Projection of future typhoons landing on Japan based on a stochastic typhoon model utilizing AGCM projections

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Abstract:
This study presents a stochastic typhoon model (STM) for estimating the characteristics of typhoons in the present and future climate conditions. Differences between statistical characteristics of present and future typhoons were estimated from projections by an Atmospheric General Circulation Model (AGCM) under a climate change scenario and are taken into account in the stochastic modeling of future typhoons as a climate change signal. From the STM results which utilize the Monte Carlo simulation, it was found that the frequency of typhoon landfall in Japan, especially in three major bay areas, will decrease and the mean value of typhoon central atmospheric pressure will not change significantly. An important point is that the arrival probability of stronger typhoons will increase in the future climate scenario.

KEYWORDS climate change; tropical cyclone; stochastic typhoon model; AGCM; frequency of landfall; central atmospheric pressure

INTRODUCTION

Global tropical cyclone activity may play an important role in driving the ocean’s thermohaline circulation, which has an important influence on regional and global climate (Emanuel, 2001). Observational evidence showed an increase of intense hurricane activity in the North Atlantic since mid 1970’s, correlated with increases in tropical SSTs (IPCC, 2007). Theory and high resolution dynamical models both consistently indicate that global warming will cause the globally averaged intensity of tropical cyclones to increase, and modelling studies consistently project decreases in the globally averaged frequency of tropical cyclones (Knutson et al., 2010). Devastating natural disaster is likely to be caused by more intense typhoons, hurricanes and cyclones which give rise to heavier rain, more extreme winds, higher waves and storm surges. Extreme tropical cyclone related events have high potential of flooding along low-lying coastal areas, including the highly-populated and asset-rich Japanese bay areas and Asian megadeltas.

Previous studies (Sugi et al., 2002; Oouchi et al., 2006) concluded that the number of tropical cyclone will decrease in a future climate, based on results from an Atmospheric General Circulation Model (abbreviated as AGCM) projection by the JMA/MRI group (Mizuta et al., 2006). Yokoi and Takayabu (2009) examined typhoon cyclogenesis using CMIP3 (phase 3 of the Coupled Model Intercomparision Project) ensemble data and concluded that the cyclogenesis area will shift eastward. Although their results are useful climatological indicators, it is difficult to apply them to estimates of specific natural hazards, such as storm surges. Since stochastic analyses are necessary for disaster reduction planning, the number and intensity of projected typhoons by a single GCM does not provide enough information, therefore a stochastic typhoon model (denoted by STM hereafter) is necessary for engineering purposes.

There are several STMs which artificially generate typhoons that can be applied in coastal engineering study (e.g. Hatada and Yamaguchi, 1996; Kato et al., 2003; Hashimoto et al., 2004; Kawai et al., 2006, 2008). Their simulation areas are typically higher than 23°N because most of these studies focused on typhoon characteristics around Japan. Thus, these models do not reproduce typhoon genesis at low latitudes, and the trajectory change to the northeast which usually takes place near Taiwan in summer.

The purpose of this study is to establish a STM for estimating characteristics of typhoons from cyclogenesis to cyclolysis in both present and future climate conditions in order to evaluate coastal hazard risks. Differences between statistical characteristics of the present and the future typhoons were estimated from projections by an AGCM under a climate change scenario and are taken into account in the stochastic modeling of future typhoons as a climate change signal. The STM is used to estimate the probability of future typhoon hazard for the three major bay areas of Osaka Bay, Ise Bay and Tokyo Bay in Japan.

DATA AND MODEL

AGCM

The Japanese government initiated the Innovative Program of Climate Change Projection for the 21st Century (abbreviated as KAKUSHIN Program, 2007) for contribution to the IPCC AR5 (Fifth Assessment Report) climate projections for the near future and end of the 21st century. One of their objectives is the quantitative evaluation of extreme weather around East Asia and Japan. The JMA/ MRI (Japan Meteorological Agency/Meteorological Research Institute) AGCM is an atmospheric GCM with T959L60 resolution (equivalent to about 20 km mesh) and is newly developed for the KAKUSHIN program (Kitoh et al., 2009). Time slice experiments were conducted for three climate periods of 1979–2004 (present climate), 2015–2031 (near future climate) and 2075–2100 (future climate) with different SSTs (Sea Surface Temperatures). SSTs are used as external forcing of the AGCM as a bottom boundary condition.

