Economic costs of extratropical storms under climate change: an application of FUND

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Extratropical cyclones have attracted some attention in climate policy circles as a possible significant damage factor of climate change. This study conducts an assessment of economic impacts of increased storm activities under climate change with the integrated assessment model FUND 3.5. In the base case, the direct economic damage of enhanced storms due to climate change amounts to US$2.8 billion globally (approximately 38% of the total economic loss of storms at present) at the year 2100, while its ratio to the world GDP is 0.0009%. The paper also shows various sensitivity runs exhibiting up to 3 times the level of damage relative to the base run.

Keywords: climate change; extra tropical storms; economic impact

1. Introduction

The increase of atmospheric greenhouse gases may change the global climate system in multiple ways, among which is the pattern of storm incidence. Storms are at the top of the list of costliest events in Europe for the insurance industry (Reinhard 2005), and the largest storms could make tangible economic loss even at a national scale. Along with tropical cyclones (Narita *et al.* 2009), extratropical storms[1] have also attracted the attention of various people in the context of climate change, especially because a number of large-sized events took place in Europe in recent decades (Dorland *et al.* 1999, Reinhard 2005).

In general, such large extratropical storms are not frequently formed, and the economic impacts of storms are thus on average not very profound, at least in rich countries (Dorland *et al.* 1999). However, global climate change might alter the picture. The reinsurance industry (Heck *et al.* 2006) has found that the economic costs of severe storm events have expanded over the last several decades, one of the drivers for which might be climate change. As climate changes further in the future, storm damages might become a more important factor even in the richest economies

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in the mid-latitudes, not to mention lower-income economies in the same latitudinal zones.

Climatologists have not yet reached a consensus on future changes in activities of extratropical cyclones under climate change, but it would be safe to say that the enhancement of extratropical storm damage under climate change is recognised as a conceivable case. While the magnitude of the change is uncertain, the physics of the atmosphere dictate that if temperature gradients change, wind and storm patterns change too. In fact, some of the well-accepted findings on this topic, the ones documented in Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, are consistent with the claim. First, the IPCC Fourth Assessment Report (2007) indicates that it is likely that there has been a net increase of extratropical cyclones in frequency or intensity over the Northern Hemispheric land since 1950, although mechanisms other than climate change (e.g. decadal-scale fluctuations) could also explain the change. Second, both IPCC's Third and Fourth Assessment Reports (2001, 2007) introduce, although not endorse, the view that the number of intense extratropical cyclones may increase under climate change (whereas the total number of storms might be reduced), citing a set of research works reaching this conclusion (Lambert and Fyfe 2005). Third, the Fourth Assessment Report describes that the 'consistent' results from different general circulation models show a poleward shift of storm tracks as a result of climate change, in other words, greater storm activities at high latitudes.

Some efforts have been made to include extratropical storms in integrated assessment models on climate change. For example, in a European context, a number of papers assess a possible increase of economic loss due to extratropical storms under climate change (Dorland *et al.* 1999, Leckebusch *et al.* 2007, Pinto *et al.* 2007, Hanson *et al.* 2004). Leckebusch *et al.* (2007) conduct regressions of daily maximum wind speeds (calculated with multiple general circulation models (GCMs)) with recorded property losses, and they conclude that storm-related economic loss in the UK and Germany would increase up to 37%. Pinto *et al.* (2007) apply a similar method to Western Europe by using a single GCM (ECHAM5/MPI-OM1) and estimate that the change of the mean annual loss of storms is in the range from −4% to 43% in the case of Germany. Hanson *et al.* (2004) estimate the future economic impact of storms in the UK with climate change. In addition to insurance losses, Hanson *et al.* discuss the forestry sector in detail, using a model incorporating the strength of the stem and the resistance of the tree to overturning. Meanwhile, Dorland *et al.* (1999 p. 513) draw on local data of property damage from a winter storm that hit the Netherlands in 1990 (Daria). They derive an exponential relationship between the damage and the maximum wind speed and conclude that "an increase of 2% in wind intensity by the year 2015 could lead to a 50% increase in storm damage ... only 20% of the increase is due to population and economic growth."

