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Methodology for the estimation of the increase in time loss due to future increase in tropical cyclone intensity in Japan

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Abstract The present paper develops a methodology for estimating the risks and consequences of possible future increases in tropical cyclone intensities that would allow policy makers to relatively quickly evaluate the cost of different mitigation strategies. The methodology simulates future tropical cyclones by modifying the intensity of historical tropical cyclones between the years 1978 and 2007. It then uses a Monte Carlo Simulation to obtain the expected number of hours that a certain area can expect to be affected by winds of a given strength. The methodology outlined has a range of applications, and the present paper shows as an example the calculation of the expected cost of mitigation of the increased downtime for Japanese ports by 2085 for a variety of economic growth scenarios.

1 Introduction

Global warming is considered one of the major challenges of the twenty-first century. One of the fears of global warming is that it might produce an increase in the frequency and intensity of tropical cyclones due to the warming of the sea (Nordhaus

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2006). A 30-year satellite record of tropical cyclones confirms this trend (Webster et al. 2005). Also, Elsner et al. (2008) examined the trends in the upper quantiles of cyclone maximum wind speeds and found a significant upward trend for wind speed quantiles above the 70th percentile. However, the accuracy of satellite-based pattern recognition remains disputed (Landsea et al. 2006). The fact is that tropical cyclones can have devastating effects, especially in poor countries, such as the 1970 Bangladesh cyclone were between 300,000 and 500,000 people killed (Landsea et al. 2006). More recently in the USA the 2005 hurricane Katrina caused major damages and left more than 1,800 people dead, triggering a debate about whether such tragic events will occur more frequently in the future. 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 2007). 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. Although this could be due to an increase in people taking out insurance, between 1980 and 2008 eight of the ten costliest natural disasters in Asia were due to typhoons in Japan after 1998, according to data from the Munich Re website (2009).

To try to understand how tropical cyclones are likely to be affected by an increase in global temperatures, a number of global climate models using powerful supercomputers have been carried out, as highlighted in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, or 4th IPCC (Giorgi et al. 2001). This report shows how 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.

Also, measuring economic damage due to storms is a complex problem. There might be several reasons for this (Nordhaus 2006). First, the impact of maximum wind speeds on damage is non-linear. This author points out that physical damage increases sharply with maximum winds. Second, not all storms last the same time as cyclone lifetime increases with maximum wind speeds. Thirdly, tropical cyclones above a certain threshold are rare events. Damage is therefore more likely to be observed at the point of non-linear failure. Given these complexities, Nordhaus (2006) calculates that damage in the Atlantic coast of the USA rises with the eighth power of the maximum storm wind speed.

Japan, being one of the countries exposed to tropical cyclones in the Pacific, has experienced severe physical damage and other, indirect economic consequences of these weather systems. 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 natural hazards without calculating the non-direct effects of tropical cyclones, such as the disruption to the transportation system or health implications due to flooding. This paper aims at closing this gap in the literature by calculating the time that a port loses when hit by a storm. Using a Monte-Carlo simulation, the authors were able to calculate the expected future loss of time due to climate change. By taking into account expected GDP growth and the corresponding necessary growth in port infrastructure, the authors were also able to calculate the expected extra required capacity in port infrastructure to cope with the increase in downtime associated with increased tropical cyclone intensity.

2 Measuring the economic impact of climate change on ports in Japan: a disaggregated approach

Most comparative studies undertaken in the field of natural hazard studies use the country/year dyad as the unit of analysis. However, the study of human–environment systems should include geo-physical variables. Land cover, location of capital cities, centres of economic activity, seaports, population density, and storm tracks all vary geographically. Statistical studies that do not account for this geographical variation using country-level data are potentially flawed (Buhaug and Rød 2006). By considering the Earth as an integrated system, the use of gridded sub-national-level data would account for the spatial variation with the help of geographic information systems (GIS). Some geo-coded data sets are already available. Other ongoing research projects aim at geo-coding key indicators, such as population density or income inequality. A recent 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 (MEA), have produced useful indicators to measure global land use and land cover patterns. Displaying and analyzing 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.

The economic impact of tropical cyclones in Japan depends on several factors such as the location of economic activity, number of storms, intensity of storms, and the topography of the affected region and other geographical attributes, such as land-use patterns. All these factors vary geographically.

Consequently, the authors propose a disaggregated computational approach to measure the economic loss caused by storms under a climate change scenario for the year 2085. In Japan, as well as in other countries, the value of economic output varies geographically. In particular, in the Japanese case the highest concentration of economic activity is located in the coastal regions of the East Coast of Central Japan. 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 ports. For this purpose the spatial location and total cargo capacity of each of the major 15 Japanese ports was used, which are located around the areas of greatest economic activity. By applying a Monte Carlo simulation the future required additional investment in port infrastructure due to climate change can be evaluated.

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, while population growth might increase vulnerability by exposing a society to more stress from the adverse effects of tropical cyclones, such as the destruction of infrastructure or coastal flooding. In addition, under a climate change scenario, tropical cyclone damage and the cost to adapt to climate change may lower overall GDP growth (Stern 2006). The present study only considers a couple of simplistic scenarios of potential GDP growth in Japan, and ignores any other possible socio-economic changes.

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 adaptation. Climate change is a gradual process and will not happen over night. Hence, climatic changes will probably be gradual and therefore enable societies to adapt to the situation (Raleigh et al. 2008).

This disaggregated approach allows for the prediction of where the most negative economic impact under a climate change scenario will most likely occur.

3 Proposed methodology

The objective of the proposed methodology is to calculate the expected time loss of various human economic activities related to a, as yet hypothetical, increase in future tropical cyclone intensity. The methodology is aimed at policy makers which need to carry out risk assessments without having to resort to the use of powerful supercomputers. To calculate this expected time loss it is necessary to formulate a computational methodology that is able to reproduce one complete year of tropical cyclones affecting a certain area. The present paper proposes that for this purpose the path of these storms should not be randomly generated; instead, they are each picked at random from a set of 809 historical tracks and the intensity of each one is varied randomly according to the distribution of expected maximum surface wind speeds that are thought to be possible in the year 2085. The year 2085 was chosen as the work of Knutson and Tuleya (2004) provides the expected distribution of maximum surface wind speeds for this year only. Although there are methods to randomly generate tropical cyclones, the computational demands of doing are so great that attempting to then use a Monte Carlo Simulation would result in a prohibitively long computational time. As a large number of historical tracks are available for the target region, and tropical cyclones generally follow the same general trajectories, by keeping the original historical it is possible to obtain a solution relatively quickly.