Received 9 December, 2009
Accepted 24 June, 2010
Observed SST from the UK Met Office Hadley Centre (HadISST) is used for the present climate experiment, and ensemble mean SSTs from CMIP3 multi-model projections of SRES A1B are employed for the future climate experiments.

**Data**

Output data from the AGCM employed in this study is the spatial distribution of sea-level pressure and wind velocity at 10 m height. Indicative typhoon data was also used which was selected from the AGCM by the JMA/MRI group (Sugi et al., 2009) employing the method of Oouchi et al. (2006); the method selects key features of typhoons such as typhoon tracks, central atmospheric pressures and maximum wind velocities every 6 hours. Murakami and Sugi (2010) tuned the typhoon identification method of Oouchi et al. (2006) to obtain a number of typhoons similar to the observed data in the Northwest Pacific. However, weaker typhoons were included into the total count and there are still biases about the intensity. Although it is difficult to represent typhoon magnitude perfectly, the biases are consistent to the estimated changes between present and future climates by dynamical model are reliable. Therefore we applied the changes in typhoon characteristics, predicted by the AGCM, to a STM.

**Stochastic typhoon model**

STMs have been developed for engineering applications. An STM is a kind of Monte Carlo simulation and it calculates key typhoon parameters as functions of central pressure, speed and direction along its trajectory, based on statistical characteristics of observed data.

The present study reports on the STM from cyclogenesis to cyclolysis without distinction of season based on the observed typhoon track data (the so-called best track data, abbrev. BT) from the RSMC-TTC (the Regional Specialized Meteorological Center, Tokyo-Typhoon Center) to assess the accuracy and bias tendencies of AGCM projections. RSMC-TTC contains 1468 observed typhoons from 1951 to 2005. The STM was originally developed by Kunitomi et al. (2005) to formulate two-dimensional probability density functions (pdf) of typhoon characteristics (e.g. cyclogenesis, central pressure, etc.) for each area of 1° by 1° in the target area of (0°N~70°N, 100°E~200°E). The 2D pdf consists of an input value and its local variation; for example, the central atmospheric pressure $p$ in an original location and its variation $\Delta p$ in the next location. Such analysis was evaluated for track direction, velocity, central atmospheric pressure, cyclogenesis and cyclolysis. Finally, the STM employs the Monte Carlo simulation which generates typhoons by combining statistical 2D pdf information. A series of simulations by our stochastic model was verified using the statistical properties of typhoons approaching Osaka Bay in the present climate (see details in Yasuda et al., 2010).

For future typhoon projections, the statistical characteristics of the future typhoon tracks (described later) is employed as input data instead of the BT. There are two mechanisms that enhance typhoon intensity. One is a change in cyclogenesis location and the other is typhoon intensity change due to warmer SST. Only changes in cyclogenesis and cyclolysis in a future climate were considered. Therefore, the sensitivities of these two typhoon characteristics were examined for the Japanese area.

**RESULTS**

**Frequency of typhoon genesis**

Figure 1a shows the number of detected typhoons per year in histograms for the present AGCM and the BT data (both 1979–2004). It is obvious that the number of simulated typhoons from the AGCM is smaller than observed.

Figure 1b shows the number of detected typhoons per year in histograms for the present (1979–2004) and the future (2075–2100) from the AGCM. The total number of typhoons simulated by the AGCM in the present and the future are 485 and 381 respectively. Both counts are smaller than the observed one of 658. The annual averages are 19 and 15 respectively. We fitted the Gaussian distribution, log-normal distribution and Weibull distribution to the histograms; the log-normal distribution was found to be the best fit. The modes of the log-normal distributions for the present and future typhoons are 20 and 16 respectively. This indicates that typhoon cyclogenesis occurrences will decrease (by 4 per year) in the future due to warming SST.

**Locations of typhoon cyclogenesis and cyclolysis**

Figure 2a and b show the histograms (analyzed from the

(a) RSMC-TTC BT data (dotted) and AGCM present (solid)

(b) AGCM present (dotted) and future (solid)

Figure 1. Histograms of cyclogenesis numbers per year and best fitted log-normal distribution comparing between observation (BT data) and projected results by AGCM for present and future.
AGCM) and pdfs (the log-normal distribution fitted) for
latitude and longitude of typhoon genesis locations
respectively. The modes of latitude pdf are 17.6°N and
18.5°N for the present (1979–2004) and the future (2075–
2100). As for the longitude, the modes are 131.5°E and
132.5°E. The locations of typhoon cyclogenesis are projected
to shift to the north-east about by 0.9° to the north and 1.0°
to the east in the future.

