Environmental Impact Assessment Review 29 (2009) 359–369

Contents lists available at ScienceDirect

Environmental Impact Assessment Review

journal homepage: www.elsevier.com/locate/eiar

Tropical cyclone losses in the USA and the impact of climate change — A trend analysis based on data from a new approach to adjusting storm losses

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ARTICLE INFO

Article history:
Received 10 July 2008
Received in revised form 19 March 2009
Accepted 20 March 2009
Available online 2 May 2009

Keywords:
Climate change
Tropical cyclones
Loss trends

ABSTRACT

Economic losses caused by tropical cyclones have increased dramatically. Historical changes in losses are a result of meteorological factors (changes in the incidence of severe cyclones, whether due to natural climate variability or as a result of human activity) and socio-economic factors (increased prosperity and a greater tendency for people to settle in exposed areas). This paper aims to isolate the socio-economic effects and ascertain the potential impact of climate change on this trend. Storm losses for the period 1950–2005 have been adjusted to the value of capital stock in 2005 so that any remaining trend cannot be ascribed to socio-economic developments. For this, we introduce a new approach to adjusting losses based on the change in capital stock at risk. Storm losses are mainly determined by the intensity of the storm and the material assets, such as property and infrastructure, located in the region affected. We therefore adjust the losses to exclude increases in the capital stock of the affected region. No trend is found for the period 1950–2005 as a whole. In the period 1971–2005, since the beginning of a trend towards increased intense cyclone activity, losses excluding socio-economic effects show an annual increase of 4% per annum. This increase must therefore be at least due to the impact of natural climate variability but, more likely than not, also due to anthropogenic forcings.

1. Introduction

The number of tropical cyclones that make landfall on the US Gulf and Atlantic coasts has increased distinctly in the period 1950–2005, as shown by Fig. 1.[1] Cyclones are also causing greater economic losses in the form of loss or damage to material assets (see Fig. 2). Fig. 3 indicates the main factors behind the observed increase in frequencies and losses. The principal causes are socio-economic developments (cf. Berz, 2004; IPCC, 2007a,b), primarily, population growth, greater wealth and increased settlement of areas exposed to natural hazards. Other causes are changes in vulnerability to natural extremes and concentrations of people and material assets in conurbations. The trends observed may also be affected by natural and anthropogenic climate change. In this paper 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, 871). We do not see ourselves 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. The IPCC states that humans have, “more likely than not”, contributed to a trend in intense tropical cyclone activity since the 1970s. Any increase in losses could, more likely than not, be partly related to anthropogenic climate change.

Our aim in this paper is to exclude socio-economic impacts from the losses, thus enabling us to identify potential trends that may be due to climatic changes.

Höppe and Pielke (2006) called for an agreed and peer-reviewed method for loss normalisation. Our paper adds an approach to the discussion of appropriate methods.

The losses for the period 1950–2005 are adjusted to the socio-economic level of 2005 to eliminate the effect of socio-economic developments. The adjusted losses are then subjected to a trend analysis. Any remaining trend would not be attributable to socio-economic developments.

Miller et al. (2008) are conducting a similar analysis of worldwide annual losses for a number of weather-related natural catastrophes. To obtain comparable loss data, they adjust their losses with reference to trends in per capita wealth, inflation and population. A trend analysis

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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.

0195-9255/$ – see front matter
doi:10.1016/j.eiar.2009.03.003

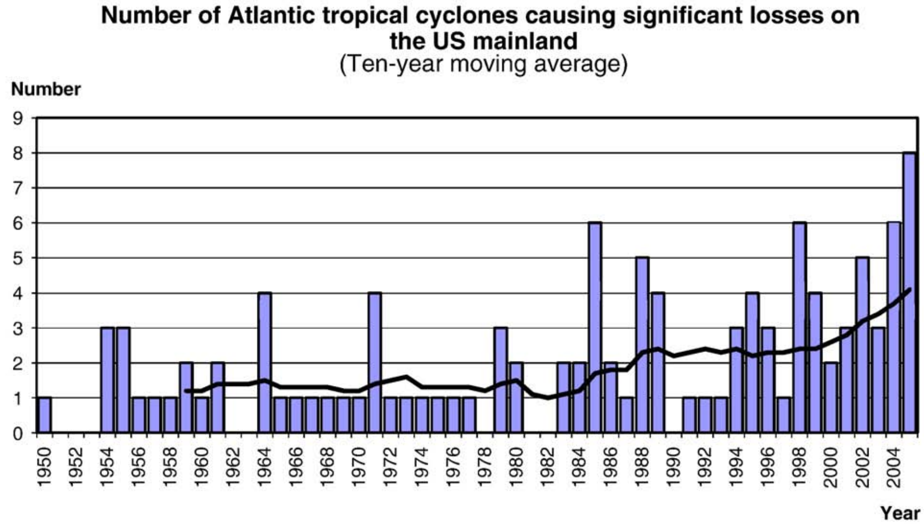

Fig. 1. Annual frequencies of tropical cyclones that have caused significant losses on the US mainland (data source: Munich Re, NatCatSERVICE®, 2007; chart: author).

of the adjusted loss data shows an annual increase of 2%, a remaining, positive trend which cannot be accounted for by global socio-economic developments. However, the trend is statistically significant only for the period 1970–2005 and is heavily influenced by the extreme hurricane seasons in 2004 and 2005.

This paper concentrates solely on tropical cyclone losses on the US Atlantic and Gulf coasts. Tropical cyclones in the USA provide particularly interesting investigative material, because the losses being especially heavy due to high concentrations of values in the parts of the eastern USA exposed to storms. They account for a major share of worldwide natural catastrophe losses. In addition, the availability of requisite data is relatively good in the case of the USA.

2. Method

The main object of the study is to test the hypothesis that climate-change factors are to some extent responsible for the increase in losses. To identify trends that may be due to climate change, the loss data have to be adjusted to exclude socio-economic impacts. Normally, loss data are inflation-adjusted only for comparison purposes. However, population trends and the quantity and value of assets in the exposed areas account for much greater changes than an appreciation in the value of money.

Nordhaus (2006) demonstrates one way of adjusting the figures to exclude the effects of increased wealth. He adjusts storm losses in relation to gross domestic product (GDP) in the year of occurrence. However, GDP, which reflects the value of goods and services that are produced annually, is only suitable as a means of evaluating natural catastrophe losses to a limited extent (cf. Steininger et al., 2005). The stock of material assets accumulated over decades is more significant in determining the amount of such losses than the goods and services the economy produces in the course of the year. However, since no data are available for many parts of the world on the quantity of assets, GDP has to be used. If possible, regional GDP figures should be used, since the impact of natural catastrophes is generally confined to a particular region.