To the authors' knowledge, however, no previous study of economic modelling discussed this topic in a global context, and placed it in the context of the total economic impact of climate change. In a global study of economic impacts of storms and climate change, one additional consideration needed in analysis would be the effects of income levels, which are very different across countries. Two factors are in play with regard to the relationship between affluence and disaster damages (Toya and Skidmore 2007): economic damages of natural disasters may be magnified in richer economies because a unit amount of loss in capital leads to a bigger loss of income due to high productivity of capital; on the other hand, the wealthy can insulate themselves from disasters.

This paper discusses long-term economic effects of extratropical cyclones with climate change computed by the integrated assessment model FUND 3.5. Extratropical storms are a new element in FUND. In the following, brief descriptions of FUND and the approach here to model the damage of extratropical cyclones are presented in Section 2. Section 3 shows the results. Section 4 concludes the paper.

2. Methodology: estimation of extratropical cyclone impacts with FUND

2.1. The FUND model

Version 3.5 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is used here for the analysis of climate change impacts with enhancement of tropical cyclone activities. Version 3.5 of FUND has the same basic structure as that of Version 1.6, which is described and applied by Tol (1999, 2001, 2002c). Except for the extratropical storm component that is discussed in this paper, the impact module of the model is outlined and assessed by Tol (2002a, 2002b). The latest publication using the FUND platform is Anthoff *et al.* (2009). The source code and a complete description of the model can be found at http://www.fund-model.org/.

Essentially, FUND is a model that calculates damages of climate change for 16 regions of the world, listed in Table 1, by making use of exogenous scenarios of socio-economic variables. The scenarios comprise projected temporal profiles of

Table 1. Regions considered in FUND.

Acronym	Name	Countries
USA	USA	United States of America
CAN	Canada	Canada
WEU	Western Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom
JPK	Japan and South Korea	Japan, South Korea
ANZ	Australia and New Zealand	Australia, New Zealand
EEU	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MDE	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
CAM	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama

Table 1. (*Continued*).

Acronym	Name	Countries
SAM	South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
SEA	Southeast Asia	Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam
CHI	China plus	China, Hong Kong, North Korea, Macau, Mongolia
NAF	North Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea- Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
SIS	Small Island States	Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands

population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonisation), emissions of carbon dioxide from land use change, and emissions of methane and of nitrous oxide. Carbon dioxide emissions from fossil fuel combustion are computed endogenously on the basis of the Kaya identity[2]. The calculated impacts of climate change perturb the default paths of population and economic outputs corresponding to the exogenous scenarios. The model runs from 1950 to 3000 in time steps of a year, although the outputs for the 1950–2000 period is only used for calibration, and the years beyond 2100 are used for approximating the social cost of carbon under low discount rates, a matter that does not concern this paper. The scenarios up to the year 2100 are based on the EMF14 Standardised Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al*. 1992). For the years from 2100 onward, the values are extrapolated from the pre-2100 scenarios. The radiative forcing of carbon dioxide

and other greenhouse gases used by FUND is determined based on Shine *et al.* (1990). The global mean temperature is governed by a geometric build-up to its equilibrium (determined by the radiative forcing) with a half-life of 50 years. In the base case, the global mean temperature increases by 2.5°C in equilibrium for a doubling of carbon dioxide equivalents. Regional temperature increases are calculated from the global mean temperature change multiplied by a regional fixed factor, whose set is estimated by averaging the spatial patterns of 14 GCMs (Mendelsohn *et al.*, 2000).

