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ORIGINAL PAPER

The economic impact of future increase in tropical cyclones in Japan

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Abstract This article estimates the non-first-order economic loss in Japan due to a future increase in tropical cyclones. One possible effect of global warming could be the increase in intensity of tropical cyclones. Using historical storm tracks between the years 1978 and 2007 and altering their intensities due to this potential increase in their intensity, this paper calculates the future potential regional GDP loss in a certain area that is affected by tropical cyclones. Most of the literature is concerned with physical damage and the loss of lives due to tropical cyclones. However, there are additional economic costs when sustained wind speeds are higher than 30 knots (55.56 km/h), a level that generally will lead to a precautionary cessation of many human activities. Using a Monte Carlo simulation, the paper calculates the potential economic costs for the year 2085 under a climate change scenario with a linear one-per cent yearly increase in CO_2. Using a spatial distribution of economic activity in Japan, it is possible to forecast which parts of the country are likely to experience the highest loss risk.

Keywords Climate change · Natural hazards · Tropical cyclone · Economic loss · Japan

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1 Introduction

There is consensus that climate change is already a reality. The earth has become 0.74 degree Celsius warmer over the last 100 years (Carius et al. 2008: 15). One of the effects of global warming is that it will generate an increase in the intensity of tropical cyclones due to the warming of ocean temperature with adverse economic and social consequences (Nordhaus 2006b: 4). A thirty-year satellite record of tropical cyclones confirms this trend (Webster et al. 2005: 1846). However, the accuracy of satellite-based pattern recognition remains questionable (Landsea et al. 2006: 452). Tropical cyclones claimed thousands of lives and caused enormous economic damage. More recently, in the United States, the 2005 hurricane Katrina caused major damages at an estimated cost of US$ 30 billion[1] and left more than 1,800 people dead, triggering a debate about whether such extreme weather events will occur more frequently in the future. The economic costs are enormous and increasing: The annual average global costs of weather-related natural hazards have increased from US$ 8.9 billion from 1977 to 1986 to US$ 45.1 billion from 1997 to 2006 (Bouwer et al. 2007: 753). In the Pacific too, typhoons have been responsible for large economic losses and claimed hundreds of lives. In 2006, typhoon Durian left 800 people dead in the Philippines alone (Munich Re Group 2007: 45). Even in countries such as Japan, where loss of life due to tropical cyclones is rare, the economic damage has been enormous and appears to be increasing.

Reinsurance companies rate cyclones and associated flooding as the most costly natural disaster today. In 2006, windstorms were responsible for 91% of total losses from natural disasters (see Fig. 1). Only 9% of losses were due to volcanic eruptions and earthquakes (Munich Re Group 2007: 45). Moreover, in 2006, windstorms including tropical cyclones accounted for 79% of total insured losses, an equivalent of US$ 13 billion. In the case of Japan, typhoon Shanshan caused losses of US$ 1.2 billion in 2006 (Munich Re Group 2007: 45). It is estimated that for 2006, 40% of all recorded loss events were associated with windstorms (Munich Re Group 2007: 45). Although there is a general agreement that tropical cyclones are likely to increase in intensity, there is yet no consensus on the future frequency of these events (Giorgi et al. 2001).

Measuring economic damage due to cyclones is a complex problem. One expert lists three reasons for this (Nordhaus 2006b): first, the impact of maximum wind speeds on damage is nonlinear. Physical damage is somehow low for low wind speeds and then increases sharply with maximum winds. Second, not all tropical cyclones last the same time as cyclone lifetime increases with maximum wind speeds. Third, tropical cyclones above a certain threshold are rare events. Damage is therefore more likely to be observed at the point of nonlinear failure. Given these complexities, it is rather difficult to predict and measure the real damage of tropical cyclones.

Japan, being exposed to tropical cyclones in the Pacific, has experienced severe physical damage and other indirect economic consequences that this article aims to estimate. These include the loss in economic productivity due to downtime in the public transportation system or other important industries, such as ports. Much of the existing research focuses on the physical damage of windstorms and storm surge damage without calculating the

[1] This figure reflects the insured market loss. It does not include the flood and storm-surge losses which are covered under the National Flood Insurance Program (NFIP) Munich Re Group (2005). "Katrina and Rita: Munich Re Estimates Total Insured Market Losses at up to US$ 40bn." Press Release. Munich: Munich Re Group. Available at: http://www.munichre.com/en/press/press_releases/2005/2005_09_28_press_release.aspx Accessed on 25 July 2008.

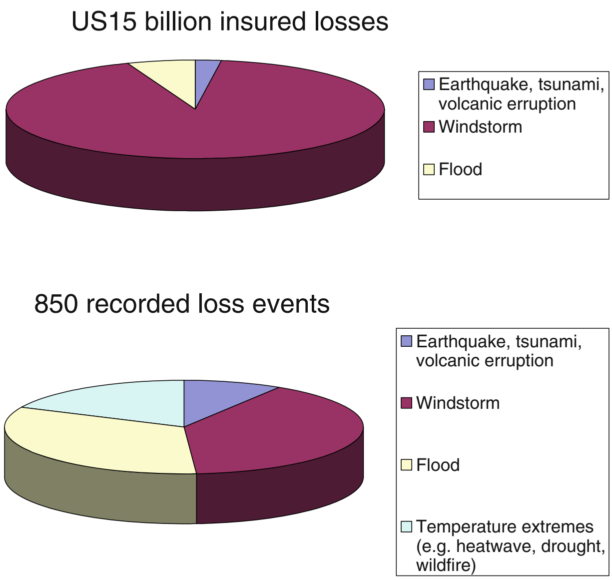

Fig. 1 Insured and total losses in 2006. *Source*: Munich Re Group (2007)

non-direct effects of tropical cyclones, such as the disruption to the transportation system or health implications due to flooding. The following analysis aims at closing this gap in the literature by calculating the non-direct effects measured in the productive man-hours lost when a certain area is hit by a tropical cyclone.