Pielke et al. (2008) adjust losses to discount the effects of inflation, population growth and increased wealth. Population changes are measured using the ratio of current population to population in the year of the storm event. Changes in wealth are ascertained by applying

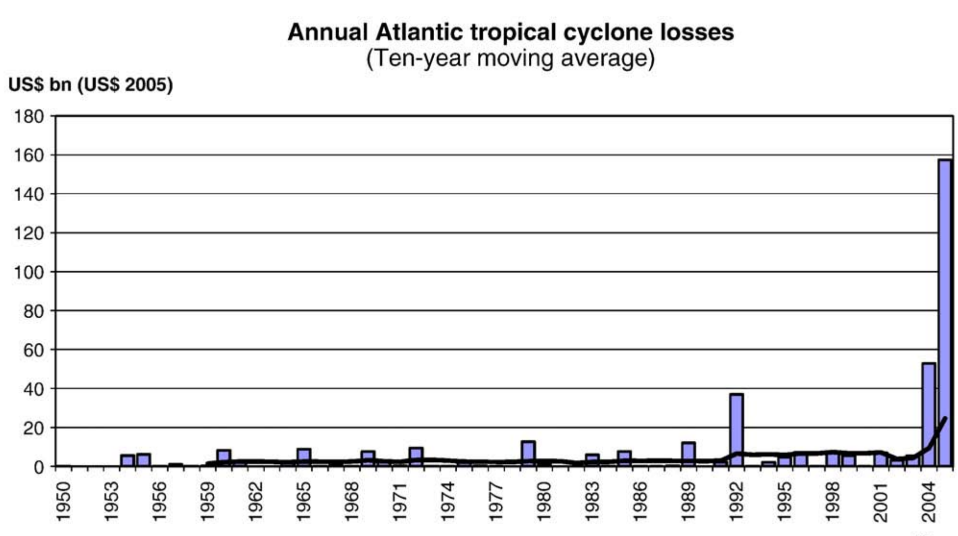

Fig. 2. Annual inflation-adjusted losses caused by Atlantic tropical cyclones that made landfall on the US mainland in US$ bn (US$ 2005) (data source: Munich Re, NatCatSERVICE®, 2007; chart: author).

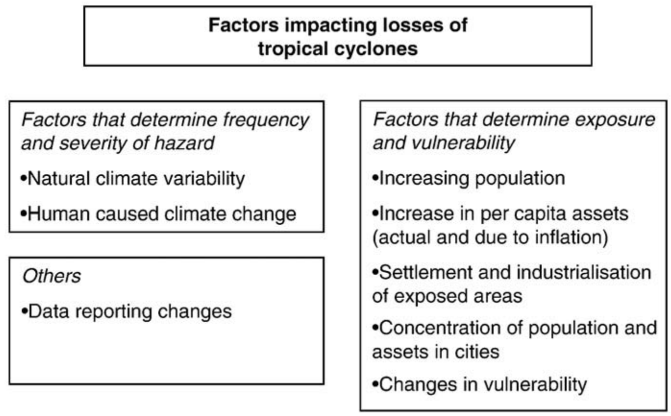

Fig. 3. Principal factors that can influence the increase in tropical storm losses (source: author).

the ratio of current per capita wealth to per capita wealth in the year of the storm. The adjusted loss is established by multiplying the inflation-adjusted loss by population change and per capita change in wealth. This approach, so-called "Normalized Hurricane Damages", was first used by Pielke and Landsea (1998) for the USA. It was subsequently adopted by Miller et al. (2008) and others and adapted to other regions and natural catastrophe types.

Collins and Lowe (2001) take Pielke and Landsea's (1998) approach a stage further by substituting the change in population with the change in the number of residential units. The losses are then adjusted according to the change in wealth per residential unit. There are also a number of other studies that have used housing values to adjust losses. Crompton and McAneney (2008), for instance, used the number and mean value of dwelling units to adjust losses due to weather disasters in Australia.

We eliminate the socio-economic components from the losses on the basis of changes in regional capital stock, which is the value of the material assets in the region expressed in US dollars (US$). Since storm losses are essentially a function of storm intensity and material assets located in the area, we believe it is more appropriate to apply an adjustment based on capital stock than on the general evolution in wealth measured by GDP or change in population and per capita wealth. The adjustment is based on the change in the capital stock index of all US counties in which a specific wind speed was exceeded (>63 km/h). The rationale is that wind speeds above this threshold cause substantial losses. Our method is founded on the papers by Pielke and Landsea (1998), Collins and Lowe (2001) and Pielke et al. (2008), referred to above.

The adjustment per storm j can be described as:

$$\mathrm{loss}_{2005,j} = Loss_{y,j} \cdot \left(\frac{\mathrm{capital\_}stock\_index_{2005,j}}{\mathrm{capital\_}stock\_index_{y,j}} \right) \quad (1)$$

$\mathrm{loss}_{2005,j}$ storm j losses adjusted to socio-economic conditions in 2005
$\mathrm{loss}_{y,j}$ inflation-adjusted losses from storm j with the socio-economic conditions of year of occurrence y.
$\mathrm{capital\_}stock\_index_{2005,j}$ Index for the value of all material assets in 2005 in the US counties affected by storm j
$\mathrm{capital\_}stock\_index_{y,j}$ Index for the inflation-adjusted value of all material assets in occurrence year y in the US counties affected by storm j

Amounts are in inflation-adjusted US$ (US$ 2005).

Adjusted losses from storm j ($loss_{2005,j}$) are ascertained by multiplying the actual loss ($loss_{y,j}$) by a factor expressing the ratio of 2005 capital stock ($capital\_stock\_index_{2005,j}$) to actual capital stock in the year of occurrence ($capital\_stock\_index_{y,j}$). The adjusted losses thus obtained provide better comparability as they are no longer affected by the socio-economic conditions obtaining in the different years.

The approach described here is different from the one in Pielke et al. (2008) in three respects. Firstly, the adjusted loss in Pielke et al. (2008) is established by multiplying the inflation-adjusted loss by population change and per capita change in wealth. In the approach described in this paper, we do not take into account the general evolution in wealth but the value of capital stock that is at risk.

Secondly, Pielke et al. (2008) take socio-economic effects into account only in the worst hit counties, i.e. normally those located right on the coast, where storm intensity is greatest. The method presented here takes into account the whole region affected by the storm event, which comprises all the counties in which a specific wind speed is exceeded. One could assume that an approach taking into account only the counties along the coast will overestimate the loss adjustment because the growth in population and values is expected to be much higher on the US coast. But there is no large difference in the mean annual growth rate of capital stock between coastal counties only (1950–2005: 3.2%) and the exposed counties away from the coast (1950–2005: 3.1%).[2]

Thirdly, wealth differences within the USA are taken into account. This is made possible by an established database of capital stock time series for all counties located in the area affected by North Atlantic cyclones. The time series can be used to factor into the adjustment the different regional levels and differences in the rate at which the capital stock evolves, capital stock serving in our approach as an approximation of level of wealth. Wealth differences are relevant since they take into account the different wealth levels of the individual US states, a factor not addressed in the approach used by Pielke et al. They were not able to do so because the change in per capita wealth in their approach was based on national figures relating to fixed assets and consumer durable goods (as an approximation of the level of wealth).

