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# Simulation of economic losses from tropical cyclones in the years 2015 and 2050 – the effects of anthropogenic climate change and growing wealth

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## Abstract

This paper simulates the increase in the average annual loss from tropical cyclones in the North Atlantic for the years 2015 and 2050. The simulation is based on assumptions concerning wealth trends in the regions affected by the storms, considered by the change in material assets (capital stock). Further assumptions are made about the trend in storm intensity resulting from anthropogenic climate change. The simulations use a stochastic model that models the annual storm loss from the number of storms and the loss per storm event. The paper demonstrates that increasing wealth will continue to be the principle loss driver in the future (average annual loss in 2015 +32%, in 2050 +308%). But climate change will also lead to higher losses (average annual loss in 2015 +4%, in 2050 +11%). In order to reduce the uncertainties surrounding the assumptions on the trend in capital stock and storm intensity, a sensitivity analysis was carried out, based on the assumptions from current studies on the future costs for tropical storms.

*Keywords:* climate change, tropical cyclones, natural catastrophes, insurance

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# 1 Introduction

Since the severe storm losses in 2004 and 2005, there has been increasing speculation in the media and in the scientific world about the losses that may be expected from tropical cyclones in the future and about the role that human-induced climate change may play in this context. However, the question of what additional losses can be expected due to socio-economic trends is only seldom discussed. In other words, what will be the trends in population and material assets, and their geographical distribution in the regions impacted by storms, and what will be their impact on losses. Even more than anthropogenic climate change, it has to be expected that future increases in population and in the assets threatened by storms will lead to loss increases. This paper shows that the principle loss drivers in the future will continue to be socio-economic ones. Nevertheless, anthropogenic climate change will also lead to noticeable loss increases.

Three influencing factors need to be analysed if we are to answer the question of how future costs for tropical cyclones will develop. Firstly, the change in the risk situation that may result from climate change. In other words, the change in frequency and regional distribution of the storms, as well as any increase in their intensity. Secondly, any change in the susceptibility to storms of people and material assets, or what is known as their vulnerability. Thirdly, we need to analyse at the increase in material assets and population that is at risk from the storms, or what is known as exposure.

The simulations in the study are based on a stochastic model that simulates an average annual loss. The model comprises two components. The first component determines the number of storms` in a particular year. The second component determines the loss for each of these storms. The annual loss is obtained from the number of storms and the individual loss per storm, as the sum of two random processes. The high variability in the annual storm loss that can be seen in reality is thus simulated through the variation in the number of storms per year and the variation in the individual loss. By way of example, the model is applied to losses from tropical cyclones in the USA. An average annual storm loss is simulated for the US coastline along the Atlantic and Gulf of Mexico, such as might arise under the conditions expected for the years 2015 and 2050. The conditions for future storm losses are determined by assumptions about the increase in material assets in the cyclone-prone regions (exposure), as well as assumptions about the change in the risk situation (frequency and intensity of the cyclones) as the result of global warming. The susceptibility of the exposed material assets to cyclones (vulnerability) is assumed to remain constant. A supplementary analysis simulates the average annual loss that results for three different storm categories: light, weak to moderate, and strong to devastating.

On the one hand, this paper provides an additional module for research into the additional costs of tropical storms caused by anthropogenic climate change. In addition, it addresses the question of the overall cost of future storms, both as a result of anthropogenic climate change, and from the future increase in material assets in the storm-prone regions. The IPCC believes the increase in material assets will represent a key factor for future storm losses (cf. IPCC, 2007b). However, apart from Pielke Jr. (2007), and Pielke Jr. et al. (2000), no quantitative studies have been carried out up to now.

The paper is structured as follows: the following section gives an overview of the status of research into the change in the risk situation (frequency, regional occurrence, and intensity of tropical cyclones) as a result of global warming, the level and change in vulnerability, and the increase in material assets and population in the storm-prone regions of the USA. After that, we shall present the model, and the loss data it is based on. Section four describes the assumptions and the results of the simulation of the average annual loss in 2015 and 2050. The simulations are based on increases in storm intensity of 0.9% (2015) and 3% (2050), as well as on increases in the material assets at risk of 36% (2015) and 297% (2050). The following section looks at the uncertainties surrounding the various assumptions. These include uncertainties about the change in the risk situation, the trend in capital stock (material assets) in the storm-prone regions, and the relationship between storm intensity and the resulting loss (vulnerability). For this sensitivity analysis, the model was based on assumptions from three current studies that also analyse the future cost of tropical cyclones using three different methods. In section six, we divide the storms into light, weak to moderate, and strong to devastating storms, and repeat the simulations for these three categories. The paper ends with conclusions on the significance of the results for insuring losses from tropical cyclones.

## 2 Overview of the status of research

In order to answer the question of what loss amount could result from tropical cyclones in the year 2015, or 2050, assumptions need to be made about the change in the risk situation (frequency, regional distribution and intensity of storms), the level of and change in susceptibility to such storms (vulnerability), and the change in material assets at risk from the storms (exposure situation).

## 2.1 Change in the risk situation

The risk situation from tropical cyclones covers their occurrence (frequency and regional distribution) and the intensity of the storms. Among other things, climate change affects ocean temperature, the atmosphere, and the circulation and evaporation of water. The changes it gives rise to could affect tropical cyclones. However, the relationships are complex and are not fully understood at this point in time (cf. Wang and Lee, 2008).

For example, there is no current consensus on how the global number of tropical cyclones might change as a result of global warming (cf. WMO, 2006, IPCC, 2007a, Knutson et al., 2008). The results of a survey of storm experts conducted by Pielke Jr. (2007) on the expected change in frequency for 2100 (2050) range from a predicted 40% (20%) reduction to a 40% (20%) increase. For the Atlantic, Bengtsson et al. (2007) expect the frequency of the storms to remain constant (see also IPCC, 2007a). In contrast, Emanuel et al. (2008) calculated a slight increase in the number of storms in the Atlantic. Similarly, there has been no consensus so far among storm experts on what changes might occur in the tracks of tropical storms, or what shifts there might be in the regions affected (cf. WMO, 2006).

