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Damage Costs of Climate Change through Intensification of Tropical Cyclone Activities: An Application of FUND

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Abstract: Climate change may intensify tropical cyclone activities and amplify their negative economic effects. We simulate the direct economic impact of tropical cyclones enhanced by climate change with the integrated assessment model FUND 3.4. The results show that in the base case, the direct economic damage of tropical cyclones ascribed to the effect of climate change amounts to $19 billion globally (almost the same level as the baseline (current) global damage of tropical cyclones) in the year 2100, while the ratio to world GDP is 0.006%. The US and China account for much of the absolute damage, whereas small island states incur the largest damage if evaluated as the share to GDP. The results also show that they are sensitive to the choice of baseline and of the wind-speed elasticity of storm damage.

Key words: climate change; tropical storms; economic impact

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1. Introduction

It is a well-accepted fact that tropical cyclones (hurricanes, typhoons) sometimes cause large economic effects. Hurricane Katrina, which hit the Caribbean and the southern United States in August 2005 and whose direct economic loss is estimated to be over $125 billion,[5] is a vivid example of how substantial the economic impacts of tropical cyclones can be. Worryingly, tropical cyclone activity may be enhanced with the rise of global atmospheric temperatures, with corresponding negative economic effects in the future. Although storm activities vary greatly from year to year, and their general trends are thus not easily discernable, scientific evidence increasingly provides support for this claim. For example, the IPCC's Fourth Assessment Report (IPCC, 2007) recognizes substantial increases in intensity and duration since the 1970s as for the incidence of tropical storms or hurricanes. It also estimates that it is likely that under standard projections, tropical cyclones will intensify in parallel with increases of the global mean temperature, and that such enhancement of activities could bring about significant impacts on human activities including crop failures, death and injuries, and flood damages such as loss of property.

The basic physics of tropical cyclones are fairly well identified (e.g., Emanuel, 2003, 2005), and it is in fact logical to infer that global climate change should increase damages by tropical cyclones. Tropical cyclones are defined as cyclones that originate over tropical oceans (those with maximum winds over 33ms-1 are called hurricanes in the western North Atlantic and eastern North Pacific regions, and typhoons in the western North Pacific), while they may move out of the tropics after their genesis. The source of energy for tropical cyclones is heat transfer from the ocean, which induces upward motion of air in the lower atmosphere, causes convection, and eventually forms self-sustaining patterns of winds and rainfall. Tropical cyclones generally develop only over seawater whose surface temperature is greater than 26˚C. The mechanism of their formation suggests that the rise of sea surface temperature due to greenhouse effects should lead to some amplification of tropical cyclone activities, and scientists have reached a consensus on this general point. On the other hand, details of

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[5] According to Munich Re (2006a).

climatology on tropical cyclones are very complex and remain uncertain to a large extent because of the non-linearity of their generation mechanism and their interconnectedness to large-scale patterns of global atmospheric-hydrological circulations such as El Niño.

Assessment of damages due to tropical cyclones have already drawn a great interest of various groups of people, notably of the (re)insurance industry (e.g., Munich Re, 2006b; Swiss Re, 2006). Academically, the enhanced effects of tropical cyclone with climate change has also been a question for economists, and several estimates have been presented (Cline, 1992; Fankhauser, 1995; Tol, 1995; Downing et al., 1996; Nordhaus, 2006).

One of the big debate items in development economics recently has been the role of geographical attributes on economic growth (e.g., Gallup et al., 2000; Acemoglu et al., 2001; Easterly and Levine, 2003), and some useful studies on the economics of natural disasters are found in this set of studies (e.g., Kahn, 2005; Toya and Skidmore, 2007). Their primary question is whether burdens of frequent natural disasters could inhibit economic growth, or whether wealth could mitigate loss from natural disasters. For example, Toya and Skidmore (2007) conducted a cross-country analysis to estimate the relationships between measures of social or economic development and the effects of natural disaster and identified an inverse relationship between income and natural disaster losses.

Most of the current studies specifically assessing the economic impacts of climate change still focus on baseline changes of weather patterns in the future, and extreme events such as hurricanes are often not considered in their analyses. For example, major recent econometric studies on the impacts of climate change on agriculture (e.g., Schlenker et al., 2005; Deschênes and Greenstone, 2007) do not explicitly take into account potential significance of extreme weather events in productivity loss, while some agronomic studies attempted to address this question with regard to crop growth but without any monetary assessment (e.g., Rosenzweig et al., 2002; Porter and Semenov, 2005).