Like Pielke et al.'s (2008) normalisation method, our adjustment of the loss data assumes vulnerability to be constant over time. Sachs (2007), however, demonstrates that the losses do not increase proportional to capital stock or wealth, calculating loss elasticity in relation to change in capital stock to be less than one. As our adjusted losses increase relative to capital stock by a ratio of 1:1, they tend to be overestimated. Any positive trend in adjusted loss data would accordingly be lower. But Miller et al. (2008) assume the actual reduction in vulnerability to tropical cyclones in the USA to be moderate.

3. Data

To convert storm losses occurring in different years to a comparable socio–economic level, information is required on the region affected, the capital stock located there and the loss caused.

The region affected by a storm comprises all the counties in which the storm caused substantial losses. This can be ascertained using the relevant wind field, which defines the area extent of the storm. It is the area in which a specific wind speed has been exceeded. In our case, 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. Considerable losses occur if this limit is exceeded. The wind fields are calculated using the storm track dataset provided by the National Oceanic and Atmospheric Administration (NOAA Coastal Services Center, http://maps.csc.noaa.gov/hurricanes/download.html).

To ascertain the capital stock in the relevant counties, we use a geographic information system (GIS) to combine 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 the storm and in 2005.

[2] Thanks to Joel Gratz for providing us with the list of 177 coastal counties applied in Pielke et al. (2008).

Annual estimates of capital stock are available in the USA in the form of national data on fixed assets and consumer durable goods. However, details of fixed assets and consumer durables are not available for the individual states and counties (according to a written reply received from the Bureau of Economic Analysis on 23 August 2006). We have therefore estimated capital stock time series for the individual counties and entered them in a database which includes all the counties located in the area affected by North Atlantic cyclones. Capital stock details for each of the 1756 counties is available for the period 1950–2005. It has been estimated using the number of housing units and the median home inflation-adjusted value in US dollars (US$ 2005).

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

$$\text{capital\_}stock\_index_{2005,j} = \sum_{i=1}^{I}\left(\left(residential\_units\_in\_counties\_beneath\_wind\_field_j\right)_{2005,i}\cdot median\_value_{2005,i}\right) \tag{2}$$

$$\text{capital\_}stock\_index_{y,j} = \sum_{i=1}^{I}\left(\left(residential\_units\_in\_counties\_beneath\_wind\_field_j\right)_{y,i}\cdot median\_value_{y,i}\right) \tag{3}$$

Index i represents the states affected by storm j, index y the year of the storm event. All data are in inflation-adjusted US dollars (US$ 2005).

The concept of “residential unit” as a statistical factor comprises houses, apartments, mobile homes, groups of and individual rooms used as accommodation. Relevant data for every county are available from the U.S. Census (U.S. Department of Commerce, 1993; U.S. Census, Census 2000 Summary File 3). No data are available on average residential unit value, which we have therefore calculated using the data on median home value available for every US state from U.S. Census (U.S. Census, Historical Census of Housing Tables, http://www.census.gov/hhes/www/housing/census/historic/values.html).[3] Both the residential unit and median home value factors are surveyed every ten years in the US Census. Data for the intervening years have been generated by linear interpolation. The figures for the period 2001–2005 have been extrapolated.

One drawback encountered when using capital stock to eliminate socio-economic effects from losses is that storm losses are largely made up of building repair costs. Whilst buildings may, in some cases, be completely destroyed, 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.

A further drawback when using the capital stock factor is that the calculations are based only on the price and number of residential units and take into account neither asset values within those units nor infrastructure and industrial and office premises. 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 simply 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.

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

As well as calculating the capital stock in the counties affected, it is also necessary to ascertain the economic losses caused by a storm. A number of very different institutions assess natural catastrophe losses such as UN or national authorities, aid agencies like the Red Cross, and of course insurance companies. Each institution has its own method of evaluating losses and there is no standard procedure. Loss assessments accordingly vary depending on source and are of limited comparability. 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).

For our purposes, economic losses are understood to be material asset losses sustained as an immediate consequence of a storm. Intangible losses and indirect consequences are not included. The loss accordingly comprises damage to residential, industrial and office buildings and to infrastructure as well as losses to contents and to moveable property outside buildings, e.g. vehicles. Losses sustained as an indirect consequence, on the other hand, are not included. These would include, for instance, higher oil prices caused by the suspension of drilling activity in the Gulf of Mexico or longer-term effects such as increased insurance premiums. On the other hand, prices tend to increase in the wake of natural catastrophes due to a surge in demand for construction and repair services. These factors are included in the loss data, loss estimates being largely based on the cost of reinstating items that have been destroyed.[4] We calculate the economic losses using data 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 in the database, which now contains more than 25,000 entries, including all great natural catastrophes of the past 2000 years and all loss events since 1980.[5] Direct material losses and the corresponding insured losses are recorded for each catastrophe. Loss assessments are based, according to availability, on well documented official estimates, insurance claim payments or 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 visits are used to produce well documented and clearly substantiated loss figures, which are then entered in the NatCatSERVICE® database (cf. Faust et al., 2006; Munich Re, 2001, 2006). Information provided by the Property Claims Service (PCS) is key to NatCatSERVICE® estimates of US tropical cyclone losses.[6]

As shown in Fig. 3, one factor behind the loss trends may be the technique used to record and evaluate the losses (the data reporting factor). This may, for instance, be due to the increasing number of options available for obtaining information on catastrophes. However, loss data may also be deliberately manipulated, i.e. intentionally overestimated or underestimated. For example, we note that the number of natural catastrophes and the loss figures recorded in NatCatSERVICE® for the People's Republic of China have increased significantly since the

[3] The distribution of residential units and their values is a function of geography. The tendency for wealth to concentrate on coasts means that using the median home value for a state is going to skew the results to emphasise inland locations, where there is likely to be less wealth. Unfortunately, data on the median home value at county level are not available.

[4] For examples illustrating the estimation of aggregate direct and indirect economic losses, see Kemfert (2007).

[5] 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).