On the other hand, there are clearer indications that global warming is leading to an intensification of the storms. For example, the destructive force of tropical storms in most of the oceans has been increasing since the mid 1970s. This increase correlates strongly with the sea surface temperature (SST) (cf. Emanuel, 2005a, Hoyos et al., 2006, IPCC, 2007a, Webster et al., 2005). According to Barnett et al. (2005), there is in turn a connection between sea surface temperature and anthropogenic emissions of greenhouse gas (see also Elsner, 2006, Mann and Emanuel, 2006). Barnett et al. have already been able to determine a very significant impact over the last 40 years. If the oceans continue to warm up, storms may therefore be expected to become more intense (cf. IPCC 2007a, WMO, 2006). However, the sea surface temperature is not the only factor that influences intensity. Other factors, such as wind shear, may even be more significant. If this is factored in, the result for the Atlantic by the end of the 21st century is a 7.4% increase in intensity (Emanuel et al., 2008), or an increase in wind speeds of roughly

6% (Bengtsson et al., 2008, Knutson and Tuleya, 2004).[1] According to Vecchi et al. (2008), with anthropogenic climate change, the interaction between the ocean basins on a global scale is crucial for understanding the effects in the tropical Atlantic. With this approach, the overall effect of Atlantic storm activity actually remains unchanged, because the different factors cancel one another out. Predictions about the change in intensity among the storm experts interviewed in Pielke Jr. (2007) vary from 0% to 36% (0% - 18%) for the year 2100 (2050).

## 2.2 Change in vulnerability

Vulnerability denotes how susceptible people and material assets are to storms. It indicates, for example, how well early warning systems and catastrophe prevention measures operate. But it also looks at how well construction standards are implemented for risks from storms, rain and storm surge. The impact of hurricane Katrina in August 2005 illustrates the vulnerability of infrastructure and municipal systems, whose safety standards proved inadequate to cope with this event (cf. IPCC 2007b).

The degree of change in loss for just a marginal change in wind speed clearly shows how susceptible people and material assets are in the face of storms. The loss susceptibility can be thought of as the elasticity of losses to wind speed (see Schmidt et al., 2009b). In equation 1, this elasticity is determined via the parameter *el* in the loss function based on Howard et al. (1972).

$$x_j = \alpha \times ws_j^{el} \tag{1}$$

The loss $x_j$ from storm $j$ is a function of wind speed $ws_j$. $\alpha$ is a constant, *el* is the parameter for elasticity.

There are various estimates in the literature for the degree of this elasticity *el*. Earlier economic papers, such as those incorporated in the Second Assessment Report of the IPCC, assume low elasticity. Cline (1992) assumes a linear increase in the loss relative to wind speed. Fankhauser (1995), on the other hand, anticipates a 1.5-fold increase. In Tol (1995), the loss increases by two units for every one-unit increase in wind speed. More recent economic papers assume higher elasticity. The correlation between wind speed and loss should at least correspond to a cubic function (cf. Hallegatte, 2007, Schmidt et al., 2009b, Stern et al., 2006).

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[1] In addition to maximum wind speeds, intensity also encompasses the duration of the storms.

Howard et al. (1972) arrive at a figure of 4.36. Nordhaus (2006) quotes insurance studies that assume a elasticity of between 4 and 6, while he himself calculates elasticity as 8.5.

The level of elasticity changes over time since vulnerability changes too. However, it is difficult to quantify this change. Vulnerability is subject to very different influences, which in some cases have opposite effects. One example of this is the improvement in building construction standards and the simultaneous increase in settlement in the storm-prone coastal areas. Hallegatte (2007) finds for the USA that there is a general increase in vulnerability over time, but that there is a reduction after a storm has struck. However, Jain et al. (2005) illustrate that the vulnerability of buildings decreases over time. This indicates that an improvement in construction standards positively influences the loss susceptibility of the buildings.

Pielke Jr. (2007) assumes constant vulnerability over time. Thus a twofold increase in the material assets affected by storms results in a doubling of the losses. In view of the complexity of the subject of vulnerability, many economic studies assuming constant vulnerability (see for example Cline, 1992, Fankhauser, 1995, Nordhaus, 1996, Tol, 1995). We shall adopt the same approach in this paper.

### 2.3 Change in material assets at risk (exposure)

The size of direct economic storm losses depends primarily on the volume of material assets in the region affected by the storm. In turn, the amount of material assets at risk from storms basically depends on trends in population figures, the economic wealth, and settlement distribution.

There have been very few quantitative analyses so far to determine the extent to which such socio-economic trends will contribute in future to additional losses. The main focus of research has been clearly on the additional cost of anthropogenic climate change. Admittedly, the IPCC believes that the increase in material assets exposed to tropical storms represents a key factor for future losses (cf. IPCC, 2007b). However, an estimate of such additional costs can only be found in Pielke Jr. et al. (2000), and Pielke Jr. (2007). In his 2007 study, Pielke Jr. applies two scenarios. The scenario with a slow increase in population and wealth assumes that the population and level of wealth in the region threatened by storms will be higher by a factor of 2.8 in 2050 compared to 2006. For the scenario with more rapid socio-economic development, a level is assumed that is seven times higher. These assumptions about the level are with annual socio-economic growth of 2.5% or of 4.9%.[2] Average estimates for the future expect the world population to increase by 1% and the per capita gross domestic product (GDP) by approximately 2.5% per annum. This gives annual socio-economic growth of 3.5%, a value that lies between the two scenarios (cf. Pielke Jr., 2007). The empirical data the author uses on population and wealth in the storm-prone coastal countries of the US give a growth figure for population and wealth for the period 1950-2005 of 4.1% per year (without inflation) (cf. Pielke Jr., 2007).[3]

## 3 Method

A stochastic model that calculates an average annual loss from a large number of generated annual losses is used as the basis for the simulations in this paper. The model consists of two components. The first component determines the number of loss events. In our case, this is the number of storms in the space of a year. The second component determines the individual loss amount for each of the separate loss events. This represents the loss per storm. The annual loss is obtained from the number of events and the individual loss per event, as the sum of two independent random processes. The high variability in the annual storm loss that can be observed in reality is thus recreated through the variation in the annual number of storms, and the variation in the individual loss. The method described in the model is normally selected in insurance mathematics if the expected loss amount needs to be calculated from several loss events, and where the number of losses and the loss amount for the individual cases is uncertain. The model described here is similar to a model presented by Katz (2002) for simulating tropical storm losses. Rootzén and Tajvidi (1997) applied a comparable method for extratropical storm losses.

