nature climate change

ARTICLES

PUBLISHED ONLINE: 15 JANUARY 2012 | DOI: 10.1038/NCLIMATE1357

# The impact of climate change on global tropical cyclone damage

Robert Mendelsohn[1]*, Kerry Emanuel[2], Shun Chonabayashi[1] and Laura Bakkensen[1]

**One potential impact from greenhouse-gas emissions is increasing damage from extreme events. Here, we quantify how climate change may affect tropical cyclone damage. We find that future increases in income are likely to double tropical cyclone damage even without climate change. Climate change is predicted to increase the frequency of high-intensity storms in selected ocean basins depending on the climate model. Climate change doubles economic damage, but the result depends on the parameters of the damage function. Almost all of the tropical cyclone damage from climate change tends to be concentrated in North America, East Asia and the Caribbean–Central American region. This paper provides a framework to combine atmospheric science and economics, but some effects are not yet modelled, including sea-level rise and adaptation.**

Although several studies argue that climate change has altered tropical cyclones, others argue that the evidence is thin. For example, tropical cyclone intensity has increased over the past 40 years as the climate has warmed[1–3]. However, this recent upward trend is still within natural variability and longer-term records do not reveal changes in underlying frequency or severity[4]. The historic record may simply not be long enough and clear enough to detect how climate may be affecting tropical cyclones; nor is the physical understanding of the phenomenon sufficient to project how future activity might change with climate. In particular, there remains significant debate about how rising greenhouse-gas concentrations affect tropical cyclones.

There is also evidence that the damage from extreme events and specifically tropical cyclones is increasing over time[5]. One explanation for this trend is that there are just more people and assets in harm's way[6,7]. Until the influence of rising vulnerability from income and population is properly controlled, it is difficult to know whether the trend in damage is due to a trend in the underlying hazards.

This paper develops a tropical cyclone integrated assessment model. The model begins with an emissions scenario for the next century. Given this emissions scenario, several climate models are used to project how climate might change by 2100. A tropical cyclone model is used in conjunction with the climate models to predict how the frequency, intensity and location of tropical cyclones change in each ocean basin of the world. The paths of the resulting tropical cyclones are followed until they strike land whereupon a damage function is used to estimate the damage caused given the intensity of each cyclone and what is in harm's way. Although each component of the model will undoubtedly improve over time, the model provides a guide for how to combine atmospheric science and economics to estimate tropical cyclone damages.

There are several innovations in this modelling exercise. With the exception of one study[8], the tropical cyclone damage literature previously linked climate to tropical cyclones using a single reported statistical relationship between wind speed and sea surface temperature[9]. Consequently, previous studies assumed that climate change has the same effect on all tropical cyclones[10–12]. This paper models how storm frequency, intensity and location may change in each ocean basin[1]. The previous literature assumes that tropical cyclone damage increases proportionally with gross domestic product (GDP)[8,10–12]. This study tests that assumption with an empirical analysis of global data. The previous literature has relied on wind power to measure storm intensity[8,10–12]. This paper reveals that minimum barometric pressure predicts damages more accurately than maximum wind speed.

## Impact of climate on tropical cyclones

For each climate scenario, a synthetic set of 17,000 storms is examined to capture detailed information about the frequency, path and intensity of storms in each ocean basin. Given the present climate, the properties of these synthetic storms are consistent with observed data[3]. Figure 1 provides a map of a sample of these synthetic storms. The predicted storm frequencies and intensities match historic data. We measure storm intensity using minimum pressure. The storms are most intense over warmer waters (near the Equator). As storms veer over cooler water (towards the poles) or land, they lose their intensity. Storms also lose their intensity if they get too close to the Equator.

Figure 2 shows how climate change affects tropical cyclone power, which is the cubed cumulative wind speed of each storm over its entire track. The results vary a great deal across ocean basins. The results also vary across the climate models. Power consistently increases only in the northwestern Pacific. All of the other ocean basins experience both increases and decreases in power. Some climate models predict particularly large increases in power in the North Atlantic. Average effects are more moderate in the other ocean basins as the changes cancel each other out across different climate models. These large regional inconsistencies among the climate model results are consistent with other variables such as tropical precipitation, which differ widely across models on regional scales.

