

# Effect of a global warming-induced increase in typhoon intensity on urban productivity in Taiwan

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Received: 4 June 2009 / Accepted: 21 August 2009 / Published online: 2 October 2009  
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**Abstract** A number of scientists have recently conducted research that shows that tropical cyclone intensity is likely to increase in the future due to the warming effect of greenhouse gases on surface sea temperatures. The aim of this paper is to establish what would be the likely decrease in the productivity of urban workers due to an increase in tropical cyclone-related downtime. The methodology used simulates future tropical cyclones by magnifying the intensity of historical tropical cyclones between the years 1978 and 2008. 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. It shows how annual downtime from tropical cyclones could increase from 1.5% nowadays to up to 2.2% by 2085, an increase of almost 50%. This decrease in productivity could result in a loss of up to 0.7% of the annual Taiwanese GDP by 2085.

**Keywords** Climate change · Typhoon · Tropical cyclone · Intensity increase · Productivity · Urban areas

## Introduction

One of the fears associated with 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 2006). A 30-year satellite record of tropical cyclones confirms this trend (Webster et al. 2005). Also, Elsner et al. (2008) examined 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 in the 1970 Bangladesh cyclone where between 300,000 and 500,000 people were killed (Landsea et al. 2006). More recently in the United States, the 2005 hurricane Katrina caused major damage and left more than 1,800 people dead, triggering a debate about whether such tragic events will occur more frequently in the future.

The western north Pacific Ocean is the area where tropical cyclones appear most frequently, accounting for approximately one-third of these phenomena (Imamura and Van To 1997). In 2006, typhoon Dorian 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 most costly natural disasters in Asia were due to typhoons in Japan after 1998, according to data from the Munich Re website (2009).

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To try to understand how tropical cyclones are likely to be affected by an increase in global temperatures, a number of global climate models have been investigated using powerful supercomputers, as highlighted in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (4th IPCC, see Giorgi et al. 2001). This report shows how, although there is 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. Generally speaking, such damage can be divided into two components: direct damage relating to the physical destruction, and indirect damage due to the loss of productive time during the tropical cyclone passage. Hallegatte (2008) explains how the indirect costs include “business interruption in the event aftermath, production losses during the reconstruction period, and service losses in the housing sector”. Other such losses could include increases in energy prices, loss of workers’ incomes or increases in insurance premiums following the passage of major events. This latter author points out how total socio-economic damage can be much larger than the direct economic impact. Forecasting the direct damage is not an easy task. Nordhaus (2006) points out why there are several reasons for this: non-linearity of wind damage, different storm lifetimes and the rarity of large tropical cyclones. Given these complexities, Nordhaus (2006) calculates that damage to the Atlantic coast of the United States rises with the eighth power of the maximum storm wind speed, although this seems high compared to that calculated by other researchers. Also, he cites how the insurance industry used damage functions of between the fourth and eighth power. In earlier research, Howard et al. (1972) reported that damage could rise by between the power of 4.36 and 6.7. Later, Pielke (2007) decided to present damage as being proportional to the third, sixth and ninth power of wind speed, in order to bind all the sets of probable possibilities. Hallegatte (2007) for his part carried out an assessment of hurricane damage to the east coast of the United States, and found that a 10% increase in potential intensity can cause a 54% increase in the mean normalized economic losses. This latter author used a damage function where the damage is related to the third power of the wind speed, and an extra parameter  $\alpha(s)$  that measures the local vulnerability at each point  $s$  along the coast.

Very little research has so far gone into estimating the indirect economic damage of tropical cyclones, and Hallegatte (2007) points out how additional research is necessary to understand these indirect impacts. These effects include, for example, the loss in economic productivity due to downtime in the public transportation system, important industries and commerce. Urban areas in particular can be greatly affected by the passage of a tropical

cyclone, with their inhabitants leaving work early and shuttering houses and shops before its arrival and taking shelter until it has passed. Hallegatte (2008) found that the total losses due to a disaster affecting the area of Louisiana in the United States increase non-linearly with respect to direct losses when the latter exceed US \$50 billion (for instance when direct losses exceed US \$200 billion, total losses are twice as large as direct losses). The model given by this author attempts to reproduce the disruption in production that takes place after the event, and is useful when modeling the effects of high intensity events. However, in many countries in the Asia-Pacific region, most tropical cyclone-related downtime is due to low-intensity but high-frequency events, where the downtime is directly related to the duration of the event. As tropical cyclones grow larger, the number of hours that a given area of a country will be affected by them will increase in the future.

The current paper attempts to understand the potential consequences of this indirect damage on the urban productivity of Taiwan, a country frequently exposed to tropical cyclones in the Pacific. To do so, a Monte Carlo simulation was used, which was able to calculate the expected future loss of time due to climate change in the next 75 years.

## Methodology

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, and 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 gathered with the help of geographic information systems (GIS) would account for the spatial variation.

The economic impact of tropical cyclones in Taiwanese urban areas 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. Hence, we propose a disaggregated computational approach to measure the economic loss caused by storms under a climate change scenario for the year 2085. In Taiwan, like in other countries, the value of economic output varies geographically, and is concentrated on a north–south axis along the west coast. The present study, however, expects that this economic distribution will not change, and that future population growth will retain the current population distribution pattern. Such a simplistic study is perhaps less realistic than studies that account for socio-economic future changes but is easier to interpret.

The objective of this study is essentially to calculate the expected time loss of various human economic activities related to an, as yet hypothetical, increase in future tropical cyclone intensity. The simulation used does not randomly generate the tropical cyclones; instead, they are each picked at random from a set of 831 historical tracks. It then randomly alters the strength and size of each tropical cyclone according to the expected future distribution of maximum wind speeds proposed by Knutson and Tuleya (2004). This could then be compared with the control case showing the expected number of hours that would be lost each year by using the unaltered historical tropical cyclones (“control scenario”). The results given are for year 2085, as the work of Knutson and Tuleya (2004) provides the expected distribution of maximum surface wind speeds for this year only. Although methods to randomly generate tropical cyclones are available, the computational demands of doing so 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 tracks it is possible to obtain a solution relatively quickly.

