Deutsches Institut für
Wirtschaftsforschung

DIW BERLIN

Discussion Papers

802

Silvio Schmidt • Claudia Kemfert • Peter Höppe

Tropical Cyclone Losses in the USA and the Impact of Climate Change: A Trend Analysis Based on a New Dataset

Berlin, June 2008

IMPRESSUM

DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin
Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
http://www.diw.de

ISSN print edition 1433-0210
ISSN electronic edition 1619-4535

Available for free downloading from the DIW Berlin website.

Discussion Papers of DIW Berlin are indexed in RePEc and SSRN.
Papers can be downloaded free of charge from the following websites:

http://www.diw.de/english/products/publications/discussion_papers/27539.html
http://ideas.repec.org/s/diw/diwwpp.html
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=1079991

Tropical cyclone losses in the USA and the impact of climate change

A trend analysis based on a new dataset

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

Abstract

Economic losses caused by tropical cyclones have increased dramatically. It can be assumed that most losses are due to increased prosperity and a greater tendency for people to settle in exposed areas, but also that the growing incidence of severe cyclones is due to climate change. 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 2005 socio-economic values so that any remaining trend cannot be ascribed to socio-economic developments. In the period 1971–2005, losses excluding socio-economic effects show an annual increase of 4% per annum.

Keywords: Climate change; tropical cyclones; loss trends.
JEL Code: Q54, Q50, Q51

[a] Humboldt University, Berlin and Munich Re Group, Munich, Germany, e.mail:sischmidt@munichre.com
[b] German Institute of Economic Research and Humboldt University, Berlin, Germany, e-mail: ckemfert@diw.de
[c] Munich Re Group, Munich, Germany, e-mail: phoeppe@munichre.com

1 Introduction

The number of tropical cyclones that make landfall on the US Gulf and Atlantic coasts has increased significantly.[d] Cyclones are also causing greater economic losses in the form of loss or damage to material assets, as shown by Figures 1 and 2. Figure 3 indicates the main factors behind the observed increase in frequencies and losses. The principal causes are socio-economic developments (cf. Berz, 2004 and IPCC, 2007a and 2007b), and 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, as again confirmed by the latest IPCC report.[e] The report indicates it is more probable than not that humans are in part responsible for the observed rise in tropical storm activity in a number of regions (cf. IPCC 2007a).

We have not so far been able to clarify what proportion of losses is already attributable to natural and anthropogenic climate change (cf. IPCC, 2007b). According to Höppe and Pielke Jr. (2006), this is mainly due to the stochastic nature of weather extremes, the length of the available time series, the inferior quality of some time series data and the parallel impact of socio-economic and climate-related factors on the loss data. It is, therefore, difficult to obtain valid quantitative results.

One way of obtaining clearer information is to exclude socio-economic impacts from the losses, thus enabling us to identify potential trends that may be due to climate change.

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, tending instead to indicate a new exposure situation very probably due to the impact of climate change.

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

---

[d] 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.

[e] Climate change is understood to refer to that due to natural and anthropogenic causes. We use the term “natural climate change” to designate climate fluctuations not attributable to human influence on the earth’s climate system but caused by the system itself. Anthropogenic climate change results from greenhouse gas emissions caused by humans which increase atmospheric greenhouse gas concentrations and in turn result in global warming. Changes in climatic conditions due to global warming lead to changes in the incidence of weather extremes.

losses with reference to trends in per capita wealth, inflation and population. A trend analysis 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 the climate-change factor is already 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 shows the flow of goods and services, is only suitable as a means of evaluating natural catastrophe losses to a limited extent (cf. Steiniger 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 Jr. et al. (2007) 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 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 Jr. 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 Jr. and Landsea's (1998) approach a stage further by substituting the change in the number of residential units for the change in population.
The losses are then adjusted according to the change in wealth per residential unit.

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 of all US counties in which a storm caused substantial losses. Our method is founded on the papers by Pielke Jr. and Landsea (1998), Collins and Lowe (2001) and Pielke Jr. et al. (2007), referred to above.

The adjustment per storm j can be described as:

$$Loss_{2005,j} = Loss_{y,j} \cdot \left(\frac{Capital\_stock_{2005,j}}{Capital\_stock_{y,j}} \right) \quad (1)$$

$Loss_{2005,j}$ storm j losses adjusted to socio-economic conditions in 2005

$Loss_{y,j}$ inflation-adjusted losses from storm j with the socio-economic conditions of year of occurrence y.

$Capital\_stock_{2005,j}$ Value of all material assets in 2005 in the US counties affected by storm j

$Capital\_stock_{y,j}$ 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 ($capital\_stock_{2005,j}$) to actual capital stock in the year of occurrence ($capital\_stock_{y,j}$). The adjusted losses thus obtained provide better comparability as they are no longer affected by the socio-economic conditions obtaining in the different years.

This is a significant improvement on Pielke Jr. et al. (2007) in two respects. Firstly, Pielke Jr. et al. (2007) take socio-economic effects into account only on the basis of evolution in population and wealth in the worst hit counties, i.e. normally those located right on the coast, where storm intensity is greatest. The impact of socio-economic developments on the losses is thus likely to be overstated because the growth in population and values is particularly dynamic on the US coast. On the other hand, the trend has been less positive or even negative in the hinterland. If losses are adjusted to a comparable socio-economic level based only on developments along the coast, the evolution imputed to the region as a whole will be too dynamic and the adjusted losses overestimated. 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 was exceeded.

Secondly, wealth differences within the USA are taken into account. This is possible through a 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, in our approach capital stock serving as an approximation of level of wealth. Wealth differences are relevant since they take account of the different wealth levels of the individual US states, a factor not addressed by the Pielke Jr. et al. approach. It was not possible to do so because the change in per capita wealth was based on national figures about fixed assets and consumer durable goods (as an approximation of the level of wealth) in this approach.