The fact that cyclone damages have a two-way interrelationship with long-term growth (i.e., relative cyclone impacts fall with economic growth, but cyclone damage reduce economic growth) suggests that the impact assessment of tropical cyclones and climate change would make a suitable topic for climate-economy integrated assessment models. However, major recent studies of integrated assessment models such as Mendelsohn et al. (2000) and

Nordhaus and Boyer (2000) do not explicitly incorporate the effects of tropical cyclones in their climate-economy models – perhaps because the science is still ambiguous.

The purpose of this paper is to show and discuss long-term economic effects of tropical cyclones with climate change computed by the integrated assessment model FUND 3.4. To be sure, earlier versions of FUND already had a component on tropical cyclone damages, and some studies using FUND have presented results including effects of hurricanes (e.g., Tol, 1999), but the model's tropical cyclone component was not specifically evaluated before. In fact, tropical cyclones were omitted by Tol (2002a) and all versions of FUND based on that paper. In the following, brief descriptions of FUND and our approach to model the damage of tropical cyclones are presented in Section 2. Section 3 shows the results. Section 4 concludes.

2. Methodology: Estimation of Tropical Cyclone Impacts with FUND

2.1. The FUND model

We use Version 3.4 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) for our analysis of climate change impacts with enhancement of tropical cyclone activities. Version 3.4 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 tropical cyclone component which will be discussed in this paper, the impact module of the model is outlined and assessed by Tol (2002a, b). The latest publication using the FUND platform is Anthoff et al. (2008). 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 socioeconomic variables. The scenarios comprise of projected temporal profiles of population growth, economic growth, autonomous energy efficiency improvements and carbon efficiency improvements (decarbonization), 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. 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, though the outputs for the 1950-2000 period is only used for calibration, and the years beyond 2100 are used for the approximating the social cost of carbon under low discount rates, a matter that does not concern us in this paper. The scenarios up to the year 2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Legett 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 buildup 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, which are the primary determinant of regional climate change damages (except for tropical cyclones, as discussed below), 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 besides tropical cyclones: agriculture, forestry, water resources, sea level rise, energy consumption, unmanaged ecosystems, and human health (diarrhea, vector-borne diseases, and cardiovascular and respiratory disorders). In our version of FUND, tropical 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 macroeconomic 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. In this paper, however, we do not use this policy-assessment function of the model.

2.2. Tropical cyclones

We calculate the economic damage of climate change through tropical cyclone activities with the following function:

$$\frac{TD_{t,r}}{Y_{t,r}} = \alpha_r \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\varepsilon} \left[\left(1 + \delta \cdot \theta_r T_{t,global}\right)^{\gamma} - 1 \right] \qquad (1)$$

Note that the equation represents the effect of a deviation of tropical cyclones from its baseline (i.e., not the total level of cyclone damages). TDt,r and Yt,r are the damage due to tropical cyclones (increase relative to pre-industrial) and GDP in region r and time t, respectively. αr is the factor determining the baseline level of cyclone damages for region r (see table 2). The data of cyclone damages are drawn from the Emergency Events Database (EM-DAT: http://www.emdat.be/) by the WHO Collaborating Center for Research on the Epidemiology of Disasters (CRED). The CRED EM-DAT is an international initiative which assembles and organizes the data of natural disaster damages collected by various institutions worldwide (i.e., UN organizations, governments, NGOs, universities, private firms, 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,[6] it is more comprehensive than other similar types of dataset and thus the best available at present. The coefficient αr is estimated by averaging storm damages in the dataset over the period 1986-2005. It should be noted that storm impacts vary greatly year to year, and the level of the coefficient is extremely sensitive to what period is chosen and averaged. We address this issue by conducting a set of sensitivity runs, which are discussed in the next section.