In order to understand the possible effect of an increase in storm intensity it is necessary to see the relationship with present day conditions. Hence the effects in the year 2085 are analysed by taking two different scenarios into account:

- 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.
- A "Climate Change" scenario, where the intensity of the historical tropical cyclones will be modified as detailed in subsequent sections.

3.1 Assumptions

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

1. Typhoon tracks will not change in the future. Although the 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 1950's". This would mean that there are neither more storms nor the tracks are more intense than before the 1950's according to these last authors, and thus it is thus not clear that the changes in tropical cyclones currently observed are not due to a naturally-occurring cycle.

2. 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 increase the frequencies of these events. A number of studies on tropical cyclone frequency in warmer climate have been made, but the results of these are contradictory, and are still regarded as inconclusive (Giorgi et al. 2001).
3. There is a general relationship between the maximum sustained wind speed and the size of the tropical cyclone. This subject is the object of intense debate at present. The authors do not want to enter into this debate in the present paper, but provide some statistical analysis of wind speeds and radii to give a basis for this assumption (see Section 3.6.1. of the present paper).
4. Any wind which is 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. This is particularly the case of ports, although this parameter could be changed if the model was to be applied to different economic activities.
5. The topography and population distribution of the target country (in this case Japan) will not change in the future. The geography of a country can generally be considered to be highly stable within a period of a hundred years. In the case of Japan the population is considered to have peaked, and it is predicted to start decreasing in the near future. However, it is possible that through immigration or other measures Japan will somehow stabilize its population, and dramatic changes in the population appear unlikely. GDP per capita is likely to increase in the future, though for the past 15 years or so the Japanese economy has been stagnating. GDP growth will be evaluated in a simplistic manner, with only two linear rates of growth of GDP considered (1% and 2% annually).

By making these assumptions the model can be said to be conservative, meaning that it will provide a lower estimate of the possible consequences of climate change. If the tropical cyclone tracks were to shift northwards and the typhoon season were to become longer then this would exacerbate the results provided in the present paper.

3.2 Simulation methodology

A Monte Carlo simulation was used to obtain the Expected Loss of Time in one future year. The Expected Loss of Time can be defined as the sum of each of the values of lost time due to storms 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,

$\hat{\vartheta}(c)$ Expected Loss of Time
$\vartheta(c)$ Loss of Time obtained from one simulation
N Number of simulation runs

The need for a Monte Carlo Simulation is obvious, as the present simulation produces completely different results in each simulation run (for example, the region of Tokyo in Japan could be affected by two typhoons in 1 year, and the next by none). To obtain an overall picture it is thus imperative to use a Monte Carlo Simulation. For each scenario a total of 4,000 simulation runs were carried out, taking approximately 2 days to run on a Pentium 4 2.8 GHz Processor. A one-off 40,000 simulation run was also carried out to verify the accuracy of various numbers of simulation runs. A 4,000 simulation resulted already in approximately 99% accuracy, considered adequate. The schematic view of the computational methodology is shown in Fig. 1.

3.3 Tropical cyclone data

The tropical cyclone data was obtained from the website of the Japan Meteorological Agency (2008), which provides best track data for tropical cyclones in the western North Pacific and South China Sea between 1951 and 2007. This data shows, 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
- Longitude
- Maximum Wind Speed
- Longest radius of 50 knot winds or greater
- Longest radius of 30 knot winds or greater

Unfortunately the data prior to 1977 only shows the storm paths and not the radius or wind speeds, and hence this data could not be used. Nevertheless, the 30 years of useful data still provides a total of 809 tracks of tropical cyclones, which cover the area well, as can be seen by Fig. 2. This figure shows the tracks for all tropical cyclones in the Australasia region between 1985 and 2005.

In order to calculate a geographical distribution of lost time due to tropical cyclones, the authors divided Japan in 1472 equally sized grid cells. Each cell represents a unit of analysis containing a unique value of the historical and simulated loss of time due to 30 and 50 knot winds.

3.4 Generation of number of tropical cyclones

A random number of tropical cyclones is 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 storms in the Western North Pacific and China Sea between 1971 and 2006, as published by the Japan Meteorological Agency.

