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CONSIDERATION OF APPLICABILITY OF STOCHASTIC TROPICAL CYCLONE MODEL FOR PROBABILITY ASSESSMENT OF STORM SURGE

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ABSTRACT: Storm surge risk is basic and important information for design of coastal structure, but its probability assessment is difficult because the frequency of devastating TC is not so high. Furthermore, storm surge damage is very sensitive to not only its intensity but also its track and translation speed. Therefore, the estimation of occurrence probability of devastating disaster from our limited observation data has uncertainty. Recently, we have developed Global Stochastic Tropical cyclone Model (GSTM). The comparison of observation data and simulation results of GSTM showed the reasonable reproducibility of macroscopic statistics of TC parameters such as central pressure, translation direction and speed. However, the verification area of previous study was too large to consider the applicability to risk assessment of local bay scale. Therefore, the microscopic and detailed verification of GSTM is necessary. In this study, we tried to evaluation of reproducibility of TC parameters which was calculated by GSTM at small region as a local bay scale. Furthermore, we improved GSTM by implementation of the cluster analysis of observation data to the process of estimation of the joint Probability Density Function (joint PDF) of temporal correlation of TC parameters. At last of this study, a case study approach by storm surge simulation was performed in order to explain the practical meaning of GSTM. Synthetic TC data based on historical TC track was generated and they were used for input to numerical model for estimating the water height of storm surge at regional scale. Then, the TC track of the worst-case scenario for Yatsushiro bay located in center of west Kyushu Island was decided. Finally, the occurrence probability of the worst-case scenario was calculated from GSTM results.

Keywords: Stochastic model, tropical cyclone, storm surge, cluster analysis.

INTRODUCTION

The current hazard map of storm surge of west Kyushu Island was prepared based on the assumption that the devastating and intense Tropical Cyclone (TC) which correspond to TC Vera, approached to Kyushu Island with the same track as the TC Bart. The Vera is one of the most destructive TC Japan experienced in 1959, and its central pressure at landing was 930 hPa. On the other hand, the Bart is the one of the most destructive TC west Kyushu Island experienced in 1999, and its central pressure at landing was 950 hPa. The bottom line is the virtual TC which has a potential to wreck the devastating damage has been used for disaster prevention planning of storm surge. However, we don’t know much about the occurrence probability of this virtual TC. One of the reasons is that the occurrence frequency of devastating TC disaster is very low. Therefore, the observation TC data at given port is limited. And another reason is that the disaster damage is sensitive to not only the intensity of TC but also its track and translation speed.

One approach to increase the number of TC events for a particular region is to use of a stochastic downscaling method that can generate many artificial TC data sets which cannot be obtained with a physical model. This stochastic method which is based on the Monte Carlo simulation (MC simulation) has been referred to as the Stochastic Tropical cyclone Model (STM). In the STM, the developing process of TC is calculated statistically from given statistical parameters.

Some researchers have proposed STMs in the past. The most widely adopted method is an AutoRegression model (AR model) in which given TC parameter such as central pressure is expressed as a function of some TC parameters, which contains random component (For example, Vickery et al. (2000)). AR model is simple, but some researchers tried to some classifications of TC data before the calibration of AR model coefficients in order to improve the performance of AR model, and they decided AR model coefficients by each class. However, the criterions of these classifications were different between each study and region, and the classification method was based on some assumptions. Therefore, the suggestion of the generalized AR model is difficult.

Recently, we proposed new Global STM (GSTM) based on temporal correlation of TC parameters.

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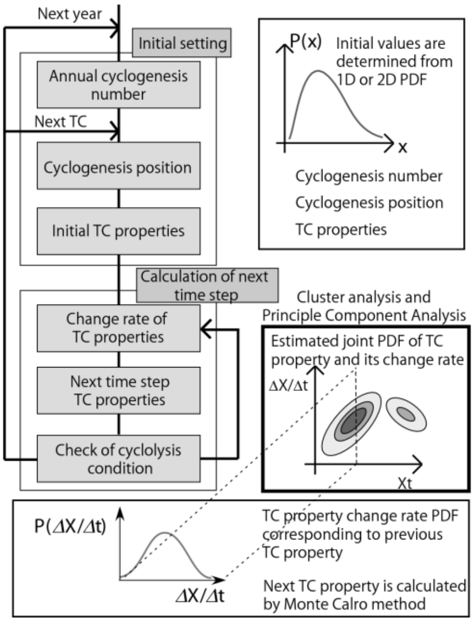