## Forecast of baseline damage

The present annual global damage from tropical cyclones is US$26 billion (which is equal to 0.04% of the gross world product (GWP)[13]. This is the expected damage per year given

[1]Yale School of Forestry and Environmental Studies, 195 Prospect Street, New Haven, Connecticut 06511, USA, [2]Massachusetts Institute of Technology, Department of Atmospheric Science, 77 Mass. Ave. Cambridge, Massachusetts 02139, USA. *e-mail: robert.mendelsohn@yale.edu.

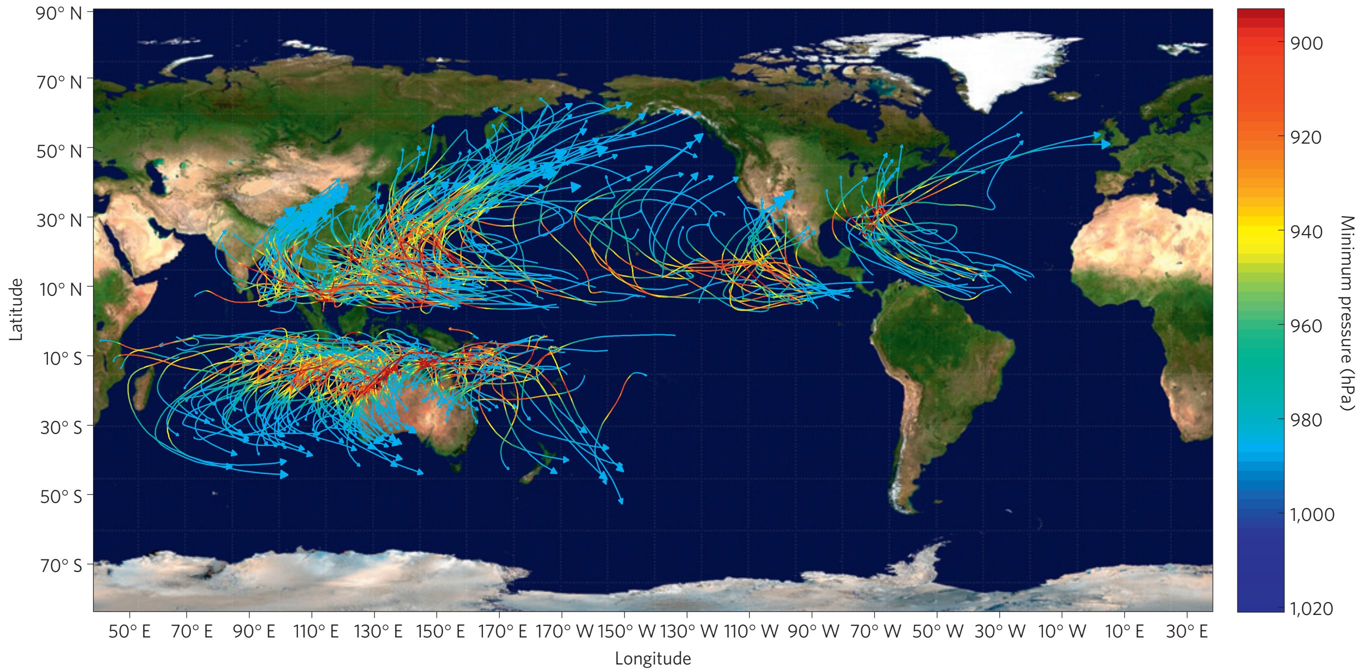


**Figure 1 | Storm tracks and minimum pressure for a sample of synthetic storms.** The tracks show that storms are more frequent in the western Pacific. The minimum pressure (hpa) or storm intensity is measured by their colour. Storm intensity is higher over the warm waters near the Equator and lower over the cooler waters towards the poles.