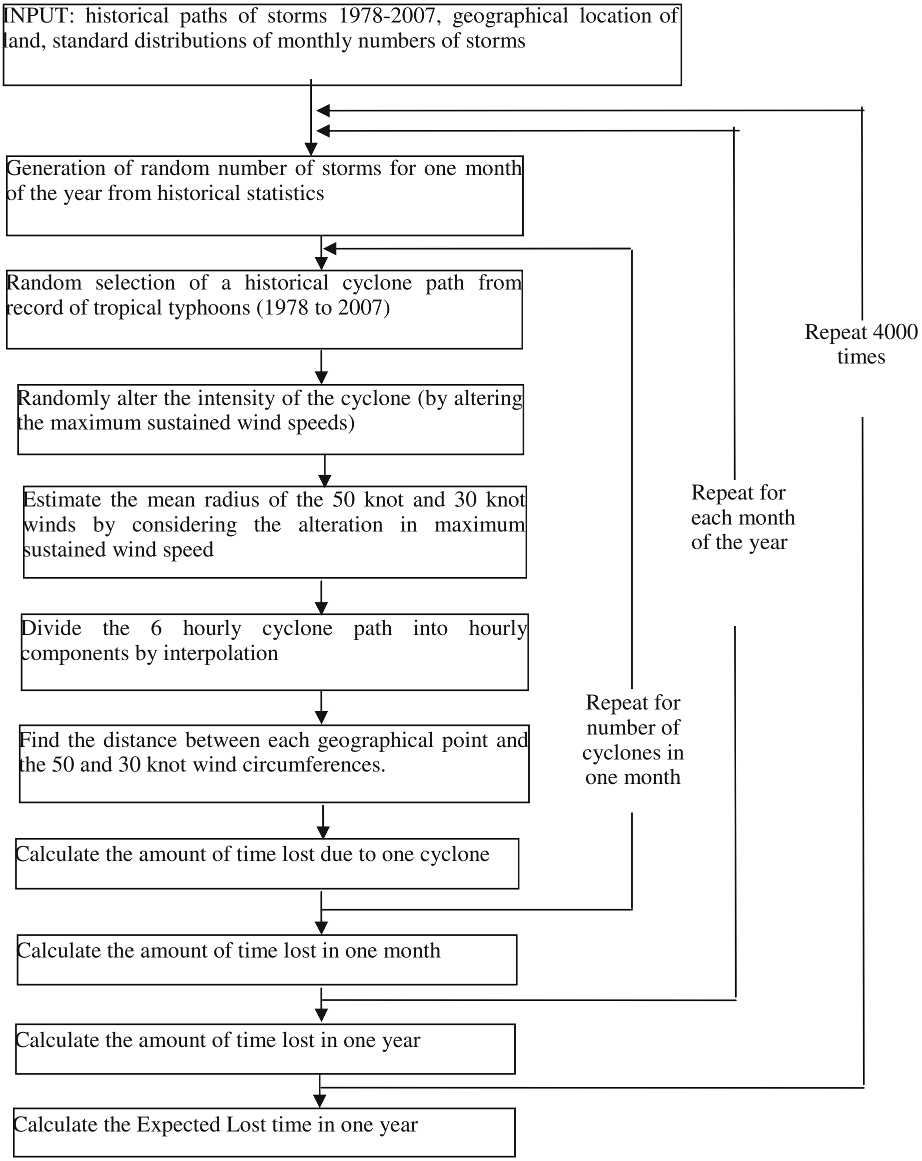


Fig. 1 Main loop of computation

After the number of tropical cyclones in each month has been generated, the methodology then selects for each cyclone in the month one random historical cyclone from the record of all the tropical cyclones between 1978 and 2007.

3.5 Increase in tropical cyclone intensity in the year 2085

The assumptions regarding the increase in storm intensity in the year 2085 are derived from the work of Knutson and Tuleya (2004). These authors carried out 1,300

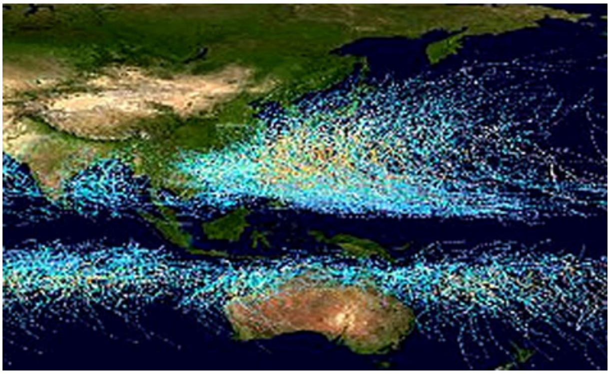


Fig. 2 Tropical cyclone tracks in Australasia (produced by Nilfanion of the Wikipedia website and released into the public domain)

5-day idealized 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°C to +2.4°C, which assume 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.

Knutson and Tuleya (2004) computed histograms of the maximum surface wind speed for four different types of hurricane simulation (Pan convection, Emanuel 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 storm intensity and near-storm precipitation rates related to the increase in Surface Sea Temperature.

Figure 3 shows the general trend given for an increase in maximum wind intensity. The method proposed in the present paper 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

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

Month	Normal	SD
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

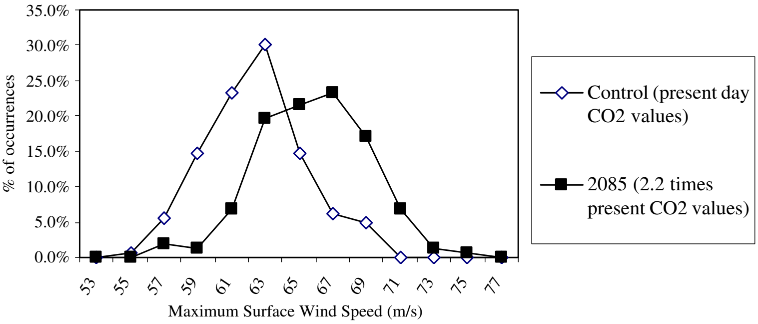


Fig. 3 Resolved inner-grid convection hurricane intensity simulation, Knutson and Tuleya (2004)

speeds of a hypothetical future tropical cyclone can be modelled. This intensity multiplier is normally greater than 1, 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. In this way, although the tracks of the storms do not deviate from that of the historical norm, the intensities and shapes of the storms can be made to change slightly.

3.6 Effect of maximum sustained wind speed on radius of tropical cyclone

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.

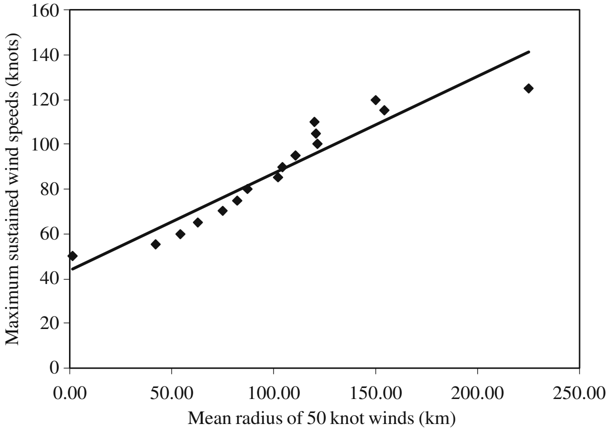
Once the maximum sustained wind speed of the storm throughout its life has been modified as shown in the previous section, the radius of the sustained 30 and 50 knot winds must be established. It is necessary however to understand by how much will this radius grow if the maximum sustained wind speed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

3.6.1 Historical analysis of maximum wind speed and radius of storm

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, an analysis of all the data points from 1978 to 2007 was carried out. All the data was 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, with the results shown in Figs. 4 and 5.

