A preliminary impact assessment of typhoon wind risk of residential buildings in Japan under future climate change

Kazuyoshi Nishijima¹, Takashi Maruyama² and Mathias Graf³
¹Technical University of Denmark
²Disaster Prevention Research Institute, Kyoto University
³ETH Zurich

Abstract:

This paper performs a quantitative impact assessment of the climate change on typhoon wind risk, focusing on residential buildings in Japan. The risk is assessed based on (1) the typhoon event set extracted from the simulation by the super-high resolution atmospheric general circulation model developed within the KAKUSHIN program; (2) the probabilistic typhoon modeling scheme developed by our group; (3) a fragility model empirically estimated on the basis of the damage report on typhoon Songda in 2004 and the reproduced wind field by a mesoscale meteorological model; JMA-NHM. The main results are that in the future (2075–2099) at most locations of Japan: (1) extreme wind events (10-minute sustained wind speed exceeding 30 m/s) are more likely to occur; (2) the median of the annual maximum wind speed decreases; (3) the expected number of damaged residential buildings decreases, assuming that the profile of the building portfolio remains unchanged. Based on these results, the assumptions and inputs to the assessment are critically reviewed. Thereby, the needs of further research efforts toward more credible and comprehensive assessment are addressed.

KEYWORDS Climate change; risk; impact assessment; adaptation; tropical cyclone

INTRODUCTION

Global-scale meteorological monitoring networks have revealed that the global climate has significantly changed over the last decades. Large amount of scientific work has suggested that further change of the climate may occur in the future. In response to these, various political as well as non-political protocols on action plans for mitigating the climate change have been proposed at different levels of the society; only to find it difficult to reach the envisaged goals. Presently, there seems a general agreement that actions have to be undertaken also on the adaptation of the society to the emerging climate change.

For the purpose to facilitate decisions on the adaptive actions, a large amount of efforts have been devoted worldwide to develop more credible models for the projection of the future climate – numerical models of the climate as well as models for the growth of the human society. Correspondingly, quantitative assessment of the impact of the climate change on the human society has become possible for various types of risks; among others, the risks due to natural hazards affected by the climate change.

The Kakushin program is a research program supported by the Ministry of Education, Culture, Sports, Science, and Technology in Japan, which aims at providing scientific basis for policy making on the adaptation to the emerging climate change in general and contributions to the forthcoming IPCC AR5 report in particular. Within the Kakushin program, five research teams were organized and each of them has conducted a research project with a specific target. One of these research projects is the project “Projection of the change in future weather extremes using super-high-resolution atmospheric models” (Kitoh et al., 2009). In this project a super-high-resolution atmospheric model has been developed (Mizuta et al., 2012). Together with the Earth Simulator a projected future climate has been simulated. The simulation results are facilitated to perform the impact assessment of the climate change on various types of natural hazard risks.

This paper investigates the probabilistic assessment of the impact of the climate change on infrastructure, based on the outputs from the simulations. Focus is given on the typhoon wind risk of residential buildings in Japan; however, the same approach can be applied for tropical cyclone wind risk of structures in other regions. The objectives are: (1) to demonstrate that tools to assess the impact are readily available, if not yet these are perfect, and present a preliminary result of the assessment, thereby, (2) to address the needs for further sophistication of the tools toward more credible and comprehensive assessment of the risks.

APPRAOCH

Procedure outline for the impact assessment

The impact of the climate change on the typhoon risk is assessed in the following procedure. Firstly, typhoons simulated with the super-high-resolution atmospheric general circulation model (AGCM) under current and future climates are extracted. Secondly, based on the extracted typhoons, probabilistic typhoon models are developed for each of the climates. Using the developed probabilistic typhoon models, stochastic typhoon events are simulated by Monte Carlo simulations. Thirdly, a model representing the wind resistant performance of the residential buildings is statistically developed based on the damage report on typhoon Songda in 2004 together with the JMA-NHM (Japan...
Typhoons extracted from AGCM simulation

The simulations are performed for three different periods; i.e. 1979–2003 (current), 2015–2039 (near future), and 2075–2099 (future). For these simulations, the IPCC AR4 A1B scenario is employed as the boundary conditions to the AGCM. Two sets of the simulation results are available, which are labeled as MRI-AGCM3.1S and MRI-AGCM3.2S (Mizuta et al., 2012). The latter set is utilized in this study, and the impact assessment is undertaken for the future climate relative to the current climate.