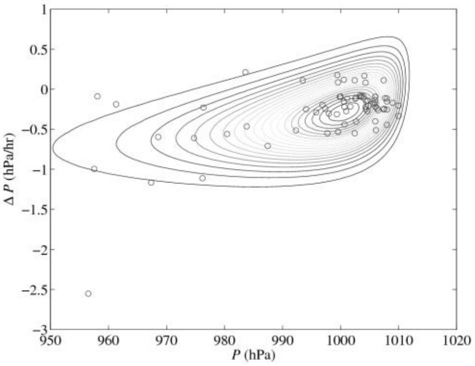
Fig. 1 Flow chart of Global Stochastic Tropical cyclone Model (GSTM)

The comparison of observation data and simulation result of GSTM in given region showed the good reproducibility of statistics of TC parameters (Nakajo, 2011). However, the region of verification was too large to consider the coastal risk assessment of local bay area. Therefore, microscopic verification of GSTM is necessary.

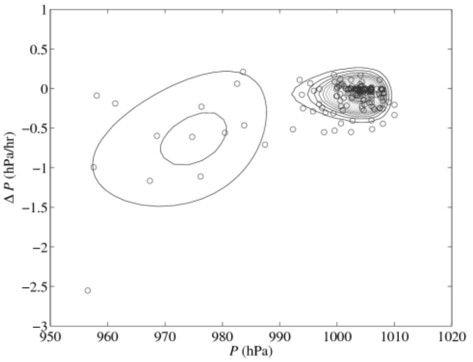
In this study, we tried to evaluation of reproducibility of TC parameters which was calculated by GSTM at small region as a local bay scale. Furthermore, we improved GSTM by implementation of the cluster analysis of observation data to the process of estimation of the joint Probability Density Function (joint PDF) of temporal correlation of TC parameters. At last of this study, a case study approach by storm surge simulation was performed in order to explain the practical meaning of GSTM. Synthetic TC data based on historical TC track was generated and they were used for input to numerical model of Surge, WAve and Tide (SuWAT) for estimating the water height of storm surge at regional scale. Then, the TC track of the worst-case scenario for Yatsushiro bay located in center of west Kyushu Island was decided from the results of SuWAT simulation. Finally, the occurrence probability of the worst-case scenario was calculated from GSTM results.

GLOBAL STOCHASTIC TROPICAL CYCLONE MODEL

The entire developing process of TC from generation to disappearance is a target of GSTM. The calculation process of GSTM had already been presented in the last proceedings of APAC (Nakajo, 2011). But the previous GSTM scheme had a problem that should be improved for reproducibility of the statistics of TC parameter. **Fig. 1** shows the flow chart of GSTM. The following paragraphs describe the summary of GSTM scheme and the detail of improved point.



(a) Unimodal joint PDF



(b) Bimodal joint PDF

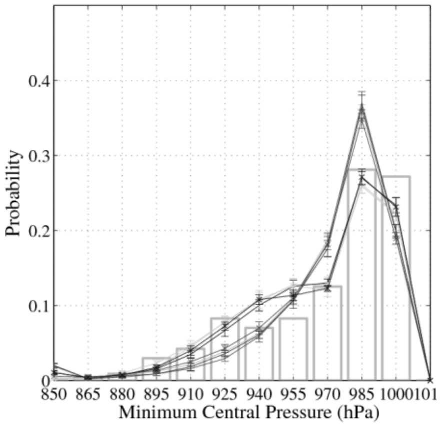
Fig. 2 Approximated joint PDFs of central pressure and its change rate at given region (137°E, 8°N)

Cyclogenesis Process Model

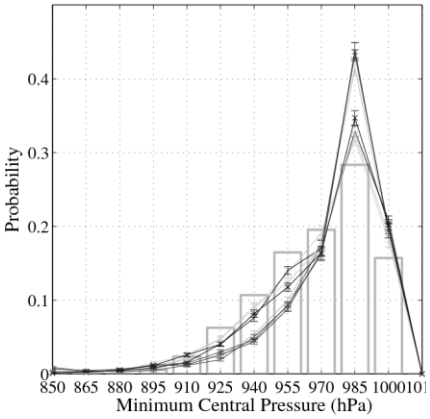
The GSTM can be divided into three major parts. The first stage in GSTM is a cyclogenesis process. The annual number of cyclogenesis events in global, the locations of cyclogenesis, and the initial TC parameter values are determined statistically in this order, by using the MC simulation, based on their approximated Probability Density Functions (PDF) estimated from observation data. The modeling TC parameters in GSTM are three, translation direction and translation speed, central pressure.