To be noted is how these graphs show almost the totality of the points provided in the database of the Japan Meteorological Agency. 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. Over 98% of the data reading of the Japan Meteorological Agency show maximum sustained wind speeds of 100 knots or less. However for the data points were the maximum sustained wind speed is greater than 100 knots (1.78% of data) the relationship is not so clear. In any case, the effect

Fig. 4 Maximum sustained wind speed vs. radius of 50 knot winds

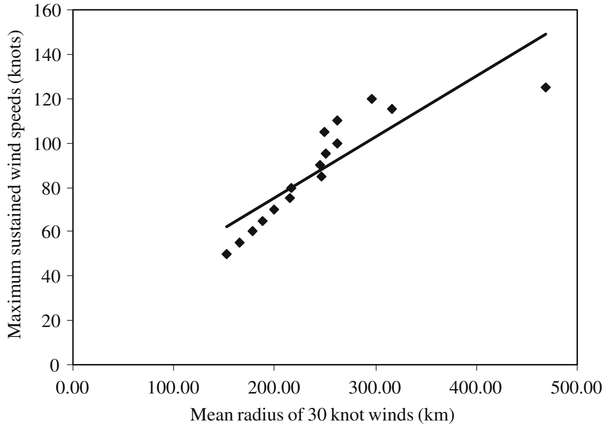


on the present simulation is minor, as most of the time loss is not caused by the most intense tropical cyclones but by the more average ones.

A statistical analysis reveals a significant, positive relationship between maximum wind speed and the observed storm radius. On average, we expect that with an increase in wind speed, storm radius will increase as the coefficient is positive. The results demonstrate that 16% of the variance in the 30 knot wind radii and 60% of the variance of 50 knot wind radii can be explained by the variance in changing maximum wind speed. It can thus be concluded 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 of the shape:

$$R = b_0 + b_1 W_{\max} + e \tag{2}$$

Fig. 5 Maximum sustained wind speed vs. radius of 30 knot winds



Where b_0 and b_1 are 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

$$R_{30} = 46.744 + 2.168\, W_{\max} + e \tag{3}$$

$$R_{50} = -81.345 + 2.099\, W_{\max} + e \tag{4}$$

An interesting observation to be made from Fig. 4 is how there appears to be a threshold for a storm to develop an area of persistent 50 knot winds. At maximum wind speeds 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 methodology. Historically, many storms fail to reach this 55 knot speed. However, in a future in which increased CO_2 concentrations may cause an increase in the intensity of tropical cyclones, more storms might reach this threshold and start to affect greater areas.

3.6.2 Procedure to modify the wind radius

By using the relationship shown in Eqs. 3 and 4 it is possible to estimate the increase in radius of the storm once the increase in maximum sustained wind is known. The

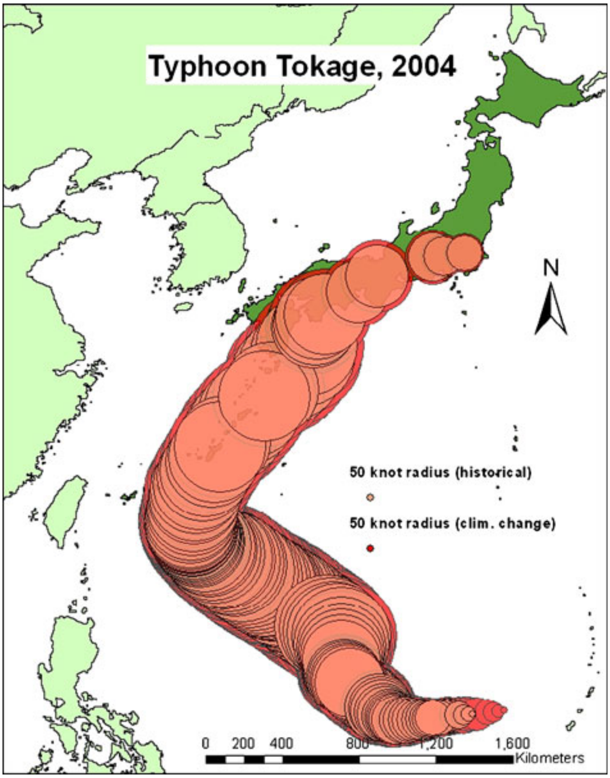


Fig. 6 Track showing the radius of the 50 knot winds for a recorded (typhoon Tokage 2004) and modified storm taking climate change into account

relationship between the maximum sustained wind speed and the area of the tropical cyclone is greatly debated. Although Eqs. 3 and 4 show a fairly clear relationship, the authors believe that it is worth to carry 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 Eqs. 3 and 4

The authors are trying to propose a conservative methodology, and as such relationship with b_1 higher that that shown in Eqs. 3 and 4 would result in even greater time losses, and as such was not considered.

Finally, once the data of the storm has been modified, the radius and position of the tropical cyclone for each hour of its life is calculated by interpolation (the data from the 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 an historical tropical cyclone would be transformed by using the methodology described in previous paragraphs is shown in Fig. 6. This figure shows the path of typhoon Tokage in 2004, with the area of the historical and modified persistent 50 knot winds shown in different colours.

4 Results

The methodology shown in the previous sections can be used for a variety of purposes to aid policy makers and engineers make informed decisions about possible future levels of risk due to tropical cyclones. The next section will highlight one application of this methodology, some of the results that can be computed with it, and possible implications of these results.

4.1 Computation of wind related downtime

Tropical cyclones do not affect people equally as they are limited in space and time. The model assumes that a tropical cyclone that reaches wind speeds of more than 30 knots will disrupt many human activities. 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 UK and the USA. Flights are normally cancelled when a typhoon crosses the flight path, 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. The Port Designer's Handbook (Thoresen 2003) recommends limits for oil tankers of

- between 20 and 30 knots for berthing of oil tankers
- of up to 40 knots for loading and unloading
- of 55 knots before the tanker should leave port

In practise the port activity is generally impaired once it is difficult for vessels to berth, and generally it can be considered that a gale force wind will prevent the port from functioning. "Downtime" is thus the time during which a port is not able to operate due to high winds, and results in all cargo operations ceasing, workers being sent home and can even end in ships being ordered to remain at sea if the winds are too high. Generally speaking this would happen after 30 knots is reached, as according to the Beaufort wind force scale a moderate gale (over 27 knots) would make it difficult to walk against the wind. Anything over 34 knots ("fresh gale") would cause twigs to be broken and cars to veer on the road, which would clearly represent a hazard for the use of vehicles inside the port, workers to go or return to work and crane operations. Wind of over 48 knots are classified as a "Whole Gale" or "Storm", with trees broken off or uprooted, saplings bent and deformed and considerable tumbling of waves with heavy impact. At this point it is clearly hazardous for any economic activity to take place.