The component (yt,r/y1990,r)ε 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:[7] 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, their wealth can insulate themselves from disaster

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[6] Toya and Skidmore (2007) point out three additional factors which would reduce the reliability of economic estimates in the EM-DAT. First, the database only includes direct costs of disasters and omits indirect costs. Second, governments of low-income countries have an incentive to overstate the damage of disasters in order to draw foreign assistance. Third, data collection is a challenging issue in low-income countries because the poor often lack access to established markets and insurance.

[7] Tol and Leek (1999) give detailed discussions on the causal link between income levels and damages of natural disasters.

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 after Toya and Skidmore (2007).

The relative annual cyclone damages increase with warming temperatures. The rise of tropical sea temperatures, which is part of the global climate change phenomenon, is a factor raising the maximum wind speed of cyclones, and cyclones with greater wind speed cause greater damages. $[(1+\delta\theta rTt,global)\gamma - 1]$ in equation (1) is the equation calculating this effect.

In the equation, δ is the parameter indicating how much wind speed increases per degree warming. The level of δ is set to be 0.04, after the consensus statement by WMO (2006).[8] Tt, global signifies the global average temperature increase since pre-industrial times (in degree Celcius) at time t. The temperature levels are factored by regional coefficients θr, representing the relative responsiveness of sea surface temperatures to the global temperature increases in tropical areas where cyclones affecting the respective regions originate (figure 1 shows which parts of tropics correspond to respective regions). It should be noted that designated zones in figure 1 generally do not overlap with the actual land areas of the regions – for example, hurricanes affecting Western Europe do not form in Europe but in the tropical Northern Atlantic, thus the designated plot for WEU is located in the Atlantic, as seen on the map. The configurations shown in figure 1 are chosen to be consistent with actual track records of cyclones and reflect the following stylized facts about tropical cyclones (Emanuel, 2003): by definition, tropical cyclones generate in the tropics (23.4˚N - 23.4˚S); tropical cyclones are rarely formed around the equator below 5˚ North and South; once formed, tropical cyclones move clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere and head poleward; almost no tropical cyclones are recorded in the Southern Atlantic. It should be also noted that the CRED EM-DAT data do not show any record of tropical cyclone damages in Central and Eastern Europe (EEU) and in North Africa (NAF), and thus the corresponding areas for those two regions are not indicated on the map. The coefficients θr are calculated as the ratios of the average sea surface temperature increases for the areas indicated in figure 1 to the global average surface temperature increases and are estimated by using the default 2.5˚x2.5˚surface temperature outputs by MAGICC/SCENGEN 5.3 (whose model descriptions are found at http://www.cgd.ucar.edu/cas/wigley/magicc/).

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[8] Exact quote of the statement: “Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures.”

Finally, γ is a parameter representing the relationship between the cyclone damages and the wind speed, which is in our case a function of tropical sea surface temperature increase. It is conventional to assume that storm damages are proportional to the third power of wind speed (see for example, Emanuel, 2005). This assumption is based on the law of physics that the kinetic energy of wind affecting a unit area per unit of time is proportional to the cube of wind speed. This convention is recently challenged by Nordhaus (2006), who proposed a much greater figure (namely 8) for describing storm damages based on his statistical analysis of US hurricane impacts. For justification of his conclusion, he referred to the fact that the stress-fracture relationship of engineering objects or structures is highly non-linear – in other words, storm damages do not have to be proportional to the wind energy of storms. While his argument deserves attention, a high exponent is hardly a consensus yet. In our analysis, we use the exponent of 3 for standard runs and increase the level of γ for a sensitivity run.

Similar to the rest of the impact module for FUND (see Tol, 2002a for descriptions), the tropical cyclone component has a separate function estimating mortality in addition to that for economic damages:

$$\frac{TM_{t,r}}{P_{t,r}} = \beta_r \left(\frac{y_{t,r}}{y_{1990,r}} \right)^{\eta} \left[\left(1 + \delta \cdot \theta_r T_{t,global} \right)^{\gamma} - 1 \right] \tag{2}$$