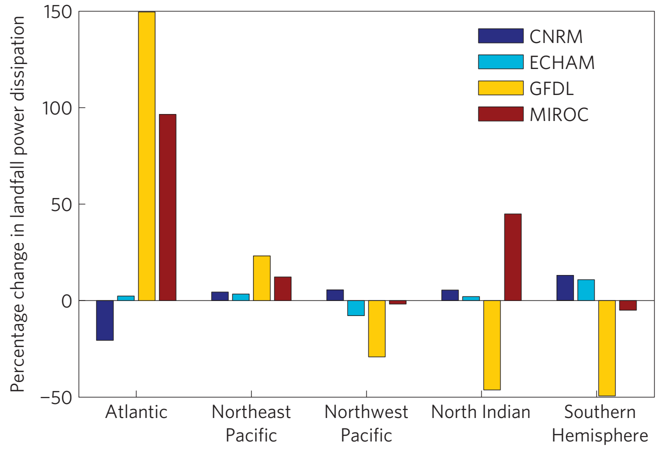


**Figure 2 | The impact of climate change on tropical storm power by ocean and climate models.** Storm power consistently increases across all climate models for only the northeast Pacific. Although not consistent across climate models, average storm power increases markedly in the North Atlantic. Other regions see only moderate average effects as climate models predict both increases and decreases of storm intensity.

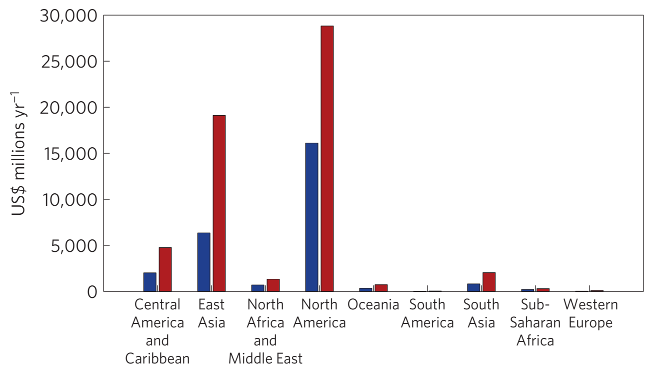


**Figure 3 | Present and future baseline tropical cyclone damage by region.** Changes in income will increase future tropical cyclone damages in 2100 in every region even if climate does not change. Changes are larger in regions experiencing faster economic growth, such as East Asia and the Central America–Caribbean region.

present conditions. Conditions will be different by 2100. Future population is expected to increase to 9 billion as a result of changes in fertility and mortality rates[14]. GDP is predicted to increase markedly assuming that long-term growth rates for developing countries are 2.7%, emerging countries are 3.3% and developed countries are 2%. Given projected baseline conditions in 2100, global baseline damage more than doubles to US\$56 billion $yr^{-1}$ (0.01% of GWP). Baseline damage grows because of higher income. Note that baseline conditions assume the present climate. Future damage as a fraction of GWP falls because the estimated elasticity of income and population density in the damage function is less than 1.

Figure 3 shows the present and future baseline damage (without climate change) from tropical cyclones by region. The baseline damage increases over time solely because more is in harm's way. Over the century, income, and therefore capital, rises considerably and so every region sees an increase in damage. Neither present nor future baseline damage is evenly distributed across the world. The future economic damage from tropical cyclones is less than US\$1 billion $yr^{-1}$ per year in Europe and South America because there are few storms. The damage is relatively low in Africa primarily because there is relatively little in harm's way. East Asia and North America account for about 88% of baseline global damage because these regions have both powerful storms and a lot in harm's way. Damage grows rapidly in Asia and Central America because of high expected economic growth.

## Forecast of climate change damage

The damage from climate change is the difference between the total damage in 2100 with climate change and the 2100 baseline damage with the present climate. Climate change is expected to cause

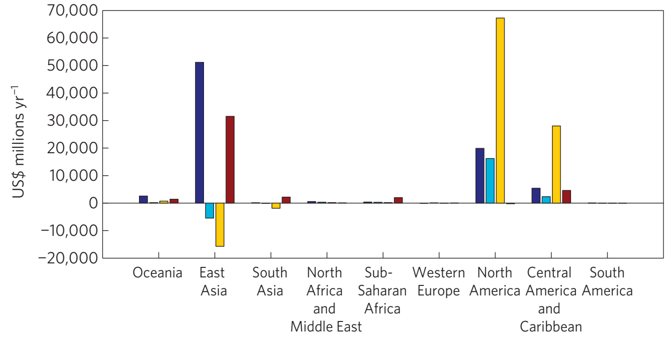


**Figure 4 | Climate change impacts on tropical cyclone damage by region in 2100.** Damage is concentrated in North America, East Asia and Central America–Caribbean. Damage is generally higher in the CNRM and GFDL climate scenarios.