4.1.1 Northwards shift of expected effects of typhoons

Using the procedure described in previous sections it is thus possible to compute the expected number of hours (i.e. downtime) that each part of a country, such as Japan, is likely to lose in the future due to increased tropical cyclone intensity (Fig. 7b, c). 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. 7). A direct comparison between these figures shows how there is a northwards shift in the expected amount of hours lost. This is an interesting finding of the present simulation, 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:

1. 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
2. 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

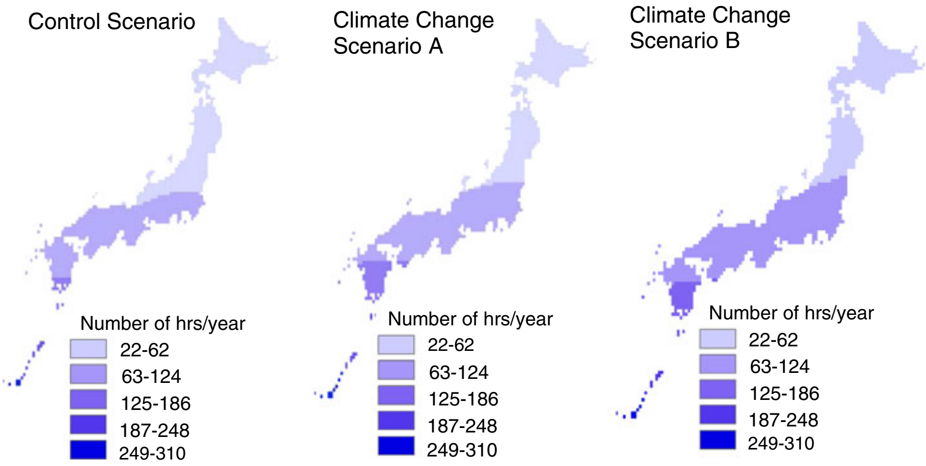


Fig. 7 **a**–**c** Expected number of hours per year affected by 30-knot winds for various scenarios

> 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 as per Figs. 4 and 5. 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 an interesting effect of the simulation, 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. The present simulation is indirectly able to reproduce this effect, as just explained.

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 damage. Unfortunately, this increase in expected physical damage can not be easily computed. To do so, the amount of damage corresponding to a given tropical cyclone intensity would need to be defined. In turn, this damage is likely to depend on other factors such as the population density of the area and the local economic activities. Also, the degree of insurance protection is likely to affect the consequences of this damage. In Japan it is usual for the government to pay for up to 90% of the infrastructure damage caused by typhoons (with the other 10% coming usually from prefectural governments). Private individuals are typically minimally covered by insurance, amounting typically to 30% of the value of the property.

In other countries, however, private insurance companies often provide cover against the consequences of typhoon attack, with the national government providing ultimate aid in case of the more dramatic cases of damage (such as the US Government in the case of the 2004 Hurricane Katrina). Insurance companies usually are covered by larger re-insuring global companies. These companies are likely to increase their premiums in a future where storms increase in intensity, and these additional costs will ultimately be born by individuals. Hence this increased cost of insurance is also an important factor in determining the future costs of increased tropical cyclone intensity.

4.1.2 Increase in port downtime

Figure 8 show the average hours that certain Japanese ports can be expected to be affected by 30 knot winds for both the control and future climate change scenarios (for both Scenarios A and B). These figures show clearly how the southern parts of Japan suffer the effect of tropical cyclones more than the northern parts, and this will be the case even in a hypothetical future of greater average storm intensities. On average each of the ports can be expected to be affected by 30 knot winds by between 18% to 43% more time between the control and climate change scenarios A and B, respectively. However, as Figs. 9, 10 and 11 show, downtime is also seasonal in nature. In Japan, the typhoon season is typically from around July to September, and hence most of the downtime usually occurs during these months. A 18% increase

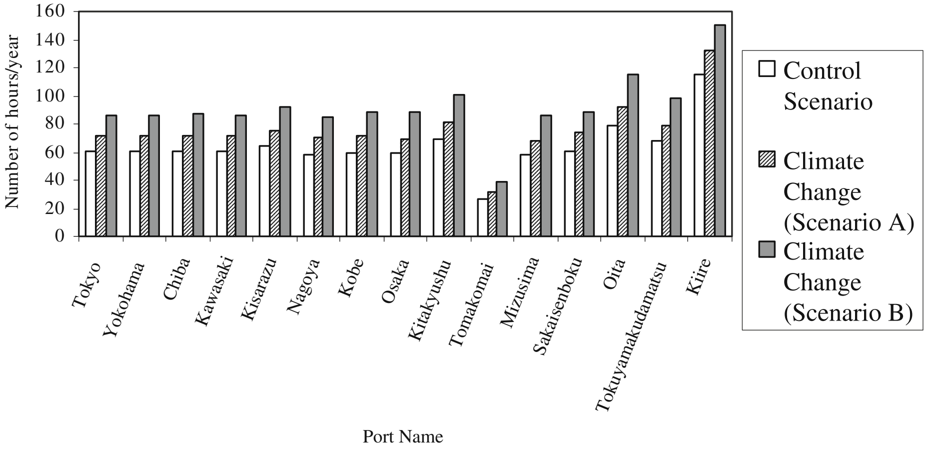


Fig. 8 Expected hours that selected Japanese ports are affected by 30 knot winds for the control and climate change scenarios

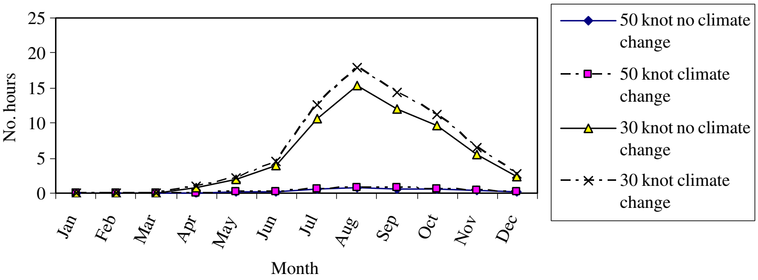


Fig. 9 Expected hours that the Port of Yokohama will be affected by various winds for the control and climate change events for each month of the year (Scenario A)