Typhoons are extracted from the simulation results, see Murakami and Sugi (2010). For the current climate 592 typhoons are extracted; for the projected future climate 468 typhoons are extracted. The extracted typhoons are represented in terms of the central pressure as well as the position of the typhoons at each time. Supplement Figure S1 illustrates the extracted typhoons. These together with sea surface temperature assumed in the simulations are utilized as the input for developing the probabilistic models for the occurrence and the transition of typhoons.

Probabilistic modeling of typhoon

A number of probabilistic modeling approaches of tropical cyclones have been developed, see e.g. Fuji i and Mitsuta (1986) and Vickery et al. (2000), and Mori (2012) for the overview. In this study the probabilistic typhoon modeling proposed by Graf et al. (2009) is employed. The model consists of four component models; i.e. occurrence model, transition model, wind field model and surface friction model. The first two models are probabilistic, whereas the last two are deterministic.

Two versions of the occurrence and transition models are developed for the current and future climates using the AGCM simulation results; on the other hand, the models for wind field and surface friction developed in Graf et al. (2009) are employed without modification. Note that the information on the radius of maximum wind speed, which is required to develop a complete transition model, is not available from the simulation results. Therefore, in the study it is tentatively assumed that the distribution of the radius of the maximum wind speed does not change in the projected future climate, and the distribution that is estimated in Graf et al. (2009) is employed. The outputs from the suite of the component models are the probabilistic characteristics of the maximum 10-minute sustained wind speeds at 10 m height at each location in Japan for individual typhoon events and their frequencies. Note that the wind speed computed by the probabilistic typhoon model is calibrated with the wind speeds observed at JMA meteorological stations. Hereafter, it is denoted by $y_{NHM, 10\text{min}, \text{MAX}}$. It should be emphasized that the occurrence and transition models for the current climate are developed based on the AGCM simulation results, instead of the actual historical typhoons archived in e.g. the JMA Best track data. The reason for this is, by doing so, it is anticipated that the effects of the biases inherited in the AGCM on the assessments are alleviated (see also Discussion).

Fragility modeling of residential buildings

The assessments of the typhoon wind risk require a model that represents the wind resistant performance of structures as a function of wind speed. The typhoon Songda in 2004 is selected to develop such a model, since a report on the damage statistics of the residential buildings is available.

The damage statistics are reported at municipality level in Kyushu, Japan, see Tomokiyo et al. (2009). The report differentiates the degree of damages, i.e. minor, moderate and major damages, and summarizes the number of damaged buildings for each degree of damages at each municipality. These statistics are utilized together with the Census data. Note that the model developed here does not differentiate the degree of damages. The model describes the probability of damage occurrence for a single building. This is estimated through the ratio of the number of damaged buildings over the total number of residential buildings, which is approximated by the number of households in the Census data, in a given area as a function of the maximum wind speed during the typhoon event. Hereafter, the model is called fragility model.

In order to develop the fragility model, the wind speeds at respective municipalities are required. For this purpose, the strong wind field of typhoon Songda is numerically reproduced using the JMA-NHM together with the JMA-RANAL data as the initial condition and the JMA-RSM data as the boundary condition, see Maruyama et al. (2010). The fragility model is estimated by the least-squares method, and is obtained as:

$$P_d(y_{NHM, \text{MAX}}) = 5.1 \cdot 10^{-9} \cdot y_{NHM, \text{MAX}}^{4.0},$$