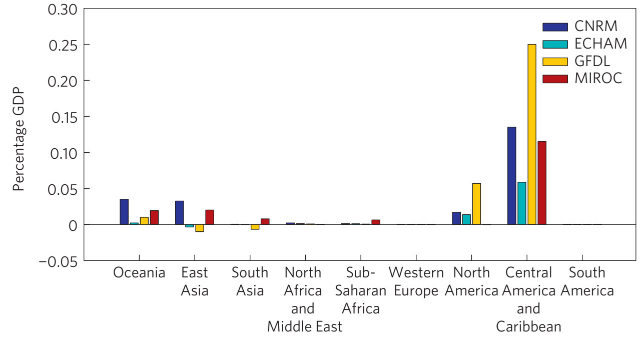


**Figure 5 | Climate change impacts on tropical cyclone damage divided by GDP by region in 2100.** The ratio of damage to GDP is highest in the Caribbean–Central American region but North America, Oceania and East Asia all have above-average ratios.

global tropical cyclone damage to increase by US$53 billion yr$^{-1}$ (almost double the 2100 baseline). These aggregate global results are consistent with most of the findings in the literature concerning the effect of climate change on damage induced by tropical cyclones[10–12] except for one study that predicts much smaller damages[8]. The climate change damage is equal to 0.01% of GWP in 2100.

The results in this paper, however, reveal that the distribution of climate-change damage is not even across the world. Figure 4 shows the damage caused by climate change in each region. North America has the highest average damage of US$26 billion yr$^{-1}$, which is half of the global damage. East Asia and Central America–Caribbean average damages of US$15 and US$10 billion yr$^{-1}$ respectively. The increased intensities of North Atlantic and western North Pacific storms are causing these effects. The average additional damage in the remaining regions of the world combined is just US$2 billion yr$^{-1}$. The rest of the world has small effects, partly because climate change has mixed impacts on tropical cyclones in nearby oceans. North Africa–Middle East and South America are rarely struck by tropical cyclones in this data set. The storms striking Europe tend to be of low intensity. Sub-Saharan Africa does get hit by tropical cyclones but there is relatively less in harm's way.

Figure 5 shows the damage divided by GDP by region. This measure reveals which regions face the highest risk from tropical cyclones. The Caribbean–Central American region has the highest damage per unit of GDP with 0.37%. North America, East Asia and Oceania also have above average rates of damage per unit of GDP because all of these regions are predicted to have more frequent high-intensity storms.

The countries predicted to have the largest impacts and the largest impacts per GDP are all predicted to have more frequent high-intensity tropical cyclones. The two countries with the highest average aggregate damage are the United States (US$25 billion yr$^{-1}$) and China (US$15 billion yr$^{-1}$). Of all the affected countries, these two have the largest future economies at risk. The countries with the highest damage per unit of GDP tend to be tropical islands. These islands have particularly high damage per unit of GDP because each storm affects a much larger fraction of their economy.

As well as changes in the expected damage caused by climate change, it is also important to understand the probability distribution of tropical cyclone damage. The probability density function of damage is highly skewed, leading to substantial damages in the tail of the distribution. With the present climate, almost 93% of tropical cyclone damage is caused by only 10% of the storms. Stated another way, the remaining 90% of tropical cyclones cumulatively cause only 7% of the damage. Tropical cyclone damage is a fat-tailed phenomenon, where the tail of the distribution is more influential than the body.

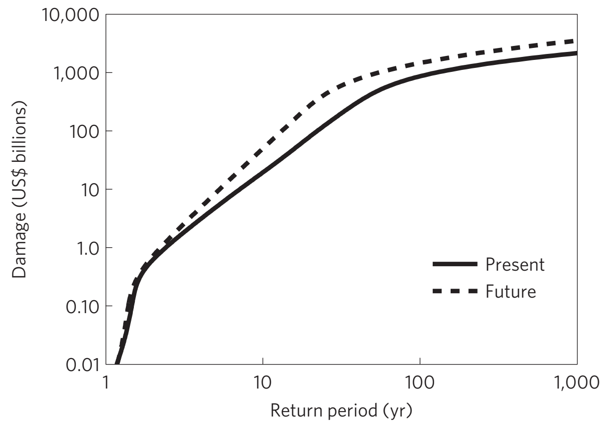


**Figure 6 | Present and future return period by damage in GFDL climate scenarios.** The return period is 1/probability and reflects the expected time over which an event occurs. The axes are in logs to illustrate the fat tail of the probability density function. Climate change tends to make the distribution even more skewed, resulting in shorter return periods for high (but not low) damage storms.