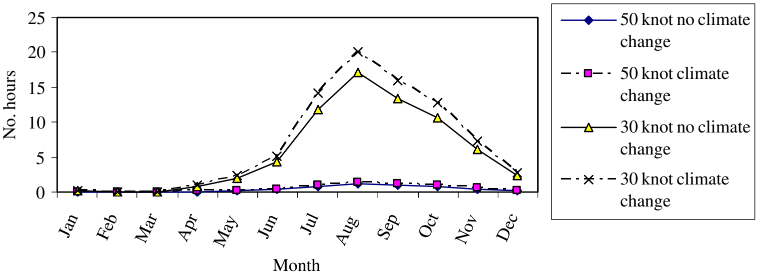


Fig. 10 Expected hours that the Port of Kitakyushu will be affected by various winds for the control and climate change events for each month of the year (Scenario A)

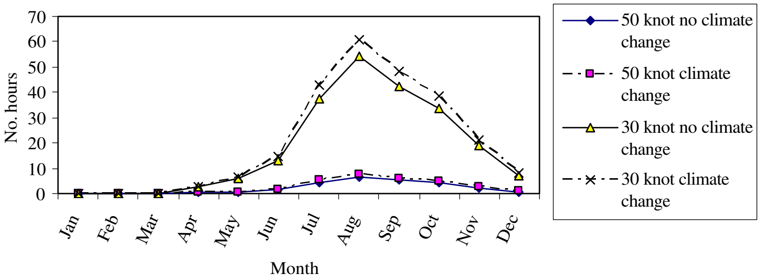


Fig. 11 Expected hours that the Port of Naha will be affected by various winds for the control and climate change events for each month of the year (Scenario A)

in downtime during these months actually has a pretty severe effect, especially for the southernmost regions (quite dramatic in the case of Naha Port, in Okinawa, Fig. 11).

4.2 Economic evaluation of port downtime

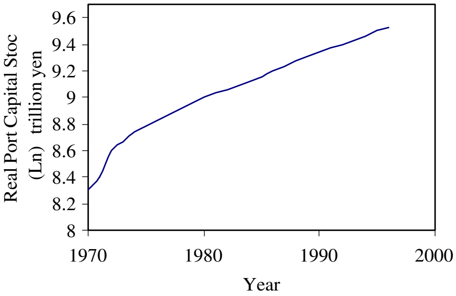
4.2.1 Relationship between real port capital stock and GDP growth

Due to the fact that Japan is constituted by a series of islands and the economy is heavily trade-orientated, port capital formation has been indispensable for the growth of the Japanese economy. Figures 12 and 13 show how there is a direct correlation between the natural logarithm of the Real Port Capital Stock (*RPCS*) and the growth in Japanese GDP (Kawakami and Doi 2004). The RPCS could be defined as the total value of all port infrastructure and stock in Japan ports. These authors analysed the causal relationships between GDP, private capital, user transport cost and port capital and the magnitude of effects of port capital formation on private capital formation on GDP in a multivariate time-series framework. From their research it is clear that for the Japanese economy to grow there must be a continuous expansion of*RPCS*.

4.2.2 Future increase in Japanese

To evaluate the future need for *RPCS* it is first necessary to evaluate the potential size of the Japanese GDP at the 2085 horizon. Estimating future growth rates

Fig. 12 Growth in *RPCS* in Japan, 1990 Prices in trillion yen (Ln)



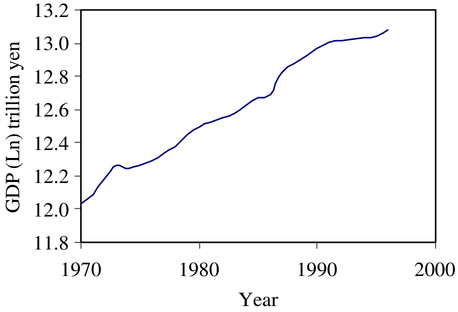


Fig. 13 Growth in GDP in Japan, 1990 Prices in trillion yen (Ln)

of countries is a notoriously difficult thing to do, as new technologies, rates of population growth and sociological changes all influence the patterns of economic growth. The Japanese case is even more difficult than others, due to, amongst other reasons:

- a rapidly greying population (with a forecasted drop in population about to start)
- economic stagnation during the last 15 years
- unknown influence of other raising Asian countries

It is not the purpose of this paper, however, to go into the uncertainties of Japanese GDP economic growth and therefore two fairly simplistic scenarios were chosen, with rates of growth of either 1% or 2%. This could be considered as likely for the Japanese economy judging by recent economic performance and the above mentioned problems. The forecasted GDP growth according to these two scenarios can be seen in Fig. 14.

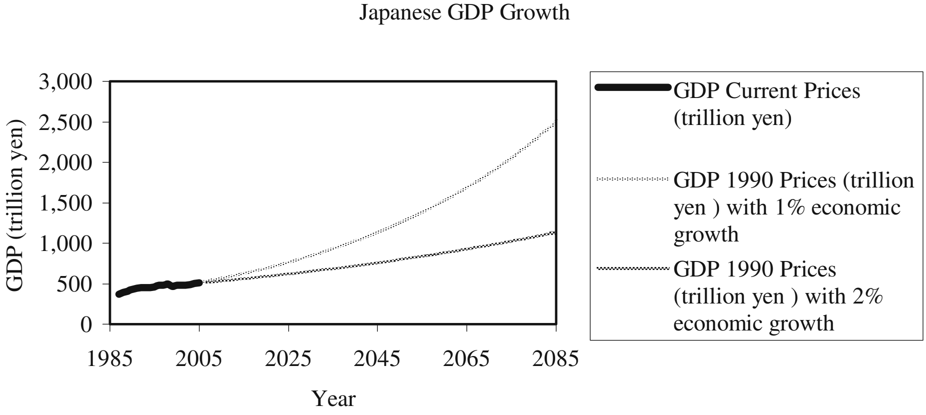


Fig. 14 Future projections of Japanese GDP growth

4.2.3 Evaluation of increase in need for real port capital stock

Following the research of Kawakami and Doi (2004), it is clear that it is necessary for the *RPCS* to expand to allow GDP growth to occur. By looking at Fig. 13 the ratio *R* between *GDP* and *RPCS* for the years 1975 to 1995 is given by

$$R = \frac{GDP}{RPCS} \approx 1.38 \tag{5}$$

This *R* is the ratio of the natural logarithm of the *GDP* and *RPCS*. By using this ratio it is possible to obtain the required *RPCS* necessary in the future for both scenarios of economic growth outlined previously. By taking natural logarithms of Fig. 14 and applying the relationship shown in Eq. 5 and then converting back into normal units Fig. 15 is obtained.