#### Assumptions

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

1. Typhoon tracks, 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 as indicated by the 4th IPCC. A consensus statement from the 6th International Workshop on Tropical Cyclones of the World Meteorological Organisation (2006) states that “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”. 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.
2. There is a general relationship between the maximum sustained wind speed and the size of the tropical cyclone. This point is not clearly established for the case of large typhoons (Knutson et al. 2001). However, the authors do not want to enter into this debate in the present paper. Nevertheless, an statistical analysis of wind speeds and radii will be provided later that provides some background for this assumption.
3. The topography and population distribution of Taiwan will not change in the future.
4. Any wind higher than 30 knots will result in the temporary shutdown of all human economic activities.

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 typhoon season were to become longer or the frequency of the storms increased then this would exacerbate the results provided in the present paper.

#### Simulation methodology

A Monte Carlo simulation was used to obtain the “Expected Loss of Time”  $\hat{\vartheta}(c)$  in one future year. The Expected Loss of Time can be defined as the sum of each of the values of time lost due to storms for 1 year  $\vartheta(c)$  for all the simulation runs divided by the number of simulated runs  $N$ , or,

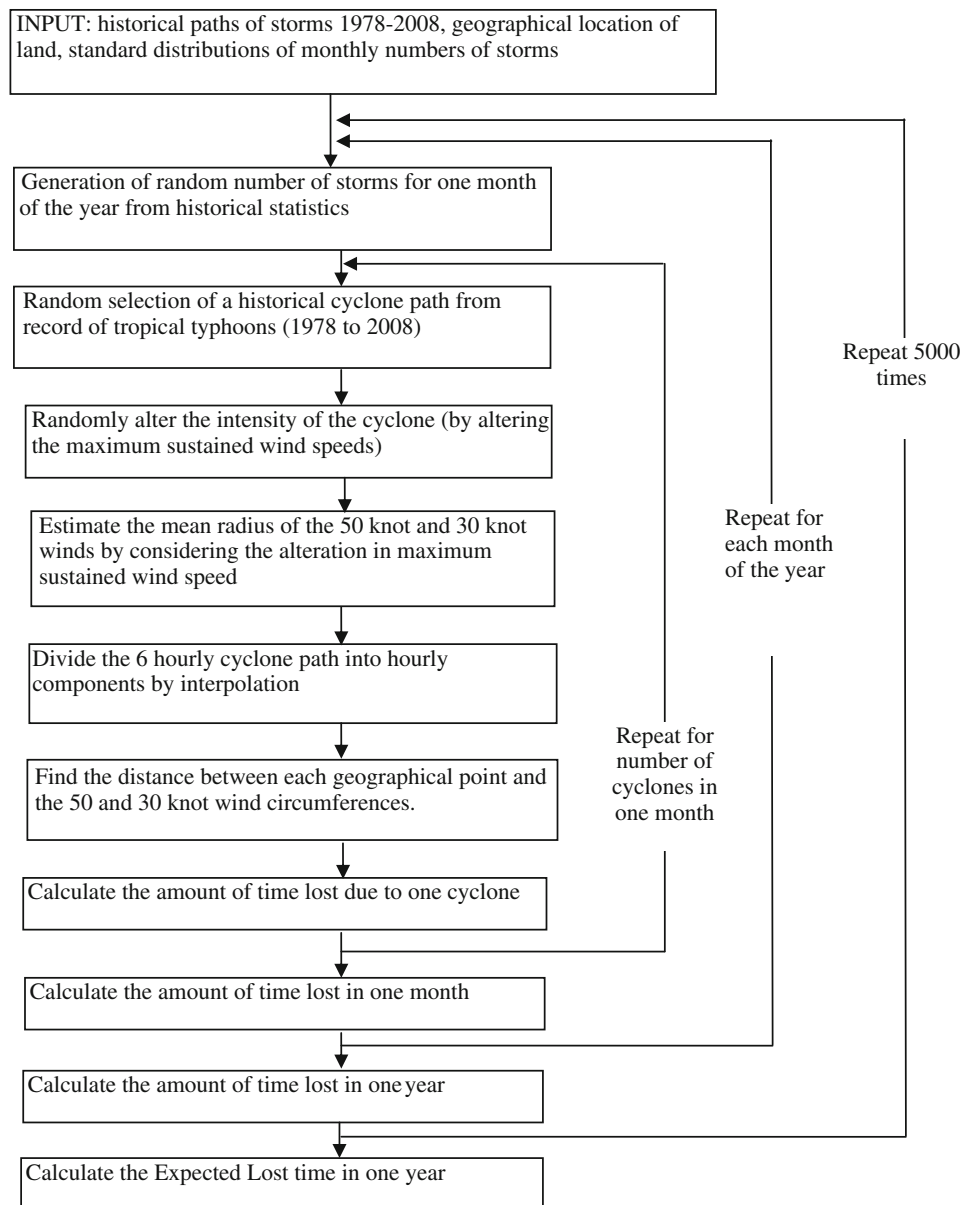
$$\hat{\vartheta}(c) = \frac{\sum_1^N \vartheta(c)}{N} \quad (1)$$

The reason for using a Monte Carlo simulation is that each simulation run produces completely different results. For example, the region of Tokyo in Japan could be affected by two typhoons in 1 year, and none in the next. For each scenario, a total of 5,000 simulation runs were carried out, giving over 99% accuracy as compared to the results of a 40,000 simulation run. A schematic view of the computational methodology is shown in Fig. 1.