In order to calculate the economic loss due to future increase of typhoon intensity in Japan, it is important to understand where economic activity is located. The highest concentration of economic activity is situated in the coastal regions of the East Coast of Central Japan. For our model, we use a disaggregated variable of gross domestic product (GDP) based on Norhaus' G-Econ project.[2] This dataset provides a spatial distribution of 1990 GDP, average elevation, distance from coastline, and population count for a 1° latitude × 1° longitude (Nordhaus 2006a). By applying a Monte Carlo simulation, we can calculate a spatial probability distribution of future income loss in Japan. This disaggregated approach allows for predicting where the economic impact will be most severe if global mean temperatures continue to rise.

2 Non-first-order economic loss of climate change in Japan: A spatial approach

Tropical cyclones are events with geographical boundaries. They occur in space and time. Often, they do not pass over inhabited land. But when they do, they are likely to cause disruptions, or worst, they can claim lives. In order to measure the economic impact of future increase of typhoons in Japan, we need to know where Japan's economic activity is located. In most countries, the value of economic output is not evenly distributed across the country. Urban centres are often the engines of economic growth. In Japan, the highest

[2] The full data set is available at: http://gecon.yale.edu. Accessed on 4 April 2010.

concentration of economic activity is located in the coastal regions of the East Coast of Central Japan. In sum, the damage caused by tropical cyclones depends on several factors such as the location of economic activity, number of tropical cyclones, intensity of tropical cyclones, and the topography of the affected region and other geographical attributes, such as land-use patterns.

Historical storm tracks and satellite imagery allow us to geo-code tropical cyclones. These data sets are available. However, until recently, there was a lack of socio-political databases that attempted to rescale from political to geophysical scaling (Nordhaus et al. 2006: 3). Scholars argue that this gap occurred because of the need to assess and to evaluate national economic and energy policies (Nordhaus et al. 2006: 3). Ongoing research projects aim now at geo-coding socio-economic key indicators, such as economic income or population density.[3] A World Bank study identifies 'hot spots', areas that are prone to multi-hazards, such as storms, droughts, floods, volcanoes, and earthquakes (Dilley et al. 2005). Global environmental assessments, such as the Millennium Ecosystem Assessment (MA), have produced other useful indicators to measure global land-use and land-cover patterns. Displaying and analysing data in a spatial and temporal scale can provide policy makers and practitioners with powerful tools for planning, agenda setting, and evaluation of the effectiveness of their policies.

Consequently, this article proposes a disaggregated variable approach to measure the non-first-order economic loss caused by cyclones for the year 2085. The present model proposes a methodology to estimate the time loss due to tropical cyclones and presents an application to calculate the expected downtime in various economic activities.

It is worth noting that the present study only accounts for limited future socio-economic changes, such as population growth or economic growth. Growing wealth reduces vulnerability to climate change, whilst population growth might increase vulnerability by exposing more people to more stress from the adverse effects of tropical cyclones, such as the destruction of infrastructure or coastal flooding. In addition, tropical cyclone damage and the cost to adapt to climate change may lower overall GDP growth (Stern 2006: 153). Such a simplistic study is perhaps less realistic than studies that account for socio-economic future changes but is easier to interpret. Moreover, Japan's population and GDP growth figures are estimated to remain relatively constant over the coming decades.

Another factor that shapes a society's vulnerability is its capacity to adapt. Climate change is a gradual process and will not happen overnight. Hence, climatic changes will probably be gradual and therefore enable societies to adapt to the situation (Raleigh et al. 2009). The proposed disaggregated variable approach allows for the prediction of where the most negative economic impacts under a given climate change scenario are most likely to occur.

3 Measuring economic loss

The methodology in this paper calculates the expected time loss of various human economic activities related to an, as yet hypothetical, increase in future tropical cyclone intensity.[4] To

[3] See the work of the Center for International Earth Science Information Network (CIESIN) at Columbia University's Earth Institute: http://www.ciesin.org/. Accessed on 4 April 2010.

[4] The methodology used in this paper is based on the following paper: Esteban M, Webersik C, Shibayama T (2009) Methodology for the estimation of the increase in time loss due to future increase in tropical cyclone intensity in Japan. Clim Change. doi:10.1007/s10584-009-9725-9, http://www.springerlink.com/content/u568p666t2h04075/.

calculate the expected time loss, it is necessary to formulate a computational methodology that is able to reproduce one complete year of tropical cyclones affecting a given area. For this purpose, and in order to save computational time, the path of these storms is not randomly generated. Instead, they are each selected at random from a range of 809 historical cyclone tracks, and the intensity of each one varies randomly according to the distribution of expected maximum surface wind speeds that are thought to be possible in the year 2085 (Knutson and Tuleya 2004). Although there are methods to randomly generate tropical cyclones, the computational demands of simulating are high. As a large number of historical tracks are available for Japan and tropical cyclones generally follow the same general trajectories, by keeping the original historical, it is possible to obtain results relatively easily.

In order to understand the possible effect of an increase in tropical cyclone intensity, it is necessary to compare the relationship with present-day conditions. As a result, the effects in the year 2085 are analysed by taking two different scenarios into account: first, we use a "control" or present-day scenario. In this scenario, the Monte Carlo simulation is carried out without considering any variation in the future intensities of the tropical cyclones. Second, we use a "climate change" scenario, where the intensity of the historical tropical cyclones will be modified, as explained in subsequent sections.

