Coastal Engineering 83 (2014) 65–71

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Evaluation of future storm surge risk in East Asia based on state-of-the-art climate change projection

Tomohiro Yasuda [a,*], Sota Nakajo [b], SooYoul Kim [c], Hajime Mase [a], Nobuhito Mori [a], Kevin Horsburgh [d]

[a] Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[b] Faculty of Engineering, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
[c] Graduate School of Engineering, Tottori University, 4-101, Koyama-cho Minami, Tottori 680-8552, Japan
[d] National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool, Merseyside L3 5DA, UK

ARTICLE INFO

Article history:
Received 24 July 2012
Received in revised form 13 August 2013
Accepted 3 October 2013
Available online 29 October 2013

Keywords:
Climate change
GCM
Tropical cyclone
Storm surge
Extreme value statistics

ABSTRACT

The present study evaluates future storm surge risk due to tropical cyclones (typhoons) in East Asia. A state-of-the-art atmospheric general circulation model (GCM) outputs are employed as the driving force for simulating storm surges associated with the projected changes in climate. The reproducibility of tropical cyclone (TC) characteristics from the GCM in the Northwest Pacific (NWP) is confirmed by comparing with the observed best track data, and future typhoon changes were presented. Storm surge simulation is carried out for East Asia, with the finest nested domain on the Japanese coast. The probability of maximum storm surge heights with specified return periods is determined using extreme value statistics. We show a strong regional dependency on future changes of severe storm surges.

1. Introduction

Strom surges resulting from tropical storms are a global hazard, affecting low-lying coastlines at low latitudes in every ocean. In the Northwest Pacific (NWP), the annual number of typhoons making landfall in Japan has been highly variable in recent years (e.g. it was 10 in 2004 and 0 in 2008). The more severe hurricanes and typhoons typically produce heavier rains, stronger winds, higher waves and more extreme storm surges. Outputs from global climate models (Kitoh et al., 2009) show that large-scale variations in the atmosphere are projected globally, and the impacts of climate change on sea surface temperature distributions (SSTs) can affect the intensity of tropical cyclones, typhoons and hurricanes (Emanuel, 2005).

Changes to extreme weather within climate change projections are inhomogeneous in both time and space. It is still unclear which regions are expected to be most affected by climate change, and the temporal variation of climate change impacts over decadal timescales is also uncertain. Therefore, it is necessary not only to consider mean impacts on the global scale but also to estimate the extreme impacts in individual regions. It has been suggested that typhoons will become more intense and that the areas influenced and the timing of stormy periods may change (Webster et al., 2005). Relatively small changes to both waves and storm surges may cause exceedance of present coastal defense design criteria; these are usually determined from statistical analysis of historical records of extreme hazards. As a result, the freeboards of coastal defenses may become progressively deficient and coastal areas will become increasingly vulnerable.

There are several approaches to projecting the impact of climate change on coastal disasters, such as statistical approaches employing a stochastic typhoon model (Hashimoto et al., 2004; Kawai et al., 2006, 2008; Mori, 2012; Yasuda et al., 2010), worst case evaluation with extreme scenarios (Kiri et al., 2004), and dynamic estimation of potential maximum storm surge (Yoshino et al., 2008). Although these approaches are useful for engineering assessments, there are some potential problems with the methods. Stochastic models for future climate assessment depend on a scenario which assumes knowledge of the future changes in TC number, track, intensity and duration. While the ensemble mean of GCM outputs suggest, a shift in the mean spatial distribution of TC components', GCMs usually have a large bias when reproducing extreme climates (Mori, 2012). Subsequent evaluation using biased distributions of extreme scenarios could overestimate the mitigation response needed by authorities. Nevertheless, risk estimation based on statistical analysis is important for realistic engineering planning (i.e. how the return periods of storm surges and waves are affected by climate change).