In equation (2), TMt,r and Pt,r are the mortality due to tropical cyclones (increase relative to pre-industrial) and the population in region r and time t, respectively. βr 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 after Toya and Skidmore (2007). The number of death 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 specific 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 shows FUND's outputs on the change in economic damage and mortality of tropical cyclones in the year 2100. The results represent increased damages relative to the scenario without climate change. In the base case, the climate-change-induced economic damage amounts to \$19 billion (1995 US dollar per year), which is roughly the same as the expected global total economic damage in 2005 (\$19 billion). The increase of global temperature (3.2˚C since pre-industrial) is a reason for a large amount of the increased damage,9 but the high level of loss is also due to the expanded size of economy at 2100, which is almost 8 times the 2000 level. Figure 2 shows the time trends of increased direct economic loss of tropical cyclones and its share to the world GDP for the base case (1986-2005 baseline). The graph shows continuous increase of absolute cyclone damages, while the ratio of damage to GDP grows more slowly, and its rate of increase gradually diminishes. At 2100, the ratio reaches 0.0057% of the world GDP. The rise of world GDP more than offsets the reduced vulnerability to disasters due to affluence (which lowers damage per unit amount of economic output) for the absolute level of damage, while the share of damage to the world GDP is much more visibly influenced by the income effect. Table 3 also shows that intensified storms would cause over 2,000 additional deaths at the year 2100 in the base case. The monetized value of those fatalities amounts to \$6 billion, which is approximately 30% of the enhanced direct economic damage of \$19 billion. The value of lost life included, the increased damage due to enhanced cyclones corresponds to 0.0074% of the world GDP at 2100.

Table 3 also shows the results of sensitivity runs. As noted before, cyclone damages are extremely variable year by year, and the choice of baseline period is very influential on the results. As an additional case, we extend the averaging period by ten years (1976-2005). Also, we shift the averaging period earlier by 5 years, to be in accordance with the claim that the year 2005 (when Katrina struck) was an anomalous year in the hurricane record (the opinion reviewed and discussed by Nordhaus, 2006). As table 3 shows, the direct economic damage is in fact smallest in the case of 1981-2000 (without 2005) baseline (about 40% less in the GDP ratio compared to the 1986-2005 case). Meanwhile, the difference among the different sets of baseline is less prominent with respect to mortality.

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[9] $(1+0.04\cdot3.2)^3-1 = 0.435$

Figure 3 shows the regional disaggregation of damages (direct economic loss) for cyclone-sensitive regions. The Katrina effect (unusually high hurricane damage in 2005) is in fact visible in the results for USA, and the ratio of increased damage to GDP at 2100 falls in the range from 0.006% to 0.02%, depending on the choice of baseline. The figure shows that with the absolute damage level over \$2.5 billion, the USA and China dominate the accounting of global monetary cyclone damages. However, Small Island States show the highest level of damage if evaluated relative to GDP, amounting to more than 0.03% of GDP. Figure 4 shows the increased damages of tropical cyclones as a fraction of the total costs of climate change. Data represent the results for the year 2100 in the base case, and the results are shown as ratios to both the gross (i.e., only damages are considered) and net (both benefits and damages are summed) total impacts. In figure 4, the relative impact is again highest in the Small Island States, and a few other regions (USA, Central America, South Asia) exhibit cyclone damages amounting to over one percent of the total damages. However, the gross and net total damages greatly differ (often in sign) in all regions and clear patterns are not discernible.

The other sets of results shown in table 3 are those of sensitivity runs for different values of parameters. The income elasticities of cyclone 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). The higher and lower values of δ (the parameter representing how much wind speed increases per degree warming) are set to be consistent with the range stated by WHO (2006). The results show that the changes of income elasticity raise of lower estimates by around 10%, whereas the higher and lower δ bring about larger deviations from the base case, approximately by 30%. Table 3 also lists the results for the case of a high exponent γ (8, following Nordhaus, 2006). They indicate that the exponent is a very influential parameter determining the level of damage, showing more than tripled damages in all categories in comparison with the base case.