3.1 General assumptions

Trying to predict the consequences of climate change is complex and difficult. In order to understand the limitations of the current model, it is therefore crucial to highlight several assumptions on which it is based:

First, we assume typhoon tracks will not change in the future. Although the Intergovernmental Panel on Climate Change (IPCC) highlights how some authors have found a poleward shift in storm track, it also points out how other studies (Bromirski et al. 2003) suggest that "storm track activity during the last part of the 20th century may not be more intense than the activity prior to the 1950s".

Second, we assume that storm track intensities remain the same, meaning that stronger tropical cyclones will still follow the same tracks, and that overall the density of storm tracks will remain the same, with the same overall intensity density.

Third, we assume the frequency and seasonal distribution of tropical cyclones will not change in the future. It is possible that future increases in sea temperature will make the tropical cyclone season longer and that the frequency of these events will be increased. A number of studies on tropical cyclone frequency in warmer climate have been made, but the results are often contradictory and are still regarded as inconclusive (Giorgi et al. 2001).

Fourth, we assume there is a general relationship between the maximum sustained wind speed and the size of the tropical cyclone. This is currently highly controversial. A statistical analysis of wind speeds and radii will be given in order to give a basis for this assumption, although it is beyond the scope of this paper to enter this debate in more detail.

Fifth, any wind higher than 30 knots (55.56 km/h) will generally lead to a precautionary cessation of many human activities. Therefore, any geographical point within the 30 knot radius of the storm will be considered to be suffering downtime due to that storm and will experience GDP loss.

Sixth, the topography and population distribution of Japan will not change in the future. The geography of a country can generally be considered to be highly stable within a period of 100 years. In the case of Japan, the population has peaked, and it is predicted to start decreasing in the future. However, it is possible that through immigration or other measures, Japan will somehow manage to stabilize its population, and dramatic changes in the population are not likely. GDP per capita is expected to increase in the future, though for the past 15 years or so the Japanese economy has been stagnating. In the model, the authors do not assume any changes in GDP growth in the future.

By making these assumptions, the model can be said to be conservative, meaning that it provides a conservative estimate of the possible consequences of climate change. If tropical cyclone tracks were to shift northwards and the typhoon season were to become longer, then this would aggravate the results shown here. One disadvantage of making rather simplistic model assumptions is the issue of precision and accuracy. A model based on the above-mentioned assumptions is likely to have high precision but low accuracy. More specifically, if we had to repeat the model, it would show fairly similar results, but the results are likely to be far from the actual value, i.e. future tropical cyclones could have different storm tracks and intensities than predicted for the year 2085.

3.2 Geohazards, vulnerabilities, and risks

The impact of tropical cyclones on people and economies depends on the adaptive capacity of a society and on its vulnerabilities. Japan, being one of the richest countries worldwide, has the economic capacity to prepare for and to respond to geohazards. Accordingly, the country has a relatively low economic loss risk. Besides ports, Japan's economy is not as climate-sensitive when compared to agricultural-dependent societies, such as the Philippines. However, Japan's tropical cyclone vulnerability varies across space. Ranging from a cool moderate climate in the north to a tropical south, it is mainly the South, the islands of Okinawa Prefecture and Kyushu, which have been historically most affected by tropical cyclones. This, however, may change in the future if typhoon tracks start moving northwards. More generally, three factors shape vulnerability, in the present and the future. As defined by the IPCC, vulnerability is a function of exposure, sensitivity, and adaptive capacity.

$$\text{Vulnerability} = f(\text{exposure, sensitivity, adaptive capacity})$$

Cited in Yusuf and Francisco (2009: 2) and according to the IPCC's Fourth Assessment Report, exposure is the rate and magnitude of climate change, and climate sensitivity is a measure of the climate system's response to sustained radiative forcing (Intergovernmental Panel on Climate Change 2007). The adaptive capacity of a country, community, or individual is linked to social and economic development, including resource base, social capital, institutions, type of governance, national income, health, and technology. Additional barriers and limitations to adapt relate to individuals' perceptions of climate change risks, the availability of information, and personal preferences, in addition to social and cultural dimensions (Nelson et al. 2007). Adaptation and response measures to climate change impacts are often voluntary and depend on the adaptive capacity, available options, and limitations. According to Nelson, Adger, and Brown, adaptive capacity provides the "preconditions necessary to enable adaptation, including social and physical elements, and the ability to mobilize these elements" (Nelson et al. 2007). In sum, Japan has a relatively low vulnerability to geohazards and high adaptive capacity, hence the relatively small economic loss of less than 1% of annual GDP, as predicted in the following simulation.

3.3 Modelling change

The authors employ a Monte Carlo simulation in order to obtain the expected loss of time in one future year (Esteban et al. 2009). The expected loss of time can be defined as the sum of each of the values of lost time due to tropical cyclones for 1 year for all the simulation runs divided by the number of simulated runs or:

$$\hat{\vartheta}(c) = \frac{\sum_1^N \vartheta(c)}{N} \tag{1}$$

where, $\hat{\vartheta}(c)$ is the expected loss of time; $\vartheta(c)$ is the loss of time obtained from one simulation; N is the number of simulation runs.The need for a Monte Carlo simulation is evident, as the simulation produces completely different results in each simulation run, for instance, the region of Tokyo in Japan could be affected by two cyclones in one year, and the next by none. To get an overall picture, it is thus crucial to use a Monte Carlo simulation. For each scenario, a total of 4,000 simulation runs were made, and then a one-off 40,000 simulation run was also carried out to ascertain the accuracy of various numbers of simulation runs. A 4,000 simulation resulted already in $\sim$99% accuracy, considered adequate.