#### Tropical cyclone and urban 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 2008. Unfortunately, prior to 1977 there is no satellite data available and hence tropical cyclones prior to this date could not be used. Nevertheless, the 30 years of useful data still provides a total of 831 tracks of tropical cyclones, which cover the area well, as can be seen by Fig. 2. Around 15% of the tropical cyclones tracks make landfall in Taiwan, which is hit every year on average by 3.5 typhoons, although the average between 1992 and 2004

**Fig. 1** Main loop of computation



was slightly higher at around 4.6 per year (Chang and Chiu 2007). Due to the relative small size of the country, the number of tracks is adequate for the purposes of the present simulation. The data from the Japan Meteorological Agency shows, for each storm, snapshots of storm geometry and wind speed at various intervals.

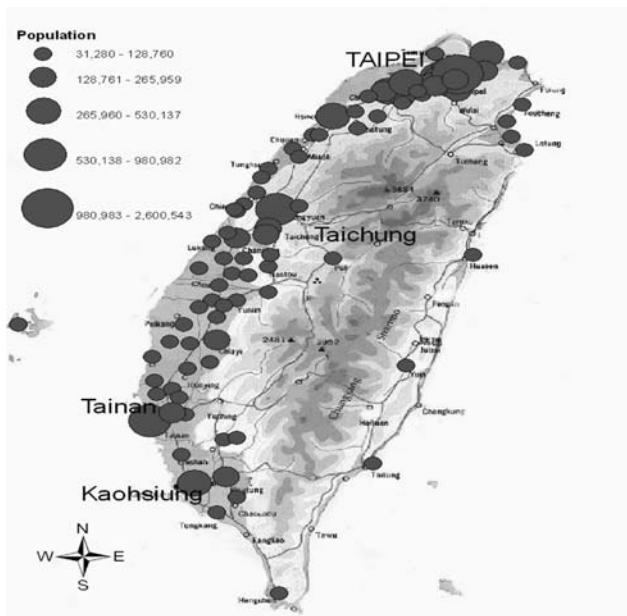
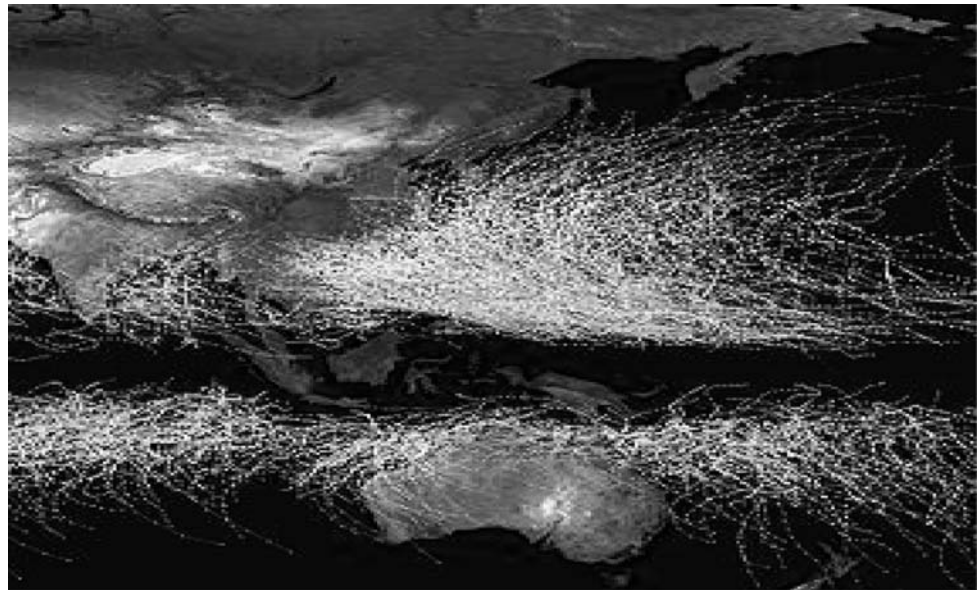
To calculate the geographical distribution of urban downtime due to tropical cyclones, the geographical coordinates and population of the top 89 cities in Taiwan were used, as shown in Fig. 3. This data is provided online at the CIESIN website of Columbia University (Gridded Population of the World 2009).

#### 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 analyzing the number of storms in the Western North Pacific and China Sea between 1971 and 2006, as published by the Japan Meteorological Agency.

After the number of tropical cyclones in each month has been generated, the simulation then selects for each cyclone in the month one random historical cyclone track from the record of all the tropical cyclones between 1978 and 2008.

**Fig. 2** Tropical cyclone tracks in Australasia 1985–2005 (produced by Nilfanion of the Wikipedia website and released into the public domain)



**Fig. 3** Major population centers in Taiwan

Increase in tropical cyclone intensity in the year 2085

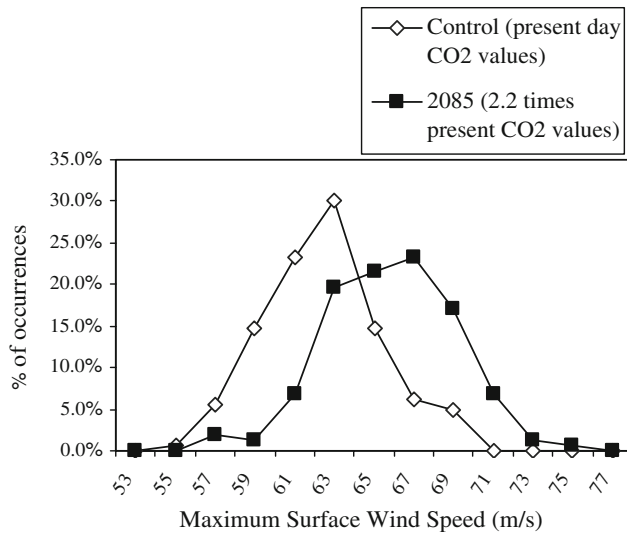
The assumptions regarding the increase in storm intensity in the year 2085 are derived from the work of Knutson and Tuleya (2004). These authors carried out 1,300 five-day idealized simulations using a high-resolution version of the Geophysical Fluid Dynamics Laboratory (GFDL)  $R_{30}$  hurricane prediction system. These simulations were carried out for a surface sea temperature change of between +0.8 and +2.4°C, which assume a linear +1% compounded yearly increase in CO<sub>2</sub> over a period of 80 years (up to the year 2085), in order to calculate the surface sea

**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

temperature. This +1% yearly increase means that CO<sub>2</sub> levels would reach 2.2 times the control value (that of 2004) by the year 2085. These authors acknowledge how other radiative forcing agents besides greenhouse gases may have important effects on the global climate, but quantification of their past and possible future forcing remains even more unclear than for greenhouse gases. Although these authors continuously refer to CO<sub>2</sub> and greenhouse gases, it appears that they only actually considered CO<sub>2</sub> emissions in their model.

