534)
<i>N</i>	78	77
<i>R</i> <sup>2</sup>	0.3368	0.3315
Dependent variable: ln (loss/GDP)	Model 6	Model 7
Constant	−31.86** (3.700)	−30.96** (3.703)
ln (wind speed)	5.042** (0.8245)	4.833** (0.8259)
<i>N</i>	78	77
<i>R</i> <sup>2</sup>	0.3210	0.3043

Model 4 and 6 include all storms for the period 1950–2005 recorded in both databases

Model 5 and 7 Katrina 2005 is excluded

Because *Year* is tested to be not significant it is not included

Standard error in brackets

\* Significance with a significance level of 10%

\*\* Significance with a significance level of 5%

\*\*\* Significance with a significance level of 1%

Model 4 and Model 5 estimates the Nordhaus (2006) intensity function using the ordinary least squares method. Losses are based on Nordhaus (2006) for 78 identical storms during the period 1950–2005 recorded in the NatCatSERVICE® too

Model 6 and Model 7 estimates the Nordhaus (2006) intensity function using the ordinary least squares method. Losses are based on NatCatSERVICE® for 78 identical storms during the period 1950–2005 recorded in Nordhaus (2006) too

different levels of wealth inland and between individual states were also taken into account.

The adjusted individual losses were then aggregated to show annual adjusted losses, and a time-series analysis performed. Any remaining trend in these adjusted losses cannot be ascribed to socio-economic developments. A positive but not significant trend was identified for the period 1950–2005. However, a positive, statistically significant trend was identified for the period from the start of the last “cold phase” (1971) until 2005.<sup>23</sup> Annual adjusted losses increased on average by 4% during this period compared with 5% for annual losses adjusted to exclude inflation but not greater wealth.<sup>24</sup> Due to large fluctuations in annual losses, the annual growth rates were calculated

on the basis of average annual loss in the respective phases of the Atlantic Multidecadal Oscillation. The current paper analyses the loss data using a different method. The technique used in Schmidt et al. (2008) allows us to draw indirect conclusions only about the impact of climate changes, the losses being adjusted solely to exclude increases in wealth (see Schmidt et al. 2008 regarding adjustment inaccuracies). Climate change is just one of a number of other factors that may impact losses. Changes in society’s vulnerability to storms, another factor not included in the adjustment and therefore still reflected in the loss data, can thus be assumed to have a bearing on any trend in the adjusted losses. The current paper does not use losses adjusted to reflect changes in wealth. Instead it establishes the sensitivity of storm losses to changes in socio-economics and climate-induced storm intensity, and the manner in which these factors have developed historically. The historical impact of socio-economics and climate-related change on the losses can then be deduced by combining relative loss change, based on a change in the relevant factor, with the change in those factors observed during past decades in absolute terms. Thus, instead of eliminating the influence of socio-economic factors, as was the case with Schmidt et al. (2008), we explicitly included them. Although shortcomings also have to be taken into account when interpreting the results obtained with the approach presented here, we believe it is a more apposite

<sup>23</sup> Sea surface temperatures in the North Atlantic fluctuate due to the Atlantic Multidecadal Oscillation (AMO), referred to either as a “cold phase” or a “warm phase”, depending on the deviation from the long-term average. Warmer phases cause greater tropical storm activity (cf. Emanuel 2005; Webster et al. 2005). The terms “cold phase” and “warm phase” are contested among tropical cyclone experts (cf. Goldenberg et al. 2001; Zhang and Delworth 2006; Kossin and Vimont 2007; Mann and Emanuel 2006). Among those positing an AMO influence the beginning of the last “cold phase” is under discussion. We refer to Goldenberg et al. 2001 taking 1971 as the beginning.

<sup>24</sup> Were one to look at the Pielke et al. (2008) dataset over the same period, the quantitative findings would be identical.

way of explaining the impact of socio-economics and climate-related change on US storm losses.

## Conclusion

The objective of this paper was to establish how sensitive tropical cyclone losses are to socio-economic and climate changes and how these factors have evolved in the last 50 years. Conclusions have been drawn about the part the factors play in the observed increase in losses. The results show that, historically, the increase in losses due to socio-economic changes was approximately three times higher than that due to climate-induced changes.