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[2] As is usual, no account is taken of the effect of inflation. The figures in Pielke Jr. (2007) are in 2006 prices (US$ 2006).

[3] Official data is only available for population trends in the counties of the USA, but not for the trend in economic wealth (Bureau of Economic Analysis, in writing 23.08.2006). Pielke Jr. therefore bases the calculation of the combined growth in population and wealth in the coastal regions on data on the national per capita level of wealth (cf. Pielke and Landsea, 1998, Pielke Jr. et al., 2008).

## 3.1 Model description

### 3.1.1 Frequency

The number of cyclones is characterised by the random variable *N(t)*, with the random number of storms within the time interval [0;*t*]. It is assumed that the random variable *N(t)* is Poisson distributed (cf. also Katz, 2002, Nordhaus, 2006, Hallegatte, 2007). The probability that precisely *k* storms occur within the time interval is therefore:

$$\Pr\{N(t)=k\}=\frac{\mu^k}{k!}\exp^{-\mu} \tag{2}$$

The parameter $\mu$ corresponds here to the expected value for the number of storms within the time interval.

### 3.1.2 Loss per storm

The random variable $X_k > 0$ represents the loss that is caused by the *k*-th storm within the time interval. In reality, it can be observed that many storm events occur with small losses, while just a small number of storm events can cause major losses. This implies that the frequency distribution of the losses follows a distribution similar to lognormal distribution. This is also assumed for the distribution *F* of the random variable $X_k$. The distribution of the losses is described as follows via the density *f* of the lognormal distribution:

$$f(x)=\frac{1}{\sigma x\sqrt{2\pi}}\times\exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right) \tag{3}$$

It is furthermore assumed that the different $X_k$ are independent of one another, and that the sampling of $X_k$ is independent from the sampling of *N(t)*.

### 3.1.3 Annual loss

The loss from all storms within the time interval [0;*t*] is the total of losses for the individual storm events. For a time interval of one year, this annual loss is *D(t)*:

$$D(t)=X_1+X_2+\cdots+X_{N(t)};\ N(t)\geq 1;\ \text{otherwise}\ D(t)=0 \tag{4}$$

### 3.1.4 Model parameter

Assuming that a time series is available for the annual number of observed storms, the parameter $\mu$ required for the random process of the frequency can be calculated from $\{n_y, y=1, 2,..., m\}$. In this instance, $n_y$ stands for the number of storms in the year $y$ within a time series of $m$ years. The estimate for parameter $\mu$ corresponds to the average number of storms per year within the time series.

$$\hat{\mu} = \frac{n}{m}; \text{ where } n = \sum_{y=1}^{m} n_y \tag{5}$$

It is furthermore assumed that a data set of observed storms in the form $\{x_k(y), k = 1, 2,..., n_y; y = 1, 2,..., m\}$ is available for a description of the distribution of losses per storm. $x_k(y)$ describes the loss from the $k$-th storm in the year $y$. The mean, the standard deviation, and the minimum and maximum for this distribution of $x_k(y)$ are used to describe the distribution $F$ for the random variable $X_k$.

## 3.2 Model estimate

### 3.2.1 Description of the data

For the estimation of the model parameters, a dataset of observed storms was used from the Munich Reinsurance NatCatSERVICE®. For the period 1950-2005 , the NatCatSERVICE® recorded 113 North Atlantic storms that caused losses on the US mainland. Some of these storms made landfall several times. In other words, after its first landfall, the storm moved back out over the open sea. After that, it made landfall a second time, and sometimes a third time, in a different location. We divided these storms into separate storm events, since the state of the storm changes due to the renewed energy it derives from the warm surface layers of ocean water. The dataset used therefore encompasses a total of 131 storm events. In the case of storms with multiple landfall, we have distributed the total loss among the different storm events.[4]

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[4] We made the distribution by determining the region in question for each landfall. The share of the total loss for the particular region affected was ascertained using the overall and regional losses reported by the Property Claims Service (PCS) (cf. PCS, https://www4.iso.com/pcs). The total loss from the NatCatSERVICE® was divided in this ratio. The NatCatSERVICE® itself has only details about the total loss from a storm. For some storms we were unable to make this distribution. For example, if the storm had a second landfall in the same state, or if PCS did not include the storm in its catastrophe history, since PCS only record storm events above a particular loss amount.

We adjusted the losses from the individual 131 storm events to the socio-economic conditions of the year 2005. This allows us to eliminate the influence that inflation and changes in population and wealth have on losses over time. The loss data are therefore in US$ prices from 2005 and at the level of wealth in 2005. In other words, the losses are given as if all 131 storms had occurred in the year 2005. The loss $x_k(y)$ required for the parameter estimate is obtained by adjusting the inflation-adjusted loss $x_j(y)$ caused by storm $j$ in the year $y$. For this, the inflation-adjusted loss $x_j(y)$ is multiplied by the ratio between the capital stock in the year 2005 in the region affected by storm $j$, denoted as $cs_j(2005)$, and the inflation-adjusted capital stock in the same region in the year $y$, denoted as $cs_j(y)$. The capital stock encompasses the value of all material assets in the region affected.

$$x_k(y) = x_j(y) \times cs_j(2005) \div cs_j(y) \tag{6}$$

Following the adjustment, there is an adjusted loss $x_k(y)$ for each loss $x_j(y)$ that is at the level of wealth in the year 2005.[5]

### 3.2.2 Estimate of model parameters and simulation of basic scenario

In the period 1950-2005, the dataset recorded 131 storm events. According to formula (4), this gives an average of 2.34 storms per year for $\mu$. The average loss per storm is US$ 4,266 million (in the prices and at the level of wealth in 2005). Table 1 contains statistical values for the distribution of frequency, the average annual loss and the loss per storm event.

