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

Silvio Schmidt[a], **Claudia Kemfert**[b], **Peter Höppe**[c]

Abstract

Tropical cyclones that make landfall on the coast of the USA are causing increasing economic losses. It is assumed that the losses are 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. 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

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1 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),[1] 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 (cf. IPCC, 2007). 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 already believes it is more likely than not that tropical storm intensity has increased in some regions during recent decades. No definite pronouncement is made as to the proportion of losses that is now, or will in future, be attributable to climate change.

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 we use the term "climate change" with reference to the definition of the IPCC as in its Fourth Assessment Report. Therefore "Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity" (IPCC, 2007, p. 871). We do not see us in the position to make quantitative statements about the separate effects due to natural climate variability and caused by human activity. According to Höppe and Pielke Jr. (2006) this is unlikely to be determined unequivocally in the near future. But even the effect whole climate change (natural and anthropogenic caused) has on loss trends is worth to look on in more detail. We take an interest in to extract the signal due to socio-economic changes and the signal due to climate related storm intensity from the storm losses. This will help better to understand what are behind the observed increase in economic losses due to tropical cyclones.

The literature on the current role of climate change 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 Jr. (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 Jr. 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 Jr. and Landsea (1998). The authors find no evidence for long-term trends in normalized losses. We expanded on the Pielke Jr. et al. (2008) approach in Schmidt et al. (2008), and noted a positive trend for the period 1971–2005 that can at least be interpreted as a natural climate fluctuation impact.

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[1] 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.

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.

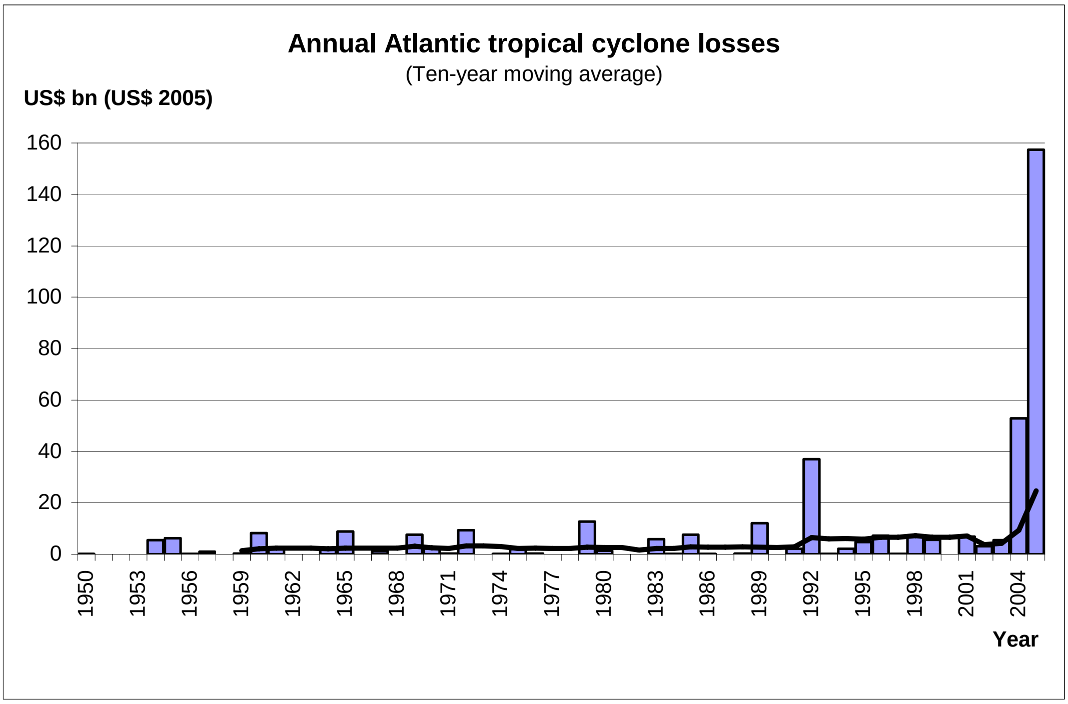

Figure 1: Annual losses recorded in NatCatSERVICE® caused by Atlantic tropical cyclones that made landfall in the USA in inflation-adjusted US$ bn (2005 values). The figures only relate to windstorm and storm surge losses (source: authors).