3.4 Tracking tropical cyclones

The tropical cyclone data were obtained from the Japan Meteorological Agency that provides best track data for tropical cyclones in the Western North Pacific and South China Sea between 1951 and 2007 (Japan Meteorological Agency 2008). This data gives, for each storm, snapshots at various intervals (6, 3, and 2 h depending on the location and intensity of the storm) of the storm geometry and wind speed, such as storm grade, latitude and longitude, maximum sustained wind speed, and longest radius of 50- and 30-knot winds.

Unfortunately, the data prior to 1977 only shows the storm paths and not the radii or wind speeds, and hence this data could not be used. Nonetheless, the 30 years of useful data still provides a total of 809 tracks.

In order to calculate a geographical distribution of time and economic loss, the authors divided Japan in 1472 (to model the expected time lost) and in 119 (to model GDP loss) equally sized grid cells. Each cell represents a unit of analysis containing a unique value of the historical and simulated time affected by 30- and 50-knot winds.

Table 1 Probability distribution functions of number of tropical cyclones per month

Month	Normal	Standard deviation
January	0.47	0.55
February	0.14	0.35
March	0.33	0.67
April	0.72	0.77
May	1.08	1.09
June	1.78	1.25
July	4.00	1.63
August	5.58	1.69
September	4.86	1.34
October	3.75	1.48
November	2.39	1.25
December	1.28	0.90

3.5 Calculating the number of tropical cyclones

A random number of tropical cyclones was generated for each month of the year from the probability distribution parameters given in Table 1. These parameters were obtained by analysing the number of cyclones in the Western North Pacific and South China Sea between 1951 and 2007, as published by the Japan Meteorological Agency. After generating the number of tropical cyclones in each month, the computer model then selects for each cyclone in the month one random historical cyclone from the record of all the tropical cyclones between 1978 and 2007. Picking random historical cyclones has its methodological pitfalls. As described in the Fourth IPCC Assessment Report, forecasting from historical records is problematic, as this does not take decadal cycles into consideration (Intergovernmental Panel on Climate Change 2007). The authors are aware of this limitation by accepting the possibility that relatively high prediction errors will be present in the results. Nevertheless, the fact that almost 30 years of data are used in the simulation means that some of this variation in decadal cycle will already be picked up, and the prediction errors are probably thus within reasonable limits.

3.6 Measuring the increase in cyclone intensity in 2085

The assumptions regarding the increase in cyclone intensity in the year 2085 are derived from the work of Knutson and Tuleya (2004). The authors carried out 1,300 five-day idealised simulations using a high-resolution version of the Geophysical Fluid Dynamics Laboratory (GFDL) R30 hurricane prediction system. These simulations were carried out for a surface sea temperature (SST) change of between +0.8° to +2.4°C that assumes a linear +1% yearly increase in CO_2 over a period of 80 years (up to the year 2085) in order to calculate the SST. This +1% yearly increase means that CO_2 levels would reach 2.2 times the control value (that of 2004) by the year 2085. As Knutson and Tuleya only provide results for the year 2085 and we base our model on their results, we decided to base our results on this year only.

Knutson and Tuleya (2004) computed histograms of the maximum surface wind speed for four different types of hurricane simulation (Emmanuel convection, Pan convection, Kurihara convection, and resolved inner-grid convection). Each is based on a different type of convection scheme and hence produces slightly different maximum surface wind speed histograms. However, they all result in an increase in both cyclone intensity and near-storm precipitation rates related to the increase in surface sea temperature (SST).

Figure 2 shows the general trend given for an increase in maximum wind intensity. The method proposed in the article simplifies the 2085 histogram into a probability distribution curve and uses this to modify the intensity of historical storms. The computer simulation thus randomly generates an “intensity multiplier” from this probability distribution curve and multiplies it by the maximum wind speeds throughout the life of the historical storm. In this way, the maximum wind speeds of a hypothetical future tropical cyclone can be modelled. This intensity multiplier is normally greater than one, resulting in a storm of greater intensity than that of the historical record on which it is based, but it can also be less than one and result in a weaker storm. As a result, although the tracks of the storms do not deviate from those of the historical storms, the intensities and shapes of the storms can be made to change slightly.

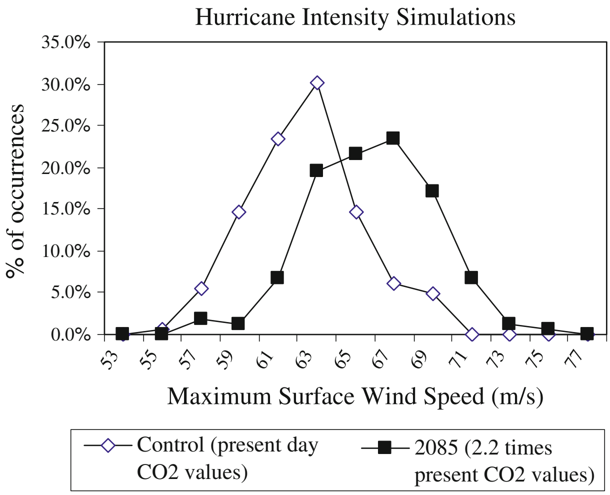

Fig. 2 Resolved inner-grid convection hurricane intensity simulation, Knutson and Tuleya (2004)

3.7 Linking maximum wind speed to cyclone radius

The data of the Japan Meteorological Agency provides radii for the sustained 30- and 50-knot winds at various time intervals. This data can be used to model the tropical cyclone as two concentric circles, with the "30-knot wind" representing the area which is affected by 30-knot winds or higher and with the "50-knot wind" representing the area which is affected by 50-knot winds or higher.

Once the maximum sustained wind speed of the cyclone throughout its life has been modified as shown in the previous section, the radius of the sustained 30- and 50-knot winds must be established. It is necessary, however, to understand by how much will this radius grow if the maximum sustained wind speed increases from that of the historical storm.