This study employs the typhoon tracks, sea level pressure (*Slp*) and sea surface wind at 10 m elevation (U_{10}) from the state-of-the-art GCM projection based on time-slice experiments. Firstly the accuracy of these data is verified by comparison with observed data from the NWP and future changes of typhoon track, genesis number and intensity are discussed. Secondly, storm surge simulations for East Asia are conducted with forcing with *Slp* and U_{10} from the GCM directly. Finally, the extreme

* Corresponding author.

0378-3839/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coastaleng.2013.10.003

value statistics are considered and storm surge values with particular return periods, which is 100 years in this study, are calculated, enabling a quantitative estimate of the future storm surge risk for East Asia.

2. Climate projection

CMIP5 (Coupled Model Intercomparison Project phase 5) (2011) was launched to contribute to IPCC AR5 (Fifth Assessment Report). CMIP5 is a standard experimental protocol for studying the output of coupled ocean–atmosphere GCMs. MRI-AGCM, one of the state-of-the-art GCMs, performs simulation at a resolution of TL959 (triangular truncation 959 with linear horizontal Gaussian grid), which corresponds to about a 20 km mesh in the global domain. The model has the finest resolution in the CMIP5 models. The model has been developed by the Meteorological Research Institute of the Japan Meteorological Agency (MRI/JMA) (Kitoh et al., 2009). Time-slice experiments were conducted for three climate periods of 1979–2003 (present climate), 2015–2039 (near future climate) and 2075–2099 (future climate), each with different sea surface temperatures (SSTs). SSTs were used as external forcing of the AGCM as a bottom boundary condition. The observed SST from the UK Met Office Hadley Centre (HadlSST: Rayner et al., 2003) was used for the present climate experiment; ensemble mean SSTs from the CMIP3 (Coupled Model Intercomparison Project phase 3) (2007) multi-model projections of SRES A1B were employed for the future climate experiments. Global atmospheric data in 3 or 6 h intervals were available with extremely high resolution. Output data from the MRI-AGCM, employed as forcing for storm surge simulations in this study, were the spatial distribution of sea level pressure *Slp* and ocean surface wind U_{10}. Indicative typhoon data were also used, selected from the AGCM by the MRI group (Murakami and Sugi, 2010) 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 h. The model is tuned using the typhoon identification method to obtain a number of typhoons similar to the total observed number globally.

There are two versions of MRI-AGCM which are named 3.1S and 3.2S. MRI-AGCM3.1S is a minor upgrade version of CMIP3, whereas 3.2S is the latest version, employing new schemes and parameterizations. The model has been developed through joint discussions with natural disaster assessment groups (i.e. DPRI Kyoto University and ICHARM) in the KAKUSHIN Program (2007), aiming to reduce the bias of the rainy season front near Japan, the high-pressure system spreading in the Pacific Ocean, the TC (typhoon) numbers approaching Japan, and underestimation of autumnal rain. Further model information is listed in Table 1. Although no detailed explanation is provided here, it is considered that the cumulus convection scheme is the most effective contributing factor for the improvement of the precipitation and cyclogenesis in the NWP.

Table 1
Model information on MRI-AGCM. MRI-AGCM3.1S is a minor upgrade of CMIP3 while 3.2S is the latest version employing new schemes and parameterizations.

	MRI-AGCM3.1S	MRI-AGCM3.2S
Horizontal resolution	TL959 (20 km)	TL959 (20 km)
Vertical levels	60 (top at 0.1 hPa)	64 (top at 0.01 hPa)
Time step	6 minutes	10 minutes
Cumulus convection	Prognostic Arakawa–Schubert	New Yoshimura scheme
Cloud	Smith (1990)	Tiedtke (1993)
Stratocumulus	Kawai and Inoue (2006)	Null
Radiation	Shibata and Aoki (1989), Shibata and Uchiyama (1992)	JMA (2007)
Gravity wave drag	Iwasaki et al. (1989)	Iwasaki et al. (1989)
Upper limit	Relaxation-Newton method	Rayleigh friction
Sea surface	JMA scheme	JMA scheme + skin SST
Land surface	SIB0109 (Hirai et al., 2007)	SIB0109 (Hirai et al., 2007)
Boundary layer	Mellor–Yamada Level2	Mellor–Yamada Level2
Aerosol (direct)	SO_4^{2-}-aerosol only	5 species
Indirect effect	Null	Null