Using these model parameters as a basis, we simulate the annual storm loss for 10,000 years with a Monte Carlo simulation. Table 2 shows the results of the simulation. Our model can adequately explain the annual number of storms and the average annual loss observed. The simulated average annual loss, at US$ 9,136 million (in 2005 prices) was slightly below the observed average annual loss of US$ 9,980 million (in 2005 prices).

The following section now applies this model to simulate the average annual loss while incorporating assumptions on climate-driven and socio-economic changes.

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[5] See Schmidt et al. (2009a) for a detailed description of adjusting storm losses for socio-economic developments. For an alternative approach, also see Pielke Jr. et al. (2008).

**Table 1:** Distribution of frequency, annual loss and loss per storm for the 131 storms in the dataset.

| | N | Mean | S.D. | Min. | Max. |
|---|---|---|---|---|---|
| Frequency | 56 | 2.34 | 2.16 | 0 | 10 |
| Annual loss in million US$ (US$ 2005) | 56 | 9,980.3 | 23,250.3 | 0 | 157,400.1 |
| Loss per storm in million US$ (US$ 2005) | 131 | 4,266.4 | 12,311.7 | 0.05 | 122,824.3 |

**Table 2:** Results of the Monte Carlo simulation of frequency and annual loss in the dataset (baseline scenario).

| | N | Mean | S.D. | Min | Max |
|---|---|---|---|---|---|
| Frequency | 10,000 | 2.31 | 1.53 | 0 | 10 |
| Annual loss in million US$ (US$ 2005) | 10,000 | 9,135.8 | 13,781.7 | 0 | 135,360.8 |

## 4 Simulation of the average annual loss for 2050 and 2015

First of all, the assumptions on the three influencing components are described: the risk situation, the loss elasticity to wind speed (vulnerability) and the material assets at risk. Next, the assumptions are transferred to the frequency distributions used in the simulations for the number of storms and the individual loss amount. After that, the results of the simulations are presented. The section begins with the longer-term perspective (simulation for 2050). The assumptions and results for the medium-term perspective (simulation for 2015) are then supplemented.

## 4.1 Assumption on change in risk situation (frequency and intensity)

While we believe that a change in frequency is possible as a result of anthropogenic climate change, our simulations are based on the assumption that there will be no change in frequency as long as no consensus has been reached on this matter (see section Status of research). That's in agreement with Pielke Jr. (2007) and Nordhaus (2006). As regards intensity, we assume that the maximum wind speeds will increase by 3% up to the year 2050.[6] The assumption is based on Bengtsson et al. (2007), who calculated a 6% increase in the maximum wind speeds by the end of the 21st century in comparison with the end of the 20th century. This is based on an emission scenario where no climate protection measures are taken (SRES A1 scenario of the IPCC, cf. Nakicenovic et al. 2000). For our assumption on the year 2050, we halved the increase in wind speeds determined by Bengtsson et al. (2007). The associated assumption of a linear increase in wind speeds was taken for reasons of simplification.[7]

In the simulations, no allowance is made for the influence of the natural variation in climate known as the Atlantic Multidecadal Oscillation (AMO). In the course of the natural fluctuation in the sea surface temperature, there is a change in both the intensity and the frequency of storms in the North Atlantic.

## 4.2 Assumption on loss elasticity and the change in it over time (vulnerability)

In the loss function (see equation 1), we assume a loss elasticity to wind speed of 3 (as does Hallegatte, 2007, Pielke Jr., 2007, and Stern et al., 2006). An elasticity of 3 must be seen as a conservative assumption. Pielke Jr. (2007) also makes allowance for scenarios with elasticity of 6 and 9, while Nordhaus (2006) calculates an elasticity of 8.5.

As described in the section on the status of research, it is extremely difficult to quantify the change in loss susceptibility (vulnerability) over time. In the simulations, we therefore assume that there is no change in loss elasticity to wind speed. The loss from a storm thus increases proportionally to the increase in the level of material assets affected by the storm.

## 4.3 Assumption on the change in the level of material assets at risk

For the year 2050, we assume that the capital stock in the eastern states of the USA that are affected by North Atlantic cyclones is 297% higher than it was in 2005. This increase by a

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[6] The maximum wind speed is the average of the wind measurements within one minute.

factor of four results if we assume an annual increase in capital stock of 3.1% (excluding inflation). In the period between 1950 and 2005, after adjustment for inflation, the capital stock increased by an average of 3.1%. We assume that this average growth will continue in the future.

No data on regional capital stocks is available for the USA. For the period 1950 to 2005, we have therefore made an approximate calculation of the capital stock in each case based on the number of housing units in the US counties affected and their average value in 2005 US$ prices.[8]

## 4.4 Transferring the assumptions to the model

As a result of global warming, maximum wind speeds will increase by 3% by the year 2050. The frequency distribution $F$ of the random variable $X_k$ (loss per storm) has been shifted accordingly. This gives the new frequency distribution, as affected by anthropogenic climate change, for the storm loss $F_{cc}$:

$$F_{cc} = F \times (1 + cc)^3 \tag{7}$$

The parameter $cc$ stands for the change in wind speed resulting from climate change and is 0.03. Due to the assumed elasticity of 3, the frequency distribution $F$ shifts by a factor of 1.093 to the new distribution $F_{cc}$. This modified frequency distribution is used for the simulation of the average annual loss resulting from climate change in 2050.