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. 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.

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.[2]

Section 2 of this paper 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. Section 3 describes the necessary data and the data sources. The results of the loss function estimate are presented in Section 4. 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.

2 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.[3]

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:

$$Loss_j = f\left(Capital\_stock_j, Wind\_speed_j\right), \text{ j being the windstorm event.} \quad (1)$$

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

$$Loss_j = \beta_1 * Capital\_stock_j^{\beta_2} * Wind\_speed_j^{\beta_3} \quad (2)$$

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[2] 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 (Sachs, A. (2007): *Using spatial analysis to establish a relationship between hurricane attributes and damages*, http://www.gsd.harvard.edu/academic/fellowships/prizes/gisprize/ay06-07/sachs.pdf, download 29.12.2007).

[3] There are strong indications that the intensity of tropical cyclones is affected by climate change (cf. Emanuel, 2005, Webster et al., 2005 and Barnett et al., 2005).

We use the Levenberg-Marquardt algorithm to estimate this non-linear loss function.[4]

3 Data[5]

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).

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 dollars (at 2005 values).

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

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

Index i represents the states affected by storm j. Amounts are in inflation-adjusted US$ (at 2005 values).

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 U.S. Census (cf. Bureau of the Census, 1993, and U.S. 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 U.S. Census (cf. U.S. Census, Historical Census of Housing Tables, http://www.census.gov/hhes/www/housing/census/historic/values.html, download 27.07.2007). Both factors,

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[4] A detailed explanation of the variables and parameters can be found in Table 1.

[5] This chapter largely corresponds to our comments on the Schmidt et al. (2008) data and data sources.

residential unit and median home value, are surveyed every ten years in the U.S. 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. As a result, the capital stock figures used are lower than the actual figures.

Pielke Jr. et al. (2008) uses an alternative method for estimating capital stock. Capital stock is ascertained from the population of the relevant county 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).

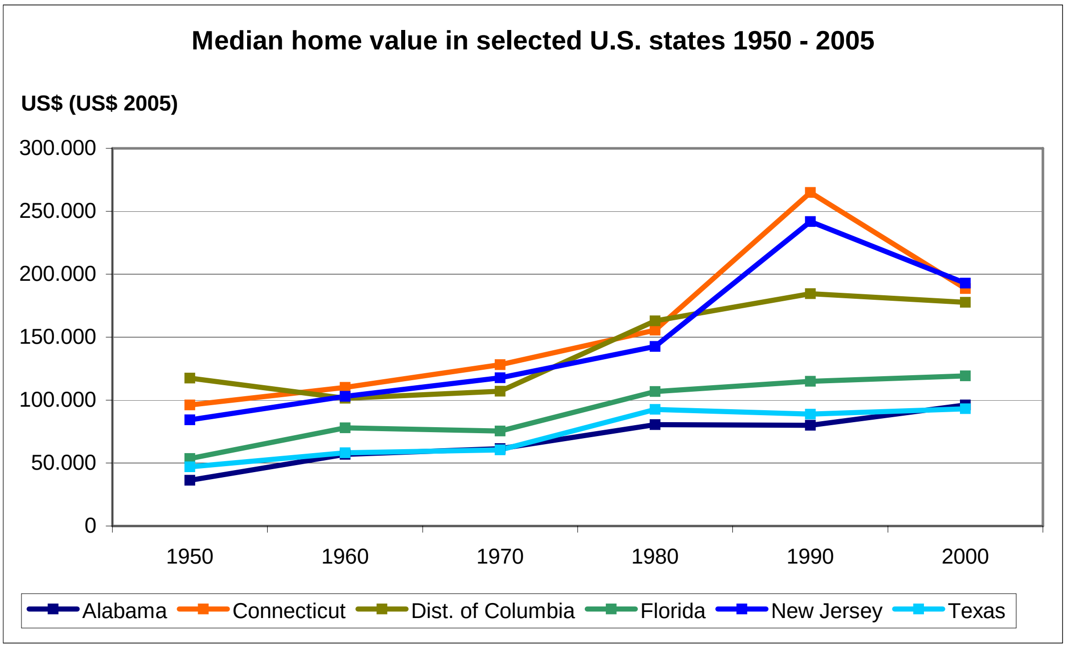

Figure 2: The level of wealth varies from one US state to another. This can be seen from the example of the median home value in inflation-adjusted US$ (2005 values). (Data source of nominal average values: U.S. Census, http://www.census.gov/hhes/www/housing/census/historic/values.html, download 27.7.07;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