[6] Annual loss data from the NatCatSERVICE® database are not very different from the annual loss data in Pielke et al. (2008). In most of the years – with the exception of 1960, 1979 and 2005 – differences are not large. For some storms in particular, there are larger discrepancies, e.g. for Donna (1960) the NatCatSERVICE® provides a loss estimate of US$ 1250 million (current US$) compared to US$ 397 million in the dataset in Pielke et al. (2008). For Katrina (2005) the NatCatSERVICE® gives a figure of US$ 125bn compared to US$ 107bn in the other dataset (cf. Pielke et al., 2006). Some storms are not found in both datasets.

country opened up to the outside world in the early 1980s. Moves by the state to influence reported losses may be prompted by the desire to obtain more international aid or the wish to play down a catastrophe so as not to give cause for outside intervention. We therefore also ascertained for which parts of the world reliable, long-term NatCatSERVICE® loss data are available, by devising a method for checking data quality. The results of the analysis indicate that US loss data should only be used from 1950 (cf. Faust et al., 2006). Miller et al. (2008) draw the same data-quality conclusions.

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. 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 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, e.g. if storms made landfall twice in the same state or if the loss was below the threshold at which storms are recorded in PCS catastrophe history. The following data are available for each storm event: region affected shown as counties affected, wind speed at landfall and hurricane intensity categories (Saffir–Simpson Scale), population figures and capital stock in the counties affected, total direct material losses and insured losses.

4. Adjustment results

The adjustment procedure will now be explained using Hurricane Frederic (1979) as an example. Frederic made landfall on the border between Mississippi and Alabama. Florida, Kentucky, Louisiana, Maryland, Ohio, Pennsylvania, Tennessee and West Virginia were also hit. Frederic caused a loss of US$ 6192 million (US$ 2005) in all. Based on 2005 values, the capital stock index in the 221 counties affected is one-and-a-half times that of 1979, i.e. the loss would have been 50% greater if Frederic had occurred in 2005. Adjusted to socio-economic conditions in 2005, the storm losses thus amount to US$ 9075 million.

Table 1 is a comparison of the storms that produced the highest losses. The greatest losses to date were caused by Katrina (2005) and Andrew (1992), in terms of adjusted and non-adjusted losses. Based on adjusted losses, they are followed by Donna (1960), Diane (1955), Camille (1969) und Betsy (1965), storms from preceding years. If, as is usually the case, only inflation is taken into account, Katrina and Andrew are followed by recent storms: Ivan (2004), Charley (2004), Rita (2005) and Wilma (2005).

There are also considerable differences in the loss figures for individual years. Table 2 shows inflation-adjusted annual losses for the period 1950–2005 and the corresponding annual figures for adjusted losses. Fig. 4 is a graph showing annual adjusted losses. Adjustment increases the losses substantially. If inflation is taken into account, the average annual tropical cyclone losses for the period 1950–2005 amount to approx. US$ 6977bn (US$ 2005). Taking the increase in the value of material assets into account, that figure rises to US$ 9980bn (US$ 2005).

Based on the normal inflation-adjusted figures, the years with the greatest losses were 2005, 2004, 1992, 1979, 1989 und 1972, compared with 2005, 2004, 1992, 1960, 1955 und 1965 for the adjusted loss figures. Below the top three, the order in the case of total annual losses, as with individual storms, varies considerably (see Table 2).

Table 1
The 30 largest storms arranged in descending order by adjusted losses.

Ranking	Storm	Date	Storm category at landfall	Losses in US$ million (US$ 2005)	Adjusted losses in US$ million (US$ 2005)	Ranking (original loss)
1	Hurricane Katrina II	29.08.2005	4	122,824	122,824	1
2	Hurricane Andrew I	24.08.1992	4	35,724	44,065	2
3	Hurricane Donna I	10.09.1960	4	4987	34,237	19
4	Hurricane Diane	20.08.1955	TS	5834	20,694	17
5	Hurricane Camille	17.08.1969	5	7571	19,614	12
6	Hurricane Betsy II	10.09.1965	4	8325	19,087	10
7	Hurricane Ivan	16.09.2004	3	18,612	18,670	3
8	Hurricane Charley I	13.08.2004	4	16,444	16,466	4
9	Hurricane Rita II	24.09.2005	3	15,851	15,851	5
10	Hurricane Hugo	21.09.1989	4	11,039	14,804	7
11	Hurricane Wilma	24.10.2005	3	14,300	14,300	6
12	Hurricane Agnes II	22.06.1972	TS	9084	13,345	9
13	Hurricane Carla	09.09.1961	4	2612	12,546	25
14	Hurricane Carol II	31.08.1954	2	3172	10,526	23
15	Hurricane Frances	03.09.2004	2	9306	9280	8
16	Hurricane Hazel	15.10.1954	3	2035	9141	33
17	Hurricane Frederic	12.09.1979	4	6192	9075	15
18	Hurricane Alicia	17.08.1983	3	5886	8354	16
19	Hurricane Jeanne	15.09.2004	3	8272	8241	11
20	Hurricane Fran	05.09.1996	3	6479	7974	14
21	Hurricane Celia	03.08.1970	3	2286	7931	28
22	Hurricane Dora	09.09.1964	2	1576	7783	38
23	Tropical storm Allison	05.06.2001	TS	6624	6682	13
24	Hurricane Donna III	12.09.1960	2	2267	6126	29
25	Hurricane David I	03.09.1979	2	2861	5539	24
26	Hurricane Isabel	18.09.2003	2	5310	5308	18
27	Hurricane Donna II	12.09.1960	2	997	5074	46
28	Hurricane Eloise	16.09.1975	3	1997	4760	34
29	Hurricane Georges	20.09.1998	2	4197	4540	21
30	Hurricane Floyd	14.09.1999	2	4692	4497	20

The adjacent column shows their ranking in terms of actual original loss figure. Storms that made landfall several times are divided into individual, per-landfall occurrences, each designated by a Roman numeral (source: author).

Losses adjusted by change in capital stock yield better comparability as they are no longer influenced by the varying socio-economic circumstances of the different years. Potential trends are thus no longer due to socio-economic changes. To determine whether the surmised climate-change impact is present, the loss data will now be subjected to a trend analysis.

5. Trend analysis

Any residual trend in annual adjusted losses is determined using a linear regression (ordinary least squares fit):

$$\ln\left(\text{loss}_{2005,y}\right) = \alpha + \beta \cdot time_y + \varepsilon_y \quad (4)$$

Year y losses adjusted to 2005 ($\text{loss}_{2005,y}$) are expressed by the factor *time* in year y, α being a constant and ε_y the error term. If β is positive, this indicates an upward trend over time. As well as performing an analysis to establish a possible trend, we also calculate the average growth rate in annual losses w, which can be found using the geometric mean:

$$w = \left(\frac{\text{loss}_{2005,n}}{\text{loss}_{2005,1}}\right)^{1/(n-1)} - 1 \quad (5)$$

Value n being the number of years analysed in the time series. Average growth rate is thus calculated in accordance with the loss in the first and last years of the time series.

