

# APPLICABILITY OF d4PDF DATASET TO GLOBAL STOCHASTIC TROPICAL CYCLONE MODEL

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*Disaster damage caused by tropical cyclone has grown every year. However, our experience of tropical cyclone is not enough to evaluate very low frequent and catastrophic disaster event. Stochastic tropical cyclone model has been used for assessment of tropical cyclone disaster. Global stochastic model was improved by using a lot of ensemble Global Climate Model simulation data (d4PDF) instead of limited number of observation data. The model bias included d4PDF was corrected by each regional grid by simple statistical method and interpolation. The accuracy of new model was verified at representative regional area in different basins. Generally, the improvement is remarkable where tropical cyclones rarely passed. The variation of joint PDF of tropical cyclone change rate between previous model and present model agree with model improvement. As an example of application, the frequencies of strong tropical cyclone events of two cases were estimated.*

*Keywords: tropical cyclone; return period; stochastic model*

## INTRODUCTION

### Difficulties on the Assessment for Low Frequent and Large Disaster Event

Tropical cyclones come to Japan every year. And severe damages were brought our society and economics. In 2018, the typhoon Jebi attacked the Kansai area, and significant damage occurred by storm surge and high wave for the first time in about 60 years (Mori et al., 2019). Then in 2019, the typhoon Hagibis attacked the Kanto area, and longtime heavy rain brought severe flood in wide region. After these historical disaster experiences many infrastructure and systems were built. The number of fatalities were rapidly decrease, but damages of economics is still serious.

Assessment of catastrophic tropical cyclone disaster is very difficult. First, the number of observation data of tropical cyclone landing on certain area is not enough to discuss about catastrophic risk. Generally, we only can use the last 60 to 70 years data of tropical cyclones because the limitation of global monitoring system like as weather satellite. Second, the damage caused by tropical cyclone is very sensitive to its track. Even if we estimated the intensity of tropical cyclone by using extreme value analysis, the uncertainty of their tracks makes difficult to assess the risk of coastal disaster. For this reason, until today, many stochastic tropical cyclone models using Monte Carlo method are developed to make artificial tropical cyclone data from observation data. Then these data have supported the risk assessment of catastrophic hazard.

First type of stochastic model was born in the middle of 19 centuries (Russell, 1968, Vickey and Twisdale, 1995). After that, a lot of variations were developed. I classified them under three types. These are local model (Russell, 1968), basin-wide full-track model (Vickery et al., 2000, James and Mason, 2005) and global full-track model (Emanuel et al., 2008, Lee et al., 2016). Of course, they use different approaches for modeling of tropical cyclone development. But here we focused on the difference on the modeling area. Especially, global models are very few because most models are based on auto-regression analysis, and they need arbitrary classification of tropical cyclone track. We developed global stochastic model need no advance classification in 2014 (Nakajo et al., 2014). The reproducibility is not bad, and we got reasonable result. However, the limitation of original observation data affected the model accuracy, especially in minor region of tropical cyclone disaster. This weak point is common and unavoidable for stochastic tropical cyclone model.

### Potential of Large Ensemble Simulation Data of GCM

By the way, we can use simulation results of Global Climate Model, called GCM. For example, the d4PDF is one of available data including numerous ensemble simulation results (Mizuta et al., 2017). For making this dataset, one model developed by the Meteorological Research Institute Japan was used. The project of the d4PDF was conducted the assessment of climate change effect, but here we only focused on the historical simulation results. In the d4PDF simulation, the long-term trend of sea surface temperature is not included. And one-hundred perturbations of initial and boundary conditions were considered for ensemble simulations. Numerous simulations make numerous tropical cyclones. From one-hundred times of past 60-year simulations, we got 515,206 tropical cyclones. Observation data is