4.2.4 Additional real port capital stock needed due to climate change

To obtain the cost of mitigation it is necessary to calculate the additional *RPCS* needed due to a hypothetical climate change. To do this it is necessary to know the distribution of *RPCS* throughout Japan and how much downtime can be expected in each port at the 2085 horizon. From Fig. 7 it is possible to find the increase in downtime of each port by 2085. Table 2 shows cargo volumes for the top 15 Japanese Ports by cargo volume as published by Chiba Prefecture website in Japan (2008). It is assumed that *RPCS* closely follows the distribution of port cargo. Thus, the amount of extra percentage of *RPCS*, C_p, that each port requires due to climate change can be calculated using

$$C_p = \left(\frac{L_c - L_s}{Y}\right)\frac{P_c}{P_a} \tag{6}$$

where L_c is the lost time in the control scenario, L_s is the lost time in the climate change scenario, Y is the number of hours in one year, P_c is the cargo volume in each port and P_a is the sum of the cargo of all the ports considered.

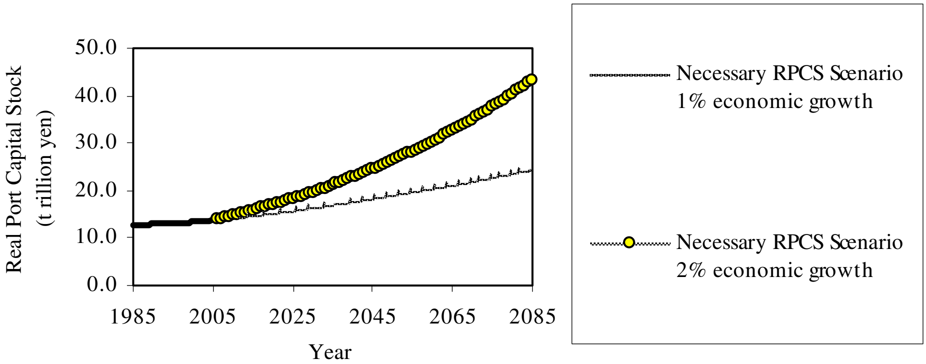


Fig. 15 Growth in Necessary Real Port Capital Stocks (trillion yen) for different growth scenarios without taking into account climate change

Table 2 Required increase in capacity in the 2085 climate change scenario

Port name	Lc (30 kt winds) h/year average	Ls (30 kt winds) h/year average	Cargo volume in 2005 (unit 1,000 tons)	% of total cargo of top 15 ports	Cp extra capacity needed as a % of total real port capital stock scenario A	Cp extra capacity needed as a % of total real port capital stock scenario B
Tokyo	60.70	71.30	92,032	6.12	0.007	0.018
Yokohama	60.20	71.10	133,280	8.86	0.011	0.026
Chiba	61.20	71.60	165,715	11.02	0.013	0.032
Kawasaki	60.20	71.10	93,218	6.20	0.008	0.018
Kisarazu	64.60	75.50	64,756	4.31	0.005	0.013
Nagoya	58.70	70.60	187,134	12.45	0.017	0.038
Kobe	59.60	71.80	91,182	6.06	0.008	0.020
Osaka	59.60	69.10	93,142	6.19	0.007	0.021
Kitakyushu	68.80	81.10	101,705	6.76	0.009	0.024
Tomakomai	27.20	31.60	107,747	7.17	0.004	0.009
Mizusima	58.5	68.30	102,159	6.79	0.008	0.021
Sakaisenboku	60.8	74.10	73,048	4.86	0.007	0.015
Oita	79.3	92.50	66,400	4.42	0.007	0.005
Tokuyamakud.	67.9	78.40	66,238	4.41	0.005	0.015
Kiire	115.4	132.40	65,856	4.38	0.008	0.018
Sum			1,503,612	100.00	0.13	0.29

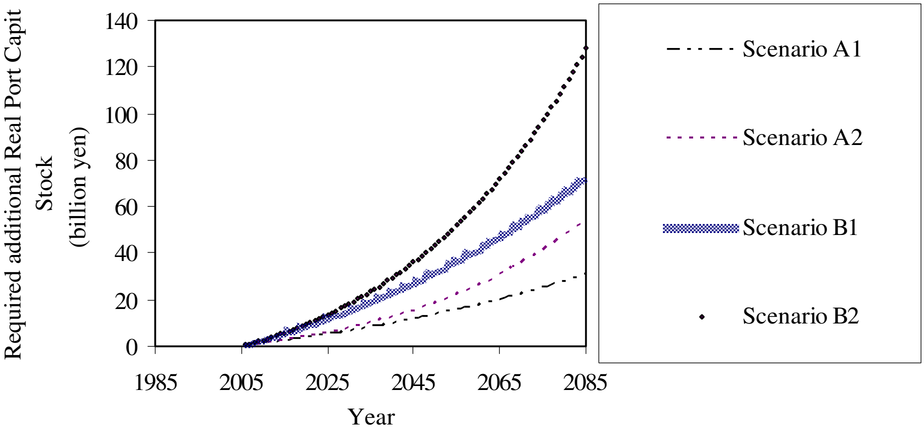


Fig. 16 Required additional Real Port Capital Stocks (billion yen) due to climate change for different growth scenarios due to simulated increases in port downtime

Hence, the mitigation cost of each port, M_p, can be given by:

$$M_p = C_p \cdot RPCS_i \tag{7}$$

where $RPCS_i$ is the future value of $RPCS$ obtained from Fig. 15.