Our results fall in the range of earlier estimates. The results exhibit higher values of damages than those of precedent studies showing increased hurricane impacts on the United States under a doubling of CO2 (\$0.8 billion by Cline (1992), \$0.2 billion by Fankhauser (1995) and \$0.3 billion by Tol (1995); Fankhauser (1995) also estimates the global impact as \$2.7 billion). The FUND's base case calculates the enhanced direct economic damage in the US with doubled CO2 (2.5˚C increase from pre-industrial: for the base run, this level is reached at around the year 2078) to be about \$6 billion. It should be noted, however, that the differentials between the FUND results and the other estimates are much reduced if the above figures are converted into the share to the current US GDP, which is around \$10 trillion (as opposed to \$34 trillion computed by FUND for US GDP at 2078). Meanwhile, our estimates are generally lower than the values presented by Downing et al. (1996), who estimated that enhanced effects of natural disasters by climate change amount to 0.1333% of gross world product under the business-as-usual (IS92a) scenario and 0.0149% under the low population, high energy efficiency (IS92d) scenario (both medium projections, aggregated effects up to 2100). Also, our estimates of climate change impact on cyclone damages are significantly lower than those of Nordhaus (2006), who concluded that intensified hurricane damages would decrease the US GDP by 0.064% (\$8 billion) as a result of climate change (i.e., 2.5˚C increase of tropical sea surface temperature). Finally, the results of FUND show far more conservative projections than Stern's (2006) assessment that the total costs of extreme whether could reach up to 1% of world GDP by 2050.

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 and not adjusted with equity weights (see Anthoff et al., 2008 for a detailed discussion on that topic). The results show that in a relative sense, the marginal costs from cyclone damages are negligible in the total marginal costs.

4. Discussion and Conclusion

We simulated the economic impact of tropical cyclones enhanced by climate change with the integrated assessment model FUND 3.4. The results show that in the base case, the direct economic damage of tropical cyclones ascribed to the effect of climate change amounts to \$19 billion globally (almost the same level as the baseline (current) global damage of tropical cyclones) at the year 2100, while the ratio to the world GDP is 0.006%. The USA and China account for much of the absolute damage, while the Small Island States incur the largest damage if evaluated as share of GDP. The results also show that they are sensitive to the choice of baseline (e.g., the Katrina effect) and of parameter levels such as that of the wind-speed elasticity of storm damage.

Just like any other model analyses, this study has limitations, and three of them are worth noting. First, our computation adopted exogenous savings rates to simulate long-run growth paths under amplifying storms. However, actual investment behavior in presence of natural disasters is much more nuanced than the way we simulated with the simple model, and more accurate modeling would require endogenous decision functions of investment with representations of risk aversion of economic agents and of maturity of insurance markets (Tol and Leek, 1999). While this effect on the total growth rates could be negligible in large, less storm-prone economies, it could play a significant role for the growth path of smaller, cyclone-ridden economies. Second, the model calculated damages of intensifying tropical cyclones as a separate component in the impact module in favor of analytical clarity and simplicity. This means that the model ignores some combined effects of enhanced cyclones with other factors, such as a coupling effect of sea level rise and stronger cyclones. Third, the incompleteness of knowledge in the science of tropical cyclones is always a constraint for studies such as ours. Particularly, we assume that tropical storms would become more intense, but kept frequency and range at their present values. The presence of reliable information about spatial and temporal responsiveness of storm patterns to climate change would improve the robustness of analysis and also might change this paper's conclusion.

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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
SAM	South America	Argentina, Bolivia, Brazil, Chile, Colombia, 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

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 $billion	α_r (% of GDP)	Number of casualties	β_r (per million people)
USA	13	0.15	115	0.39
CAN	5.6E-03	7.4E-04	0.15	4.9E-03
WEU	1.5E-04	1.7E-06	0.80	2.1E-03
JPK	2.0	0.033	92	0.54
ANZ	0.043	0.010	1.4	0.067
EEU	0	0	0	0
FSU	7.9E-03	1.7E-03	2.1	7.09E-03
MDE	0	0	0.35	1.4E-03
CAM	0.71	0.18	1090	8.2
SAM	0.020	1.3E-03	7.3	0.024
SAS	0.44	0.094	7985	6.9
SEA	0.36	0.041	1177	2.4
CHI	1.9	0.20	348	0.29
NAF	0	0	0	0
SSA	0.021	5.9E-03	87	0.14
SIS	0.83	0.57	213	4.9