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. 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. 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 Jr. (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 Jr., 2005, Pielke Jr. 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.[6] Our economic loss calculations are based on the figures obtained from Munich Re's NatCatSERVICE® database.

Founded in 1974, NatCatSERVICE® 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.[7] 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® database (cf. Faust et al., 2006, Munich Re, 2001 and Munich Re, 2006). Information provided by the Property Claims Service (PCS) is a key element of the NatCatSERVICE® estimates of insured tropical cyclone losses in the USA.

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[6] Examples illustrating estimation of aggregate direct and indirect economic losses can be found in Hallegatte (2007) and Kemfert (2007).

[7] 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, 2007, 46).

The NatCatSERVICE® 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.

The NatCatSERVICE® estimates also include windstorm and storm surge losses, and flood caused by rainfall accompanying the storm. However, since equation (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.[8]

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.[9] Capital stock in the counties affected, wind speed at landfall and windstorm and storm surge losses are available for each storm event.

4 Results

The following equation appears in the section describing the method:

$$Loss_j = \beta_1 * Capital\_stock_j^{\beta_2} * Wind\_speed_j^{\beta_3} \tag{2}$$

The regression parameter values estimated for this equation are:

β_1 = 0.0000232

β_2 = 0.441

β_3 = 2.797

Regression parameter β_1 gives the value of the constants. Parameters β_2 and β_3 indicate by how much the loss changes if *capital stock* or *wind speed* increase or decrease by one unit, β_2 showing loss elasticity relative to changes in capital stock and β_3 loss elasticity relative to changes in intensity (in this case, wind speed). According to coefficient of determination R^2, the estimated function can account for 31% of the variance in the dependable variable *loss*.[10]

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[8] The flood loss data are based on NatCatSERVICE® and National Flood Insurance Program (NFIP) data.

[9] 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® were split in the same proportions. NatCatSERVICE® 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.

[10] Regression analysis details are shown in Table 1.