The extra percentage of Real Port Capital Stock required, C_{total}, and the total cost of mitigation, M_{total}, can be obtained by

$$C_{total} = \sum_{1}^{n} C_p \tag{8}$$

$$M_{total} = \sum_{1}^{n} M_p \tag{9}$$

where n is the number of ports considered.

Assuming that the distribution of typhoon intensity will increase linearly between the present and future distributions shown in Fig. 3, then the growth in $RPCS$ required due to climate change is given by Fig. 16.

Table 3 summarises all the scenarios that are considered throughout this paper and the results given in Fig. 16. It can thus be concluded that a total of between 30.6 to 127.9 billion additional Yen could potentially be needed by the year 2085 to

Table 3 Summary of downtime scenarios

Scenario	GDP growth rate (%)	b_1	M_{total} (*bn yen*)
Control scenario 01	1	N/A	N/A
Control scenario 02	2	N/A	N/A
Climate change A1	1	1	30.63
Climate change A2	2	See Eqs. 3 and 4	54.23
Climate change B1	1	1	72.24
Climate change B2	2	See Eqs. 3 and 4	127.88

expand all ports in the country to cope with the increase in downtime associated with the increase in typhoon intensity given in Knutson and Tuleya (2004).

4.3 Implications

The scientific evidence that climate change is a serious issue is compelling. 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).

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 industry. Adaptation to climate change is essential for the future growth of the Japanese economy. Port planners should therefore factor in this potential future increase in storm intensity when designing port capacities (to be able to prevent delays due to increased downtime) and sea defences (to limit damage due to higher possible future waves). Failure to do so could lead to future bottlenecks in the shipments of products and extra damage due to higher potential waves destroying existing breakwaters and infrastructure. 30 to 128 billion Japanese Yen is not a great deal of additional capacity required, but it is emphasized how this is just the cost of dealing with the additional downtime expected as a consequence of greater intensity storms. The cost of dealing with other consequences of a hypothetical future of more intense tropical cyclones is not included in this simulation. These would include the reparation of what insurance companies call "First Order Losses" (direct destruction caused by these events) and the cost of reinforcing structures to deal with higher significant waves.

5 Discussion

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 model uses the results provided by Knutson and Tuleya (2004) to develop a methodology to evaluate the future economic consequences of an increase in tropical cyclone intensity. 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. This fact is highlighted in the 4th IPCC Report. The objective of the present 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 increase port downtime, but it can be adapted for assessing other economic damage, such as disruption to commercial aviation or loss of time in major cities. 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 USA it is fairly common for companies to insure against the consequences of a business interruption due to a natural disaster, such as hurricane Katrina.

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.

The methodology outlined in this paper 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 typhoon routes or frequencies. Hence, it does not allow for the prediction of events which are significantly different to those of the last 20 years. Policy makers should be aware of this major limitation. 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 paper 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
- 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 materialize.

The wind speed distributions shown in Fig. 3 are derived from the work of Knutson and Tuleya (2004) and are not actually consistent with observed distribution of wind speeds as they are based on these authors' simulations. Actual wind speed distribution is positively skewed. However, in order to be consistent it was better to use both the control and 2085 results of Knutson and Tuleya (2004) rather than the actual (skewed) distribution of wind speed and the future (non-skewed) distribution of Knutson and Tuleya (2004). In the present simulation, the intensity multiplier is obtained by shifting the probability distribution functions shown in Fig. 3 and then applying them to the real historical tropical cyclone data (which obviously follows a skewed distribution). Hence the results should not be greatly affected, though as can be seen in Fig. 3 the shape of the control and 2085 scenario are not the same (showing how by 2085 the probability distribution will probably be even more skewed). Nevertheless, most of the time loss is caused by the more common tropical cyclones which occur regularly each year, and the influence of the bigger typhoons (with return periods of 20 to 50 years) is *comparatively* minor in the present simulation.

Also to be noted is how the regression model of storm size on wind speeds is likely to contain correlated residuals (see Figs. 4 and 5), and thus the R_{50} and R_{30} variables given by Eqs. 3 and 4 are overly influenced by the radius of the largest storm. This is inevitable considering that little data is available for the largest storms given the relatively small size of the typhoon data available. Nevertheless, this contributes to the lowering of the gradient of the relationship, and thus ensures that the results are conservative (i.e. b_1 in the present work could be lower than the actual b_1, which could result in larger storms in the future than what is predicted in the current paper).

The current model reproduces the number of storms that happen on each month, but does not do it temporally. Each storm is given a number, but not a period of the month when they act. Hence, the effect of overlapping storms cannot be reproduced. This can have quite a significant effect, as if a port was to be hit in rapid succession by two storms it probably would not open during the interval in between them, as by the time it carried out the necessary preparations for re-opening it would have to be preparing for shut-down again. This effect is likely to intensify in the future, especially during the summer months when one storm can be quickly followed by the next one.

With respect to the cost of the port downtime, 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 grow more or less linearly at between 1% and 2% per year. It is not the purpose of this paper to enter a macro-economical debate on the long-term growth of the Japanese economy, as the main objective is to quantify the effect of a storm intensity increase on a given future GDP. In this simulation only the top 15 ports were used, as most of the Japanese economic activity is centred on the areas of Osaka, Nagoya and Tokyo. Of these top 15 ports the majority are centred on these locations with only a few located in Hokkaido or Kyushu. Hence, the final effect is to give a distribution of how the major ports in Japan will be affected and what extra level of future investment will be necessary to mitigate the effects of climate change. Although a greater number of ports could have been used in the simulation, the results would not change as most of the smaller ports are still concentrated around the same areas.

6 Conclusion

The present paper proposed a new methodology that would allow policy makers to quickly evaluate different types of economic risks for potential future increases in tropical cyclone intensity. The methodology is fairly quick, with a typical 4,000-run Monte Carlo Simulation being performed in under two days in a typical desktop PC. The paper uses as its basis the results of Knutson and Tuleya (2004) although it can be easily adapted for different storm intensity scenarios. The model was then applied to calculate how much it would cost to mitigate the effects of downtime in ports associated with this increase in tropical cyclone intensity. Although, due to the great uncertainties associated with climate changes, the results of this exercise should be viewed with caution, they can provide a feel of the magnitude of the cost of mitigation measures against this specific problem.

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