Developing Process Model and Improved Point

The subsequent developing process model provides the PDFs of change rates of TC parameters as functions of their values at the previous time step. That is to say, certain TC parameter of next time step is calculated from joint PDF of TC parameter and its change rate at each location. This joint PDF was approximated based on Principle Component Analysis (PCA) of observation data.



(a) Area 1 (120-160°E, 10-20°N)



(b) Area 2 (120-160°E, 30-40°N)

Fig. 3 Comparison of the accuracy of GSTM with different joint PDF model by the histogram of minimum value of central pressure while TC was passing through given areas

- Bars; Observation
- Red lines; Unimodal joint PDF model

Two dimensional normal distributions along two principle components axes were synthesized. With this joint PDF, appropriate PDF of change rate of TC parameter can be calculated depending on given TC parameter of previous time step. Then, the change rates of TC parameters are determined statistically with the MC simulation, and TC parameters of next time step are calculated from multiplication of the change rate and time increment.

In this study, the applicability of bimodal joint PDF for accuracy improvement was investigated. Previous joint PDF will be referred as unimodal joint PDF for convenience from here. The cluster analysis was performed to categorize observation data into two groups automatically before the PCA process. As a base algorithm of the cluster analysis, the K-mean method was adopted, and the Euclidean distance was used for the criterion of clustering. The unimodal joint PDF was made from each cluster, and then the bimodal joint PDF was synthesized with a weight of the ratio of each cluster data. Examples of joint PDFs of central pressure are presented as contour lines in **Fig. 2.** In these figures, circle plots means observation data, and the ridge lines of these joint PDFs correspond to the principal component axes. As can be seen from these figures, there is a temporal correlation between central pressure and its change rate at given region (137°E, 8°N). This knowledge shows the fact that when the central pressure of previous time step is small, the change rate will be likely to small. In addition, it can be estimated that the bimodal joint PDF is suitable for representation of the observation data distribution from these figures. That is, the joint PDF value of **Fig. 2**(b) is high where the plots of observation data are dense, compared with **Fig. 2**(a).

Cyclolysis Process Model

The final part is a cyclolysis process model. The cyclolysis condition is checked every time step, and if TC is survived, calculation goes to next time step. The criteria of cyclolysis were assumed the following three conditions.

1. TC moved into area where no TC arrived in the past.
2. The central pressure of TC reached to 1015 hPa which is equal to peripheral atmospheric pressure.
3. The cyclolysis condition was met after the MC simulation based on cyclolysis probability estimated from observational data.

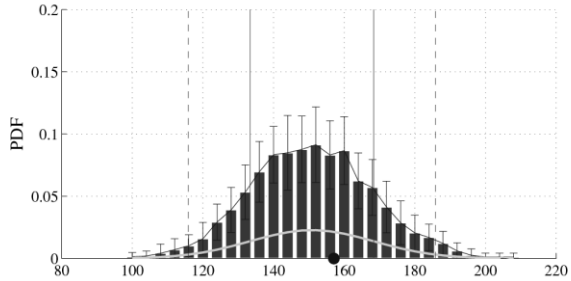
In the case that one of above three conditions is satisfied, the corresponding TC was regarded as being disappeared.

THE ACCURACY VERIFICATION OF GSTM AT REGIONAL COASTAL AREA

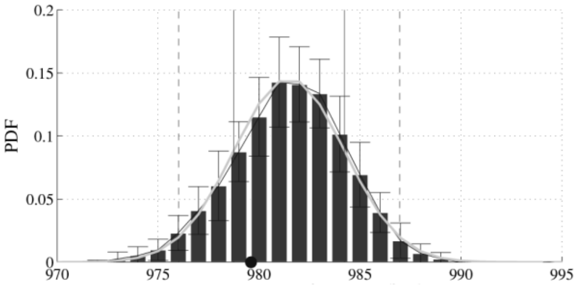
In this study, the global TC data of IBTrACS (NOAA) was used as source for calibration of coefficients of GSTM. Ideally, in order to perform strict verification, first we have to separate observation data of TC to two groups. That is, one data is for model calibration and another is for model verification. But in this study, all observation data was used both for model calibration and verification, because observation data was not so many at local area.