(1)

where $P_d(y_{NHM, \text{MAX}})$ is the probability of damage occurrence as a function of $y_{NHM, \text{MAX}}$, the maximum wind speed at 10 m height from the surface computed with the JMA-NHM. In Figure 1 the solid line represents the estimated fragility model. The mean damage ratio together with the range within one standard deviation is also shown for each of the bins.
WIND RISK UNDER FUTURE CLIMATE

ranging from 20 [m/s] to 50 [m/s] with the interval of 5 [m/s]. As seen in Figure 1, the estimated probability of damage occurrence well fit to the mean damage ratios; however, it should be mentioned that there is significant scatter in the damage ratios, as indicated by the ranges. One of the possible reasons is the quality of the data, which were collected municipality-wise by experts or non-experts, or based on the reporting by affected people. Another possible reason is the approximation of the wind speeds at individual buildings by the wind speed at one location in the municipality that the buildings belong to.

It is assumed that the model developed in this way is representative for other typhoon events as well as other regions in Japan. Note that the fragility model employed in the current study should be considered to be tentative, see further discussion in Discussion.

Calibration of wind speeds

The wind speed computed with the JMA-NHM is considered as wind speed spatially and temporally averaged; the extents of which, however, are not explicitly known. Therefore, a calibration of the wind speeds is carried out using the observed wind speeds at the NeWMeK observation stations in Kyushu, see Maruyama et al. (2010). The reason why the calibration is carried out with the NeWMeK wind observations is that more observation stations are installed in Kyushu area in comparison to the JMA meteorological stations. The relation for the calibration is obtained as:

\[ Y_{\text{NewMeK,10min,MAX}} = 0.83 \cdot Y_{\text{NHM,MAX}} \]

where \( Y_{\text{NewMeK,10min,MAX}} \) is the maximum observed 10-minute sustained wind speed at a NeWMeK observation station. Assuming that the observational characteristics of the NeWMeK and JMA meteorological stations are identical; i.e. \( Y_{\text{JMA,10min,MAX}} = Y_{\text{NewMeK,10min,MAX}} \), and substituting this relation and Equation (2) into Equation (1), the fragility model is obtained as:

\[ p_d(Y_{\text{JMA,10min,MAX}}) = 5.1 \cdot 10^{-9} \cdot \left( \frac{Y_{\text{JMA,10min,MAX}}}{0.83} \right)^{4.0} \]

Thus, the probabilistic typhoon model and the fragility model can be integrated through the wind speed \( Y_{\text{JMA,10min,MAX}} \).

Measure of risk

Denote by \( N_j^B \) and \( N_j \) respectively the number of buildings at location \( j \) and the number of buildings that are damaged by typhoons in a given year. The number \( N_j \) is a random variable and can be written as:

\[ N_j = \sum_{k=1}^{K_j} N_{j,k} \]

where \( N_{j,k} \) is the number of damaged buildings in the event of the \( k \)-th typhoon in a year, and \( K_j \) is the number of typhoon events in the year relevant to the buildings at location \( j \), which is also a random variable. The definition of the building risk \( \bar{R}_j \) at location \( j \) is given as the expected value of the number \( N_j \) relative to the total number \( N_j^B \) of the buildings:

\[ \bar{R}_j = E \left[ \frac{N_j}{N_j^B} \right] = E \left[ \frac{K_j}{\sum_{k=1}^{K_j} N_{j,k}} \right] = E \left[ \frac{K_j}{\sum_{k=1}^{K_j} R_{j,k}} \right] \]

\[ = E[K_j] \cdot E[R_{j,k}] \]

where, \( R_{j,k} = \frac{N_{j,k}}{N_j^B} \). Here, it is assumed that \( R_{j,k} \) are independently identically distributed. \( E[R_{j,k}] \) is defined using the probability density function \( f_{Y_j}(y) \) of the maximum wind speed \( Y_j \) at location \( j \) in a single typhoon event, and the probability \( p_d(y) \) of the damage occurrence as:

\[ E[R_{j,k}] = \int_{y_{\min}}^{y_{\max}} f_{Y_j}(y)p_d(y)dy \]

Thus, given the probability \( p_d(y) \) of damage occurrence, the building risk \( \bar{R}_j \) at location \( j \) is characterized by two wind hazard components: the mean frequency \( E[K_j] \) of typhoon events relevant to location \( j \) in a given year, and the probability density function \( f_{Y_j}(y) \) of the maximum wind speed in an event.