As described by Tol (2002a), the model considers the damage of climate change for the following categories, as well as extratropical cyclones: agriculture, forestry, water resources, sea level rise, energy consumption, unmanaged ecosystems, human health (diarrhoea, vector-borne diseases, and cardiovascular and respiratory disorders), and tropical cyclones. In the version of FUND here, extratropical cyclones are treated as a separate category, rather than as a factor elevating damage levels of existing categories (e.g. crop damages from enhanced floods). Impacts of climate change can be attributed to either the rate of temperature change (benchmarked at 0.04°C per year) or the level of temperature change (benchmarked at 1.0°C). Damages associated with the rate of temperature change gradually fade because of adaptation.

FUND also has macro-economic and policy components. Reduced economic output due to damages of climate change is translated into lower investment (with exogenous saving rates) and consequently slower growth rates. With policy variables such as those representing carbon abatement measures, FUND can be operated as an assessment tool for long-run climate policy. However, this paper does not use this policy-assessment function of the model.

2.2. *Extratropical cyclones*

Extratropical cyclones are modelled with the FUND framework similarly in spirit to the modelling of tropical cyclone impacts (Narita *et al.* 2009). A key idea behind the formulations is the well-accepted fact that the income level is an influential factor on the size of disaster damage for an economy, through two opposing factors resulting from an income rise, namely, aggravation of capital loss and better disaster preparedness (Toya and Skidmore 2007). The economic damage due to an increase in the intensity of extratropical storms follows the equation below:

$$\frac{ETD_{t,r}}{Y_{t,r}} = \alpha_r \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\varepsilon} \delta_{hemisphere} \left(\frac{C_{CO2,t}}{C_{CO2,pre}}\right)^{\gamma}, \tag{1}$$

$ETD_{t,r}$ and $Y_{t,r}$ are the damage due to extratropical cyclones (increase relative to pre-industrial) and GDP in region r and time t, respectively. Note that Equation (1) represents the effect of a deviation of extratropical cyclones from its pre-industrial (i.e. not the total level of storm damages). α_r is the factor determining the benchmark level of cyclone damages for region r (see Table 2). The data for cyclone damages are drawn from the Emergency Events Database (EM-DAT: http://www.emdat.be/) by the WHO Collaborating Centre for Research on the Epidemiology of Disasters (CRED). The CRED EM-DAT is an international initiative that assembles and organises the data of natural disaster damages collected by various institutions worldwide (i.e. UN organisations, governments, NGOs, universities, private firms

Table 2. Baseline impact of tropical cyclones on property (direct economic damage) and mortality (based on 1986–2005 averages of the CRED EM-DAT data).

	Direct economic damage		Mortality	
	Loss in US$ billion	α_r (% of GDP)	Number of casualties	β_r (per million people)
USA	1.1	0.012	78	0.29
CAN	0.53	0.017	20	6.3E-02
WEU	2.5	0.021	58	0.12
JPK	0.19	1.0E-03	57	0.11
ANZ	0.20	0.028	5	0.12
EEU	0.20	4.6E-03	13	0.050
FSU	0.064	4.4E-03	44	0.13
MDE	0.031	1.6E-03	27	0.053
CAM	0.25	4.4E-03	55	0.13
SAM	0.021	3.6E-04	26	0.047
SAS	1.4	0.055	263	0.20
SEA	0.15	0.006	65	0.086
CHI	0.18	0.017	138	0.11
NAF	1.0E-03	2.8E-05	15	0.038
SSA	1.8E-03	0.055	31	0.20
SIS	0.51	0.043	156	1.6

and the press). The database contains basic data on the occurrence and the effects of more than 17,000 disasters in the world from 1900 to the present (Scheuren *et al.* 2008). Although the dataset has the weakness that its economic damage data are listed on a reported basis from different institutions and lack consistency, it is more comprehensive than other similar types of dataset and thus the best available at present. The CRED data have a distinct category of extratropical cyclones, and the study draws on the damage data from that subgroup.[3] The coefficient α_r is estimated by averaging storm damages in the dataset over the period 1986–2005. It should be noted that storm impacts vary a great deal from year to year, and the level of the coefficient is extremely sensitive to what period is chosen and averaged. This issue is addressed by conducting a set of sensitivity runs, which are discussed in the next section.