These authors also note how surface sea temperature is not the only factor that affects the intensity of tropical cyclones. For example, other factors such as vertical wind shear can also play a crucial role, although how to correctly apply this is at present still under discussion. For this reason, Knutson and Tuleya (2004) chose not to include



**Fig. 4** Resolved inner-grid convection hurricane intensity simulation, Knutson and Tuleya (2004)

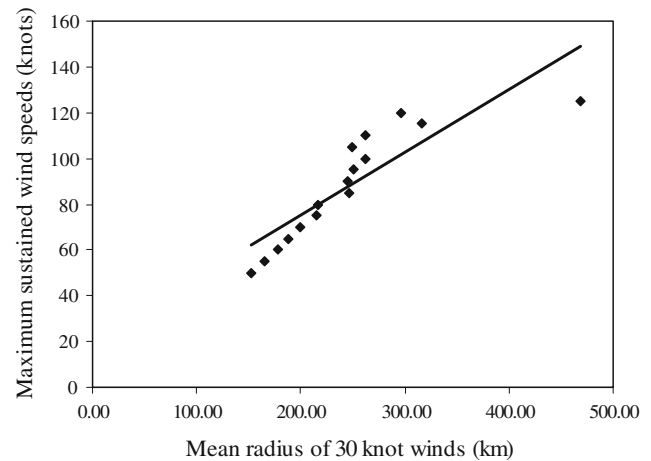
this effect, as they take the view from Emanuel (2000) that it is possible to obtain useful information on the relative distribution of intensities from knowledge of the potential intensity alone. Further discussion on this can be found in Chan (2006), Emanuel et al. (2008) or Vecchi et al. (2008).

Knutson and Tuleya (2004) computed histograms of the maximum surface wind speed for four different types of hurricane simulation, all of which result in an increase in both storm intensity and near-storm precipitation rates related to the increase in surface sea temperature. The method used in the present paper simplifies the 2085 histogram into a probability distribution curve, and uses this to modify the intensity of historical storms as shown in Fig. 4.

The computer simulation 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. This intensity multiplier is normally  $>1$ , resulting in a storm of greater intensity than that of the historical record on which it is based, but it can also be  $<1$  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.

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

The data of the Japan Meteorological Agency provides radii for the sustained 30 knot winds at various time intervals. This data can be used to model the tropical cyclone as a circle representing the area affected by 30 knot winds or higher.



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

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 knot wind must be established. It is necessary, however, to understand by how much this radius will grow if the maximum sustained wind speed increases from that of the historical storm.

#### Historical analysis of relationship between maximum wind speed and radius of storm

To understand the effect of the maximum sustained wind speed of the storms on the radii of the 30 knot winds, an analysis of all the data points from 1978 to 2008 was carried out. All the data was analysed collectively by grouping it together according to the maximum wind speed, independently of which storm it came from. Then, an average of the radius for each maximum wind speed could be obtained, with the results shown in Fig. 5.

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 76% of the variation in the 30 knot wind radii can be explained by the variation 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:

$$R_{30} = b_0 + b_1 W_{\max} + e \quad (2)$$

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

$$R_{30} = 46.744 + 2.168 W_{\max} + e \quad (3)$$

Figure 5 shows an outlier. The influence of this outlier on the curve is relatively minor, and results in an overestimation in the  $R_{30}$  for the lower  $W_{\max}$  (which is maximum at  $W_{\max} = 50$  knots, with a 1.87% difference to what it would have been if this outlier was removed), though this in turn results in an under-estimation at the higher  $W_{\max}$  (for example at  $W_{\max} = 100$  knots, there is a 0.72% difference). If this outlier is removed, the regression analysis  $R^2$  coefficient increases to 0.94, meaning that 94% of the variation in  $R_{30}$  can be explained by the variation in  $W_{\max}$ .

An interesting observation to be made from Fig. 5 is how there appears to be a threshold for a storm to develop an area of persistent 30 knot winds. This observation is crucial to explain a great deal of the results, as in the future more storms might reach this threshold and thus develop this crucial area of wind speed.

To investigate the sensitivity of the simulation to a change in the value of  $b_1$  two different scenarios were selected:

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

As we are trying to propose a conservative methodology, a further scenario with  $b_1$  higher than that shown in Eq. 3 was not carried out, as it would result in even greater time losses.

For maximum wind speeds of between 50 and 100 knots there is a linear relationship between the maximum sustained wind speed and the increase in 30 knot area. However, for the data points where the maximum sustained wind speed is  $> 100$  knots (1.78% of data) the relationship is not so clear. The effect of these points 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 normal ones occurring with high frequency.