Like Pielke Jr. et al.'s (2007) 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.

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 1,756 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:

$$Capital\_stock_{2005,j} = \sum_{i=1}^{I} \Big(\big(residential\_units\_in\_counties\_beneath\_wind\_field_j \big)_{2005,i} \cdot median\_value_{2005,i} \Big) \quad (2)$$

$$Capital\_stock_{y,j} = \sum_{i=1}^{I} \Big(\big(residential\_units\_in\_counties\_beneath\_wind\_field_j \big)_{y,i} \cdot median\_value_{y,i} \Big) \quad (3)$$

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 (Bureau of the Census, 1993, und 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). 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 we have extrapolated.

It should be noted that one drawback encountered when using the capital stock factor to eliminate socio-economic effects from losses is that storm losses largely relate to the cost of building repairs. It is not unusual for a building to be completely destroyed, but the bulk of a storm's loss usually is related to the cost of building repairs. The loss thus depends more on the relevant material and labour costs than on property prices. Capital stock is used because of a lack of data and to reduce complexity.

A further disadvantage of the capital stock factor is that the calculations are based only on the price and number of residential units, so that neither asset values within those units nor infrastructure facilities, industrial and office buildings are taken into account. We accordingly assume that their value changes in line with that of the residential units.

Despite these drawbacks, we believe that the value of residential units provides a reasonable approximation of regional capital stock, particularly since data availability is limited and this method means that regional wealth differences can 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 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).

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.[f] 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 2,000 years and all loss events since 1980.[g] 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 and Munich Re, 2006). Information provided by the Property Claims Service (PCS) is key to NatCatSERVICE® estimates of US tropical cyclone losses.

As shown in Figure 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

---

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

[g] 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).

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 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. The following information is available on each: region affected shown as counties affected, wind speed at landfall and hurricane intensity categories (Saffir-Simpson Scale), population figures and capital stock in the affected region, total direct material losses and insured losses. To adjust the loss figures and perform the subsequent trend analysis, we use only the capital stock data for the region affected. Population, hurricane category and insured loss details have not been used in the analyses for this paper.

A number of storms made landfall several times, i.e. after initial landfall, the storm returned to the open sea before making two or three subsequent landfalls. We have divided storms of this type into their constituent phases, since their condition changes as they draw further energy from the warm surface of the sea. The dataset is thus made up of a total of 131 storm events. We have broken down the overall losses from storms with several landfalls into individual occurrences.[h]

4 Adjustment results

The adjustment procedure will now be repeated 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$ 6,192m (US$ 2005) in all. Based on 2005 values, the

---

[h] The breakdown was carried out by determining the affected region for 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 (PCS). The total loss figures from NatCatSERVICE® were split in accordance with that ratio. NatCatSERVICE® itself only has aggregate storm loss details. It was not possible to break down the figures for a number of storms, for instance, if the storm made landfall twice in the same state or if the loss was below the threshold at which storms are recorded in PCS's catastrophe history.

capital stock 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$ 9,075m.

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. Figure 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$ 6,977bn (US$ 2005). Taking the increase in the value of material assets into account, that figure rises to US$ 9,980 (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).

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):

$$\ln\left(Loss_{2005,y}\right) = \alpha + \beta \cdot time_y + \varepsilon_y \qquad (4)$$

Year y losses adjusted to 2005 ($Loss_{2005,y}$) 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:

$$w = \left(\frac{Loss_{2005,n}}{Loss_{2005,1}} \right)^{1/(n-1)} - 1 \qquad (5)$$

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. Faust, 2006, 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 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. Figure 5 shows this linear trend for the logarithmised annual adjusted losses. Hurricane Katrina's exceptionally high losses (2005) would be expected to affect the average growth rate. However, if we eliminate the losses from Katrina, we are still left with an annual increase of 2% for the period 1971–2005, although the effect of the factor *time* is not 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).

6 Discussion

The trend function is not 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 Figure 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) and 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– -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)[i]. Average annual adjusted losses during warmer phases are thus much higher than during colder phases, an indication, at least, that natural climate fluctuations have an impact on losses. The effects of natural climate fluctuations can also be seen in Figure 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.[j]

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

---

[i] Faust adjusted loss data from NatCatSERVICE® and from Pielke Jr. et al. (2007) using the Pielke Jr. et al. (2007) method.

[j] 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.

period. Thus, the annual increase in losses cannot, for the most part, be explained by socio-economic factors. This is surprising since the literature assumes these to be the main loss drivers (e.g. IPCC, 2007). Miller et al. (2008) calculated an annual increase of 8% in weather-related natural catastrophe losses worldwide, whilst loss increases accounted for by socio-economic effects amounted to only 2% per year.

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.

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, 2007). 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 Jr. et al. (2007), a method we have taken a stage further. Pielke Jr. et al. (2007) 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 Jr. et al. (2007) method. We calculated the degree of normalisation for each storm in Pielke Jr. et al. (2007) 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 Jr. et al. (2007) dataset.[k]

Figure 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 Jr. et al. (2007) method are 15% higher.

The deviations are even more apparent in a number of individual cases. Thus, using the Pielke Jr. et al. (2007) normalisation factor, Donna (1960) caused a loss normalised to 2005 of around US$ 83bn, whereas the loss amount using our method is US$ 45bn.[l] Conversely, Flossy (1956) produces normalised losses of US$ 462m compared with US$ 811m using our method.