The component $(y_{t,r}/y_{1990,r})^{\varepsilon}$ in Equation (1) represents the effect of income level on vulnerability to storms, where y is per capita income (in 1995 US$ per year) in region r at time t. Two factors are in play with regard to the relationship between affluence and disaster damages: economic damages of natural disasters (among which are extratropical storms) may be magnified in richer economies because a unit amount of loss in capital leads to a bigger loss of income due to high productivity of capital; on the other hand, their wealth can insulate themselves from disaster damages by defensive expenditure or expensive but better infrastructure resistant to disaster shocks. In Equation (1), ε is the income elasticity of storm damage and set at -0.514 (standard deviation: 0.027) after Toya and Skidmore (2007).

$\delta_{hemisphere}$ is a parameter indicating how much the number of intense storms increases. $C_{CO2,t}$ is the atmospheric CO_2 concentrations; $C_{CO2,pre}$ is the CO_2 concentrations in the pre-industrial era. The levels of parameter are set based on Lambert and Fyfe's (2005) comparison exercise of 15 GCMs with regard to atmospheric CO_2 concentrations and global incidence of storms. They showed that a majority of GCMs show an increase in the number of intense storms (i.e. storms

whose pressure is lower than 970 mb at the central grid point) with higher CO_2 concentrations, whereas the total number of storms generally declines. Their results also reveal that the sensitivity of intense storm occurrence to CO_2 increases is generally greater in the Southern Hemisphere than in the Northern Hemisphere. The present study set the levels of $\delta_{hemisphere}$ to their estimated representative numbers from the GCM results, showing that the number of intense storms would increase by 8% and 42% with a doubling of CO_2 in the northern and southern hemispheres, respectively.[4] It is assumed that only intense storms would cause substantial damage. As Lambert and Fyfe's study only documents hemispheric estimates, classifications of regions straddling two hemispheres (i.e. SAM, SAS, SEA and SIS) are made as follows. For regions whose extratropical area coverage falls only on one hemisphere (and covering tropical zones of both hemispheres), the study uses parameter value of the hemisphere where the region's extratropical areas sit, assuming that extratropical storms affect only extratropical land areas of respective regions. For example, South America's (SAM) extratropical area coverage is only in the Southern Hemisphere, and thus SAM is categorised as in the Southern Hemisphere. This criterion makes it possible to classify all regions except Small Island States (SIS). Meanwhile, the numbers of the Northern and Southern Hemispheres for Small Island States (SIS) whose area is spread across the two hemispheres were averaged. As a result of the above, the parameter $\delta_{hemisphere}$ was set as follows: $\delta_{NH} = 0.04$ (applicable to USA, WEU, JPK, EEU, FSU, MDE, CAM, CHI, NAF and SEA); $\delta_{SH} = 0.21$ (applicable to ANZ, SAM and SAS); $\delta_{SIS} = (\delta_{NH} + \delta_{SH})/2 = 0.13$ (applicable to SIS). The standard run adopted the simple assumption that the damage has a linear relationship with the CO_2 concentrations (i.e., $\gamma = 1$). In sensitivity runs, the significance of this linear assumption was investigated with different levels of γ.