Figure 6 shows a transformation of the probability damage distribution. It illustrates the relationship between the damage and the return period for the Geophysical Fluid Dynamics Laboratory (GFDL) climate simulations. The return period is 1/probability. It reflects the expected amount of time in which to observe a storm causing each amount of damage somewhere on the planet. For example, a 1% annual probability would have a 100-year return period. Both the damage and return period are in log base 10 to show what happens in the tail of the distribution. The figure shows that the probability density function of tropical cyclone damage both before and after climate change is quite skewed. The figure also shows that climate change has a negligible effect on common small storms, but increases the intensity of large storms. With the nonlinear damage function, this increased intensity translates into a significant increase in damage. The return period for highly damaging storms becomes shorter. Low-intensity storms do not change much but high-intensity storms become more frequent.

We conduct a sensitivity analysis to quantify the role that several factors play on the estimated impact of climate change on tropical cyclone damage. Three factors stand out. The predicted global damage varies a great deal across climate models: Centre National de Recherche Meteorologiques (CNRM; ref. 14; US$80 billion), European Centre for Medium Range Weather Forecasts-Hamburg (ECHAM; ref. 15; US$14 billion), GFDL (ref. 16; US$79 billion) and

Model for Interdisciplinary Research on Climate (MIROC; ref. 17; US$42 billion). The parameters of the estimated damage function are also important. Damage varies a great deal depending on the sensitivity of damage to storm intensity and income. If one uses the lower bound of the 95% confidence interval on the storm intensity coefficient (−68 instead of −86), damages fall 28%. With the standard assumption in the literature that the income elasticity is 1, the global damage increases 332%. With the standard assumption in the literature that the population elasticity is 1, global damage increases by 23%. Assumptions about future population and income growth are less important. Assuming the future global population is 10 billion (instead of 9 billion) leads to a 2% reduction in damage. A global economy that is 20% larger (than US$550 trillion) leads to a 7% increase in damage. Other potentially important uncertainties could not be quantified but are discussed below.

## Limitations

There are several limitations to the model that are not tested in the sensitivity analysis. First, using a country as a unit of observation may miss important differences within the country. Damages vary a great deal if a storm hits a city versus a rural area, but this is not yet captured in this analysis. Increases in income and population along the coast, relative to the rest of the country, will cause more damage. Second, the sensitivity of damage to storm intensity is measured only in the US in this study and it may not be representative of the rest of the world. The US may be better adapted to storms and less vulnerable because of its high technological abilities, or possibly more vulnerable to storms because of its more intensive coastal development. The sensitivity analysis reveals that the uncertainty surrounding the climate projection, the impact of storm intensity on damage and the impact of income on damage are all very important and could change the magnitude of the results and, for some regions, the sign. Third, the modelling relies on a single tropical cyclone model. There remains debate in the atmospheric science literature concerning how climate change may change future tropical cyclones and the range of possible outcomes is not reflected in this paper. Fourth, tropical cyclone damage is not well measured in every country. Low-damage storms are under-reported and this problem may be worse in some regions of the world.

Damage is not reported by cause, so storm surge, wind and freshwater flooding cannot be separated yet. The study consequently cannot compute the effect of sea-level rise, which only affects storm-surge damage[19]. If society reacts to sea-level rise by building sea walls, then there will be a lot more future buildings (behind the sea walls) that are at a lower elevation with respect to the future sea. Large storms that overtop the sea walls will cause a lot more damage. There is consequently reason to be concerned about the interaction between sea-level rise and tropical cyclones. Future research must address this missing dimension to the problem.

Adaptation policy is also not explicitly modelled. To some extent adaptation is captured in the sensitivity of damage to income and population. However, some countries have active adaptation policies and programmes that may reduce damage even more. Furthermore, as tropical cyclone damage rises over time, societies may be more likely to take precautions. Future research must address how societies should best adapt to tropical cyclones[20].

This paper focuses on improving the methodology for measuring the impact of climate change on tropical cyclone damage. Further improvements are needed. The analysis needs to be on a finer spatial scale. Sea-level rise needs to be examined in conjunction with storms. Many of the other uncertainties listed above need to be addressed. Finally, the analysis needs to examine how the damage changes as greenhouse gases are mitigated.