It should be noted when assessing the results of both this paper and Schmidt et al. (2008) that it is generally difficult to obtain valid quantitative findings about the role of socio-economics and climate change in loss increases. This is because of criteria such as the stochastic nature of weather extremes, a shortage of quality data, and the role of various other potential factors that act in parallel and interact. We therefore regard our results as being an indication only of the extent to which socio-economic and climate changes account for the increase in losses. Both studies confirm the consensus reached in May 2006 at the international workshop in Hohenkammer attended by leading experts on climate change and natural catastrophe losses (see Table 6).

**Table 6** Consensus and recommendations of the international workshop held at Hohenkammer in Germany on 25 and 26 May 2006 and attended by leading experts on climate change and natural catastrophe losses (source: Bouwer et al. 2007, supporting online material: [www.sciencemag.org/cgi/content/full/318/5851/753/DC1](http://www.sciencemag.org/cgi/content/full/318/5851/753/DC1))

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### *Consensus (unanimous) statements of the workshop participants*

1. Climate change is real, and has a significant human component related to greenhouse gases.
2. Direct economic losses of global disasters have increased in recent decades, with particularly large increases since the 1980s.
3. The increases in disaster losses primarily result from weather-related events, in particular storms and floods.
4. Climate change and variability are factors which influence disaster trends.
5. Although there are peer reviewed papers indicating storm and flood trends, there is still scientific debate over attribution to anthropogenic climate change or natural climate variability. There is also concern about geophysical data quality.
6. IPCC (2001) did not achieve detection and attribution of extreme event trends at global level.
7. High-quality, long-term disaster loss records exist, some of which are suitable for research purposes, such as identifying the effects of climate and/or climate change on loss records.
8. Analyses of long-term records of disaster losses indicate that societal change and economic development are the principal factors behind documented increasing losses to date.
9. The vulnerability of communities to natural disasters is determined by their economic development and other social characteristics.
10. There is evidence that the changing patterns of extreme events are drivers of recent increases in global losses.
11. Due to data-quality issues, the stochastic nature of extreme event impacts, the lengths of the time series, and various societal factors present in the disaster loss records, it is still not possible to determine what portion of the increase in damage may be due to climate changes caused by GHG emissions.
12. For future decades, the IPCC (2001) expects there to be increases in the frequency and/or intensity of some extreme events as a result of anthropogenic climate change. In the absence of disaster reduction measures, such increases will cause a further rise in losses.
13. The quantitative link (attribution) between storm/flood loss trends and GHG-induced climate changes is unlikely to be determined unequivocally in the near future.

### *Policy implications identified by the workshop participants*

14. Adaptation to extreme weather events should play a central role in reducing societal vulnerabilities to climate and climate change.
  15. Mitigation of GHG emissions should also play a central role in response to anthropogenic climate change, although it will have no effect on the hazard risk for several decades.
  16. We recommend further research on different combinations of adaptation and mitigation policy.
  17. We recommend the creation of an open source disaster catalogue of agreed standards.
  18. In addition to fundamental research on climate, research priorities should consider decision-makers' needs in terms of adaptation and mitigation.
  19. To better understand loss trends, there is an ongoing need to collect and improve the long-term (paleo) data and create homogenous climate and disaster-loss datasets.
  20. The community needs to agree on peer-reviewed procedures for normalising economic loss data.
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Seen from the insurance industry's perspective, the loss evolution and the principal factors influencing it can be summarised as follows: rising loss figures due to socio-economic developments do not generally cause problems for insurers, since the linear nature of the increase in premiums and sums insured (i.e. capital stock) ensures that the effective loss ratio remains constant. However, this does not apply to increases driven by storm intensity. To prevent rising loss ratios, the premium would have to be recalculated to take account of the changes in the underlying parameters. Without this, the insurer would face growing losses. We believe that this paper's findings on the role climate-related change plays in the increased losses confirms that insurance industry models should take this factor into account (see also Faust 2006).

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