Similar to the rest of the impact module for FUND (Tol 2002a, Narita *et al.* 2009), the extratropical cyclone component has a separate function estimating mortality in addition to that for economic damages:

$$\frac{ETM_{t,r}}{P_{t,r}} = \beta_r \left(\frac{y_{t,r}}{y_{1990,r}} \right)^\eta \delta_h \left(\frac{C_{CO2,t}}{C_{CO2,pre}} \right)^\gamma. \tag{2}$$

In Equation (2), $ETM_{t,r}$ and $P_{t,r}$ are the mortality due to extratropical cyclones (increase relative to pre-industrial) and the population in region r and time t, respectively. β_r signifies the regional baseline level of mortality from tropical cyclones (based on the CRED EM-DAT data, see Table 2). η is the income elasticity of storm damage and set as -0.501 (standard deviation: 0.051) after Toya and Skidmore (2007). The number of deaths computed after the equation is translated into loss of population. The mortality is also considered to be equivalent with some economic loss; as in the other impact categories in FUND, mortality due to tropical cyclones is valued at 200 times the per capita income of the affected region. This is set to be consistent with the discussion by Cline (1992), who drew on average annual wage data and estimates of the value of a statistical life.

3. Results

Table 3 summarises the results for the economic damage and mortality of extratropical storms in the year 2100. The results represent increased damages relative to pre-industrial times (i.e. without climate change). In the base case, the

Table 3. Increased economic damage and mortality of extratropical cyclones in the year 2100 calculated by FUND.

Cases	Baseline	ε	η	Γ	Direct economic damage		Mortality		Total economic damage (US$ billion)	% of world GDP
					Increase from pre-industrial (US$ billion)	Ratio to world GDP (%)	Increased number of death (from pre-industrial)	Value of lost life (US$ billion, increase from pre-industrial)		
Base	1986–2005	−0.514	−0.501	1	2.8	0.0009	148	0.5	3.3	0.0010
	1976–2005	−0.514	−0.501	1	2.1	0.0007	161	0.6	2.8	0.0009
	1996–2005	−0.514	−0.501	1	1.0	0.0003	108	0.5	1.5	0.0005
High ε and η	1986–2005	−0.487	−0.450	1	3.0	0.0009	170	0.6	3.6	0.0011
Low ε and η	1986–2005	−0.541	−0.552	1	2.6	0.0008	129	0.5	3.1	0.0010
High δ[a]	1986–2005	−0.514	−0.501	1	8.0	0.0026	476	1.7	9.7	0.0032
Low δ[b]	1986–2005	−0.514	−0.501	1	−1.7	−0.0005	−47	−0.4	−2.2	−0.0006
$\gamma = 3$	1986–2005	−0.514	−0.501	3	8.5	0.0028	1197	1.7	10.2	0.0034
$\gamma = 2$	1986–2005	−0.514	−0.501	2	5.9	0.0019	437	1.1	7.0	0.0022
$\gamma = 0.5$	1986–2005	−0.514	−0.501	0.5	1.4	0.0004	64	0.2	1.6	0.0005

Notes: (a), (b): See text for the assumptions for those runs.

extra direct economic damage from climate change enhanced storms amounts to US$2.8 billion (1995 US$ per year). This figure is approximately 38% of the expected global total economic storm damage in 2005 (US$7 billion) – that is, climate change would increase winter storm damage by slightly more than one-third. It is about one-seventh of the enhanced *tropical* cyclone damage for the same year calculated by FUND with the base assumptions (US$19 billion). The Table also shows that intensified storms would cause about 150 additional deaths (whose monetised value of life is US$0.5 billion) in the year 2100 in the base case. The increase of global temperature (+3.9°C above the pre-industrial level) causes economic damage, but the size of damage is also a reflection of the expanded size of the economy at 2100, which is nearly eight times the 2000 level. The time trends of increased direct economic loss and its share to world GDP (for the base case: 1986–2005 baseline) presented in Figure 1 show this income effect more visibly. The graph shows a rapid increase of absolute storm damages,[5] while the ratio of increased damage to GDP is more or less flat over the period, which is around 0.0008%.

Table 3 also shows the results of sensitivity runs. As already mentioned, storm damages exhibit significant inter-annual variability, and the choice of baseline period affects the results. As alternative cases, the averaging period is both extended and shortened by 10 years (1976–2005 and 1996–2005). As Table 3 shows, the direct economic damage is largest in the case of the original 1986–2005 baseline and smallest in the case of the 1996–2005 baseline. Storm damage is highest with the base years 1986–2005 because of the record storms in Western Europe in the year 1990 (US$15 billion according to the EM-DAT data). The difference among the different sets of baseline is not very strong with regard to mortality because of the advanced warning systems and strict building standards in rich countries.