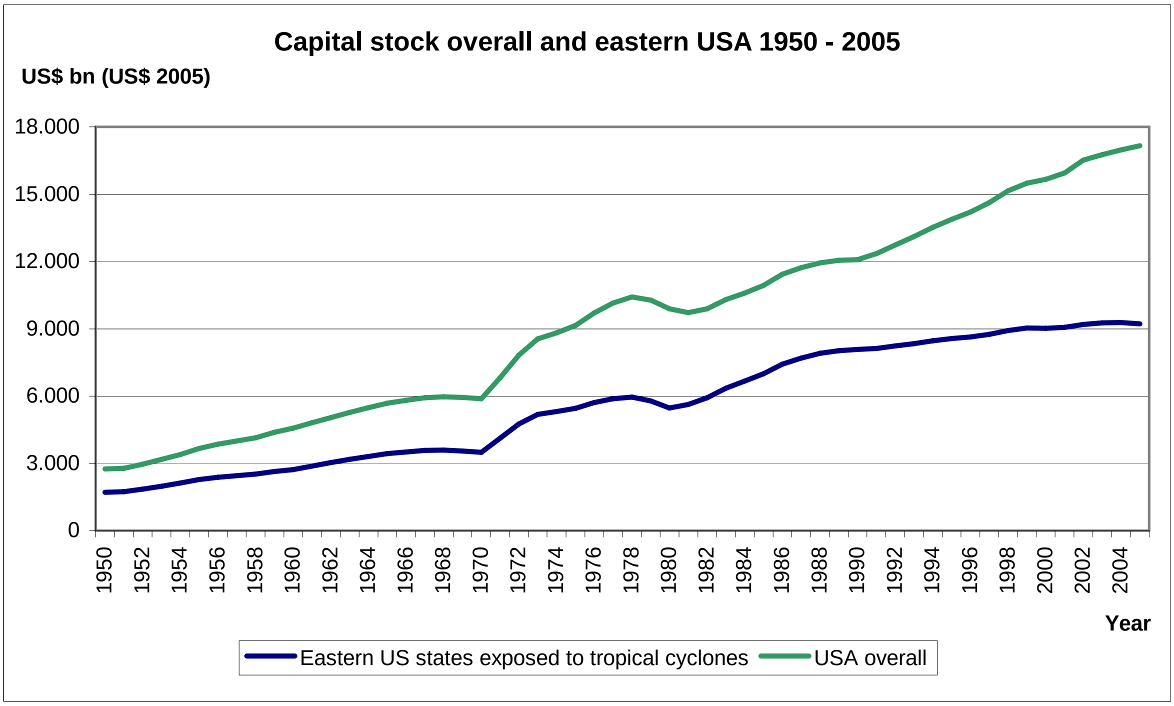

Figure 3: Capital stock evolution in the US states exposed to Atlantic tropical cyclones and overall US capital stock during the period 1950–2005, in inflation-adjusted US$ bn (2005 values). Estimated capital stock is based on the US Census of the number of housing units in the counties and the median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

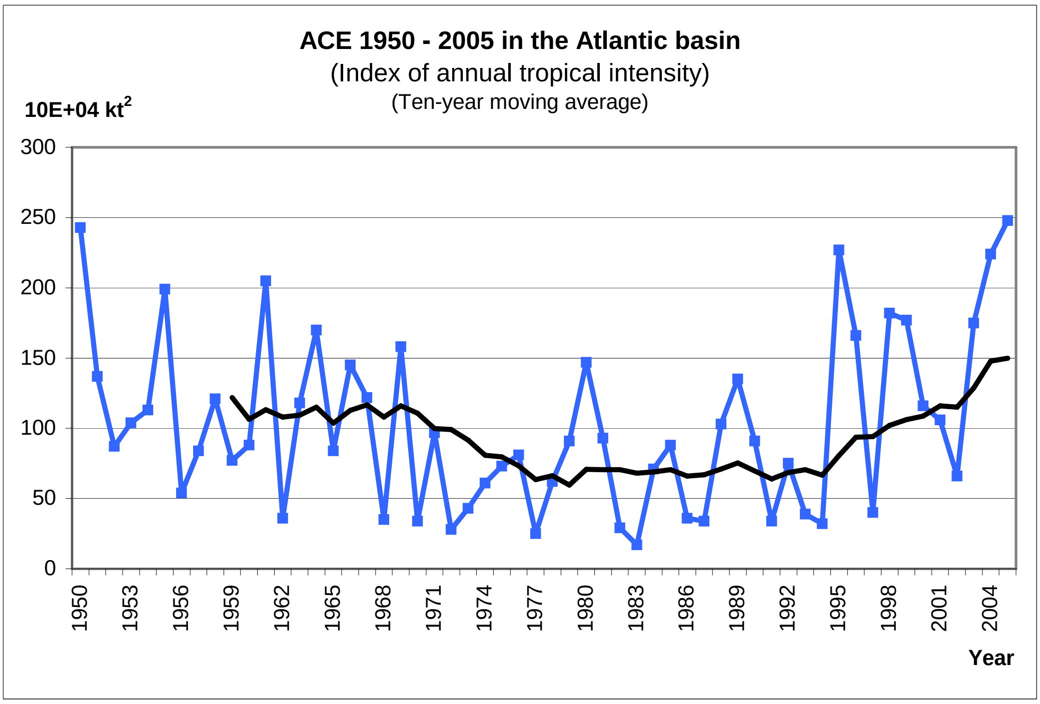

Figure 4: Evolution of annual tropical cyclone intensity in the period 1950–2005. The chart features all storm systems in the Atlantic basin, i.e. including those which did not make landfall (data source: Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanic and Atmospheric Administration (NOAA), http://www.aoml.noaa.gov/hrd/tcfaq/E11.html, download 6.3.08; chart: authors).