Whilst Pielke Jr. et al. (2007) base their normalisation on the more dynamic population growth along the coast, we consider losses to be influenced by socio-economic circumstances throughout the affected region as a whole. Discrepancies can be explained by these differences in adjustment technique. However, the regions which suffer most damage are located in the coastal area, where wind speeds are highest. Accordingly, the change in socio-economic conditions has far more impact on the coast than inland. One way of improving our adjustment approach would be to weight the change in each county's capital stock according to its proportion of aggregate storm losses. However, in order to do so, we would need the loss data for the individual counties, and these are not available to us.

---

[k] There is a slight divergence in US storm data for 1950–2005 between Pielke Jr. et al. (2007) 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).

[l] The Donna loss is made up of three constituent events, referred to as Donnas I, II and III.

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 already a substantial factor. This paper set out to establish the potential impact of natural and anthropogenic climate change on the increasing economic losses caused by tropical cyclones on the US Atlantic coast. 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.
- The assumptions made regarding adjustment to eliminate socio-economic developments have considerable impact on the results.
- 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 climate change 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, at any rate, must therefore be due to the impact of natural climate fluctuations, a view also corroborated by the results of other studies (cf. Emanuel, 2005, Webster et al., 2005, Faust, 2007).

If, however, the losses are affected by natural climate fluctuation one would expect additional global warming due to anthropogenic climate change to cause still further increases. Barnett et al. (2005) have established a link between global warming and temperature increases in the uppermost levels of the ocean. Faust (2006) found that North Atlantic cyclone activity was due to both natural fluctuations in sea surface temperatures and additional linear warming of the surface of the sea. The second factor can only be explained by global warming. Accordingly, the conclusion we draw is that our annual adjusted losses indicate, on the one hand, the impact of natural fluctuations and, on the other, an element that would appear to be caused by global warming.

Bibliography

Barnett, T. P., Pierce, D. W., Achuta Rao, K. M., Gleckler, P. J., Santer, B. D., Gregory, J. M., Washington, W. M. (2005): *Penetration of Human–Induced Warming into the World's Oceans, Science*, 309, pp. 284–287.

Berz, G. (2004): *Climate change: Modest warming, dramatic effects, Weather catastrophes and climate change – Is there still hope for us?*, Munich Reinsurance Company, Munich, pp. 98–105.

Bureau of the Census (1993): *1990 Census of Population and Housing. Population and Housing Unit Counts United States*, Washington D.C.

Collins, D. J., Lowe, S. P. (2001): *A Macro Validation Dataset for U.S. Hurricane Models*, Casualty Actuarial Society Forum, Arlington, VA, pp. 217–251, http://www.casact.org/pubs/formu/01wforum/01wf217.pdf, (download 07.08.2007).

Downton, M. W., Pielke Jr., R. A. (2005): *How Accurate are Disaster Loss Data? The Case of U.S. Flood Damage*, *Natural Hazards*, 35, pp. 211–228.

Emanuel, K. (2005): *Increasing Destructiveness of Tropical Cyclones over the past 30 Years*, *Nature*, 436, August, pp. 686–688.

Faust, E. (2006): *Verändertes Hurrikanrisiko*, http://www.munichre.com, (download 02.02.2006).

Faust, E. (2007): *Effects of warming Atlantic sea surfaces on tropical cyclone losses*, *Geophysical Research Abstracts*, 9, 11180, lecture given at the General Assembly of the European Geosciences Union 2007.

Faust, E., Höppe, P., Wirtz, A., Schmidt, S. (2006): *Trends in Natural Catastrophes – Potential Role of Climate Change*, Workshop on Climate Change and Disaster Losses. Understanding and Attributing Trends and Projections, edited by P. Höppe and R. A. Pielke Jr., pp. 89–102.

Hallegatte, S. (2007): *An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina*, accepted by *Risk Analysis*, http://www.centre-cired.fr, (download 07.12.2007).

Höppe, P., Pielke Jr., R. A. (eds.) (2006): *Workshop on Climate Change and Disaster Losses. Understanding and Attributing Trends and Projections*, http://sciencepolicy.colorado.edu/sparc/research/projects/extreme_events/munich_workshop/index.html, (download 11.01.2007).

Intergovernmental Panel on Climate Change (2007a): *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge and New York, www.ipcc.ch.

Intergovernmental Panel on Climate Change (2007b): *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, www.ipcc.ch.

Kemfert, C. (2007): *The Economics of Climate Change, Internationale Politik*, 62, *Februar*, pp. 38–45.

Miller, S., Muir-Wood, R., Boissonade, A. (2008): *An exploration of trends in normalized weather-related catastrophe losses*, *Climate Extremes and Society*, edited by H. F. Diaz and R. J. Murnane.

Munich Reinsurance Company (2001): *topics – Annual Review of Natural Catastrophes 2000*, Munich.

Munich Reinsurance Company (2006): *topics – Annual Review: Natural Catastrophes 2005*, Munich.

Munich Reinsurance Company (2007): *Topics Geo – Natural catastrophes 2006. Analyses, assessments, positions*, Munich.

National Oceanic and Atmospheric Administration (NOAA): *Storm track dataset*, http://maps.csc.noaa.gov/hurricanes/download.html, (download 12.01.2007).

Nordhaus, W. D. (2006): *The Economics of Hurricanes in the United States*, http://www.econ.yale.edu/~nordhaus/homepage/recent_stuff.html, (download 02.03.2007).

Pielke Jr., R. A., Crompton, R., Faust, E., Gratz, J., Lonfat, M., Ye, Q., Raghavan, S. (2006): *Factors Contributing to Human and Economic Losses,* paper presented at the International Workshop on Tropical Cyclones VI, San José, Costa Rica, Nov–Dec 2006, http://www.//severe.worldweather.org/iwtc/document.htm, (download 05.01.2007).