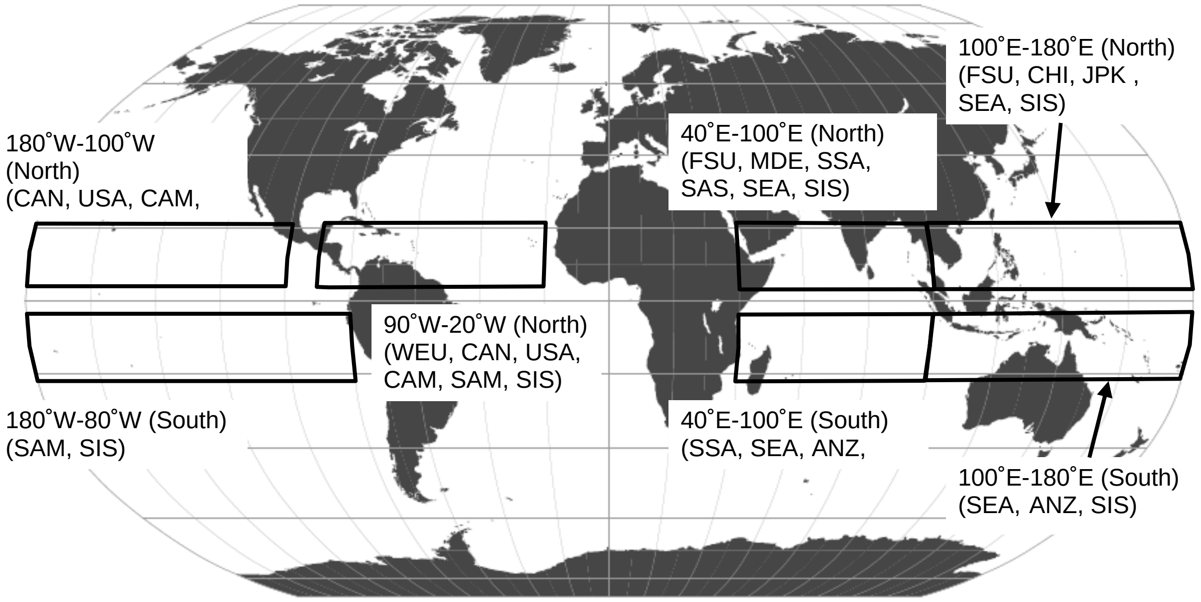
Table 3. FUND's outputs on increased economic damage and mortality of tropical cyclones in the year 2100

						Direct economic damage		Mortality			
Cases	Baseline	ε	η	δ	γ	Increase from pre-industrial (1995 $ billion)	Ratio to world GDP (%)	Increased number of death (from pre-industrial)	Value of lost life ($ billion, increase from pre-industrial)	Total economic damage (1995 $ billion)	% of world GDP
Base	1986-2005	-0.514	-0.501	0.04	3	19	0.0057	2171	6	25	0.0074
	1976-2005	-0.514	-0.501	0.04	3	14	0.0043	1817	5	19	0.0058
	1981-2000	-0.514	-0.501	0.04	3	12	0.0035	2341	6	17	0.0052
High ε and η	1986-2005	-0.487	-0.450	0.04	3	21	0.0062	2536	7	27	0.0082
Low ε and η	1986-2005	-0.541	-0.552	0.04	3	18	0.0053	1860	5	23	0.0068
High δ	1986-2005	-0.514	-0.501	0.05	3	25	0.0074	2797	7	32	0.0096
Low δ	1986-2005	-0.514	-0.501	0.03	3	14	0.0042	1580	4	18	0.0054
High γ	1986-2005	-0.514	-0.501	0.04	8	67	0.0201	8051	21	88	0.0262

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

	Pure rate of time preference		
	0%	1%	3%
Total	109	9	-3
Tropical cyclones	0.34	0.09	0.03

Figure 1. Tropical areas corresponding to the world regions (i.e., areas considered to be the origins of tropical cyclones arriving to respective regions)



* The upper bound and the lower bound of the bands are 25˚N and 5˚N in the Northern Hemisphere and 5˚S and 25˚S in the Southern Hemisphere.