First, observation data of IBTrACS and GSTM results were classified by whether TC was passing through a given area in order to demonstrate the effect of implementation of above mentioned bimodal joint PDF. As examples, the results of reproducibility verification of central pressure are shown in this paper. **Fig. 3** is a comparison of the accuracy of GSTMs into which the different joint PDF model was implemented by the histogram of minimum value of central pressure while TC was passing through given areas. Here, bars mean observation data; red and blue lines show results of GSTM which was implemented unimodal and bimodal joint PDF model for central pressure, respectively. The period of observation data was 49 years from 1960 to 2008. On the other hand, the simulations result was ensemble mean of 50 groups of 50 years data, therefore the period of total simulation data was 2500 year. In these figures, the width of standard deviation of each plot was also shown. As can be seen in **Fig. 3**, bimodal model results are in good agreement with observation data compared to that of unimodal model. The peak value of observation data was around 985 to 1000 hPa; over 985 hPa data occupied about 60% at Area 1. Compared to that of observation data, the peak of unimodal joint PDF model result slightly moved toward lower value at Area 1. On the other hand, the distribution profile of histogram of bimodal joint PDF model agreed with observation data at Area 1. This good performance of bimodal joint PDF model was also presented in the comparison at Area 2 including Japan Islands. The distribution profile of histogram of observation data varied with increase in latitude; the ratio of central pressure of middle class from 940 to 970 hPa became large. This transition process was able to be reproduced to some extent by the bimodal joint PDF model. Although the detail was not explained here, this bimodal joint PDF model was effective against central pressure and translation direction, but it was not effective against translation speed.

Next, we verified the accuracy of GSTM in the narrower region of local bay scale. Target was 2 degree square region located in west Kyushu Island (129-131°E, 31-33°N). At this region, observation data was too few for comparison with the results of GSTM. Therefore, the accuracy check was performed by using the mean value of all TC data passed through target region. The mean observation data was average of 49 year; the mean GSTM results were averages of 50 years. Here, the mean GSTM was calculated 50 times from simulation of 2500 year. In **Fig. 4**, a circle mark on X-axis means mean value of observation data and histogram shows the PDF of mean value of GSTM results for 50 year which was estimated from 50 sets samples. And error bars mean the width of standard deviations of each bin. This standard deviation of each bin was calculated from iteration data of 50 times. The vertical solid lines and dashed lines are intervals of $\mu \pm \sigma$ and $\mu \pm 2\sigma$, respectively. Here, μ and σ are mean and standard deviation of mean value of GSTM results for 50 year. First, although **Fig. 4** (a) shows the TC frequency for 100 years of observation data was slightly larger than that of peak value of histogram of GSTM results, the difference was small (it was about 5/100year). In addition, the observation data was located in interval between $\mu \pm\sigma$. Therefore, the accuracy of mean TC frequency was proved even of local bay scale. Then, the fact that the average central pressure of observation data was smaller than that of peak value of histogram of GSTM results is shown in **Fig. 4**(b). Here, average central pressure is mean value while TC was passing through a target area. Although there was a difference between them, it was small (it was about 2-3 hPa) and observation data was located in interval between $\mu \pm\sigma$. Therefore, the accuracy of average central pressure of local bay scale was also guaranteed. Given these facts, it was proved that accuracies of GSTM are not so bad to apply to assessment of storm surge risk of long term period at local bay scale.