The frequency distribution of the random variable $N(t)$ was left unchanged. The variable $N(t)$ stands for the number of storms per year.

Since we assume constant loss susceptibility over time, a doubling of the capital stock at risk results in a doubling of the losses. We assume that the capital stock at risk in 2050 is 297% higher than in 2005 (in 2005 prices). The frequency distribution $F$ of the random variable $X_k$ shifts accordingly. The new distribution of the storm loss $F_{se}$ affected solely by the increase in material assets at risk is derived from:

$$F_{se} = F \times (1 + se) \tag{8}$$

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[7] Bengtsson et al. (2007) make no statement on the form of the increase in wind speed by the end of the 21st century.

[8] For a detailed description and discussion of the calculation of the capital stock, see Schmidt et al. (2009a).

The parameter *se* stands for the socio-economic change (change in the capital stock) and is 2.97. Because of the assumed linear increase in losses relative to the level of the capital stock, the frequency distribution $F$ shifts to the new distribution $F_{se}$ by a factor of 3.97. This adjusted frequency distribution is the basis for the simulation of the average annual loss in 2050, assuming no changes in storm intensity.

The same assumptions on *cc* and *se* are used for the simulation of the total average annual loss resulting from higher wind speeds and higher capital stock at risk. The shift in the frequency distribution $F_{ccse}$ of the random variable $X_k$ reflecting the overall effect is derived from:

$$F_{ccse} = F \times \left( (1 + se) + (1 + cc)^3 - 1 \right) \tag{9}$$

The new frequency distribution $F_{ccse}$ for the random variable $X_k$ (loss per storm) is obtained by shifting the frequency distribution $F$ by a factor of 4.063. It is the basis for the simulation of the average annual loss in 2050 assuming a change in storm intensities and a higher level of capital stock.

### 4.5 Results of the simulations for the year 2050

Table 3 summarises the results of the three simulations performed on the influence of the change in risk situation, the change in the capital stock at risk, and the effect resulting from both changes. The same random variables are used in all three Monte Carlo simulations.

The change in the assumed risk situation (increase in wind speeds, constant frequency) resulting from anthropogenic climate change results in roughly an 11% higher average annual loss, or in additional losses of approx. 1 billion US$ (in 2005 prices). This is much less than would be expected from the increase in capital stock in the storm-prone regions. Because of the increase in capital stock, the average annual loss rises from 9.1 billion US$ in 2005 to 37.3 billion US$ in 2050 (in 2005 prices). This represents an increase of 308%. The average loss from North Atlantic cyclones in the year 2050, both from anthropogenic climate change and from an increase in capital stock, is 38.1 billion US$ (in 2005 prices). This represents an increase of 317% on 2005.

**Table 3:** Average annual loss and additional loss in the different scenarios for 2050.

| | **Annual loss in million US$ (US$ 2005) and loss increase (%)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1950-2005 | 2050cc | | 2050se | | 2050ccse | |
| Historical storms 1950-2005 | 9,980.3 | - | - | - | - | - | - |
| Simulation | 9,135.8 | 10,114.1 | +10.7% | 37,305.4 | +308.3% | 38,121.5 | +317.3% |

The scenarios are based on the following assumptions
2050cc wind speed +3%; increase in wealth +0%; elasticity of losses to wind speed 3
2050se wind speed +0%; increase in wealth +297%; elasticity 3
2050ccse wind speed+3%; increase in wealth +297%; elasticity 3

## 4.6 Assumptions and simulation results for the year 2015

The assumptions and results described above describe the longer-term perspective of this study, namely the effects of anthropogenic climate change, and the future socio-economic changes up to the middle of this century. However, it is also interesting, particularly for the insurance of natural catastrophes, to look at the near future. We therefore performed the simulations for a medium-term perspective as well. We simulated the loss that would result in the year 2015 with the anticipated risk situation and the increase in capital stock at risk.

The assumption remains that there will be no increase in the frequency of tropical cyclones. It is also assumed for the year 2015 that there is an increase in the wind speeds of the storms. The starting basis is once again a 6% increase in wind speeds by the end of the 21st century compared to the end of the 20th century (cf. Bengtsson et al., 2007). Assuming a linear increase, this results in 0.9 per cent higher wind speeds for 2015. The assumption for loss elasticity to wind speed is once again 3. With the assumed annual increase in the capital stock of 3.1%, the latter will be 36% higher in 2015 than in 2005 (in 2005 prices).

Table 4 summarises the results of the simulations for the year 2015.

An average annual loss that is roughly 4% higher can be expected in 2015, as result from the change in risk situation. It increases by 32 per cent because of the increase in capital stock in the regions affected by the storms. Together, both effects result in a loss of increase of 35%.

**Table 4:** Average annual loss and additional loss in the different scenarios for 2015.

| | Annual loss in million US$ (US$ 2005) and loss increase (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1950-2005 | 2015cc | | 2015se | | 2015ccse | |
| Historical storms 1950-2005 | 9,980.3 | - | - | - | - | - | - |
| Simulation | 9,461.9 | 9,870.7 | +4.3% | 12,516.7 | +32.3% | 12,803.0 | +35.3% |

The simulations for 2015 and 2050 were carried out independently of one another. Correspondingly, other random statistics were incorporated that explain the slight deviation between the simulations for the average annual loss for 1950-2005.