Figure 2. Time trends of increased direct economic loss of tropical cyclones and its share to the world GDP

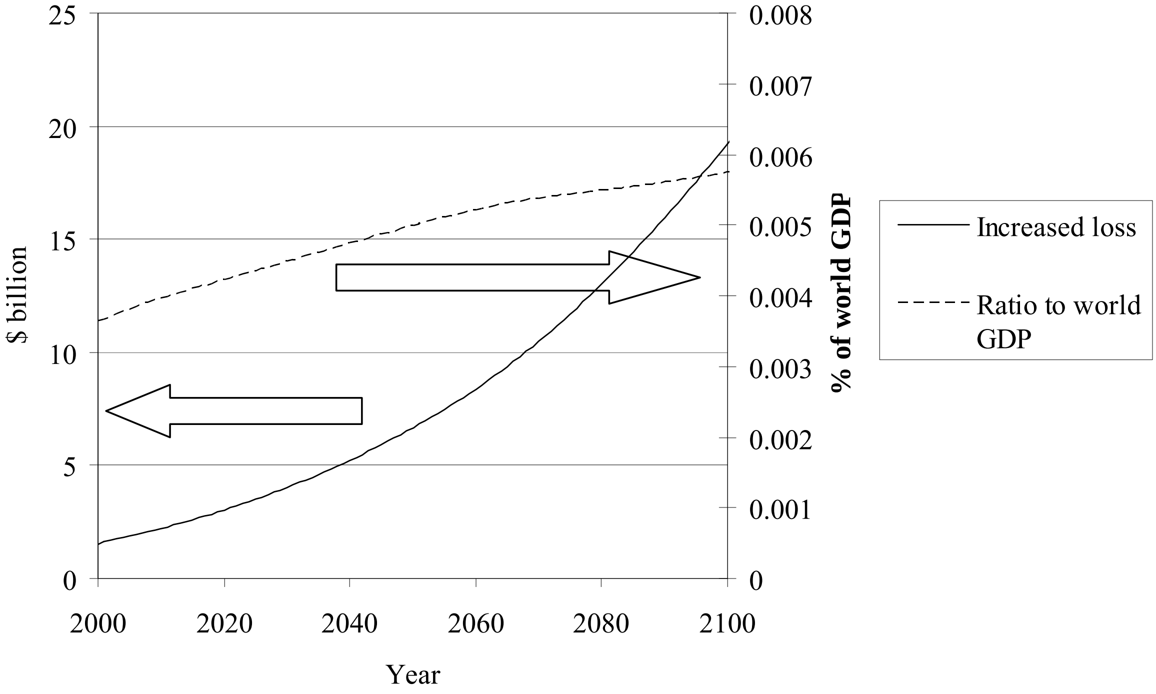
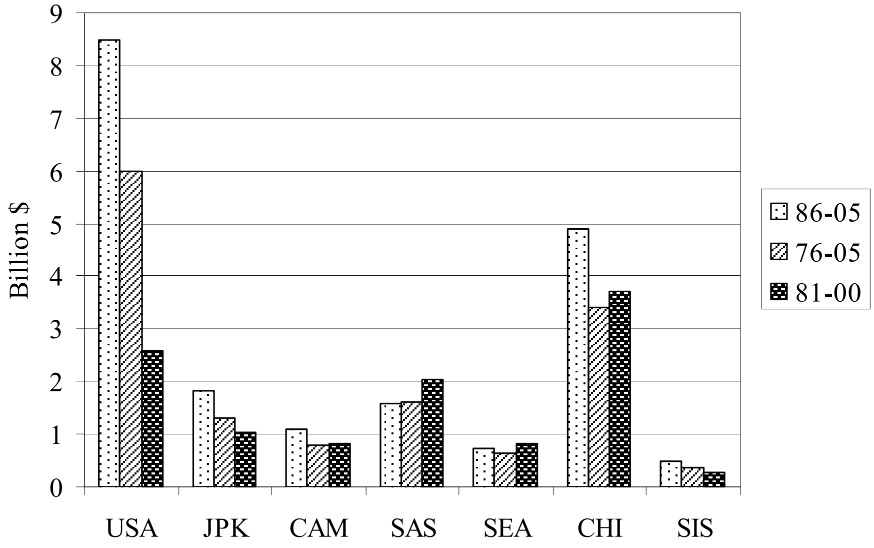


Figure 3. Increased direct economic loss (a) and its share to GDP (b) at the year 2100 for selected regions (results for the three different baseline sets are shown)

a.



b.