Pielke Jr., R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M., Musulin, R. (2007): *Normalized Hurricane Damages in the United States: 1900–2005*, submitted to *Natural Hazards Review*, http://sciencepolicy.colorado.edu/publications/special/nhd_paper.pdf, (download 11.05.2007).

Pielke Jr., R. A., Landsea, C. W. (1998): *Normalized Hurricane Damages in the United States 1925–95*, *Weather and Forecasting*, 13, 09, pp. 621–631.

Property Claims Service (PCS): *PCS Catastrophe History by State*, https://www4.iso.com/pcs, (download 14.03.2007).

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).

Steininger, K. W., Steinreiber, Ch., Ritz, Ch. (Editor) (2005): *Extreme Wetterereignisse und ihre wirtschaftlichen Folgen. Anpassung, Auswege und politische Forderungen betroffener Wirtschaftsbranchen*, Berlin, Heidelberg, New York.

U.S. Census Bureau: *Census 2000 Summary File 3*, http://factfinder.census.gov/, (download 27.07.07).

U.S. Census Bureau: *Historical Census of Housing Tables*, http://www.census.gov/hhes/www/housing/census/historic/values.html, (download 27.07.07).

Webster, P. J, Holland, G. J., Curry, J. A., Chang, H-R. (2005): *Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment*, *Science*, 309, pp. 1844–1846.

Appendix

Charts

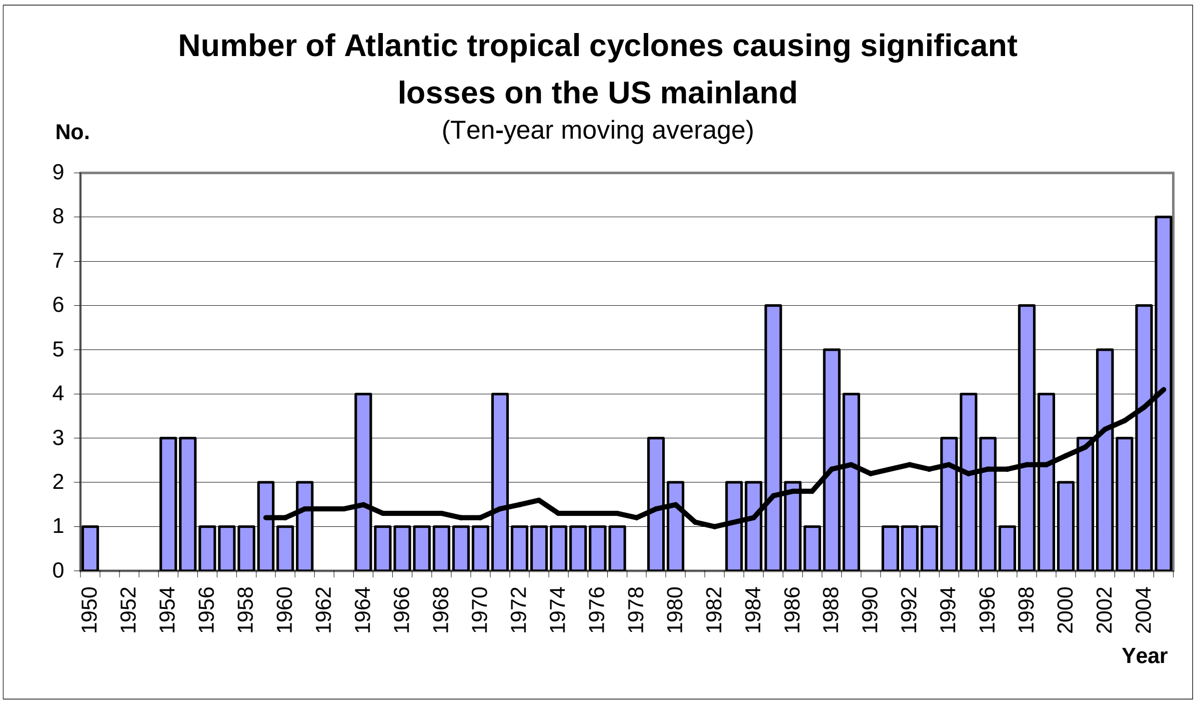

Figure 1: Annual frequencies of tropical cyclones that have caused significant losses on the US mainland (data source: Munich Re, NatCatSERVICE®, 2007; chart: author).