Due to large fluctuations in annual losses, we have calculated the growth rate on the basis of average annual loss in the respective phases of the Atlantic Multidecadal Oscillation (AMO).

Phases of unusually high and unusually low sea surface temperatures lasting a number of decades can be observed in the North Atlantic. They are caused by the Atlantic Multidecadal Oscillation (AMO). Higher sea surface temperatures lead to increased cyclone activity, which then decreases in the cold phase. The last complete warm phase lasted from 1926–1970, and the last cold phase from 1971–1994. Since 1995, the North Atlantic has been undergoing another warm phase (cf. Goldenberg et al., 2001; Emanuel, 2005).

The trend analysis for the period 1950–2005 yields no statistically significant trend in annual adjusted losses. Even if the two extreme years, 2004 and 2005, are omitted from the trend analysis, no trend can be identified in which the explanatory variable *time* is statistically significant. Thus, no conclusion can be drawn regarding a possible trend in the periods 1950–2005 and 1950–2003. If we take into account losses from the start of the last cold phase only (from 1971) we note a slight positive trend. The average annual rate of increase in adjusted losses for this period is 4%. The trend function parameters are statistically significant. Coefficient of determination (R^2) is 0.10. Fig. 5 shows this linear trend for the logarithmised annual adjusted losses. Hurricane Katrina's (2005) exceptionally high losses would be expected to affect the average growth rate. However, if we eliminate the losses from Katrina, we still find an annual increase of 2% for the period 1971–2005, although the effect of the factor *time* is not statistically significant and the coefficient of determination (R^2) decreases to 0.089. Table 3 shows the regression results in detail. Losses adjusted for inflation alone increase by an average of 5% in the period 1971–2005. Excluding losses from Hurricane Katrina, the average rate of increase is around 3% per year (see Table 4).

Table 2
Actual and adjusted annual Atlantic tropical cyclone losses in the USA, ranked by original and adjusted losses.

Year	No. of storms	Annual losses in US$ million (US$ 2005)	Annual adjusted losses in US$ million (US$ 2005)	Ranking (original annual loss)	Ranking (annual adjusted loss)
1950	1	162	3057	35	27
1951	0	0	0	48	48
1952	0	0	0	49	49
1953	0	0	0	50	50
1954	3	5524	21,478	17	7
1955	3	6177	22,645	14	5
1956	1	144	811	36	32
1957	1	1042	4065	29	25
1958	1	47	353	41	36
1959	2	201	872	33	31
1960	1	8251	45,437	8	4
1961	2	2658	12,680	21	12
1962	0	0	0	51	51
1963	0	0	0	52	52
1964	4	2427	11,793	22	13
1965	1	8804	21,579	7	6
1966	1	42	209	44	40
1967	1	1171	4078	28	24
1968	1	45	224	42	38
1969	1	7571	19,614	10	9
1970	1	2286	7931	23	17
1971	4	280	670	31	33
1972	1	9348	14,111	6	11
1973	1	44	86	43	43
1974	1	99	129	39	42
1975	1	1997	4760	26	23
1976	1	275	388	32	35
1977	1	26	30	46	46
1978	0	0	0	53	53
1979	3	12,652	20,337	4	8
1980	2	1424	2404	27	29
1981	0	0	0	54	54
1982	0	0	0	55	55
1983	2	5888	8358	15	16
1984	2	124	254	37	37
1985	6	7618	10,267	9	14
1986	2	107	139	38	41
1987	1	3	4	47	47
1988	5	307	405	30	34
1989	4	12,080	16,110	5	10
1990	0	0	0	56	56
1991	1	2153	1851	24	30
1992	1	36,915	45,497	3	3
1993	1	68	78	40	44
1994	3	2110	2611	25	28
1995	4	4752	5472	19	21
1996	3	7252	8779	11	15
1997	1	183	210	34	39
1998	6	7230	7869	12	18
1999	4	5548	5401	16	22
2000	2	34	36	45	45
2001	3	6883	6954	13	19
2002	5	3057	3110	20	26
2003	3	5480	5479	18	20
2004	6	52,853	52,876	2	2
2005	8	157,400	157,400	1	1

(source: author).

6. Discussion

The trend function is not statistically significant for the losses from 1950–2005, so that no conclusion can be drawn on a loss trend for the data over the period as a whole. However, a clear trend can be established for the period 1971–2005, losses increasing by an average of 4% per annum. This trend is shown in Fig. 4. It was to be expected that losses would have risen on average from the start of the last cold phase until the current warm phase. This is in keeping with the results of other studies on tropical storm activity. According to Emanuel (2005); Hoyos et al., (2006); IPCC, (2007a); Webster et al. (2005) sea surface temperature correlates with storm intensity. A Munich Re study indicates that average annual adjusted losses in years where the temperature deviates from the long-term average by 0.15 °C–0.45 °C are around five times higher than in years where sea surface temperatures are lower (−0.45 °C to −0.15 °C). The losses are around 50% higher than in years where temperatures are more or less in line with the long-term average. The quantity of loss data is approximately the same for each of the three classes (Faust, 2007).[7] Average annual adjusted losses during warmer phases are thus much higher than during colder phases, an indication, at least, that natural

[7] Faust adjusted loss data from NatCatSERVICE® and from Pielke et al. (2008) using the Pielke et al. (2008) method.

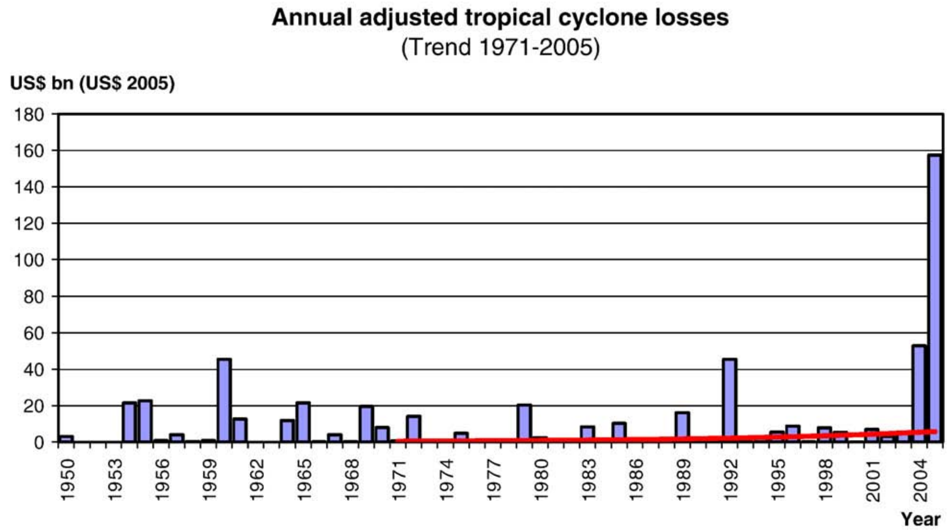

Fig. 4. Annual adjusted Atlantic tropical cyclone losses that made landfall on the US mainland in US$ bn (US$ 2005) with the 1971–2005 trend (source: author).