RESULTS

Simulation of typhoon events and its verification

Two sets of the typhoon events are generated by Monte Carlo simulations; i.e. one for the current climate and the other for the future climate. For each event set, Monte Carlo simulations for one-year period are repeated 25000 times. For each event the maximum 10-minute sustained wind speeds are computed at 2249 locations at municipality level entirely covering Japan.

The verification of the generated typhoon events is undertaken by comparing a couple of statistics of the transition of the typhoons. In Figure 2, the cumulative annual average numbers of typhoons are shown as a function of the central pressure, which travel through the latitudes of 30°N and 35°N under the current and future climates. The overall performance of the probabilistic models is acceptable in the sense that these succeed in representing two general tendencies observed from the simulations with the AGCM: (1) the overall number of typhoons travelling though these latitudes is decreasing; (2) the number of highly intensified typhoons whose central pressure is equal or less than 920 [hPa] is increasing. However, there is a discrepancy in the numbers of weaker typhoons for the latitude of 35°N under the future climate. The main reason for the discrepancy can be the smaller numbers of typhoons in the simulation with the AGCM to develop the probabilistic model.

Impact on annual maximum wind speed

In Figure 3, the changes of the distributions of the annual maximum wind speeds at two locations in Japan (Tokyo and Fukuoka) are shown. Note that these wind speeds are the ones computed at 10 m height with actual roughness conditions (Graf et al., 2009).

It is seen that the probabilities of the occurrence of higher annual maximum wind speeds (e.g. exceedance of 30 [m/s]) increase at both locations, whereas the medians of the annual maximum wind speeds decrease. This is coherent with the two observations from the simulations with the AGCM mentioned in the previous section.
Furthermore, the overall comparisons are made for the 98%-quantiles (corresponding to 50-year return period) and the medians of the annual maximum wind speeds, confirming that these observations are true for most of the locations in Japan, see Figure 4.

Impact on wind risk of residential buildings

The risks of residential buildings defined in the previous section are computed at each location in Japan under the current and the future climates. The risks are computed by estimating $E \left[ \sum_{k=1}^{K_i} R_{j,k} \right]$ in Equation (5) and $E[R_{j,k}]$ in Equation (6) based on the Monte Carlo simulations of the typhoon events. The risks tend to decrease for most of the locations, see Figure 5. The main reason for this is the decrease in the frequency of the relevant typhoon events in Japan and that the degree of the intensification of typhoons is not enough to compensate this decrease. The simple average of the change rates of the risks is 0.87. The geographical distribution of the change as shown in Supplement Figure S2 indicates the tendency that the risks increase in the northern and western parts of Japan and decrease in the southern and eastern parts. This may be explained by the change of the characteristics of the track of typhoons.

Figure 2. Cumulative annual average numbers of typhoons in the AGCM simulation and the Monte Carlo simulation as a function of the central pressure at latitudes 30°N (top) and 35°N (bottom) under the current climate (left) and the projected future climate (right).

Figure 3. Exceedance probabilities of the annual maximum wind speeds under the current and the projected future climates at Tokyo (left) and Fukuoka (right).
DISCUSSION

General issues

The numerical results depend on several critical inputs and assumptions. Among others, the probabilistic characteristics of typhoon events are crucially dependent on the outcomes from the AGCM and the employed scenario.

The numbers of typhoons in these outcomes may not be sufficient to develop credible probabilistic hazard models. The assumption that the wind resistant performance of building is uniform over Japan may not be appropriate, since the design wind loads in the building code differ in different regions of Japan. Improvements on these are addressed as future tasks.