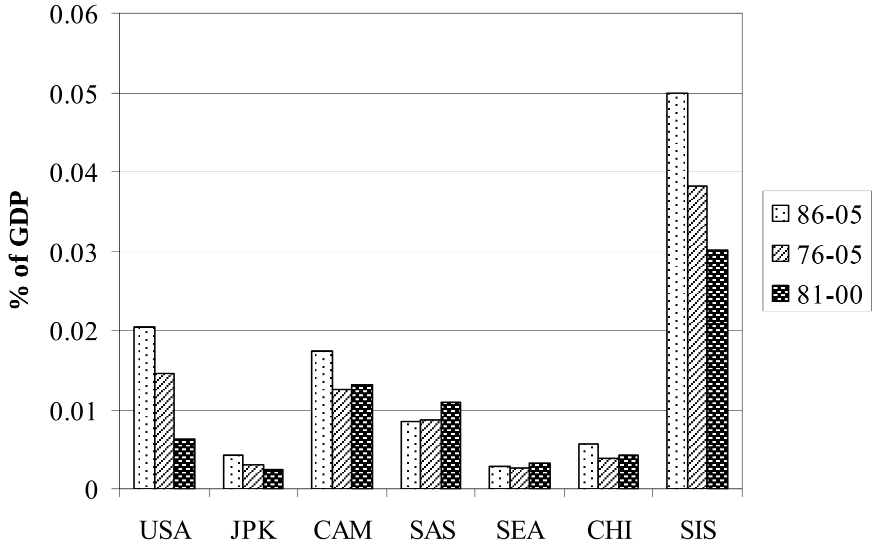
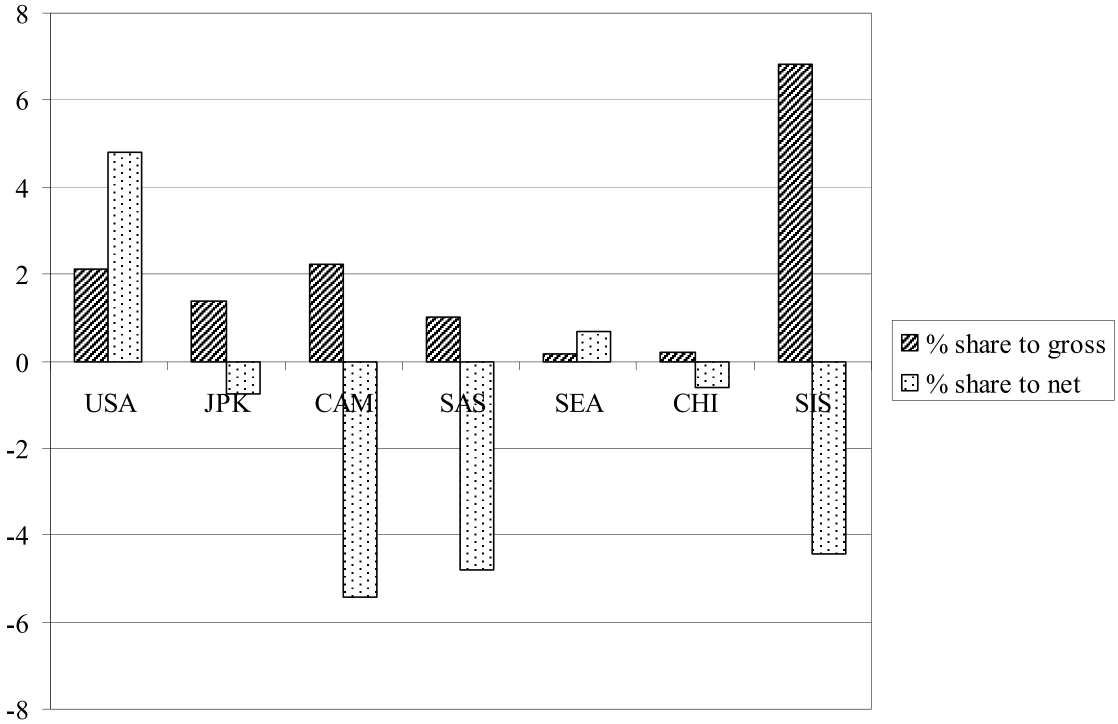


Figure 4. Increased economic damage of tropical cyclones due to climate change as a fraction of the gross (i.e., only damages are considered) and net (both benefits and damages are summed) total costs of climate change for selected regions (at the year 2100 for the base case)



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