Figure 2 shows the regional disaggregation of damages (direct economic loss) for selected regions where storm impacts have relatively high economic significance
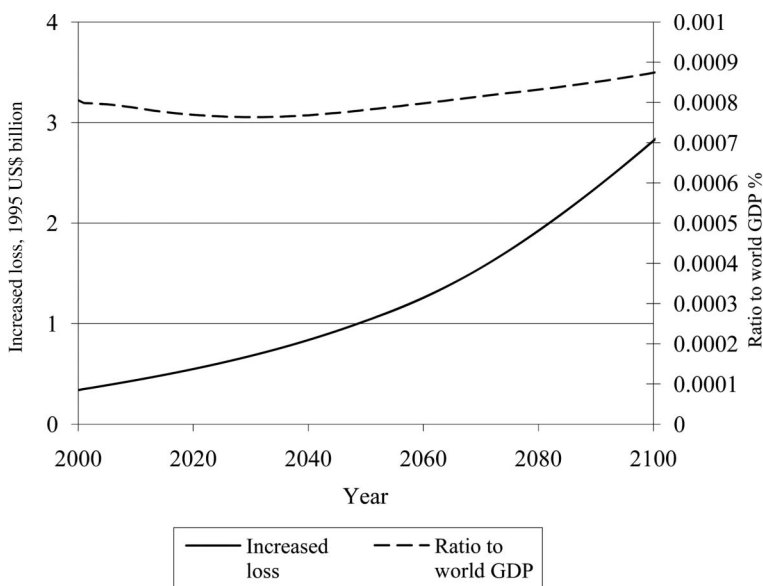

Figure 1. Time trends of increased direct economic loss of extratropical cyclones and its share to the world GDP.
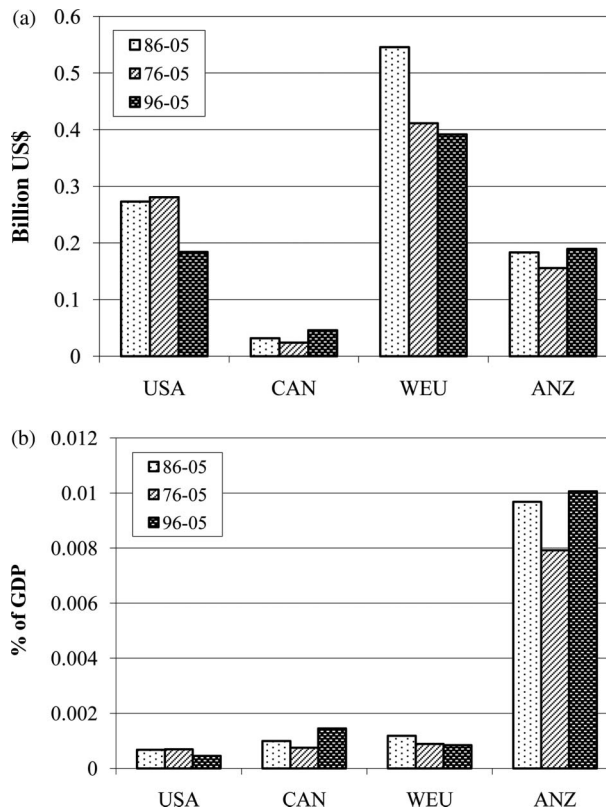
Figure 2.   Increased direct economic loss (a) and its share to GDP (b) at the year 2100 for selected regions (results for the three different baseline sets are shown).