#### Computation of wind 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 (55.56 km/h) will disrupt many human activities. According to the Beaufort wind force scale, a moderate gale (over 27 knots) would make it difficult to walk against

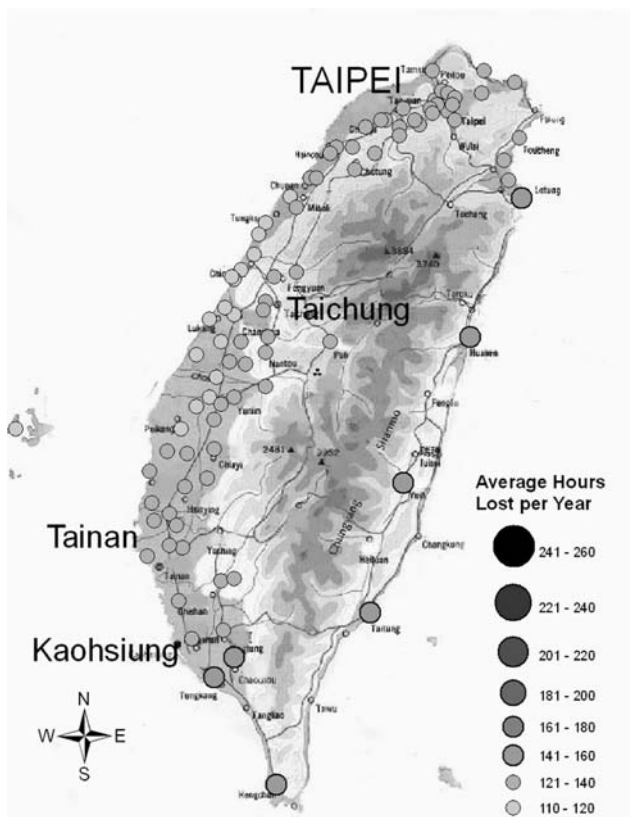
the wind. Anything over 34 knots (“fresh gale”) would cause twigs to be broken and cars to veer on the road, and would result in a gale warning in places like the United Kingdom and the United States. From this point on, normal economic activity and transport are usually disrupted, and usually results in the shutdown of factories and commerce, and workers returning home early to take shelter. Wind 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. The present simulation hence assumes that any wind higher than 30 knots will result in the complete shutdown of the whole economy in the city. There are a number of problems with this assumption, of course, as human activities do not normally follow such pattern, and such a dramatic cut-off does not exist, though economic activity will clearly be disrupted starting from winds of 30 knots and leading to a complete shutdown much before 50 knots are reached.

It should be noted, however, that the current simulation still gives a conservative estimate of the effect of tropical cyclones. Although it assumes that complete shutdown occurs when 30 knot winds occur, it does not take into account the “precautionary” cessation of activities that would occur before the storm arrives. Workers would leave work much earlier in order to catch the last trains, which would not stop operating at the onset of the storm but much before. Most shopkeepers would likewise close and board their shops in preparation for the event long before the storm arrives. If these losses were also to be included, the computed downtime could increase substantially. However, this effect is difficult to calculate and less robust than that computed by the present simulation, and it was thus considered better to leave it out in the absence of better information on how to evaluate it.

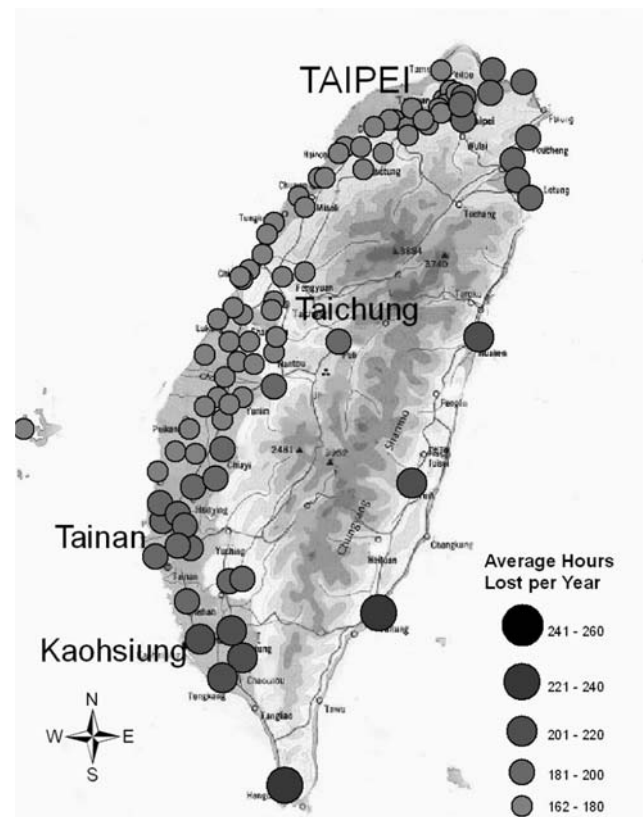
The simulation thus calculates, for each hour of the storm, which urban centers are within the radius of 30 knot winds, and adds up the amount lost throughout the year to the various tropical cyclones.

## Results

Using the methodology described in the previous section it is possible to calculate the Expected Loss of time of each urban center for the control and climate change scenarios, as shown in Figs. 6, 7 and 8. The economic and demographic data for the study was obtained from the Center for International Earth Science Information Network (CIESIN) of the Earth Institute at Columbia University website (Gridded Population of the World 2009). This website provides the population, level of economic activity and