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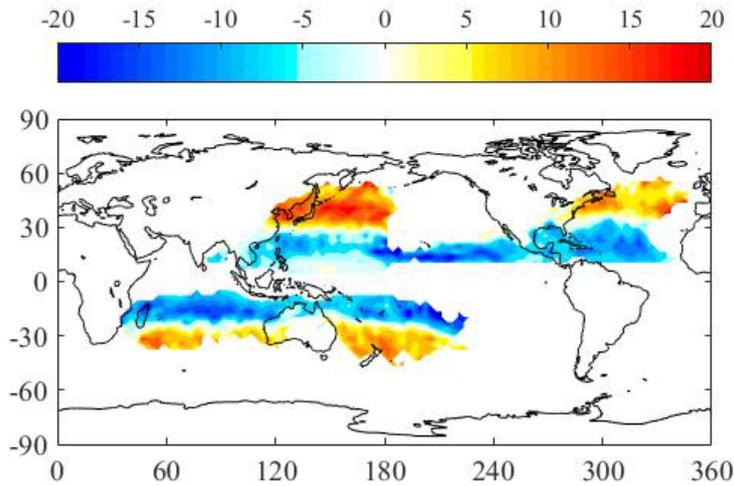


Figure 1. Differences of central pressure (hPa) between observation and the d4PDF.

about 12,000 tropical cyclones. Therefore, the d4PDF tropical cyclone data have about 43 times larger than that of observation. So, this data has a potential of breakthrough of low frequent large disaster assessment.

However, every GCM also has weak point, model bias, of course the d4PDF is no exception. For example, Figure 1 shows difference of mean value of central pressure at each region. The d4PDF tropical cyclones are stronger than actual tropical cyclone at middle and high latitude region although they are weaker than actual at low latitude region. The magnitude is not negligible. The translation direction of tropical cyclone also has a model bias, but the amount is not so large. Besides, the frequency of tropical cyclone of the d4PDF is lower than actual at middle and high latitude region. As shown in Figure 2, the frequency of annual cyclogenesis number is accord with observation data. In this figure, the error bar means the deviation of ensemble data. Figure 3 shows the frequency of tropical cyclone passing at each latitude zone. At low latitude region, the number of tropical cyclones is slightly fewer than actual, however, especially middle and high latitude region in northern hemisphere, the number is clearly less than observation data. The disagreement of the frequency of tropical cyclone directly affects to risk assessment.

### Viewpoint and Purpose

The d4PDF data has many ensemble data of tropical cyclone development process although it has also model bias. Then the stochastic model is useful tool for assessment of frequency of tropical cyclone disaster. However, its reproducibility depends on the number of original observation data. From these backgrounds, we tried to develop new global stochastic tropical cyclone model using a bias corrected d4PDF data. The originality of this research is using the GCM simulation result for stochastic tropical cyclone model calibration.

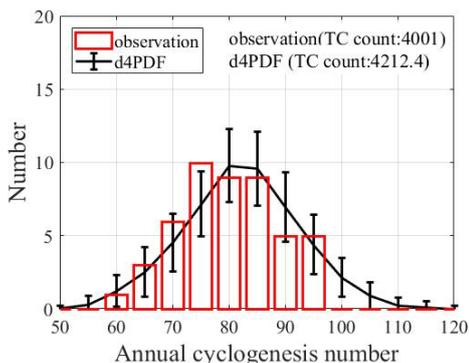


Figure 2. Global cyclogenesis number, #/year. Error bar means standard deviation of 100 ensembles.

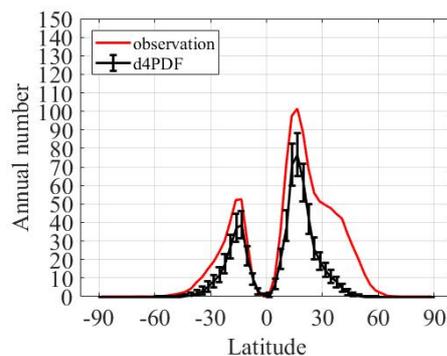


Figure 3. Frequency of tropical cyclone, #/year. Error bar means standard deviation of 100 ensembles.