The locations of typhoon cyclolysis were also analyzed. Figure 3a shows the present and Figure 3b the future
histograms and pdfs. The modes of latitude pdfs are 19.3°N
and 21.7°N, and the modes of longitude pdfs are 116.1°E
and 120.8°E, respectively. The location of typhoon
cyclolysis is also projected to shift by 2.4° to the north and
4.7° to the east.

**Modeling of future typhoons**

It was found that future typhoons projected from the
AGCM have biases and it is therefore difficult to use
the typhoon data directly to evaluate coastal disasters. To utilize
the changes in typhoon characteristics projected by AGCM,
a modification based on modelled differences was applied
to the BT data so as to better simulate future typhoons. The locations of cyclogenesis and cyclolysis of BT data are
changed proportionally according to the lognormal pdf’s
change shown in Figures 2 and 3. For example, typhoons
whose genesis area is south of 20°N shift northwards by
typically 3° (see Figure 2a) whereas those whose genesis
area is north of 30°N are relatively unchanged since here
the present and future pdfs are the same. The modified future
typhoon track may be extended or shortened which will
change the timing and location of landfall in Japan. The
stochastic procedure in the future experiment uses the
modeled future typhoon tracks as input data on a grid of 1°
by 1°.

Since the number of typhoons in the future climate is
estimated to reduce from 20 to 16 by AGCM, the average
number of typhoon genesis in log-normal pdf will be reduced
from the observed one of 24.7 to 19.5 and the standard
deviation will be also reduced from the current 5.6 to 4.3.

**Probabilistic properties of future typhoons**

The present study carried out the Monte Carlo simulation
in the STM to generate the present and the future typhoons
for 10,000 years. The STM of the present climate is based
on the BT data from 1951 to 2005 while the STM of the
future employs the modified 55 years BT data adapted to
the AGCM’s typhoon characteristic differences between
1979–2004 and 2075–2100.

Figure 4 shows the number of typhoons while Figure 5
shows the lowest central atmospheric pressure per 100 years
in the probabilistic properties of typhoons affecting three
districts (Osaka, Ise, and Tokyo Bay), from this Monte Carlo
simulation.
As shown in Figure 4, the number of possible typhoon events will decrease in each area, that is, the number of cyclogenesis typhoons is projected to become smaller in the future. The lowest central atmospheric pressures of the typhoons passing over three major bays will stay approximately the same in the future as shown in Figure 5. One of the most significant results is the suggestion that for all three major bays the possibility of intense typhoons with central atmospheric pressure lower than 960 hPa will increase in the future. Although the average typhoon intensity will not change, extreme conditions will become more severe.

**SUMMARY AND DISCUSSION**

Even with a high spatial resolution of 20 km, the JMA/MRI AGCM outputs have biases in the number and magnitude of projected typhoons. This study provides a means of using the AGCM results to anticipate the trend in typhoon characteristics in the future. By utilizing the knowledge of changes in the typhoon characteristics as a climate change signal, the STM under a future climate scenario was established.

The Monte Carlo simulation of the STM generated a
10,000-year dataset of typhoons for the present and for the future. It was found that the number of typhoons that would hit Japan will decrease by about 30 percent and the mean value of the central atmospheric pressures will not change significantly. An important point is that the arrival probability of stronger typhoons will increase in the future climate scenario.

Even though climatic changes implied from AGCM results are considered in the modeling of future typhoon tracks, there are several limitations in the STM which do not take into account changes in typhoon intensification rate due to warmer SST and changes in steering flow. Our approach is based on only one SRES climate change scenario, and there is clear uncertainty surrounding these. Sugi et al. (2009) demonstrated that projected trends in cyclogenesis depend on the SSTs that are used as the sea surface boundary condition. Further research will be required employing the output of other GCMs and other scenarios to reduce remaining uncertainties.

ACKNOWLEDGEMENTS

The present study was conducted under the framework of the “Projection of the change in future weather extremes using super-high-resolution atmospheric models,” being supported by the KAKUSHIN Program and the Kakenhi Grant-in-Aid of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT).

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