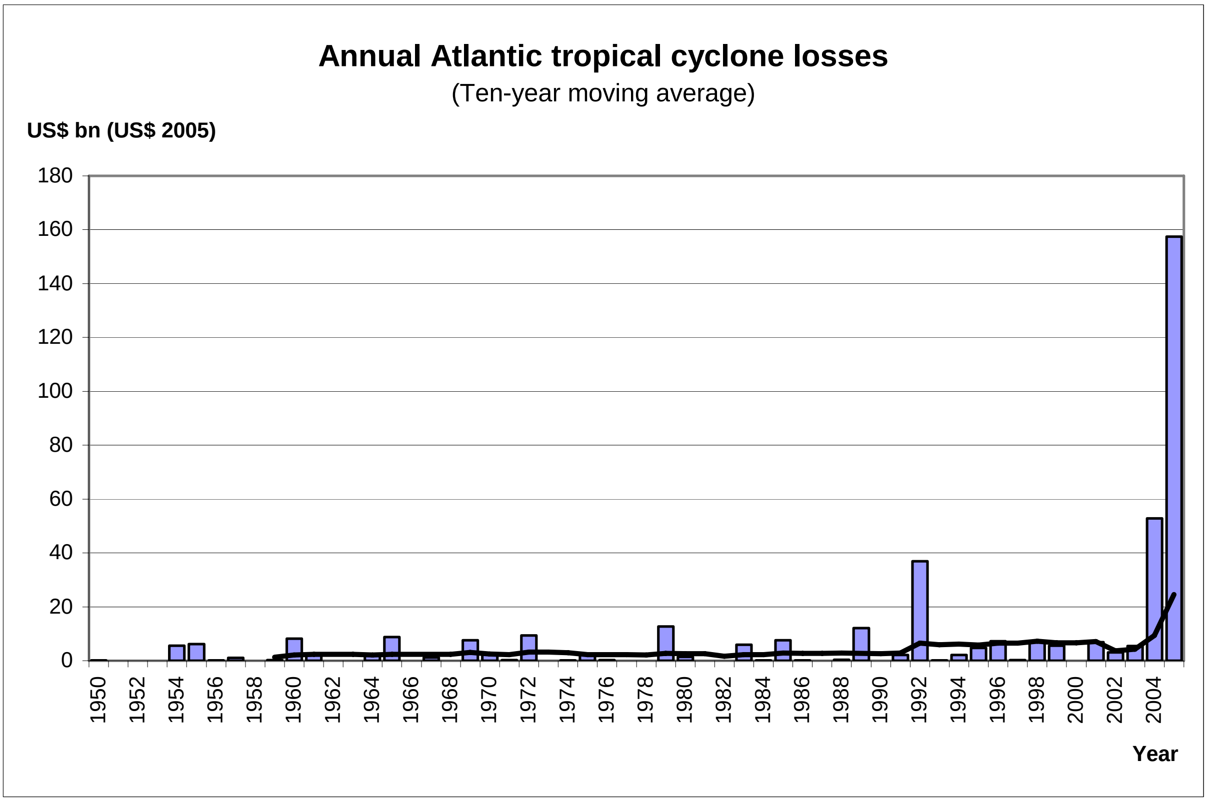

Figure 2: Annual inflation-adjusted losses caused by Atlantic tropical cyclones that made landfall on the US mainland in US$ bn (US$ 2005) (data source: Munich Re, NatCatSERVICE®, 2007; chart: author).

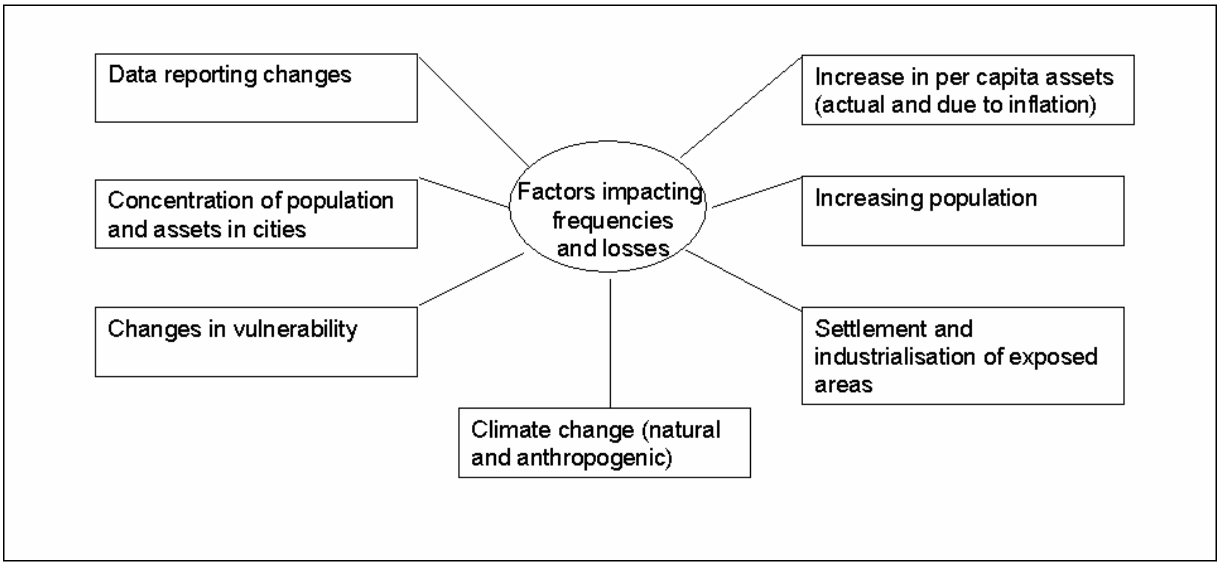

Figure 3: Principal factors that can influence the increase in tropical storm losses (source: author).