The scenarios were based on the following assumptions
2015cc wind speed+0.9%; increase in wealth +0%; elasticity of losses to wind speed 3
2015se wind speed+0.0%; increase in wealth +36%; elasticity 3
2015ccse wind speed+0.9%; increase in wealth +36%; elasticity 3

## 5 Discussion

The results of the simulations diverge significantly from the additional costs calculated by Nordhaus (2006), Hallegatte (2007) and Pielke Jr. (2007) resulting from anthropogenic climate change and from socio-economic trends. When applied to the year 2050, these studies give an average annual loss increase from anthropogenic climate change of 52% (Nordhaus, 2006), 27% (Hallegatte, 2007) and 64% (Pielke Jr., 2007).[9] Pielke Jr. (2007) predicts a loss increase of 360% in 2050 from the combined effects of climate change and socio-economic trends. The deviations between these results and the results in our simulations, and also the deviations between one study and another can be explained by the uncertainties relating to the change in risk situation, the development in capital stock at risk (which only Pielke Jr., 2007 makes allowance for) and the loss elasticity to wind change. The following section therefore presents the results of a sensitivity analysis that was carried out using the assumptions in the three studies mentioned. We will look firstly at the results for the effect of higher wind speeds.

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[9] The calculations in Nordhaus (2006) and Hallegatte (2007) relate to the end of the 21st century. Here, these have been linearly extrapolated for the year 2050.

Nordhaus (2006) and Pielke Jr. (2007) assume that the frequency of cyclones does not change. Hallegatte (2007) applies an increase in the frequency of landfalls, as a result of storms he generated synthetically, using a physical storm model. We do not make any allowance for this in the sensitivity analysis.

Nordhaus (2006) assumes an 8.7% intensification of storms by the end of the century as a result of anthropogenic climate change. This intensification is based on the 2.5°C ocean warming that he anticipates, and on the scenario posited by Knutson and Tuleya (2004), whereby each degree of warming of the sea surface temperature leads to a 3.5% increase in wind speeds. Hallegatte (2007) initially uses a physical storm model for synthetic storms under the climate conditions he expects to prevail at the end of the 21st century. In this context, he anticipates a 10% increase in the potential intensity of storms (based on Emanuel, 2005b). For the dataset of synthetic storms, he calculates an increase in wind speeds of 13%. Based on an expert survey, Pielke Jr. (2007) assumes an 18% intensification of storms by 2050 (or +36% by 2100). As regards the increase in wind speeds by the end of the 21st century, therefore, the assumptions in the three studies range from 8.7% to 36%. In this context, we have assumed a lower figure of 6% for the end of the century. Pielke Jr. (2007) and Hallegatte (2007) assume three as the elasticity of loss to wind speed, just as we have done, while Nordhaus (2006) assumes a much higher elasticity of 8.5.

If we apply the assumptions from Nordhaus (2006) in our model, we obtain a 107% higher average annual loss at the end of the 21st century. This closely matches the figure of 104% determined by Nordhaus. Based on the assumptions from Hallegatte (2007), our model produces an increase in the average annual loss of 49%. Hallegatte's own figure is 54%. The fact that we might slightly underestimate the loss increase can be explained by the fact that Hallegatte additionally allows for a greater frequency of cyclones making landfall. If the assumptions from Pielke Jr. (2007) on storm intensification are applied, our model produces a 66% greater annual loss. Pielke Jr. himself gives a figure of 64%. Using the assumptions from the three studies, we can reproduce their results. This illustrates that the deviations between the studies and the results of our simulations, and among the studies themselves can basically be explained by the assumptions made. Differences in method do not play a relevant role. Additional studies would therefore be extremely welcome if they help to reduce uncertainties on the change in frequency and intensity of futures storms, and regarding loss elasticity to wind speed.

Table 5 compares the assumptions and the results of the studies, as well as the average annual loss increases we calculated based on their assumptions.

Only Pielke Jr. (2007) investigated the impact of an increase in material assets in the affected regions. For the scenario with the slow trend in population and wealth, he assumes that the population and level of wealth in the storm-prone regions will increase by a factor of 2.8 by 2050 compared to 2006. This increase corresponds to an annual socio-economic growth of 2.5%. This value is under the 3.5% that average estimates globally assume (cf. Pielke Jr., 2007). With no change assumed for vulnerability, losses in Pielke Jr. increase in linear fashion along with the material assets at risk. With a 180% increase in wealth, this leads to a 180% increase in losses. The result of our model's 10,000-year simulation, assuming a 180% increase in wealth by 2050, is a 185% higher average annual loss (see Table 6).

According to Pielke Jr. (2007), there is a 360% increase in the annual loss for the effects from higher wind speeds and from the increase in level of wealth (exposure). We can also verify this result using our model. We arrived at an increase of 368% (see Table 6).

**Table 5:** Change in average annual loss as a result of global warming - simulations applying the assumptions from current studies.

| | **Nordhaus (2006)** (relating to the end of the 21st century) | **Hallegatte (2007)** (relating to the end of the 21st century) | **Pielke Jr. (2007)** (relating to 2050) |
|---|---|---|---|
| Assumed change in frequency | constant | increase in landfalls | constant |
| Assumed change in wind speed | +8.7% | +13% | +18% |
| Assumed loss elasticity to wind speed $el$; loss function $d = \alpha \times windspeed^{el}$ | $el = 8.5$ | $el = 3$ | $el = 3$ |
| Change in loss (result of the study) | +104% | +54% | +64% |
| Change in loss (simulation result based on study assumptions) | +107% | +49% | +66% |

As in all the other studies quoted, our simulations have only incorporated the effects from anthropogenic climate change on the intensity of storms. We have assumed that global warming leads to a linear increase in storm activity. In reality, however, the natural fluctuation in sea surface temperature in the North Atlantic, the so-called Atlantic Multidecadal Oscillation (AMO), has a much greater influence on storm activity. Depending on the deviation from the multi-year mean, one talk of a "cold phase" or a "warm phase". These phases generally last several decades. Warmer phases trigger higher tropical cyclone activity.[10] Since 1995, the North Atlantic has been in a warm phase again (cf. Goldenberg et al., 2001) whose end cannot be precisely predicted. If the years we simulated, 2015 and 2050, lie within a cold phase, the level of storm activity will be well below that of today. The assumed intensification of storms as a result of global warming would then be overcompensated for by a natural decline in storm frequency and storm intensity. The annual losses that actually occur in 2015 and 2050 should in this case be below those simulated in this study.