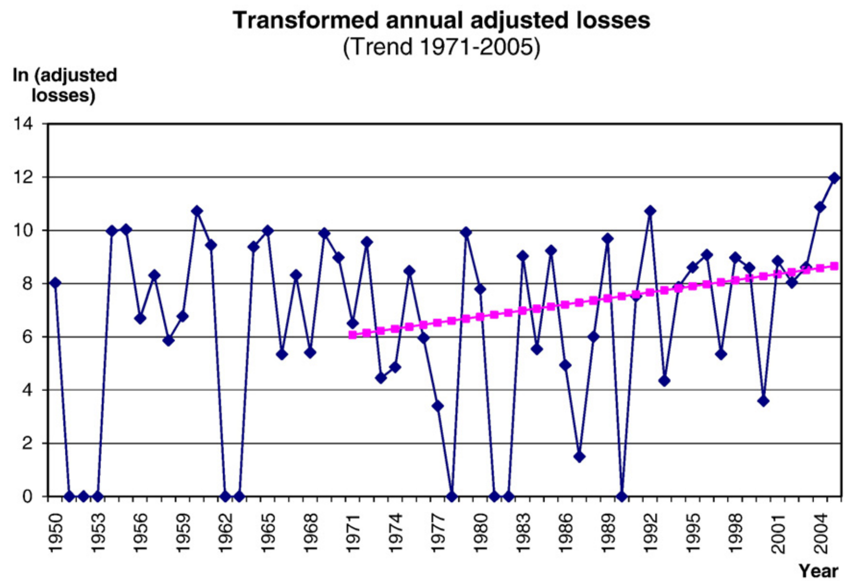

Fig. 5. Annual adjusted losses transformed using the natural logarithm. A linear, statistically significant trend can be identified for the period 1971–2005 (source: author).

climate fluctuations have an impact on losses. The effects of natural climate fluctuations can also be seen in Fig. 6, the ten-year moving average of annual losses, where the adjusted losses are more or less in line with natural North Atlantic climate fluctuations.

However, the amount of loss is not only determined by natural climate fluctuations. Since losses are essentially a function of storm intensity and material assets, the area affected by the storm is also relevant. This is clearly illustrated by the year 1992 which, despite occurring in the cold phase, is among those with the highest hurricane losses. Our database records only one 1992 storm — Hurricane Andrew. Not only was it a particularly severe storm, it also affected a part of Florida with a very high concentration of material assets.[8]

Inflation-adjusted losses increased annually by 5% between the start of the last cold phase (1971) and 2005, whilst adjusted losses show an increase of 4% per annum over the same period.[9] Thus, the annual increase in losses cannot, for the most part, be explained by socio-economic factors over this short period of time, because natural climate fluctuations lead to great variations in losses (cf. Pielke and Landsea, 1999). Our trend analysis starts at the beginning of a phase of lower cyclone activity and ends in a phase of high activity. Therefore, it is not surprising that climate-related impacts are responsible for the majority of the increase in losses.

The validity of our results is subject to a number of reservations. The relevance of the annual growth rates calculated is influenced by high annual loss volatility. We have, therefore, calculated the growth rates using the average annual loss during the different AMO phases. In addition, our assumption of a linear trend in annual loss volatility and in the cyclicity of the natural warm and cold phases is not entirely appropriate. This explains to some extent why our trend functions do not have high statistical explanatory power.

[8] Hurricane Andrew was a Category 4 storm when it made landfall on the coast of Florida but it crossed the Gulf of Mexico before making a second landfall in Louisiana, again as a Category 4 windstorm. This shows that severe storms can also occur during cold phases, although they are not as frequent as in warm phases.

[9] Were one to look at the Pielke et al. (2008) dataset over the same period, the quantitative findings would be identical (Roger Pielke Jr., personal communication).

We also have to take into account the fact that, for the purpose of adjusting the losses, cyclone vulnerability is assumed to be constant over time. One would, however, surmise that vulnerability to weather extremes decreases as economic development increases due to higher building standards and improved disaster prevention. Sachs' (2007) study of US hurricane losses calculated loss elasticity in relation to changes in wealth to be less than one. A past storm event would, in fact, cause even greater losses today because of the higher concentrations of material assets. However, the increase in losses would not be proportional to the rise in capital stock, that stock being less vulnerable today. Nevertheless, the effect of decreasing vulnerability should not be overestimated in the case of the USA. The IPCC report argues that North America's ageing infrastructure combined with a lack of building standards or failure to enforce them are factors conducive to an ongoing rise in losses (cf. IPCC, 2007a,b). Miller et al. (2008) also assume a moderate reduction only in the USA's vulnerability to tropical cyclones. The situation in other parts of the world may well be different.

If constant vulnerability is assumed, the adjusted losses will be somewhat overestimated, whilst the annual growth rate in adjusted losses will tend to be underestimated. The increase in losses is therefore likely to be at least on a par with the 4% per year calculated.

The adjustment method we have used to remove socio-economic impacts is based on the loss normalisation method described in Pielke et al. (2008), a method we have taken a stage further. Pielke et al. (2008) normalise losses to the comparison year 2005 on the basis of changes due to inflation and increases in population and national per capita wealth subsequent to the year of the storm. The change in population is determined using the figures for the worst hit counties on the US coast. In our calculations, changes in capital stock are based on all the counties affected by the storm, so that wealth differences between individual US states can also be taken into account. The two methods produce different normalised or adjusted losses.

For comparison purposes, the losses taken from the NatCatSERVICE® database were again normalised using the Pielke et al. (2008) method. We calculated the degree of normalisation for each storm in Pielke et al. (2008) by finding the ratio of normalised to nominal losses. The nominal loss for every NatCatSERVICE®-database storm was then multiplied by that factor. Four windstorms recorded in the NatCatSERVICE® database could not be taken into account because they are not included in the Pielke et al. (2008) dataset.[10]

Fig. 7 compares annual storm losses recorded in NatCatSERVICE® adjusted according to both methods. Losses normalised on the basis of the population increase in the coastal counties and national per capita wealth are higher than those adjusted to reflect change in capital stock throughout the entire region affected by the storm. If all windstorms are taken into account, the losses normalised using the Pielke et al. (2008) method are 15% higher.