The regression results can be interpreted as follows: whereas a 1% increase in capital stock 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. This means the losses respond more to climate-related than to socio-economic changes. 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 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). 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 the estimated maximum sustained velocity of a tropical storm over its entire lifetime (cf. Atlantic Oceanographic and Meteorological Laboratory (AOML), http://www.aoml.noaa.gov/hrd/tcfaq/E11.html, download 6.03.2008).[11] During the period 1950–2005, storm intensity increased by 0.4% per annum, or 23.1% in absolute terms (see Fig. 4).[12]

Given an inflation-adjusted increase in capital stock of 438% in the region investigated, and loss elasticity of 0.44 in response to a 1% change in capital stock, it can be inferred that the loss increase due to the rise in capital stock since 1950 was approx. 190%. Although storm intensity increased by only 23.1%, 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 65%. 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.

5 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, 2007), as confirmed by our results. On the other hand, the conclusions about the role of natural and anthropogenic climate change are less clear-cut. The IPCC's fourth Assessment Report defines the impact of climate change only in terms of probabilities (cf. IPCC, 2007). 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.

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[11] 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 kt^2 (1 kt = 1.852 km/h).

[12] Due to high annual ACE volatility we have calculated the average annual increase and the increase over the period 1950–2005 as a whole using ten-year average ACE.

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.[13] Pielke Jr. (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. This does not, however, apply to the papers cited in Pielke Jr. (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, 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. This is considerably lower than the number recorded in NatCatSERVICE® over the same period (1950–2005),[14] 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.

The wind-speed regression parameter obtained from the 90 windstorms is 7.2, an elasticity result very close to that obtained in Nordhaus (2006) using the complete dataset.[15] 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.[16] 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.[17] A comparison of the loss data and wind speeds for the 78 storms recorded in both datasets reveals no major deviations.[18] Accordingly, the variation in elasticity cannot be adequately explained by differences in individual storm data.

Which storms are recorded in both databases is a more significant factor. The 90 storms in Nordhaus (2006) for the period 1950–2005 yield an average wind speed per storm of 170 km/h, compared with an average of 147 km/h for the 113 storms recorded in NatCatSERVICE® over the same period. This is because, unlike Nordhaus (2006), the NatCatSERVICE® storms are predominantly of less than hurricane force (tropical storm category or

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[13] 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).

[14] The NatCatSERVICE® dataset for the period 1950–2005 comprises 113 North Atlantic storms that made landfall in the USA.

[15] Table 2 shows the regression results in detail.

[16] Details of the regression analysis are shown in Table 3. In our data, we divided storms that made landfall more than once into separate storm events. As Nordhaus does not make this distinction (2006), for comparison purposes, we have not divided the storms into separate events.

[17] Twelve of the Nordhaus (2006) storms for the period 1950–2005 are not registered in NatCatSERVICE®, whilst NatCatSERVICE® includes 35 storms not recorded in Nordhaus (2006).

[18] See Table 4 for details of the mean value test.

lower), causing only minor losses in many cases. The reason for the high elasticity in Nordhaus (2006) may be that the storm dataset only records storms with wind speeds with at least hurricane force. This assumption is borne out if storms of hurricane force or more only are included in the regression analysis performed on the NatCatSERVICE® data. Of the previous 113 storms, only 77 remain. Average wind speed per storm increases to 173 km/h and loss elasticity to wind speed increases to 5.4.[19] Consequently, loss elasticity to wind speed is affected by the structure of the underlying dataset.

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 Jr. et al. (2008), and Pielke Jr. and Landsea (1998). Pielke Jr. 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 see no evidence of any long-term trend in losses normalised using this method. 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) were based on all the counties affected by the storm, so that the different levels of wealth inland and between individual states were also taken into account.

The adjusted individual losses were then collated to show annual adjusted losses, and a time-series analysis performed. Any potential trend in adjusted annual losses would not be accounted for by 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.[20] 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. The result was surprising because it is assumed in the literature that the observed increase in losses is largely the result of socio-economic developments. This was not confirmed by our Schmidt et al. (2008) findings. Accordingly, 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

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[19] Table 3 shows the regression results in detail.

approach presented here, we believe it is a more apposite way of explaining the impact of socio-economics and climate-related change on US storm losses.

6 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 5).