The impact assessment of the risk depends on the definition of risk. For instance, defining the measure of risk in monetary terms, instead of the damage ratio as defined in this study, might result in a different conclusion, since it is anticipated that the monetary loss may be highly nonlinear to the wind speed. However, in order to facilitate the quantitative assessment of this, a vulnerability model that describes the relation between wind speed and monetary loss needs to be developed.

In the following subsections, specific issues are discussed in order to identify clear direction of the research needs toward more credible and comprehensive assessment.

AGCM performance in regard to the simulation of typhoons

The performance of the AGCM in regard to the simulation of typhoons is investigated by comparing some statistics on the typhoons in the AGCM simulations and in the JMA Best track data in the same period; i.e. 1979–2003. The statistics employed for this purpose are the annual average numbers of typhoons that travel through the several latitudes with certain values of the central pressure or smaller. Supplement Figure S3 shows the comparison results for the latitudes of 20°N and 35°N. At 20°N the statistics are in good agreement with each other; on the other hand, at 35°N significant discrepancy is observed. Clearly, further improvement of the AGCM is required.

In the change rate of the risk over Japan may be overly emphasized by the patterns of a few numbers of typhoon tracks around Japan that happened to occur in the AGCM simulation; hence, may be statistically not significant. Further investigation is suggested to verify this observation.

Modeling of wind vulnerability

The fragility model developed in this study relies on a narrow range of damage observation temporally (only on one typhoon event) and spatially (only on Kyushu, a part of Japan). It only describes the relation between the wind speed and the probability of damage occurrence; indifferent to the degree of damage or amount of monetary losses.

From a wind engineering point of view, it seems that the fragility model obtained in this study underestimates the actual probability of damage for higher wind speeds, e.g. exceeding 50 [m/s]. In order to investigate the sensitivity of the assumed fragility model on the changes of the risks, the changes of the risks were assessed with other hypothetical fragility models. These are: Probit and Logit models, and models with power functions of different exponents, all of which appears to fit to the damage data. The results diverged from the decrease of the risks to the increase of the risks.

Figure 4. Comparisons of 50-year return period wind speeds (left) and medians of the annual maximum wind speeds (right) at 2249 locations in Japan under the current and the projected future climates.

Figure 5. Change of the typhoon wind risks under the current and projected future climates.
approaches; i.e. modeling of the vulnerability accommodat-
ing physical processes leading to damages and their con-
sequential losses; see e.g. Pinelli et al. (2008) and Pinelli 
et al. (2011) for the vulnerability modeling for residential 
buildings in Florida, USA. In the case of the assessment for 
Japan, more emphasis should be given on the vulnerability 
modeling for non-structural components of buildings such 
as cladding and glazing, since these are considered to be 
the major part of the damages and losses due to strong wind 
in Japan.

Surface roughness and development of the society 

Finally, but not least, the development of the human 
society over time should have significant impact on the 
change of the typhoon wind risk. Firstly, it affects the future 
development of the climate change through the general 
consumption behavior of the society; this concerns the 
scenarios in the IPCC report. Secondly, the development of 
the human society may change the pattern of the land use 
and building density, which can result in different surface 
roughness conditions. In addition to these, for a 
comprehensive assessment of the impact, other changes of 
the societal structure such as population and geographical 
distribution thereof must be taken into account.

CONCLUSION

A quantitative impact assessment of the climate change 
on civil infrastructure is performed, taking the typhoon wind 
risks on residential buildings in Japan as an example. The 
main findings are that in the future (2075–2099) at most 
locations of Japan: (1) extreme wind events (10-minute 
sustained wind speed exceeding 30 m/s) are more likely to 
occur; (2) the median of the annual maximum wind speed 
decreases; (3) the expected number of damaged residential 
buildings decreases, assuming that the profile of the building 
portfolio remains unchanged over time. Based on these 
findings, the assumptions and inputs to the assessment are 
critically reviewed, thereby, needs of further efforts toward 
more credible assessment of the impact are identified.