3.7.1 Analysing maximum sustained wind speed and cyclone radius

In order to understand the effect of the maximum sustained wind speed of the storms on the radii of the 30- or 50-knot winds, a 29-year analysis of all the data points from 1978 to 2007 was carried out. All the data were analysed collectively by grouping it together according to the maximum wind speed independent on which storm the data came from. Then, an average of the radius for each maximum wind speed could be obtained.

For wind speeds of between 50 and 100 knots, there is a linear relationship between the maximum sustained wind speed and the increase in 30- and 50-knot areas. Exactly 98.22% of the data reading of the Japan Meteorological Agency show maximum sustained wind speeds of 100 knots or less. However, for the data points where the maximum sustained wind speed is greater than 100 knots (1.78% of data) the relationship is not so clear. The effect on the present simulation is minor, as the majority of the time loss and subsequent GDP loss is not caused by the most intense tropical cyclones but by the more average ones.

In order to test the relationship between wind speed and storm radius, the authors carried out a regression analysis that reveals a significant, positive relationship between maximum wind speed and the observed storm radius. On average, an increase in wind speed is expected to increase the storm radius, as the coefficient is positive. The statistical results show that 16% of the variance in the 30-knot wind radii can be explained by the variance in changing maximum wind speed (with similar results for the 50-knot wind radii). Hence, we can conclude that wind speed is a good predictor of storm radius. The probability is smaller than 0.001 that the impact of wind speed on storm radii is due to chance. Running a linear regression with the tropical cyclones' radius as a dependent variable and maximum sustained wind speed as an independent variable reveals a linear relationship between the two variables:

$$R = b_0 + b_1 W_{\max} + e \quad (2)$$

where b_0 and b_1 are the two parameters relating to the slope of the curve, R is the radius of the 30- or 50-knot winds, $W_{\max}$ is the maximum sustained wind speed, and e is the error. In the present case:

$$R_{30} = 48.927 + 2.160 W_{\max} + e \quad (3)$$

$$\ln(R_{30}) = 4.418 + 0.011 W_{\max} + e \quad (4)$$

A very interesting observation to be made from the data is how there appears to be a threshold for a storm to develop an area of persistent 50-knot winds. For a maximum wind speed of less than about 55 knots, there is almost never an area of persistent 50-knot winds, whilst this area appears once this threshold is reached. This observation is crucial to explain a great deal of the results that will be derived from the present model. Historically, many storms fail to reach this 55-knot speed. However, in the future in which increased GHG concentrations in the atmosphere may cause an increase in the intensity of tropical cyclones, more storms might reach this threshold and start to affect greater areas.

3.7.2 Modifying the cyclone radius

Using the relationship shown in Eqs. 3 and 4, it is possible to estimate the increase in radius of the storm by knowing the increase in maximum sustained winds. However, the relationship between maximum sustained wind speed and the area of the tropical cyclone is greatly debated. A linear relationship between wind speed and radius might not exist. To avoid that small radii are overestimated and large radii are underestimated, Eq. 4 shows a logarithmic transformation to lessen the influence of outliers. We transformed the 30-knot wind radius variable using its natural log. Equation 4, moving away from a simple linear regression model, demonstrates that extreme observations do in fact affect the slope of the regression line. Therefore, the authors believe that it is worth carrying out a sensitivity analysis of this relationship. To do so, two different scenarios were chosen:

- Scenario A: with $b_1 = 1$
- Scenario B: with b_1 as shown on Eq. 3

The authors are proposing a conservative methodology, and as such a b_1 higher than shown in Eq. 3 would result in even greater time losses and as such was not considered.

Finally, once the data of the storm have been modified, the radius and position of the tropical cyclone for each hour of its life is calculated by interpolation (the data from the

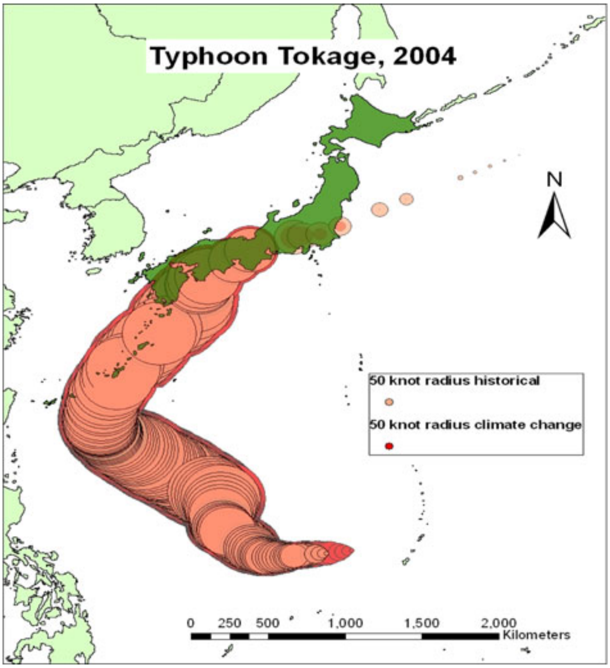

Fig. 3 Track showing the radius of the 50-knot winds for a recorded and modified tropical cyclone, typhoon Tokage in 2004, taking climate change into account

Japan Meteorological Agency is given in 6-, 3-, and 2-h intervals. Hence, it is necessary to compute the location and intensity of the storm at 1-h intervals).

A sample of how a historical tropical cyclone would be transformed by using the methodology described in previous paragraphs is shown in Fig. 3. This figure shows the path of typhoon Tokage, which crossed Japan in 2004, with the area of the historical and modified persistent 50-knot winds.