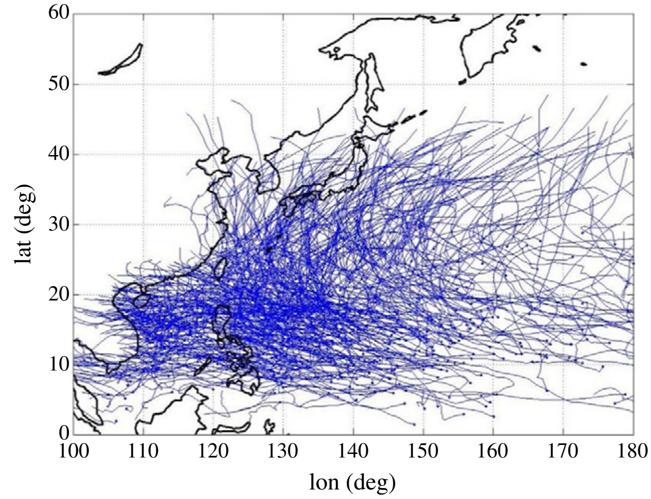

Fig. 1. Typhoon tracks from present experiment using MRI-AGCM3.2S for 1979–2003 in the Northwest Pacific.

3. TC characteristics in the NWP

The output data of TCs simulated by the MRI-AGCMs (vers.3.1S and 3.2S) were compared with observations. The observed typhoon track data (the so-called best track data, abbreviated as BT) from the RSMC-TTC (the Regional Specialized Meteorological Center, Tokyo-Typhoon Center) were employed to assess the accuracy and bias tendencies of the AGCM projections. The target area was 0°–60°N and 100°–180°E.

3.1. Tracks

Typhoon tracks from the MRI-AGCM3.2S are shown in Fig. 1 while the BT for 1979–2003 are shown in Fig. 2. Very few typhoons were generated in the area of 5°–15°N and 140°–160°E by MRI-AGCM3.1S (not shown here). A similar number of typhoons were generated in this area by AGCM3.2S compared to BT. Moreover, the genesis number distribution in this latitude band was also greatly improved in AGCM3.2S. The general trend agrees well with the BT overall: for example, the typhoons go west in the South China Sea, and the trajectory change to the northeast toward Japan takes place near Taiwan.

Fig. 3 shows annual mean ratio of typhoon numbers which is simulated by MRI-AGCM3.2S and observed in BT in each one degree grid, and differences and mean square error between two sets of data.

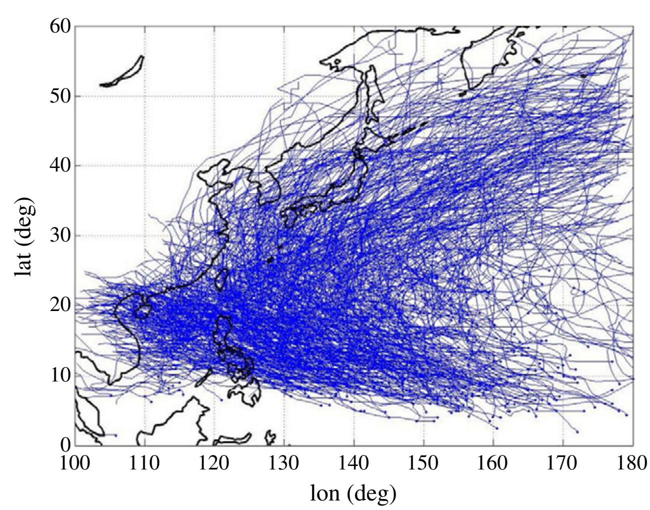

Fig. 2. Typhoon tracks from BT for 1979–2003 in the Northwest Pacific.