(namely the USA, Canada, Western Europe and Australia and New Zealand). Figure 2 shows that Western Europe is the highest in terms of the absolute level of storm damage, with an amount over the range of US$0.4 billion. On the other hand, Australia and New Zealand (ANZ) exhibits by far the highest damage relative to GDP, over the range of 0.008% of GDP.

The other sets of results shown in Table 3 are sensitivity analyses for different values of parameters. The income elasticities of storm damage with regard to direct economic loss and mortality (ε and η) are increased and decreased according to the standard deviations estimated by Toya and Skidmore (2007). With regard to the income elasticity on direct economic loss (ε), the shift of level has a relatively small impact on outcome, by less than 10%. The change in elasticity brings about a slightly larger change in mortality, up to slightly greater than 10% of the total.

Table 3 also shows the results of sensitivity runs with regard to δ. The high and low δs were set to be consistent with the upper and lower bounds in Lambert and Fyfe's comparison (from their Figure 7: this means $\delta_{NH} = 0.17$, $\delta_{SH} = 0.49$, and $\delta_{SIS} = 0.33$ for the high δ case, and $\delta_{NH} = -0.05$, $\delta_{SH} = 0$, and $\delta_{SIS} = -0.02$ for the low δ case). The last set of data listed in Table 3 varies the exponent γ, namely, $\gamma = 3, 2, 0.5$. Note that parameter δ involves the change in *frequency* of intense storms, not in *wind speed*. While storm damage is more than linear in wind speed (Emanuel 2005), it is probably linear in storm frequency. The sensitivity runs on
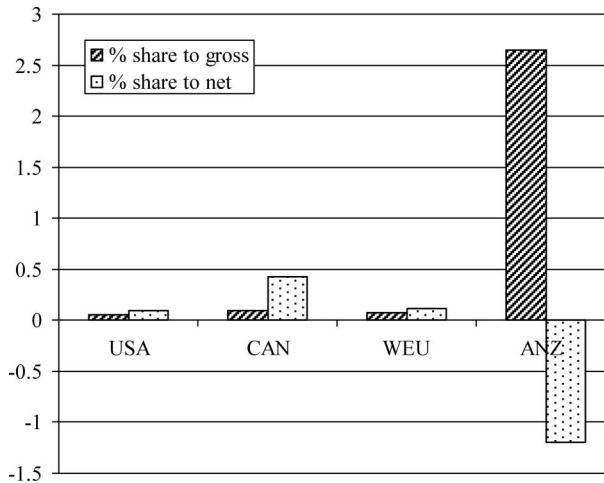
Figure 3. Increased direct economic damage of extratropical storms due to climate change as a percentage of the gross (i.e. only damages are considered) and net (both benefits and damages are summed) total costs of climate change for selected regions (at the year 2100 for the base case).

Table 4. Global marginal costs of CO_2 emissions in US$tC (the base case, simple sum for the world regions).

	Pure rate of time preference		
	0%	1%	3%
Total	144	22	1
Extratropical storms	0.03	0.01	0.01

δ and γ show that higher levels of these parameters indeed lead to greater damages up to three times relative to the base runs, but not in order of magnitude.

Figure 3 shows the increased damages of extratropical storms as a percentage of the total costs of climate change. Data represent the base results for the year 2100, and they are presented as ratios to both the gross (i.e. only damages are considered) and net (both benefits and damages are summed) total impacts. The graph does not indicate any clear, systematic patterns because gross and net total damages are very different in all regions in the first place. Table 4 shows the global marginal costs of carbon emissions calculated by FUND for the base case. The results presented are simple sums over the world regions. The results show that in a relative sense, the marginal costs from storm damages are negligible in the total marginal costs, and are even significantly less than the ones for tropical storms (about one-tenth in case of the 0% time preference; cf. Narita *et al.*, 2009).

4. Discussion and conclusion

This study estimates the economic impacts of enhanced storm activities under climate change with the integrated assessment model FUND 3.5. In the base case, the direct economic damage of enhanced storms due to climate change amounts

to US$2.8 billion globally (approximately 38% of the total economic loss of storms at present) at the year 2100, while the ratio to the world GDP is 0.0009%.