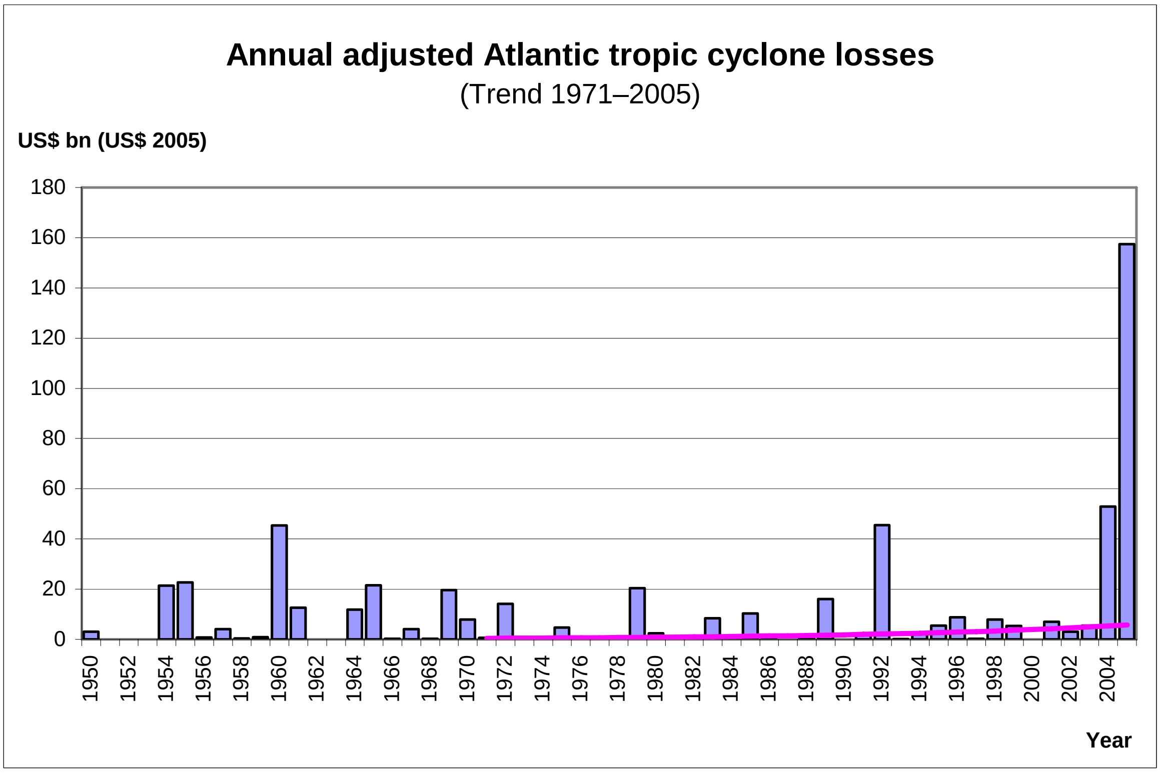

Figure 4: Annual adjusted Atlantic tropical cyclone losses that made landfall on the US mainland in US$ bn (US$ 2005) with the 1971–2005 trend (source: author).

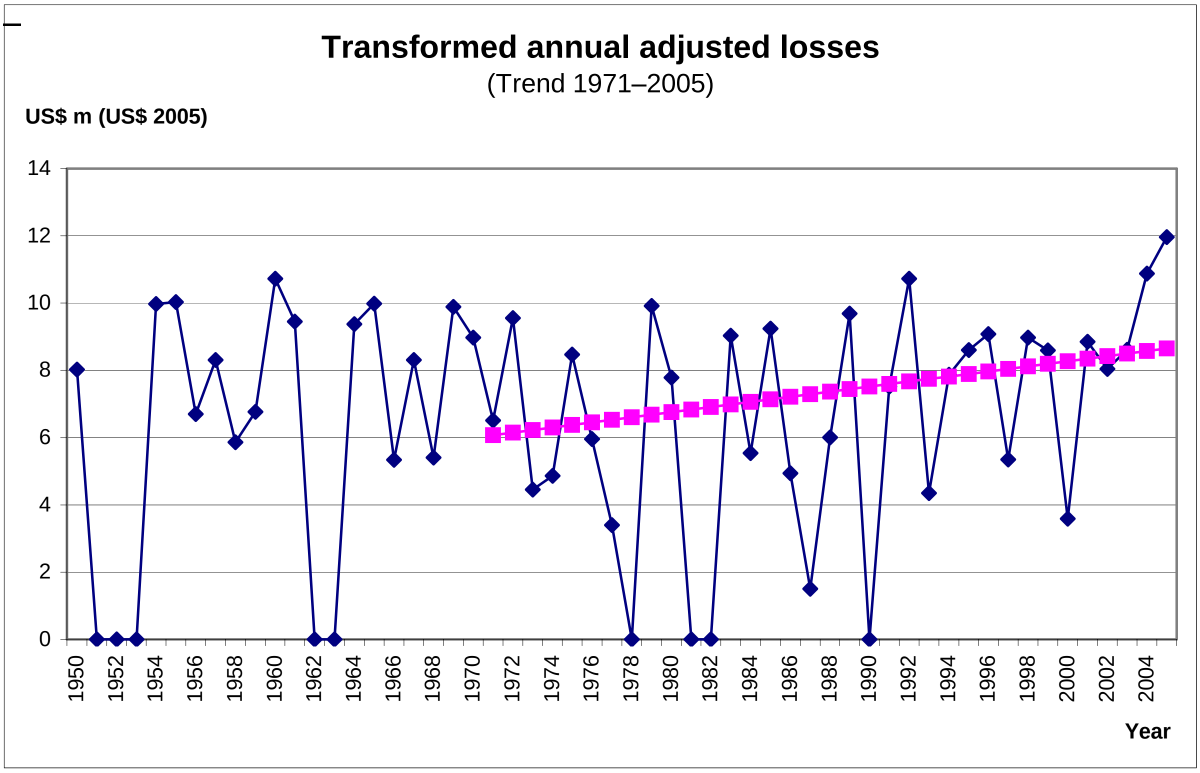

Figure 5: Annual adjusted losses transformed using the natural logarithm in US$ m (US$ 2005). A linear, statistically significant trend can be identified for the period 1971–2005 (source: author).