## Methods

A detailed account of the methods and data is available in the Supplementary Information. The integrated assessment model begins with the A1B SRES emission scenario[21]. Given this emission scenario, four climate models reveal how the climate changes: CNRM CM3 (ref. 15), ECHAM 5 (ref. 16), GFDL CM2.0 (ref. 17) and MIROC 3.2 (ref. 18). For each model, we compare the climate in the 1981–2000 period with the climate in the 2081–2100 period. CNRM predicts a global warming of 2.9 °C, ECHAM predicts 3.4 °C, GFDL predicts 2.7 °C and MIROC predicts 4.5 °C.

Several climate variables are downscaled from the general circulation climate models and used to drive a tropical cyclone model[1]. Nascent tropical cyclones are randomly seeded across each ocean. The frequency at which seedlings become storms is recorded to predict changes in frequency in each ocean basin. The tracks of storms are then predicted using a simple model that moves the storms given the large-scale atmospheric flow as simulated by the climate model. A specialized, coupled atmosphere–ocean hurricane intensity model is integrated along each track to determine the evolving wind-field evolution. The model predicts that most seed disturbances dissipate. The survivors constitute the tropical cyclone climatology for the particular model and climate. This technique performs very well when used to downscale the present climate, yielding annual storm frequency and intensity distributions in good accord with observations in each part of the world oceans[1].

For each storm track, we determine where the tropical cyclone makes landfall and its intensity at landfall. Landfalls of storms by country are then translated into damage. An empirical function explaining damage per storm is estimated from historical data from 1960 to 2009. The estimated damage functions are shown in Supplementary Table S1. US data[22] at the county level are used to estimate the US damage function. Global data[13] at the country level are used to estimate the global damage function. All of the models include population density and income to measure vulnerability. A log–log functional form fits the data most closely, implying that each independent variable has a constant elasticity. The coefficient of wind speed and minimum pressure reveal that damage is a highly nonlinear function of storm intensity. The results imply that a 20% increase in wind speed and a 1.2% reduction in minimum pressure would double damages. The US coefficients on income and population density are not statistically significant at a 95% level. The global analysis of damage reveals that the income elasticity is 0.42 and the population density elasticity is −0.20. Previous tropical cyclone studies have assumed that the income and population elasticity is unitary[9–11]. An income elasticity of less than 1 implies that higher-income people have taken measures to reduce their vulnerability, a result consistent with other empirical studies in the literature[23–25]. High population density may reduce damage because, although more people are affected, cities may be more hardened against storms than rural areas. The damage function relies on the US elasticity with respect to minimum pressure and the global elasticity of population and income. We consequently assume that the US damage sensitivity applies to the world, which may or may not be true. A sensitivity analysis is done using the 95% confidence intervals of each coefficient.

As some storms were projected to have very low minimum pressure and because the damage function is so highly nonlinear, some storms are projected to destroy more than what is in harm's way. The damage per storm was consequently truncated at US$1 trillion. There are also potential biases associated with using a country as the unit of analysis because of systematic differences within countries. For example, coastal areas subject to storms are generally denser and wealthier than the country average. To correct for this bias, the present baseline predicted annual damage per country is adjusted to match observed damage. However, this correction does not address continued changes in vulnerability within countries.

The expected damage from climate change is measured as the difference in the expected value of global damage from tropical cyclones in 2100 with and without climate change. The expected value takes into account changes in the frequency, intensity and location of storms in each basin predicted by the atmospheric science model. The expected value also takes into account the vulnerability in each country. To measure future vulnerability, we use projected population[20] and GDP in 2100 by country for both the future baseline and climate-change calculation. GDP projections are based on long-term growth rates for three groups of countries: developing (2.7%), emerging (3.3%) and developed countries (2%). These projections are uncertain so a sensitivity analysis was done for population and income.

Received 29 July 2011; accepted 1 December 2011; published online 15 January 2012

## References

1. Emanuel, K., Sundararajan, R. & William, J. Tropical cyclones and global warming: Results from downscaling IPCC AR4 simulations. *Bull. Am. Meterol. Soc.* **89,** 347–367 (2008).
2. Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H. R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **309,** 1844–1846 (2005).
3. IPCC *Climate Change 2007: The Physical Science Basis* (eds Soloman, S. *et al.*) (Cambridge Univ. Press, 2007).
4. Landsea, C. W., Harper, B. A., Hoarau, K. & Knaff, J. A. Can we detect trends in extreme tropical cyclones? *Science* **313,** 452–454 (2006).
5. IPCC *Climate Change 2001: Synthesis Report* (eds Watson, R. T. *et al.*) (Cambridge Univ. Press, 2001).