**Fig. 6** Average expected hours lost per year per urban center for control scenario



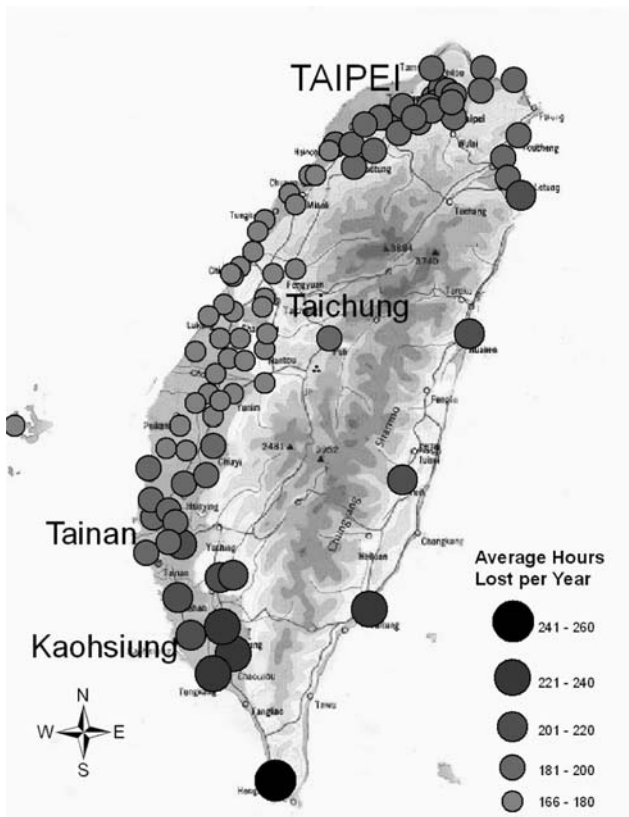
**Fig. 7** Average expected hours lost per year per urban center for scenario A

location of the top 89 Taiwanese cities, which was used to determine the level of economic activity per capita.

Figure 9 shows the categorized paths of typhoons invading Taiwan between 1897 and 2003 (Taiwan Central Weather Bureau 2009), which shows how a great many of the storms that make landfall have an east–west trajectory. Figure 9 also shows the mountain ranges that run along the center of Taiwan, from north to south of the country, which act as a natural barrier and offer a great deal of protection to the communities located to the west of them. This protection effect is likely to continue in the future, as shown by Figs. 7 and 8, with the east coast, and north and south parts of the country affected far more than the west coast. The potential future increase in tropical cyclone intensity is likely to further aggravate this effect, and for scenario B for example the Expected Time Loss at the south of the country is up to 60% greater than in the Control Scenario, compared to only around 40% greater in the center of the west coast. This is a significant finding, as it suggests how the natural characteristics of the island are able to provide some limited protection against climate change to some areas. Unfortunately, the major population centers are currently located around the north of the country in the area around Taipei and also, to a lesser extent, in the south, as

shown in Fig. 3. Figure 10 shows the total number of man-hours per year that can be expected to be lost due to tropical cyclones at present (control scenario), with Figs. 11 and 12 showing the results for the climate change scenarios. Currently, on average 1.5% of the entire productive time of the country each year is lost due to tropical cyclones, and this number can be expected to rise to between 1.7 and 2.2% by 2085 (scenarios A and B, respectively). This represents an almost 50% increase in the amount of downtime each year for the case of scenario B, and is thus significant. In GDP terms, assuming that the current GDP already includes the average effect of the current average tropical cyclone downtime, the increase in downtime could reduce the Taiwanese economy by between 0.26 and 0.7% by 2085, depending on the Scenario. Figures 11 and 12 do not include population growth in order to make comparison easy, and the true number of hours lost in the future is likely to be exacerbated by population growth. However, the percentage loss would stay the same, provided that the population distribution throughout the country does not change. Also to be noted is how most of the population is around Taipei in the north of the country, and hence the indirect economic damage of the tropical cyclones on GDP for the entire country is hugely



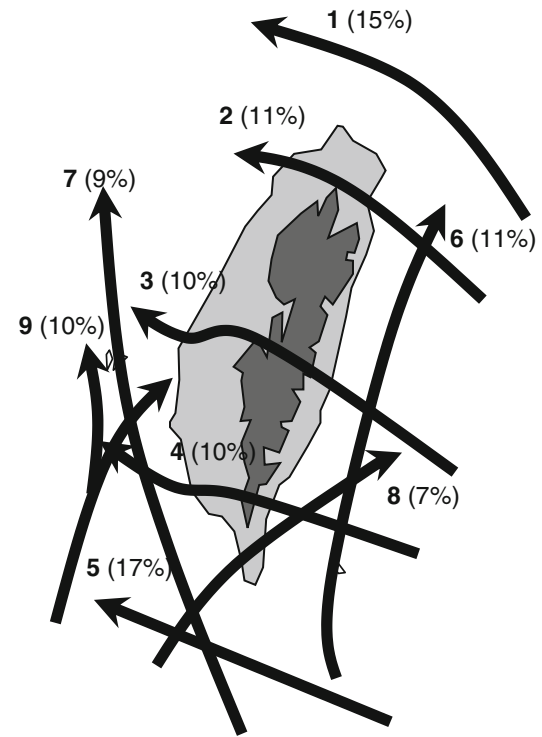


**Fig. 8** Average expected hours lost per year per urban center for scenario B

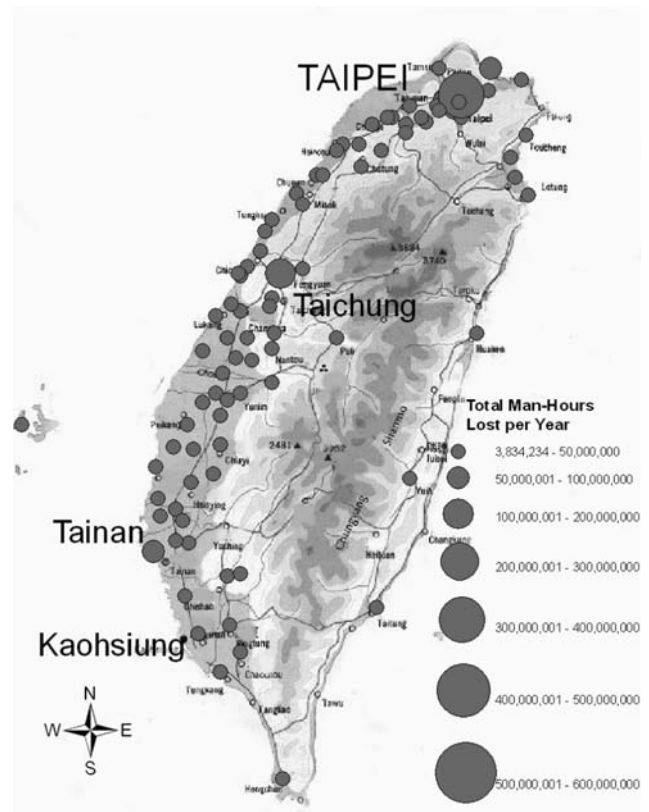
influenced by the expected Time Loss in the capital (which is exactly the same as the country average, 2.2% for scenario B).