The regional results (Figure 2) indicate that the economic effect of extratropical storms with climate change would have relatively minor importance for the US. The enhanced extratropical storm damage (less than 0.001% of GDP for the base case) is one order of magnitude lower than the tropical cyclone damage (approximately 0.01% GDP) calculated by the same version of FUND. In the regions without strong tropical cyclone influence, such as Western Europe and Australia and New Zealand, the extratropical storms might have some more significance as a possible damage factor of climate change. Particularly for the latter, the direct economic damage could amount to more than 0.006% of GDP. However, the impact is small relative to the income growth expected in these regions.[6]

The assessment falls in the range of existing estimates on Europe. Leckebusch *et al.* (2007) concluded that in the UK and Germany, storm-related loss would increase by up to 37% under climate change (i.e. the change to be seen in the late twenty-first century from the present). Pinto *et al.* (2007) showed that the change of the mean annual loss of storms is in the range from −4% to 43% in the case of Germany. Meanwhile, Hanson *et al.* (2004) estimated no significant change in storm activities in the UK until the late twenty-first century.

This study's results show different damage than Dorland *et al.* (1999), who assume an increase of wind intensity. They concluded that a 2% increase of wind intensity could lead to a 50% increase of storm loss in the Netherlands. The study here does not base its assessment on wind speed (whose global comparison data do not exist in the context of climate change), and thus these two sets of results are not directly comparable. However, their conclusion suggests that the estimates here might be rather conservative.

This paper is an initial attempt to assess global impacts of extratropical storms under climate change, and it unavoidably has some limitations. The most important one would be the state of scientific knowledge it stands on, which is still somehow elusive and does not make it possible to make detailed formulations of storm impacts for the model. In addition, the following could be noted as limitations concerning the assessment approach itself. First, the computation adopted exogenous savings rates to simulate long-run growth paths with intensifying storms, but more accurate modelling would require endogenous decision functions of investment, representing detailed features of individual savings decisions in the face of storms. Second, the model calculated damages of extratropical cyclones in making use of a separate component in the impact module in favour of analytical clarity and simplicity, but this means that the model ignores some combined effects of enhanced cyclones with other factors, such as its coupling effect with sea level rise.

Acknowledgements

Notes

1. Extratropical storms are also called extratropical cyclones, commonly signifying large-scale storms excluding tropical cyclones. The American Meteorological Society defines the term as "any cyclonic-scale storm that is not a tropical cyclone, usually referring only to

the migratory frontal cyclones of middle and high latitudes" (http://amsglossary.allen press.com/glossary). The study here draws on the CRED EM-DAT database for storm damage data (see Section 2.2 for a discussion), and thus the data classification criteria of extratropical storms are identical with that of the database.

2. The Kaya identity is expressed in the from:

$$M = P* (Y/P)* (E/Y)* (M/E) = p*y*e*m,$$

where M = emissions; P = population; Y = GDP; E = energy use; y = (Y/P) = perca-pita GDP; e = (E/Y) = energy intensity of production; m = (M/E) = the carbon intensity of energy.

3. In other words, the classification criteria of extratropical cyclones are identical with the CRED databases.

4. The representative numbers from Lambert and Fyfe's '1ppcto2x' scenario runs are used. The scenario is that CO_2 concentrations are gradually increased from the pre-industrial level to the level doubled over about 70 years and then held constant. The values of δ are calculated by averaging the enhancement of storm occurrence at the time when concentrations hit the doubled level (years 61–80) and of long-run levels (years 201–220).

5. In other words, the effect of climate change on storm damage is much less than 38% of total *at present*.

6. This is about the baseline change and not about temporal variability of incidence, and of course, the latter variability factor might justify stronger institutions against storm damage. However, this issue is beyond scope of this paper.

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