ACKNOWLEDGEMENTS

This work was conducted under the framework of the 
“Projection of the change in future weather extremes using 
super-high-resolution atmospheric models” supported by 
the KAKUSHIN Program of the Ministry of Education, Culture, 
Sports, Science, and Technology (MEXT). The calculations 
of the numerical simulations were performed on the Earth 
Simulator. The authors thank to Mr. Murakami for providing 
the datasets of the typhoon events extracted from the 
numerical simulations.

SUPPLEMENTS

Supplement 1: This includes:

Figure S1. Extracted typhoons for the current climate 
(left) and the future climate (right).

Figure S2. Geographical distribution of the change of the 
residential building risks.

Figure S3. Cumulative annual average numbers of 
typhoons in the JMA Best track data in the period of 
1979–2003 and the AGCM simulation for the current 
climate as a function of the central pressure at latitudes 
20°N (left) and 35°N (right).

REFERENCES

Fujii T, Mitsuta Y. 1986. Simulation of winds in typhoons by a 
stochastic model. Journal of Wind Engineering 28: 1–12 (in 
Japanese).

Graf M, Nishijima K, Faber MH. 2009. A probabilistic typhoon 
model for the northwest Pacific region. The seventh Asia-
pacific conference on wind engineering. APCWE7, Taipei, 
Taiwan.

Kitoh A, Ose T, Kurihara K, Kusunoki S, Sugi M, KAKUSHIN 
Team-3 Modeling Group. 2009. Projection of changes in 
future weather extremes using super-high-resolution global 
and regional atmospheric models in the KAKUSHIN 
Program: Results of preliminary experiments. Hydrological 
Research Letters 3: 49–53. doi: 10.3178/hrl.3.49.

Maruyama T, Tomokiyo E, Maeda J. 2010. Simulation of strong 
wind field by non-hydrostatic mesoscale model and its 
applicability for wind hazard assessment of buildings and 
houses. Hydrological Research Letters 4: 40–44. doi: 
10.3178/HRL.4.40.

Mizuta R, Yoshimura H, Murakami H, Matsueda M, Endo H, Ose 
T, Kamiguchi K, Hosaka M, Sugi M, Yukimoto S, Kusunoki 
S, Kitoh A. 2012. Climate simulations using MRI-AGCM3.2 
with 20-km grid. Journal of the Meteorological Society of 
Japan: (In press).

Mori N. 2012. Projection of Future Tropical Cyclone Characteris-
tics based on Statistical Model. In Cyclones Formation, 
Triggers and Control, Oouchi K, Fudeyasu H (eds). Nova 
Science Publishers, Inc. 24p. (In press).

Murakami H, Sugi M. 2010. Effect of model resolution on tropical 
cyclone climate projections. Scientific Online Letters on the 
Atmosphere 6: 73–76. doi: 10.2151/sola.2010-019.

Pinelli JP, Gurlery KR, Subramanian CS, Hamid SS, Pita GL. 2008. 
Validation of a probabilistic model for hurricane insurance 
loss projections in Florida. Reliability Engineering & System 
Safety 93 (12): 1896–1905. doi: 10.1016/j.ress.2008.03.017.

Pinelli JP, Pita G, Gurlery K, Torkian B, Hamid S, Subramanian C. 
2011. Damage characterization: Application to Florida public 
hurricane loss model. Natural Hazards Review 12 (4): 190– 
195. doi: 10.1061/(ASCE)NH.1527-6996.0000051.

Tomokiyo E, Maeda J, Tsuru N. 2009. Wind Disaster in Kyushu 
due to Typhoons in 2004 – Residential Damage in Kyushu, 
Japan. The seventh Asia-Pacific conference on wind 
engineering. APCWE7, Taipei, Taiwan, 2862–2873.

Vickery PJ, Skerlj PF, Twisdale L.A. 2000. Simulation of hurricane 
risk in the U.S. using empirical track model. Journal of 
Structural Engineering 126 (10): 1222–1237. doi: 10.1061/ 
(ASCE)0733-9445(2000)126:10(1222).