**Adaptation and vulnerability**

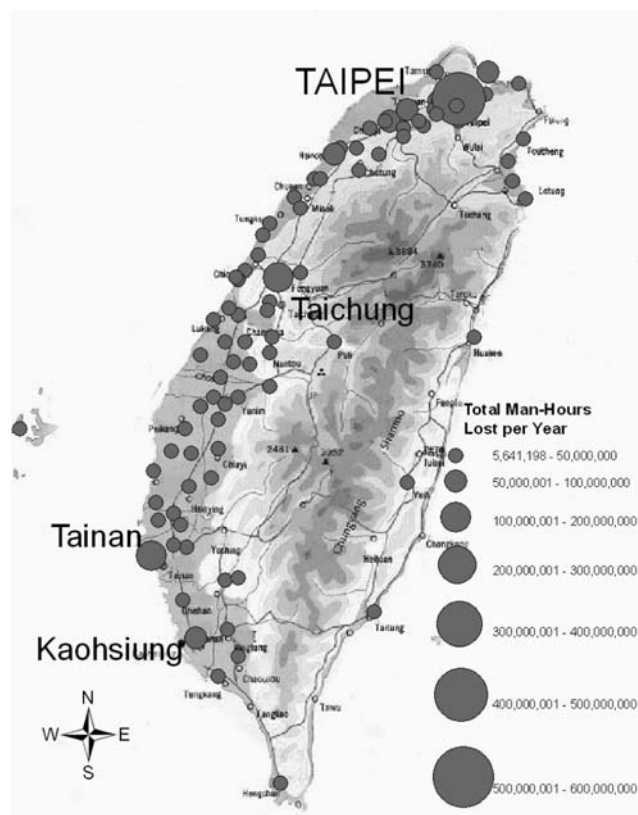
Although the possibility of having stronger future tropical cyclones has been used by many to make the case for action on energy policies (climate change mitigation), Pielke (2007) argues that policy action should focus on reducing vulnerabilities, at least in the short term. He estimates that the largest maximum potential effectiveness of a 10% reduction in the projected increase in greenhouse gases by 2050 for reducing future global tropical cyclone damage is far less than the maximum potential effectiveness of adaptation (i.e. reducing the vulnerability of people and property) by between 5:1 and 22:1, depending on the assumptions taken. Although the nature of this research is highly idealized, it indicates how a small percentage reduction in vulnerability leads to about the same effect as if greenhouse gases were immediately stabilized at 2006 concentrations.



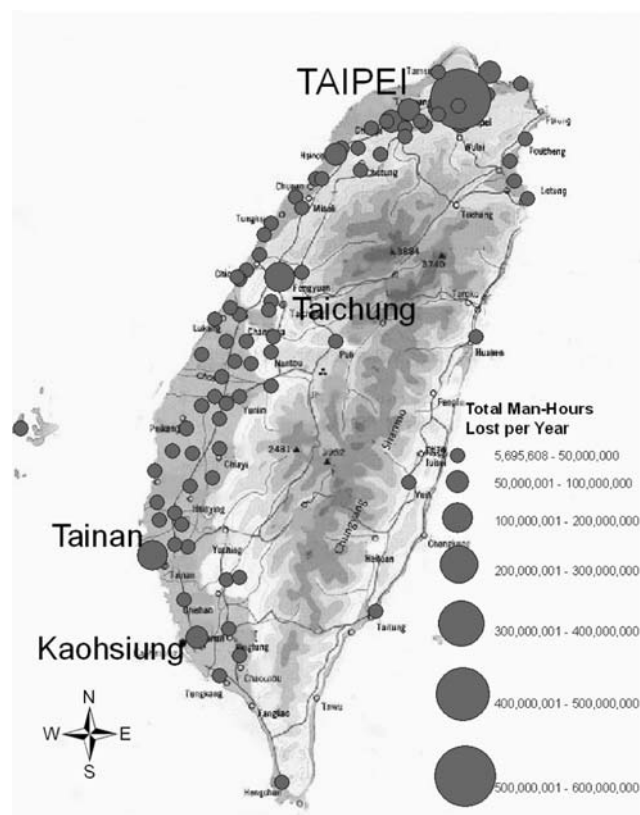
**Fig. 9** Diagram of categorized paths of typhoons invading Taiwan between 1897 and 2003



**Fig. 10** Total expected man-hours lost per urban center for control scenario



**Fig. 11** total expected man-hours lost per urban center for scenario A



**Fig. 12** Total expected man-hours lost per urban center for scenario B

Hallegatte (2007) carried out a vulnerability assessment against hurricanes for the east coast of the United States, which supported the view that there is a wind-speed-to-loss relationship. However, Hallegatte does point out that large variability in recorded economic losses arise from hurricane characteristics other than wind speed (such as the amount of precipitation) and the precise landfall position and time. Also, he does mention how the vulnerability coefficients he proposed have the same problem as the normalized economic losses proposed by Pielke and Landsea (1998) and Pielke et al. (2006), namely that they do not take into account mitigation actions and hence probably overestimate current vulnerability. Hallegatte (2007) also tries to analyse the evolution of vulnerability, and states that “it seems that vulnerability evolves with time, probably toward a reduction of vulnerability in most but not all cases”. Other authors, such as Yusuf and Herminia (2009) carried out a study of various countries in the Asia-Pacific and came up with the concept of adaptive capacity ( $A_c$ ), which they defined as the degree to which adjustments in practices, processes or structures can moderate or offset potential damage or take advantage of opportunities (from climate change). However, although this parameter would be important to determine vulnerability in developing countries, for the case of developed

countries it approaches 1, and hence it is not so useful for the case of Taiwan.