(a) TC frequency during 100 year (#/100year)



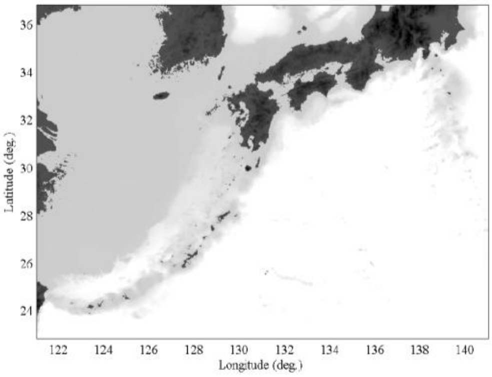
(b) Mean central pressure while TC was passing through target area (hPa)

Fig. 4 Comparison of TC parameters of GSTM results (histogram) and observation data (mean value; circle plot) Targets are TCs that were close to the west Kyushu Island (129-131°E, 31-33°N)

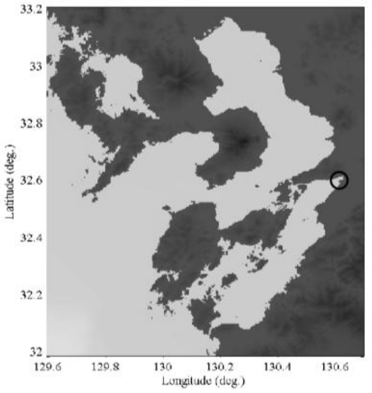
STORM SURGE MODEL

SuWAT and Tropical Cyclone Model

In this study, we used the numerical model of Surge, Wave and Tide (SuWAT) developed by Kim et al. (2008) for calculation of storm surge. The SuWAT model is based on depth integrated nonlinear shallow water equations and Simulating Waves Nearshore model (SWAN). Actually, tidal variation and wave setup are important factors for the calculation of the storm surge. However these effects were omitted in the simulations for simplicity, although SuWAT is able to calculate the storm surge including the effects of tide and wave. We used the drag coefficient C_D calculated from the relation of Mitsuyasu and Honda (1982), and manning coefficient n=0.025 in this study.



(a) First domain (Δ=2430m)



(b) Third domain (Δ=270m)

Fig. 5 Computational domains and resolutions
Circle; Yatsushiro bay

The data of atmospheric pressure and wind speed is necessary for the storm surge calculation in SuWAT. We calculated them by Fujita model (1952). In order to consider the friction of sea and land surfaces, the direction of gradient wind V_{gr} was changed with 30 degree, and its speed was reduced by a factor of 0.7. The wind speed was calculated by the sum of the modified gradient wind and the induced wind by translation speed.

Experimental Conditions

Computational domains for storm surge simulation are shown in **Fig. 5**. Color density shows the ground elevation in these figures. We prepared three domains with different spatial resolution 2430m, 810m, and 270m for nesting simulation. The first domain was the largest one, and its edge was far away 800 km from attention region, Yatsushiro bay. In this study, the attention region for storm surge risk assessment was the Yatsushiro bay which is shown as a circle in **Fig. 5** (b). Many small islands and indented coastline are located around Yatsushiro bay. Therefore, the simulation with fine grid was necessary in order to perform accurate storm surge risk assessment. Incidentally, the difference of water height at peak time of storm surge of TC Sanba (2012) between observation data and the result of hindcasting was about 0.05 m at Yatsushiro bay. In this paper, the detail result of accuracy testing of SuWAT is omitted.

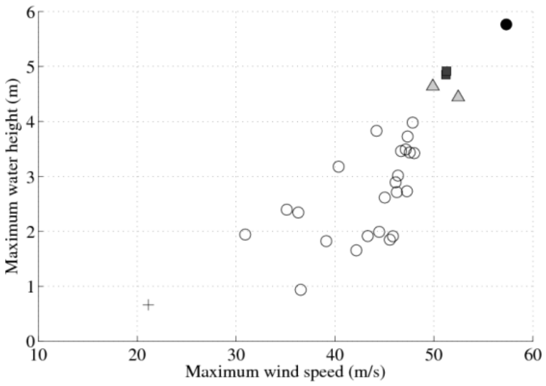


Fig. 6 The relation between maximum water heights and maximum wind speed at Yatsushiro bay caused by representative synthetic TCs

PROBABILITY ASSESSMENT OF THE WORST CASE STORM SURGE AT YATSUSHIRO BAY

Finally, the result of probability assessment of storm surge of the worst-case scenario is shown in this section. In this paper, we decided an attention region, Yatsushiro bay, for practical assessment, but the necessary approach would not change if the attention region is different.