3.8 Economic input data

The economic data used in the simulation was obtained from Nordhaus' G-Econ project. It uses a combination of demographic factors and regional income figures to estimate the gross income per cell. The data set consists of 119 cells, with a resolution of 1° latitude by 1° longitude. Due to the irregularities in the coastal area of Japan, each data point represented a variable area. The grid resolution used is sufficient to capture the huge differences in population and economic output between different areas in Japan. Japan is a country with huge imbalances in the distribution of its population. Between 77 and 89% of the country is forested and mountainous and thus unsuitable for any kind of human settlement (Kachmar et al. 2005). Consequently, the urban population is highly concentrated in a number of limited, largely low-lying coastal locations, with the greater Tokyo Metropolitan area (encompassing the Saitama, Chiba, Kanagawa, and Tokyo metropolis) numbering about 32 million inhabitants (around 26% of the total population; Marcuse and van Kempen 2000). This is considered to be the world's most populous metropolitan area and represents a large percentage of the country's GDP. The remaining of the population is highly concentrated around other cities such as Osaka and Nagoya, leaving large areas of the country practically uninhabited.

The spatial data that was used shows this variability in the spatial distribution of population and GDP distribution. Although a higher grid resolution would have been preferable, the one used for the model was adequate to calculate the regional variation in anticipation of a potential increase in typhoon intensity.

4 Empirical findings

The methodology shown in the previous sections can be used for a variety of purposes to guide policy makers and practitioners to make informed decisions about possible future levels of risk due to a potential increase of tropical cyclones. The following will estimate the potential non-first-order economic loss due to an increase in typhoon intensity in the year 2085 and will assess the possible implications of these results.

4.1 How wind related downtime affects the economy

Tropical cyclones do not affect people equally as they are limited in space and time. Generally speaking, a wind of over 34 knots is considered as a Gale on the Beaufort scale and will result in a Gale warning in places like the United States and the United Kingdom. Flights are typically cancelled or delayed when an area is affected by strong winds, and maritime ports generally have to start limiting their operations when winds are over 30 knots. The website of the Port of Dover (2008), for example, explains how there will be a general closure of the port when winds exceed 55 knots, and how in some areas of the port damage to the fenders is likely to occur when wind speeds exceed 45 knots. At around these kinds of wind speeds, the conditions inside a port become so difficult that the port cannot function properly, although much lower wind speeds will generally also lead to a cessation of many of the ports activities. In Japan, it is also common for trains to stop operating during periods of high wind speed, and this indicated how a period of high wind speed (which in the case of tropical cyclones goes together with high rainfall) would lead to most of the transportation system. In the case of Japan, typically all citizens will head home hours before a typhoon passes over the city, and restaurants and commerce in general will often politely remind customers that a typhoon is approaching, with many of them also closing during the event.

4.2 Estimation of economic loss due to future cyclone radii increase

Our simulation model based on scenario B estimates that the annual economic damage due to man-hours lost from typhoons that have an area of sustained wind speed of at least 30 knots will account for 0.15% of GDP in the year 2085 (based on 1990 GDP figures). In absolute figures, this would amount to a total of more than 7 billion US$ (1995 PPP) or approximately US$ 60 per capita. We assume in our calculations that in areas that are affected by typhoons that have an area of sustained wind speeds higher than 30 knots, most human economic activities come to a stand still. This would lead to a temporary halt in all economic productive activity. Since typhoons do not affect the entire country, a geographical distribution of economic income will be used for the calculations.

Moreover, our simulation demonstrates that the zone of people affected by storms under a climate change scenario will shift northwards (see Figs. 5, 6). By taking the economic

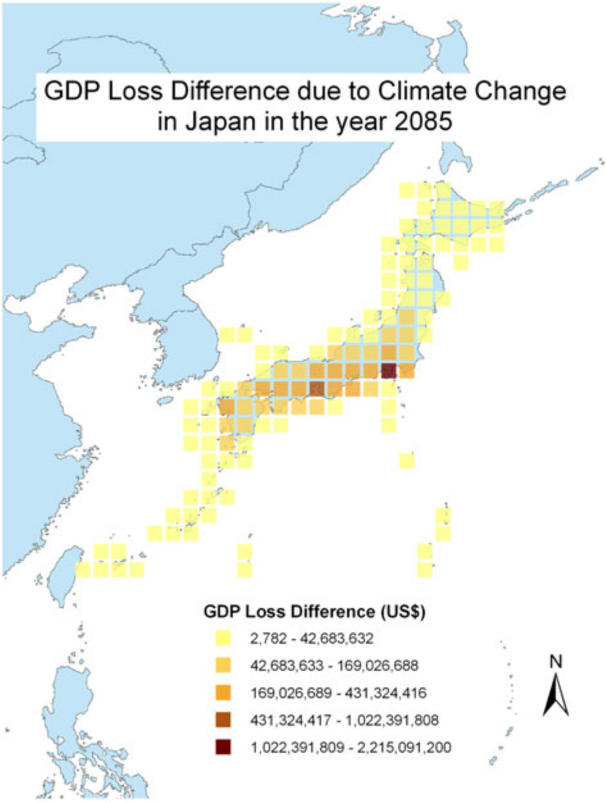

Fig. 4 Non-first-order economic loss due to potential increase in typhoon intensity in the year 2085

activity per geographical unit into consideration, the results are different. The highest loss risk is concentrated in the Eastern coastal areas of the main island of Japan where the economic activity is the highest. This includes most of the major cities, such as Tokyo, Yokohama, Nagoya, Kobe, and Osaka (Fig. 4).

The potential future loss potential is particularly high in urban areas due to economic and demographic development. The economic loss risk in coastal urban areas is likely to increase because of population growth and improving economic conditions by exposing more people and economic assets to natural hazards. This is particularly true for developing nations. With a loss potential of 22% by 2015, Tokyo ranges at the lower end compared to a 88% loss potential for cities like Shanghai and Jakarta (Bouwer et al. 2007).