The deviations are even more apparent in a number of individual cases. Thus, using the Pielke et al. (2008) normalisation factor, Donna (1960) caused a loss normalised to 2005 of around US$ 83bn, whereas the loss amount using our method is US$ 45bn.[11] Conversely, Flossy (1956) produces normalised losses of US$ 462 million compared with US$ 811 million using our method.

Whilst Pielke et al. (2008) base their normalisation on the population growth along the coast, we consider losses to be influenced by socio-economic circumstances throughout the affected region as a whole. However, this does not explain the differences in adjusted losses due to the mean socio-economic growth in the region as a whole (growth rate of capital stock at risk in the period 1950–2005: 3.1%) is nearly the same as the mean socio-economic growth along the coast (3.2%). The essential difference between the approach in Pielke et al. (2008) and the approach described here lies in the use of capital stock at risk (number of housing units and mean home value) instead of wealth at risk (population and per capita wealth) and the application of regional figures for mean home value (at state level) instead of national average on per capita wealth. As Fig. 8 shows, all factors that normalise losses resulting from wealth at risk are higher than the factors used to adjust losses based on capital stock at risk. Fig. 8 takes into account coastal counties only.

Table 3
Results of the annual adjusted loss trend analysis.

Dependent variable $\ln(\text{loss}_{2005,y})$	Model 1 1950–2005	Model 2 1950–2003	Model 3 1971–2005	Model 4 1950–2005 excl. Katrina	Model 5 1971–2005 excl. Katrina
Constant	7.766***	8.144***	4.402**	7.835***	4.656***
	(0.7325)	(0.7115)	(1.706)	(0.7155)	(1.664)
Time	−0.001409	−0.02006	0.07591*	−0.004825	0.06824
	(0.02140)	(0.02158)	(0.04158)	(0.02090)	(0.04055)
N	47	45	31	47	31
R^2	0.0001	0.0197	0.1031	0.0012	0.0890

Standard error in brackets.
* denotes significance given a significance level of 10%.
** denotes significance given a significance level of 5%.
*** denotes significance given a significance level of 1%.
Years where losses were nil have not been taken into account.
The assumption of a normal distribution of residuals is not fulfilled in Models 1, 2 and 4. Only trend model 3 is significant. For estimation purposes, we initially transformed the annual adjusted losses using the natural logarithm. Nine years in which no losses were recorded have not been taken into account. Transformed losses estimated using the ordinary least squares method are based on the following trend function:

$$\ln\left(\text{loss}_{2005,y}\right) = \alpha + \beta \cdot \text{time}_y + \varepsilon_y$$

$Loss_{2005,y}$ is the annual loss in year y adjusted to economic conditions of 2005. Parameter a represents the constant. Regression parameter β shows degree and direction of influence of explanatory time trend variable time_y, ε_y being the error term (source: author).

Table 4
Average rates of increase based on average annual loss per phase of the Atlantic Multidecadal Oscillation (AMO).

	1950–2005		1971–2005	
	Loss in US$ million (US$ 2005)	Adjusted loss in US$ million (US$ 2005)	Loss in US$ million (US$ 2005)	Adjusted loss in US$ million (US$ 2005)
Average annual loss per AMO phase				
Warm phase 1950–1970[a]	2217	8420		
Cold phase 1971–1994			3897	5354
Warm phase 1995–1970[a]	22,788	23,053	22,788	23,053
Average annual rate of increase	0.04	0.02	0.05	0.04
Average annual rate of increase (excl. Katrina)	0.03	0.01	0.03	0.02

The very high losses caused by Hurricane Katrina (2005) have a significant impact on the average loss figure for the current warm phase and thus on the average rates of increase. For this reason average annual rates of increase excluding the impact of Katrina (2005) are also given (source: author).
[a] The last complete warm phase was the period 1926–1970. Since 1995, the North Atlantic has been in another warm phase.

[10] There is a slight divergence in US storm data for 1950–2005 between Pielke et al. (2008) and NatCatSERVICE®. A number of storms are not found in both datasets, and have therefore not been included in the comparison: Storms Danielle (1980), Barry (1983), Arlene (2005) and Tammy (2005).
[11] The Donna loss is made up of three constituent events, referred to as Donnas I, II and III.

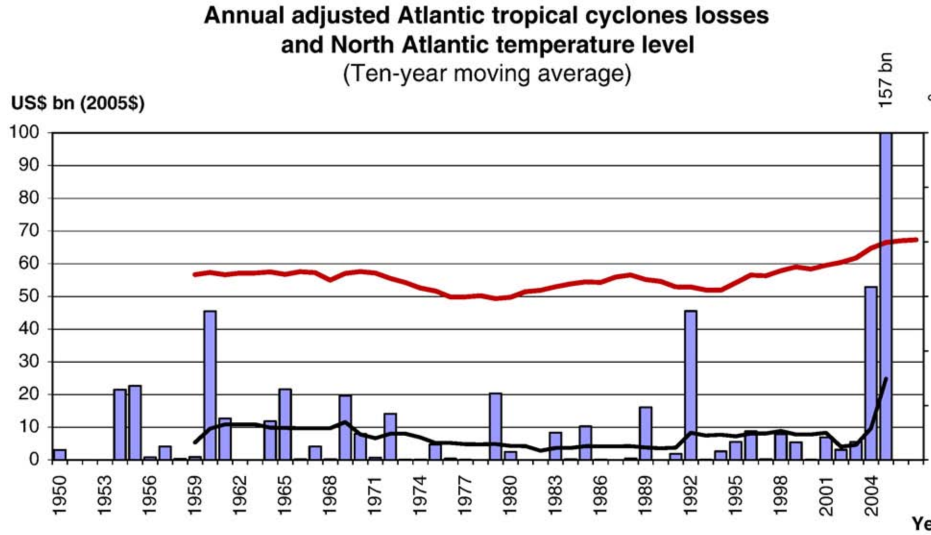

Fig. 6. Annual adjusted losses caused by Atlantic tropical cyclones that made landfall in the USA in US$ bn (US$ 2005). The ten-year average broadly follows the cycle of natural climate fluctuations (AMO) (ten-year average of mean sea surface temperature) (source of sea surface temperature: NOAA, 2007; loss data source: author).

In view of a 15% discrepancy in the resulting annual adjusted losses between the approaches described in Pielke et al. (2008) and in this paper, the approaches are not particularly dissimilar from each other.

7. Conclusion

Economic losses caused by natural catastrophes and particularly by tropical cyclones continue to increase in the USA. The issue under consideration was whether the increase in losses can be explained solely by socio-economic factors such as population and wealth increases in the regions affected or whether climate change is a substantial factor. This paper set out to establish the potential impact that climate change as a whole (due to natural and anthropogenic forcings) has on loss trends. The IPCC states that humans have, “more likely than not”, contributed to the trend towards intense tropical cyclone activity since the 1970s. Therefore, any increase in losses could, more likely than not, be partly related to anthropogenic climate change.