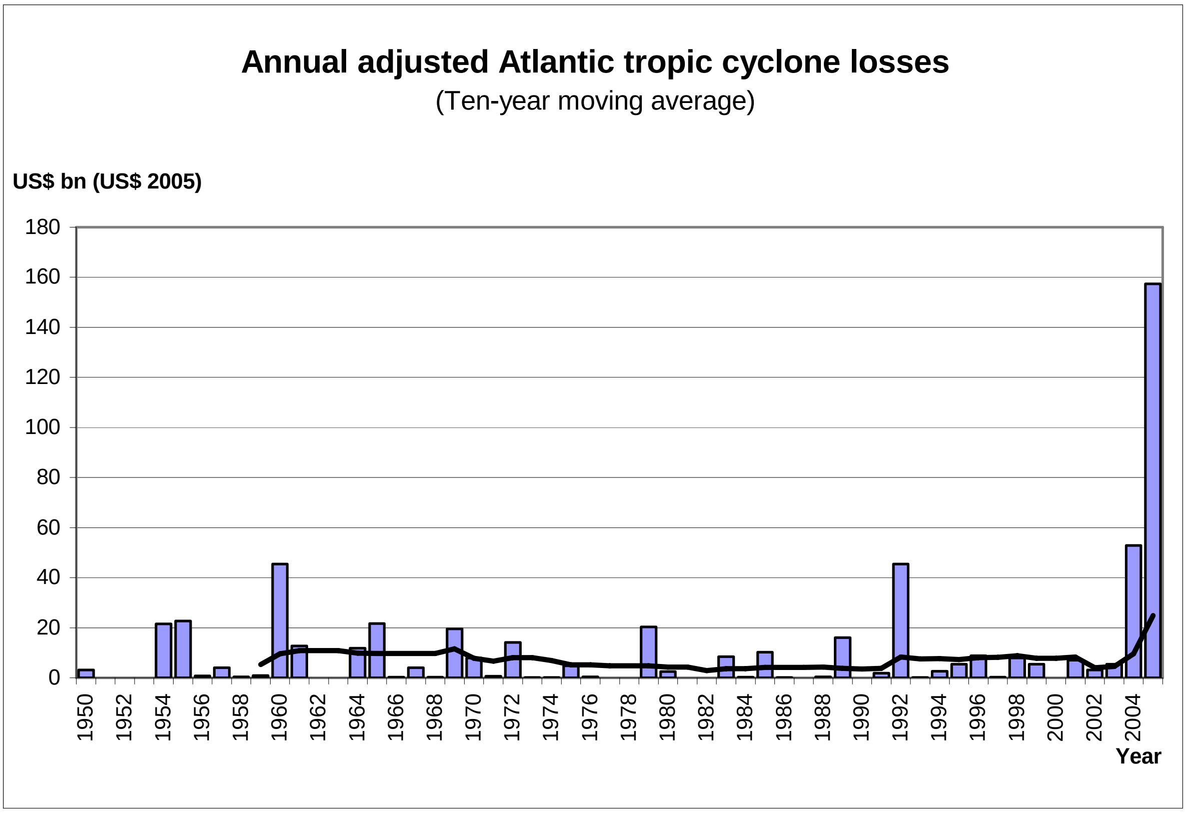

Figure 6: Annual adjusted losses caused by Atlantic tropical cyclones that made landfall in the USA in US$ bn (US$ 2005). The ten-year average broadly follows the cycle of natural climate fluctuations (AMO) made up of the warm phase up to 1970, the cold phase from 1971–1994 and a further warm phase beginning in 1995 (source: author).

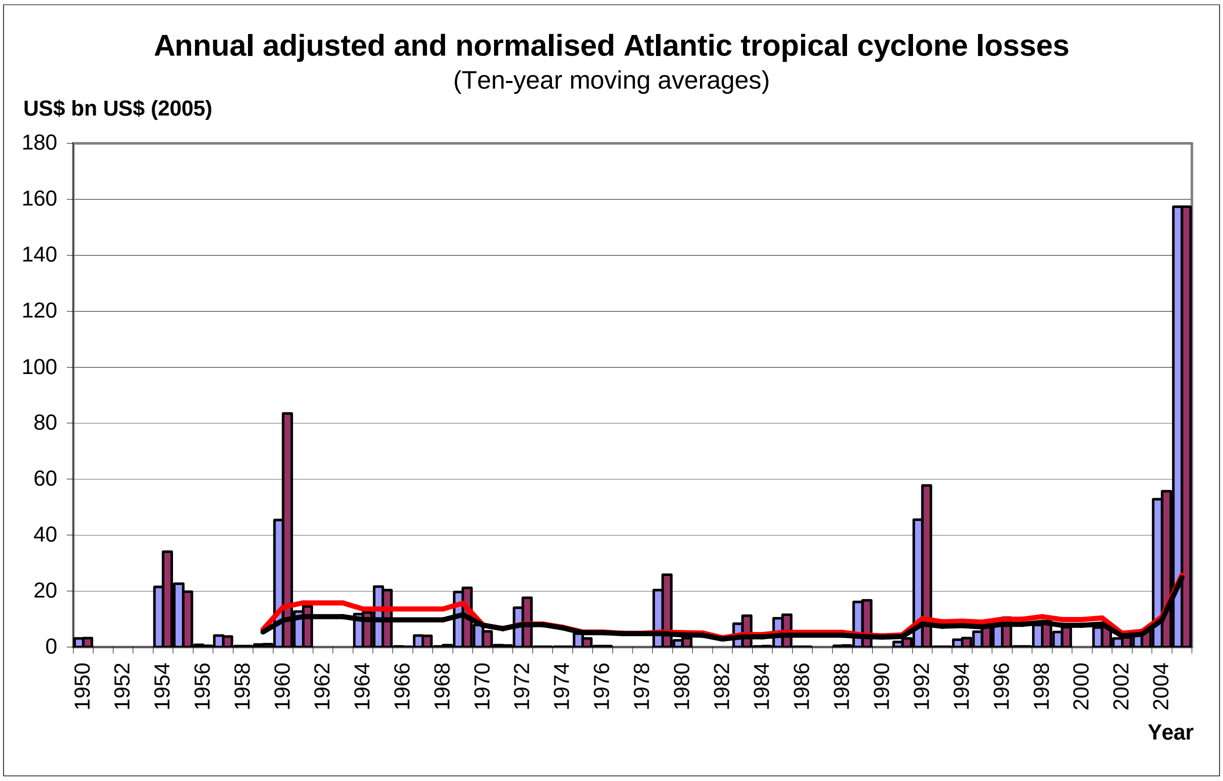

Figure 7: The blue columns show the annual losses adjusted by the change in the capital stock of the affected region (ten-year average in black). The red columns show the annual losses normalised in accordance with the Pielke Jr. et al. (2007) method (ten-year average in red). The difference compared with Figures 4 and 6 is that, in this instance, only 109 windstorms are taken into account (source: author).