It can thus be seen that vulnerability is crucial to the direct damage that occurs in countries affected by tropical cyclones and the indirect damage that occurs after the tropical cyclone has passed [as shown by Hallegatte (2008) for the case of Katrina]. However, it is not a significant factor related to the indirect economic losses that occur during the passage of the tropical cyclone. If anything, an increase in adaptation capacity would increase this part of the indirect economic loss, as noted by Pielke (2007):

In some instances not only has a cost-benefit analysis not been attempted, but neither has a more general risk assessment. Hurricane evacuation in the USA is an example of such a situation. Hurricane forecasts of storm tracks have improved steadily over the past three decades or so, yet at the same time the area of coastline warned per storm has increased over the same time period. This suggests that decision makers (including forecasters and emergency managers) have possibly become more risk averse over time and have used advance in the science of forecasting to reduce the chances of leaving part of the population unwarned. Of course, such strategies have costs in the

form of a greater number of people warned unnecessarily.

Indeed, although wind speed is only one of the factors that influences damage and other indirect losses, it would be the major component in determining when people would choose to stop working and begin to take remedial action, as the tropical cyclone alerts are based to a large extent on wind speeds.

### Implications and discussion

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 one aspect of how the GDP of a particular country can be affected by one phenomenon (the decrease in urban productivity due to an increase in tropical cyclone size). The cost of dealing with other consequences of a hypothetical future in which tropical cyclones are more intense is not included in this simulation. These would include the reparations of what insurance companies call “First Order Losses” (direct destruction caused by these events) and the cost of trying to adapt infrastructure. However, it is unlikely that adaptation measures will be able to prevent the precautionary shutdown of industries, commerce, etc., due to high winds, and thus the results shown in the present work are unlikely to be greatly affected by mitigation strategies.

Climate models form an important tool with which 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, a fact highlighted in the 4th IPCC Report. There is also a large uncertainty about future changes in tropical cyclone intensity, as highlighted in Pielke (2007), who reports how nine of the leading scholars on tropical cyclones and climate change, when asked to predict increases in tropical

cyclone intensity by 2100, give answers ranging from 0 to 36%.

One of the strong points of the proposed methodology is its relatively quick computation time, due to the simple way in which tropical cyclones are generated. It ensures that the distribution of storms is spatially similar to the historical distribution, 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 would not give better results provided that the assumptions outlined in “Methodology” remain true. This in itself is also one of the drawbacks of using this method.

By relying on historical tropical cyclones, the model has no way to predict what future changes in global climate will have on typhoon routes or frequencies, and hence these follow closely the events of the last 20 years. It would be possible to alter these routes and frequencies using the work of other authors, but at present, as highlighted above, research on this issue is still inconclusive. Thus, the assumption of keeping the routes and frequencies the same can be seen as the default starting point of any simulation to determine the productivity and economic consequences of tropical cyclones.

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 a crucial difference to the results obtained. By increasing the maximum wind speeds of the storms, the number reaching 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.

The wind speed distributions shown in Fig. 4 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. 4 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. 4, the shape of the control and 2085 scenario are not the same (showing how the probability distribution will probably be even more skewed by 2085). Nevertheless, most of the time loss is caused by the more common tropical cyclones that occur regularly each year, and the influence of the bigger typhoons (with return periods of 20–50 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 Fig. 5), and thus the value of  $R_{30}$  given in Eq. 3 is 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 those predicted in this paper).

The current model reproduces the number of storms that happen each month, but does so temporally. Each storm is given a number, but not a period of the month when they act. Hence, the effect that two or more consecutive storms can have on an area cannot be reproduced. This can have quite a significant effect, because if an area was to be hit in rapid succession by two storms it would result in productivity being greatly affected during the time in between storms also, as by the time the inhabitants recovered from the first storm they would have to start preparing for the second. This effect is likely to intensify in the future, especially during the summer months when one storm can be quickly followed by the next.

The current method does not make any assessments regarding the future growth of the Taiwanese economy or population. As long as the population distribution stays the same throughout the country, the percentage decrease in urban productivity would stay the same, regardless of the size of the economy and population. Other factors that could affect this productivity, such as population aging or changes in the population density patterns, are beyond the scope of this paper and would make it more difficult to easily interpret the results. However, the results presented in this paper do suggest that population development should be encouraged in areas sheltered from tropical cyclones. If more of the population was located in the relatively sheltered west area, this indirect economic damage would be smaller, although this western area is actually more susceptible to flooding. This latter problem

illustrates the complex challenges involved in dealing with climate change adaptation, where policy makers must assess the various benefits and problems of different strategies.

## Conclusions

The objective of this research was to calculate the effect that a future potential increase in tropical cyclone intensity would have on the productivity of urban areas in Taiwan. The paper uses as its basis the results of Knutson and Tuleya (2004), and assumes that, although tropical cyclones will increase in intensity, according to the results of these authors, their paths and frequencies will not change in the future. According to this, downtime could increase from an annual average of 1.5% nowadays to up to 2.2% by 2085, an increase of almost 50%. This in turn could cut Taiwanese GDP by up to 0.7% by 2085.

Although, due to the great uncertainties associated with climate change, the results of this simulation should be viewed with caution, they can provide a feel for the magnitude of the likely indirect economic effects of an increase in tropical cyclone intensity.

**Acknowledgments** The authors would like to thank the Japanese Society for the Promotion of Science (JSPS) for the Post-Doctoral Scholarships without which this research would not have been possible. One of the images was produced by Nilfanion on the Wikipedia Website, and released into the public domain. The authors would also like to thank two anonymous reviewers for their comments, which led to a significant improvement in the quality of the paper.

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