Our initial approach was to adjust storm losses for various years to a comparable socio-economic level before subjecting them to a trend analysis.

Essentially, the following have to be taken into account:

- The generally very limited availability and quality of long-term loss data.
- The lack of a standard method for assessing natural catastrophe losses. As a result, data on a given loss vary depending on the source. We use loss data from Munich Re's NatCatSERVICE® natural catastrophe database. This database has used a constant evaluation method since 1974. This method is also used to evaluate pre-1974 losses.

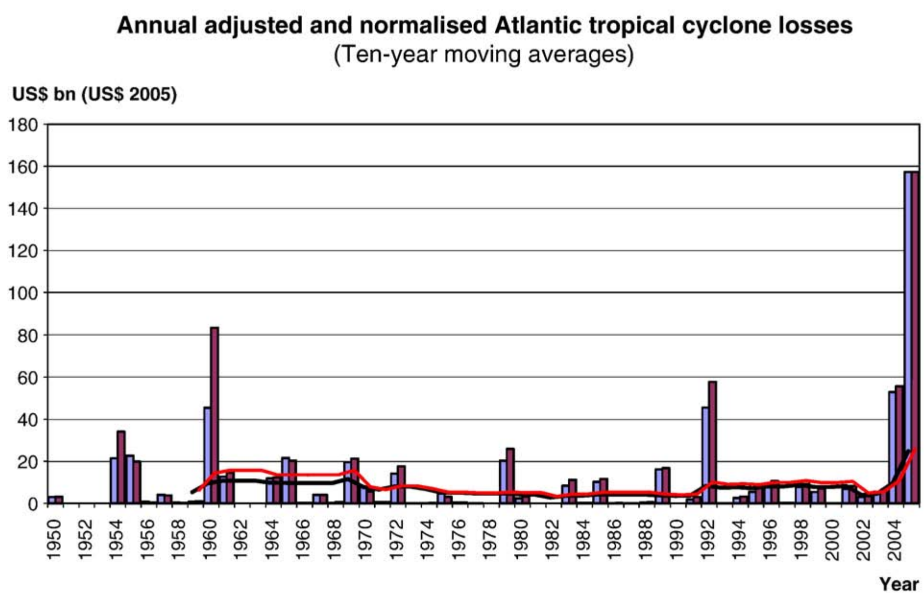

Fig. 7. The blue columns show the annual losses adjusted by the change in the capital stock of the affected region (ten-year average in black). The red columns show the annual losses normalised in accordance with the Pielke et al. (2008) method (ten-year average in red). The difference compared with Figs. 4 and 6 is that, in this instance, only 109 windstorms are taken into account (source: author). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

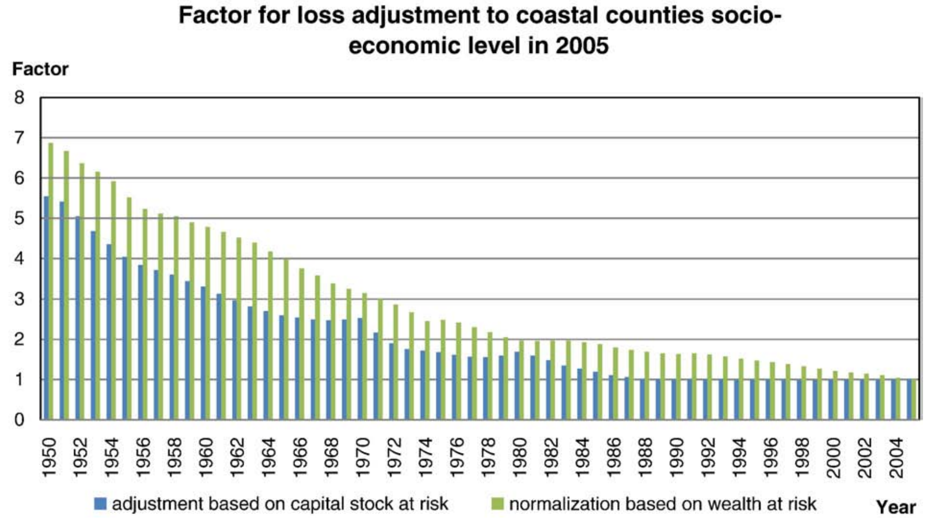

Fig. 8. Blue bars show the factors applied for adjustment of losses to 2005 socio-economic level based on capital stock at risk (e.g. losses in year 1962 will be multiplied by factor 3). Green bars show the factors applied based on wealth at risk (population in 177 coastal counties and real wealth per capita). Losses adjusted by wealth at risk will be higher than adjusted by capital stock at risk (data source: real wealth per capita from Pielke et al., 2008; population in coastal counties as applied in Pielke et al. (2008) provided by J. Gratz; data on capital stock at risk: author). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- The assumptions made regarding adjustment to eliminate socio-economic developments have considerable impact on the results. There is no agreed method for loss normalisation yet.
- The stochastic nature of storms makes it difficult to obtain valid analyses. Depending on landfall location, region affected and the varying natural storm manifestations, annual losses can be highly volatile.

Despite these limitations, we believe there is at least evidence to suggest that climatic change as a whole, due to both natural variability and anthropogenic forcings, does have an impact. For example, annual adjusted losses since the beginning of the last cold phase (1971) show a positive trend, with an average annual rise of 4% that cannot be explained by socio-economic components. This increase can at least be interpreted as a climate variability impact. There is no evidence yet of any trend in tropical cyclone losses that can be attributed directly to anthropogenic climate change. But we advance the premise that if losses are affected by natural climate fluctuations, they are also likely to be affected by additional global warming due to anthropogenic climate change. This premise is supported by indications that the intensity of tropical cyclones is affected by anthropogenic climate change. The destructive force of tropical cyclones has been increasing globally since the mid-1970s. This increase correlates very closely with the sea surface temperature (SST) (cf. Emanuel, 2005; Hoyos et al., 2006; IPCC, 2007a; Webster et al., 2005). According to Barnett et al. (2005) there is already a link between global warming and temperature increases in the uppermost levels of the ocean (see also Elsner, 2006; Mann and Emanuel, 2006). They looked at the past 40 years, in which they already found a very significant impact.[12]

Acknowledgements

The authors are grateful for useful comments and suggestions provided by Laurens Bouwer, Eberhard Faust, Roger Pielke Jr., Boriss Siliverstovs and two anonymous reviewers. All responsibility for the text lies with the authors.

[12] 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. Bengtsson et al., 2007; Chan, 2006; Emanuel et al., 2008; Knutson and Tuleya, 2004; Wang and Lee, 2008).

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