Natural climate variation may even have an effect on losses only, since anthropogenic climate change produces no change in storm activity. Using the approach taken by Vecchi et al. (2008), the factors underlying Atlantic storm activity cancel one another out. This is why storm activity remains unchanged despite global warming.

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[10] The terms "cold phase" and "warm phase" are strongly linked to the idea of natural fluctuations in climate, as described by the AMO (cf. inter alia Goldenberg et al., 2001, Zhang and Delworth, 2006, Kossin and Vimont, 2007). However, there are also climatologists who see no influence of natural variability in climate. According to this opinion, the terms "cold phase" and "warm phase" make no sense (cf. Mann and Emanuel, 2006). The phenomenon of cooler SSTs in the past ("cold phase") does not result from a natural fluctuation in climate, but from anthropogenic aerosol emissions into the atmosphere that result in temporary cooling in the atmosphere and in the sea.

**Table 6:** Change in average annual loss in 2050 as a result of socio-economic changes and of the overall effect from the change in socio-economics and wind speed - simulations applying the assumptions in Pielke Jr. (2007).

| | **Pielke Jr. (2007) - change in wealth** | **Pielke Jr. (2007) –change in wealth and wind speed** |
|---|---|---|
| Assumed change in frequency | - | constant |
| Assumed change in wind speed | - | +18% |
| Assumed loss elasticity to wind speed *el*; loss function $d = \alpha \times windspeed^{el}$ | - | $el = 3$ |
| Assumed increase in wealth | +180% | +180% |
| Assumed combined effect from changes in wealth and wind speed | - | +116% |
| Change in loss (result of the study) | +180% | +360% |
| Change in loss (simulation result, based on the assumptions from Pielke Jr., 2007) | +185% | +367% |

## 6 Simulation of the average annual loss for individual storm categories

The average annual loss only gives us a restricted picture of how the loss situation might develop in future. For example, the average annual loss between 1950 and 2005 varies by 157 billion US$ (in 2005 prices) (see Table 1). This is the result of high variability, both in terms of the number of storms, and of the single event losses, caused among other things, by the natural variation in climate. We have therefore supplemented our simulation of the additional loss increase in 2050 for the categories of light, weak to moderate, and strong to devastating storms. We describe a storm with wind speeds <33 m/s as a light storm. These are storms that do not reach hurricane strength. We categorise storms in categories H1 and H2 of the Saffir-Simpson scale, with wind speeds of 33 m/s up to 50 m/s, as weak to moderate storms. Storms with winds speeds >50 m/s, such as storms in categories H3-H5, are classed as strong to devastating storms. Figure 1 shows the distribution to the three categories of the 131 storm events recorded for the years 1950-2005.

Table 7 gives the mean empirical annual loss per storm category for the years 1950-2005. It also shows the average annual losses from 10,000 simulated years, in each case with an assumed 3% increase in wind speeds, and a 297% increase in capital stock at risk, as well as for the effect of the two factors combined.

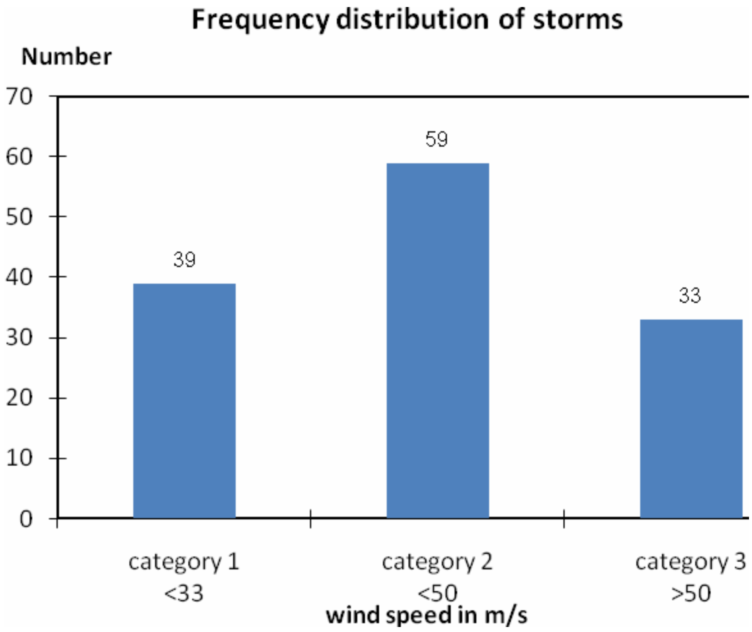

**Figure 1:** Number of storms 1950-2005 in the three storm categories.

**Table 7:** Average annual loss and additional loss in the different scenarios for 2050 according to storm category.

| | **Category** | **Number** | **Annual loss in million US$ (US$ 2005) and loss increase (%)** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 1950-2005 | 2050cc | | 2050se | | 2050ccse | |
| Historical storms 1950-2005 | I | 0.7 | 939.6 | - | | - | | - | |
| | II | 1.1 | 1,657.0 | - | | - | | - | |
| | III | 0.6 | 7,383.7 | - | | - | | - | |
| Simulations | I | 0.7 | 779.9 | 854.7 | +9.6% | 3,235.9 | +314.9% | 3,444.8 | +341.7% |
| | II | 1.0 | 1,455.7 | 1,593.5 | +9.5% | 5,657.5 | +288.6% | 5,934.2 | +307.7% |
| | III | 0.6 | 6,912.3 | 7,465.5 | +8.0% | 21,223.8 | +207.0% | 27,541.7 | +298.4% |

Classification of storms according to wind speed: category I <33 m/s, category II 33 m/s to 50 m/s and category III >50 m/s.