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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[20] Sea surface temperatures in the North Atlantic fluctuate due to the Atlantic Multidecadal Oscillation (AMO), referred to either as a cold or a warm phase, depending on the deviation from the long-term average. Warmer phases cause greater tropical storm activity (cf. Emanuel, 2005 and Webster et al., 2005).

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	0.515 (0.205)	0.441 (0.097)
Wind speed	4.394 (1.126)	2.797 (0.559)
N:	130[a]	127[a b]
R^2:	0.188	0.307
	Standard error in brackets. [a] Excluding Chantal 1989 (loss due to wind = 0, flood losses only). [b] Excluding outliers Andrew 1992, Charley 2004, Katrina 2005 (losses more than 1.5 times S.D. from mean).	

Model 2, applied to the storm events of the dataset, produces an average estimated loss per windstorm of US$ 1,455.7m (2005 values). The average observed loss was US$ 1,424.4m (2005 values). The outliers Andrew 1992, Charley 2004 and Katrina 2005 have not been included.

The Levenberg-Marquardt algorithm estimates are based on the following loss function:

$$Loss_j = \beta_1 * Capital\_stock_j^{\beta_2} * Wind\_speed_j^{\beta_3}$$

$Loss_j$ 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). $Capital\_stock_j$ is 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 β_1 is a constant. Parameters β_2 and β_3 indicate how much the loss changes if the capital stock or wind speed change by one unit (elasticity).

Table 2: Reproducing the Nordhaus (2006) results (source: authors).

Dependent variable: 1n (loss/GDP)	Model 1	Model 2
Constant	-100.7*** (15.58)	-107.9*** (25.22)
1n (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. * denotes significance with a significance level of 10% ** denotes significance with a significance level of 5% *** denotes significance with a significance level of 1%	

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):

$$\ln(Loss_{jy} / GDP_y) = \alpha + \beta \ln(Wind\_speed_{jy}) + \delta Year_y + \varepsilon_{jy}$$

$Loss_{jy}$ being the loss caused by Storm j in year y at actual prices. $Wind\_speed_{jy}$ is maximum wind speed at landfall. GDP_y is US gross domestic product in year y at actual prices. $Year_y$ is the year in which the storm occurred. ε_{jy} is the disturbance term.

Table 3: Regression analysis results applying the loss intensity function from Nordhaus (2006) (source: authors).

Dependent variable: In (loss/GDP)	Model 3	Model 4
Constant	-24.94 (26.72)	-53.02** (24.97)
In (wind speed)	4.608*** (0.5943)	5.412*** (0.9032)
Year	-0.002578 (0.01306)	0.009760 (0.01223)
N:	113	77
R^2	0.3738	0.3270
	Model 3 includes all storms for the period 1950–2005. Model 4 includes only storms for the period 1950–2005 that reached at least hurricane force (on the Saffir-Simpson Scale). Standard error in brackets. * denotes significance with a significance level of 10% ** denotes significance with a significance level of 5% *** denotes significance with a significance level of 1%	

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. Model 4 estimates the same loss intensity function with the same data. However, it includes storms exceeding hurricane force only. This applies to 77 out of 113 storms.

Table 4: Comparison of loss and wind speed data for storms recorded in Nordhaus (2006) and NatCatSERVICE® for the period 1950–2005 (source: authors).

Mean value test	Loss details[a]	Wind speed details[b]
Number of NatCatSERVICE® observations:	78	78
Number of Nordhaus (2006) observations:	78	78
Difference between mean values	4825.14 – 4094.81 = 730.326	93.6053 – 91.4744 = 2,1309[c]
Null hypothesis H_0:	The mean values of both datasets are equal.	The mean values of both datasets are equal.
Estimated standard error	2065.34	3.52667
Test statistic	t(154) = 0.35361	t(154) = 0.604224
p-value (bilateral)	0.724115	0.546584
	The difference is statistically not significant.	The difference is statistically not significant.
	[a] No homogeneity of variance between the two datasets.	[b] Homogeneity of variance between the two datasets. [c] Unit knots (1 kt = 1.852 km/h)

No statistically significant differences are observed. Accordingly, the different methods of valuation on which the two datasets are based do not result in major differences in loss and wind speed data.

Table 5: 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).

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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