Tables

Rank-ing	Storm	Date	Storm category at landfall	Losses in US$ m (US$ 2005)	Adjusted losses in US$ m (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	4,987	34,237	19
4	Hurricane Diane	20.08.1955	TS	5,834	20,694	17
5	Hurricane Camille	17.08.1969	5	7,571	19,614	12
6	Hurricane Betsy II	10.09.1965	4	8,325	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	9,084	13,345	9

13	Hurricane Carla	09.09.1961	4	2,612	12,546	25
14	Hurricane Carol II	31.08.1954	2	3,172	10,526	23
15	Hurricane Frances	03.09.2004	2	9,306	9,280	8
16	Hurricane Hazel	15.10.1954	3	2,035	9,141	33
17	Hurricane Frederic	12.09.1979	4	6,192	9,075	15
18	Hurricane Alicia	17.08.1983	3	5,886	8,354	16
19	Hurricane Jeanne	15.09.2004	3	8,272	8,241	11
20	Hurricane Fran	05.09.1996	3	6,479	7,974	14
21	Hurricane Celia	03.08.1970	3	2,286	7,931	28
22	Hurricane Dora	09.09.1964	2	1,576	7,783	38
23	Tropical storm Allison	05.06.2001	TS	6,624	6,682	13
24	Hurricane Donna III	12.09.1960	2	2,267	6,126	29
25	Hurricane David I	03.09.1979	2	2,861	5,539	24
26	Hurricane Isabel	18.09.2003	2	5,310	5,308	18
27	Hurricane Donna II	12.09.1960	2	997	5,074	46
28	Hurricane Eloise	16.09.1975	3	1,997	4,760	34
29	Hurricane Georges	20.09.1998	2	4,197	4,540	21
30	Hurricane Floyd	14.09.1999	2	4,692	4,497	20

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

Year	No. of storms	Annual losses in US$ m (US$ 2005)	Annual adjusted losses in US$ m (US$ 2005)	Ranking (original annual loss)	Ranking (annual adjusted loss)
1950	1	162	3,057	35	27
1951	0	0	0	48	48
1952	0	0	0	49	49
1953	0	0	0	50	50
1954	3	5,524	21,478	17	7
1955	3	6,177	22,645	14	5
1956	1	144	811	36	32
1957	1	1,042	4,065	29	25
1958	1	47	353	41	36
1959	2	201	872	33	31
1960	1	8,251	45,437	8	4
1961	2	2,658	12,680	21	12
1962	0	0	0	51	51
1963	0	0	0	52	52
1964	4	2,427	11,793	22	13
1965	1	8,804	21,579	7	6
1966	1	42	209	44	40
1967	1	1,171	4,078	28	24
1968	1	45	224	42	38
1969	1	7,571	19,614	10	9
1970	1	2,286	7,931	23	17
1971	4	280	670	31	33
1972	1	9,348	14,111	6	11
1973	1	44	86	43	43
1974	1	99	129	39	42
1975	1	1,997	4,760	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	1,424	2,404	27	29
1981	0	0	0	54	54
1982	0	0	0	55	55
1983	2	5,888	8,358	15	16
1984	2	124	254	37	37
1985	6	7,618	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	2,153	1,851	24	30
1992	1	36,915	45,497	3	3
1993	1	68	78	40	44
1994	3	2,110	2,611	25	28
1995	4	4,752	5,472	19	21
1996	3	7,252	8,779	11	15
1997	1	183	210	34	39
1998	6	7,230	7,869	12	18
1999	4	5,548	5,401	16	22
2000	2	34	36	45	45
2001	3	6,883	6,954	13	19
2002	5	3,057	3,110	20	26
2003	3	5,480	5,479	18	20
2004	6	52,853	52,876	2	2
2005	8	157,400	157,400	1	1

Table 2: Actual and adjusted annual Atlantic tropical cyclone losses in the USA, ranked by original and adjusted losses (source: author).

Dependent variable $\ln(loss_{2005,y})$	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*** (0.7325)	8.144*** (0.7115)	4.402** (1.706)	7.835*** (0.7155)	4.656*** (1.664)
Time	-0.001409 (0.02140)	-0.02006 (0.02158)	0.07591* (0.04158)	-0.004825 (0.02090)	0.06824 (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.				

Table 3: Results of the annual adjusted loss trend analysis. 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:

$$\ln\left(Loss_{2005,y}\right) = \alpha + \beta \cdot Time_y + \varepsilon_y$$

$Loss_{2005,y}$ 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.

	1950–2005		1971–2005	
	Loss in US$ m (US$ 2005)	Adjusted loss in US$ m (US$ 2005)	Loss in US$ m (US$ 2005)	Adjusted loss in US$ m (US$ 2005)
Average annual loss per AMO phase				
Warm phase 1950–1970*	2,217	8,420		
Cold phase 1971–1994			3,897	5,354
Warm phase 1995–1970*	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 last complete warm phase was the period 1926–1970. Since 1995, the North Atlantic has been in another warm phase.			

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