# 7 Summary

Ever since the two extreme hurricane years of 2004 and 2005, there has been a discussion in the media and the science community about the level of losses from tropical cyclones that economies will have to face in the future. A particular focus of the debate is on the influence of anthropogenic climate change. However, this is just one of the factors that will more likely than not contribute to an increase in losses. The principal factor will be the increase in capital stock affected by such storms. This is increasing because more and more people are settling in storm-prone regions, with ever-greater concentrations of material assets.

In this paper we have examined the increase in the average annual loss from Atlantic cyclones in the USA in the years 2015 and 2050, resulting from a climate-induced change in the risk situation (frequency and intensity of the storms) and by the increase in material assets at risk. A stochastic model was used for the analysis. The model simulates the storm frequency and the loss per storm event for a large number of years and then calculates an average annual loss from this. This model was adjusted for the anticipated changes in risk situation, vulnerability and material assets at risk. The results show that the increase in the average annual loss is principally caused by the increase in capital stock. Nevertheless, anthropogenic climate change will also lead to noticeable loss increases. In our study, the latter is 11% for the year 2050. That's an increase lower than the results from other studies. Based on the results from Nordhaus (2006) and Stern et al. (2006), losses could increase by 50% by 2050. According to Pielke Jr. (2007), the figure could be as high as 64%.

From a medium-term perspective (2015), losses from anthropogenic climate change will still increase by 4%. They will rise by an additional 32% due to the increasing amount and the average value of material assets in the regions affected by the storms. In evaluating the changes resulting from climate change and socio-economic trends, it should be remembered that the rise in losses resulting from socio-economic changes is offset by an increase in wealth in the form of the higher capital stock. In contrast, the increase in losses caused by climate change is not offset by any other increase. This loss increase leads to a reduction in wealth.

From the perspective of the insurance industry, which must assume the transfer of risk from weather extremes, the results should be assessed as follows. As regards coverage for "storm losses", insurers are urged to increase their technical premium rates in the USA by 4% in the medium term (by 2015). The increase in losses resulting from the rise in the capital stock (+32%) basically poses no problems for insurers since the premium will rise according to the increase in capital stock or the sum insured. As well as adjusting premiums, insurers could also respond to the changing risk situation by adjusting deductibles. With the deductible, the insured party bears the loss itself up to an agreed amount. The insurer or reinsurer is only involved when this limit is exceeded. If deductibles are not adjusted, they will be exceeded more quickly in future due to the anticipated higher wind speeds and the higher resulting loss.

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# Appendix

**Table A1:** Overview of variables and parameters.

| Designation | Explanation |
|---|---|
| $\mu$ | Expected value of the number of storms |
| $cc$ | Parameter change in wind speed as a result of global warming |
| $cs_j(2005)$ | Capital stock in 2005 in the region affected by storm $j$ |
| $cs_j(y)$ | Capital stock in year $y$ in the region affected by storm $j$ |
| $D(t)$ | Annual loss in the interval $[0;t]$ |
| $el$ | Change in loss with a marginal change in wind speed (elasticity) |
| $F$ | Frequency distribution of the random variable $X_k$ |
| $F_{cc}$ | Frequency distribution of the random variable $X_k$ because of higher wind speeds |
| $F_{ccse}$ | Frequency distribution of the random variable $X_k$ because of higher wind speeds and higher capital stock |
| $F_{se}$ | Frequency distribution of the random variable $X_k$ because of higher capital stock |
| $y$ | Index for year |
| $j$ | Index for storm |
| $k$ | Index for storm |
| $m$ | Number of years in period 1950-2005 |
| $N(t)$ | Random variable for the number of storms in the interval $[0;t]$ |
| $n_y$ | Number of storms in the year $y$ within a period of $m$ years |
| $se$ | Parameter change in capital stock as a result of socio-economic development |
| $t$ | Time index; here always = 1 (one year) |
| $ws_j$ | Wind speed of storm $j$ |
| $x_j(y)$ | Loss from storm $j$ in the year $y$ |
| $X_k$ | Random variable loss from storm $k$ |
| $x_k(y)$ | Loss from storm $k$ in the year $y$ in the prices and at the level of wealth in 2005 |
| $\alpha$ | Constant |

**Table A2:** Overview of studies to estimate future storm losses in the USA resulting from global warming.

| Study | Loss function | Assumed change in intensity | Assumed change in frequency | Result |
|---|---|---|---|---|
| Cline (1992) | Increase in intensity produces a linear increase in losses | Increase of 40-50% with 2.3-4.8°C warming | - | Average loss increases by 50% |
| Fankhauser (1995) | Increase in intensity triggers a 1.5 increase in losses | Increase of 28% with warming of 2.5°C | - | Average loss (global) increases by 42% |
| Tol (1995) | Connection is in the quadratic form $f(X) = aX + bX^2$ | Increase of 40-50% with warming of 2.5°C | constant | Increase in losses of 300 million US$ (US$ 1988) |
| Nordhaus (2006)[a] | $d = \alpha \times windspeed^{8.5}$ | Increase of maximum wind speeds of 8.7% with warming of 2.5°C | constant | Average loss increases by 104% |
| Stern et al. (2006) | $d = \alpha \times windspeed^3$ | Increase of 6% with warming of 3°C | - | Average loss increases by 100% |
| Hallegatte (2007)[b] | Physical storm model to create synthetic storms; loss function in the form $d = \alpha \times (x) \times windspeed^3$ | Increase of 10% under the expected climate conditions at the end of the 21st century | no change in absolute number | Increase in landfalls and maximum wind speed (+13%). Average loss increases by 54% |
| Pielke Jr. (2007) | $d = \alpha \times windspeed^3$ (further scenarios with elasticity of 6 and 9) | Increase of 18% by 2050 | constant | Increase in loss of 64%[c] |
| Notes | [a] Losses adjusted for economic development using GDP.<br>[b] Losses adjusted for population and wealth trends, $s$ for vulnerability index.<br>[c] Additional loss increase of 116% from the combined effect of increase in intensity and socio-economic trend. | | | |