Although the overall loss due to potential future increase of typhoons in Japan in the year 2085 is a small percentage of the Japanese overall economy, it is only one part of the overall loss figures. First-order physical losses are likely to increase, too, and they make up a much larger proportion of the total overall losses.

4.3 Cyclone tracks are shifting northwards

Using the procedure described in previous sections, it is thus possible to calculate the expected number of hours (i.e. downtime) that each part of a country, such as Japan, is likely

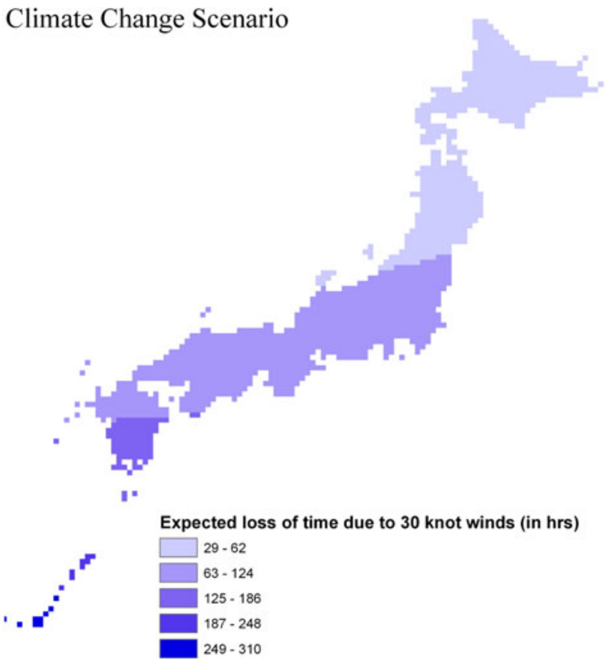

Fig. 5 Expected number of hours per year affected by 30-knot winds or higher due to windstorms for climate change scenario

to lose in the future due to increased tropical cyclone intensity (Fig. 5). This can then be compared with the control case showing the expected number of hours that would be lost each year by using the unaltered historical records (Fig. 6). A direct comparison between these figures shows how there is a northwards shift in the expected amount of hours lost. This is a very interesting finding, as although the storm tracks are not altered from the 1978–2006 storm track records, increasing the intensity of storms effectively moves their consequences northwards. The reason behind this is twofold: first, by increasing the radius of the storms that historically had already reached typhoon status a wider area is affected, and hence any typhoon that reaches the northern parts exerts its effects over a greater area. Second, many of the tropical cyclones that previously reached the north of Japan did not reach "typhoon grade". According to the data from the Japan Meteorological Agency, they typically did not have a 50- or 30-knot radius of sustained wind speeds and hence do not greatly influence human activities. The present methodology, however, will amplify the maximum sustained wind speed of the tropical cyclones; and if this goes over 50 knots, it will assign them a 50- and 30-knot radius of sustained wind speeds. This results in more "typhoon grade" tropical cyclones reaching the north of the country.

So, although the simulation does not alter the tracks of the tropical cyclones that reach Japan, as it alters their intensity, it does increase the frequency of "typhoon-grade" cyclones reaching the northern parts of Japan. This is a very important effect of the model, as it results in increased downtime in the northern areas. The physical reasoning would be that an increase in surface sea temperatures would result in tropical cyclones keeping their strength over a longer distance as they travel north, resulting in higher latitude regions being affected.

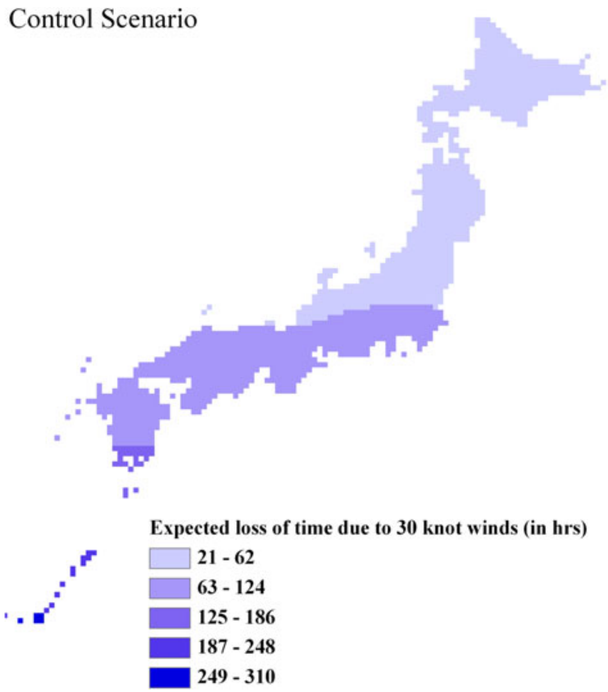

Fig. 6 Expected number of hours per year affected by 30-knot winds or higher due to windstorms for control scenario

The northern areas of Japan previously did not experience typhoons with the same frequency or intensity as the southern part. Hence, an increase in the typhoon intensity in these areas will also result in increased economic loss.