6. Pielke, R. A. Jr & Landsea, C. W. Normalized tropical cyclone damages in the United States: 1925–1995. *Weath. Forecast.* **13,** 621–631 (1998).
7. Pielke, R. A. Jr *et al*. Normalized tropical cyclone damage in the United States: 1900–2005. *Nature Hazards Rev.* **9,** 1–29 (2008).
8. Hallegate, S. The use of synthetic hurricane tracks in risk analysis and climate change damage assessment. *J. Appl. Met. Clim.* **46,** 1956–1966 (2007).
9. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **436,** 686–688 (2005).
10. Nordhaus, W. The economics of hurricanes and implications of global warming. *Clim. Change Econ.* **1,** 1–24 (2010).
11. Pielke, R. A. Jr Future economic damage from tropical cyclones: Sensitivities to societal and climate changes. *Phil. Tran. R. Soc.* **365,** 1–13 (2007).
12. Narita, D., Tol, R. S. J. & Anthoff, D. Damage costs of climate change through intensification of tropical cyclone activities: An application of FUND. *Clim. Res.* **39,** 87–97 (2008).
13. EMDAT *The OFDA/CRED International Disaster Database* www.emdat.be (Universite Catholique de Louvain, 2009).
14. *World Population in 2300* (Department of Economic and Social Affairs, 2004).
15. Gueremy, J. F., Deque, M., Braun, A. & Evre, J. P. Actual and potential skill of seasonal predictions using the CNRM contribution to DEMETER: Coupled versus uncoupled model. *Tellus* **57,** 308–319 (2005).
16. Cubasch, U., Voss, R., Hegerl, G., Waskiewitz, J. & Crowley, T. Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model. *Clim. Dynam.* **13,** 757–767 (1997).
17. Manabe, S., Stouffer, J., Spelman, M. J. & Bryan, K. Transient responses of a coupled ocean–atmosphere model to gradual changes of atmospheric $CO_2$. Part I: Mean annual response. *J. Clim.* **4,** 785–818 (1991).
18. Hasumi, H. & Emori, S. *K-1 Coupled GCM (MIROC) Description* (Center for Climate System Research, University of Tokyo, 2004).
19. Nicholls, R. J. *et al*. Ranking port cities with high exposure and vulnerability to climate change *OECD Environment Working Paper No 1*, Paris, France (2008).
20. World Bank–United Nations *Natural Hazards, Unnatural Disasters: The Economics of Effective Prevention* (World Bank, 2010).
21. IPCC *Special Report on Emissions Scenarios* (eds Nakicenovic, N. & Swart, R.) (Cambridge Univ. Press, 2000).
22. National Hurricane Center *Tropical Cyclone Reports* http://www.nhc.noaa.gov/pastall.shtml#tcr (National Oceanic Atmospheric Administration, 2009).
23. Stroble, I. & Schumaker, E. *Economic Development and Losses Due to Natural Disasters: The Role of Risk*. (Working Paper Ecole Polytechnique, 2008).
24. Tol, R. & Look, F. in *Climate Change and Risk* (eds Downing, T., Olsthom, A. & Tol, R.) 308–327 (Routledge, 1999).
25. Toya, H. & Skidmore, M. Economic development and the impact of natural disasters. *Econ. Lett.* **94,** 20–25 (2007).

## Acknowledgements

This paper was commissioned and financially supported by the Joint World Bank–United Nations project on the Economics of Disaster Risk Reduction and Recovery. The findings, interpretations and conclusions expressed in this paper are entirely those of the authors. We are grateful to W. Nordhaus, A. Sanghi, M. Toman and seminar participants at the World Bank, Yale University, and the United Nations for valuable comments and suggestions.

## Author contributions

R.M. and K.E. conceived the integrated assessment model and the climate-change experiment, K.E. carried out the atmospheric science component, S.C. and L.B. carried out the economics component and R.M. and K.E. co-wrote the paper.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.M.