Actually, we could use GSTM results directly as input data for SuWAT simulation. However, simulation data was too many. Therefore we need selection of candidate of TC data which have potential to wreak devastating disaster for first step. But we didn’t know which TC should be the candidate. Therefore, for convenience, modified observation TC data was used for input of SuWAT, alternatively. In this paper, modified observation data based on some assumptions described in following paragraphs will be called ‘synthetic TC data’. Then, the worst-case scenario TC data was chosen from result of SuWAT, and the occurrence probability of this TC was calculated from GSTM results separately.

For estimation of storm surge of the worst-case scenario, some assumptions were necessary in this study. First, the variation of water height caused by storm surge is very sensitive to TC track. Therefore, the variation of TC track had to be considered preferentially. In this study, we used observation data for candidate of TC track. The number of observation data was not strictly enough to consider all candidates. But this simple approach is necessary for first step, and the qualitative trend would not change.

Second, in order to keep the equality of all synthetic TC data, TC intensity was changed as the function of latitude. This function was estimated from curve fitting of observation data TC Sanba approached near west Kyushu Island in 2012. This central pressure change would be realistic TC scenario, because similar or slightly more intense TC had approached near west Kyushu Island 4 times during past about 50 years (Ruth, 1951, Jean, 1965, Wilda, 1970, Mireille, 1991).

Third, the assumption of the radius of maximum cyclostrophic wind speed was necessary for storm surge simulation. In this study, we used constant radius value, 80 km, which was estimated from TC model calibration when TC Sanba was close to west Kyushu Island.

The occurrence probability of the worst-case scenario was estimated by calculation of conditional probability. The GSTM results which meet the following conditions were decided as the TC of the worst-case scenario.

1. Minimum central pressure during entire lifetime of TC was not greater than 915 hPa (This is equal to minimum central pressure of TC Sanba).
2. The central pressure while TC was close to Yatsushiro bay was not greater than 950 hPa.
3. TC track was close to the worst-case scenario estimated from SuWAT simulation.

Fig. 6 shows the relation between maximum water height of storm surge and maximum wind speed at Yatsushiro bay which was calculated from SuWAT. The cross mark in this figure means the result which was based on data of original TC Sanba, and this maximum water height was equal to observation data. Generally, maximum water height had positive correlation to maximum wind speed. But in the case of moderate wind speed, the variation of maximum water height was large, because storm surge is sensitive to TC track. In this study, the maximum water height of the worst-case scenario was about 5.8 m. In the subsequent quasi-worst-case scenario, the water height was about 5.0 m.

The all tracks of these devastating TCs passed through the north side of Yatsushiro bay toward northwest. In addition, important information is the distance between Yatsushiro bay and the nearest point of each TC track. If it was too long or too short, the maximum water height was not so high. The distance of the worst-case scenario was about half of the radius of maximum cyclostrophic wind speed. Although actual TC track of worst-case scenario would depend on ground topography, general trend will not so different with this study by simple TC model.

Finally, the occurrence probability of this worst-case scenario was estimated from GSTM results. From 25,000 year simulation, the number of TC which met the conditions above mentioned was only 10. Therefore, the rough estimation of occurrence probability was estimated about 2,500 year. Of course, this estimation of probability was based on the assumption that the probability of more intense TC is ignorable, because it is too small. As for the next step, the relationship among the maximum water height, TC track variation and occurrence probability is interesting research target.

CONCLUSIONS

Global Stochastic Tropical cyclone Model which is based on temporal correlation on TC parameters was improved by implementation of the cluster analysis, and its accuracy verification was performed. The performance of bimodal joint PDF model of TC central pressure and translation direction was better than that of unimodal joint PDF model. The longitudinal transition of histogram of TC parameters of improved GSTM results agreed with that of observation data. Then, the results of accuracy verification in the narrower region of local bay scale showed the potential of GSTM for application of storm surge risk assessment at local bay scale.

The storm surge simulation of synthetic TCs by using SuWAT provided the water height variation of candidate of worst-case scenario. Then, it was shown that the tracks of devastating TCs passed through the north side of attention point toward northwest. The highest value of maximum water height of attention point was recorded when the distance was about half of the radius of maximum cyclostrophic wind speed. Finally, the occurrence probability of the worst-case scenario at Yatsushiro bay was estimated about 2,500 year.

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