5 Discussion of major findings

Climate models form an important tool to investigate the potential change in tropical cyclones. They contain hypotheses relating to how the climate system works and yield fairly different results depending on these assumptions. The present article uses the results provided by Knutson and Tuleya (2004) to develop a model to evaluate the future economic consequences of an increase in tropical cyclone intensity. It would have been interesting to start with a selection of climate scenarios describing the consequences resulting from certain a-priori conditions, as the present study only captures a relatively small part of the variability of the earth's weather system. As mentioned earlier, tropical cyclones are influenced by several other, natural factors, such as decadal cycles and global dimming. As Knutson and Tuleya's analysis does not take additional natural, long-term variability into consideration and our analysis is based on Knutson and Tuleya's results, we decided not to include additional natural factors. It must be understood that at present, there is a large overall uncertainty in future changes in tropical cyclone frequency as projected by climate models with future greenhouse gas concentrations as emphasised in the Fourth IPCC Assessment Report (Intergovernmental Panel on Climate Change 2007).

The objective of the paper is to provide policy makers with a tool to assess the degree of magnitude of the economic consequences of this potential future increase in tropical cyclone intensity. The methodology proposed was used to estimate the economic losses due to the man-hours lost. This methodology is also relevant to the calculation of insurance payouts, which tend to be one of the most common ways to quantify the economic damage of a natural disaster. For example, in the United States, it is possible for companies and industries to insure against the consequences of a business interruption due to a natural disaster, such as hurricane Katrina in 2005.

One of the proposed methodology's strong points is its comparatively quick computation time, due to the simple way in which tropical cyclones are generated. It ensures that the distribution of storms spatially is similar to the historical one, and thus allows the use of the Monte Carlo technique to quickly obtain estimates of economic consequences. A more complex generation method would require the use of powerful computers and thus would make it difficult for a policy maker to obtain answers in a relatively short amount of time. Another advantage of the model is the use of spatial economic data. As discussed earlier, tropical cyclones are limited in space and time and therefore do not affect the whole territory of a particular country. By employing spatial data, the authors account for this geographic variation.

The methodology outlined in this article, however, does have a number of drawbacks. For example, by relying on historical tropical cyclones, it has no way to predict what future changes in global climate will have on cyclone tracks or frequencies. Hence, it does not allow for the prediction of events that are significantly different to those of the last 20 years. At present, as highlighted by a consensus statement from the 6th International Workshop on Tropical Cyclones of the World Meteorological Organisation "although recent climate model simulations project a decrease or no change in global tropical cyclone numbers in a warmer climate there is low confidence in this projection" (World Meteorological Organisation 2006). Thus, in the absence of any clear guidance from other authors on this point, the assumption of keeping the routes and frequencies the same can be seen as the default starting point of any simulation to determine economic risks.

Also, the model relies on the assumption that larger maximum wind speeds correlate with larger tropical cyclones. This point is not clearly established for the case of large typhoons (Knutson et al. 2001). However, the approach of the present article is merely to adjust the size of historical storms by a random amplification factor if they already had a radius of area affected by at least 30 knot winds, and to give a previously small storm that reached a stronger maximum sustained wind speed a radius of area affected by 30 knot winds.

This second point makes the crucial difference to the results of the present simulation. By increasing the maximum wind speeds of the storms, the number of those which reach a certain threshold where they will start to have an effect on human activities—by having an area of persistent 30-knot winds—will increase. This threshold is clearly identified in the present paper; and if more storms reach it due to climate change, then it is likely that the economic consequences highlighted in this paper will materialise.

With respect to the economic loss, a number of assumptions were made regarding the future growth of the Japanese economy. These are based on the fairly conservative assumption that the Japanese economy will not grow significantly in the future. However, it can be assumed that GDP figures are higher in the year 2085; therefore, the absolute figure may be much higher than calculated but the ratio of 0.15% may remain stable. Socio-economic implications also depend on the overall variability of extreme weather conditions, especially as loss events are nonlinear events, as mentioned earlier. By keeping the variation in both the natural and the social systems relatively low, we can allow for an easy comparison in space and time, and within Japanese regions and economies.

In addition, it is fair to assume that not all economic activities will come to a standstill when a 30-knot or higher cyclone passes over an inhabited territory. It would be indeed interesting to incorporate detailed historical data in the model to better understand their socio-economic implications, for example by incorporating low hazard but high resulting risk events. However, this would add complexity to the analysis making comparison within Japan and other regions more difficult.

6 Concluding remarks

The scientific evidence that climate change is a serious global challenge is convincing. The Stern Report claims that "the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more" (Stern 2006: vi). The results of the present simulation can be seen as an attempt to move from the general approach followed by the Stern Report into a more detailed assessment of the overall cost to a particular country. Adaptation to climate change is essential for the future growth of the Japanese economy.

Although the cost of dealing with physical damage—or so-called first-order loss—of a hypothetical future of more intense tropical cyclones is not included in this paper, it measures the economic non-first-order loss in Japan due to a potential future increase in tropical cyclone intensity. The model in this paper calculates how much GDP would be lost due to man-hours lost when tropical cyclone intensity increase, with Japan likely to experience a 0.15% loss in annual GDP or approximately US$ 60 per capita for the year 2085. The methodology is fairly quick, with a typical 4,000-run Monte Carlo computer simulation being performed on a personal computer within a day. Moreover, the paper uses a methodology that can be easily adapted for different storm intensity scenarios and for other countries.

Future research could aim at incorporating additional variables such as infant mortality rates—as a proxy for the level of development—to better measure the level of vulnerability to natural hazards in countries that are more severely affected by tropical cyclones, both economically and socially. These countries include the Philippines, Bangladesh, or Haiti. There is a large body of research on the physical and economic damage of tropical cyclones, but there is limited understanding of how natural hazards impact on a country's development path, in particular in the developing world.

Whilst urban populations in coastal settings grow and prosper, the loss potential is increasing steadily (Bouwer et al. 2007: 753). This development can reach a point where the costs of natural hazards may potentially outpace economic growth (Webersik 2010). Although, due to uncertainties associated with climate changes, the results of this paper should be viewed with caution, they can provide a feeling of the magnitude of the possible costs of climate change.

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