**GLOBAL STOCHASTIC TROPICAL CYCLONE MODEL**

**Overview of GSTM**

The model components and simulation flow of Global Stochastic Tropical Cyclone Model (GSTM) has in common with previous our model (Nakajo et al., 2014). In this study we used a bias corrected d4PDF data instead of observation data (IBTrACS, Knapp et al., 2010). The tropical cyclone track data was extracted from the original d4PDF simulation result based on some conditions concerning pressure drop, vorticity and so on. We calculated translation speed and direction from these track data. In our model, three properties of tropical cyclone at each site are modeled, central pressure, translation speed and translation direction. The GSTCM can be divided into three major parts: cyclogenesis part, development part, and cyclolysis part. In our model, all given model parameters were calculated in advance using a 3 by 3-degree grid and the actual Monte Carlo simulation was conducted with a 1-degree grid where interpolated statistical values were used. The Probability Distribution Function of the annual global number of cyclogenesis events can be approximated by a lognormal distribution. The locations of cyclogenesis areas are determined statistically based on global cyclogenesis frequency distribution of d4PDF. The initial TC parameter values are determined statistically based on the PDF of each parameter as estimated from d4PDF data.

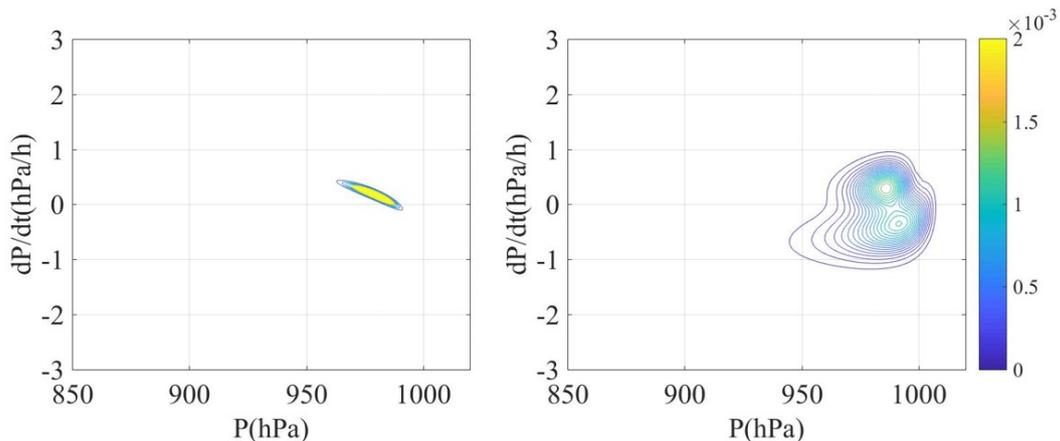
The subsequent development process in the GSTM provides the rates of change of TC parameters as functions of their values at the previous time step. This relation is modeled by joint PDF composed by normal distributions estimated from the Principal Component Analysis and the cluster analysis by each 3 by 3-degree grid. When the previous time step value is given, the PDF of the change rate is calculated from joint PDF, and next time step value is determined statistically by using Monte Carlo simulation. The dissipation of tropical cyclone is one of the important factors of GSTM. However, the frequency of d4PDF is not corrected. Therefore, in this model, we used observation data (IBTrACS) instead of d4PDF for the calculation of dissipation rate at each region. The main part of GSTM is estimation of joint PDF concerns the probability of tropical cyclone development. Joint PDF was created from composition of normal distribution function along two principal component axes. By using the PCA and the cluster analysis, we attempted to express the probability of unexperienced event and to mitigate a restriction caused by deterministic factor.

**Bias Correction process**

We corrected model bias of d4PDF by using very simple method. We assumed tropical cyclone properties at local region follows the normal distribution. The mean value and standard deviation of d4PDF were modified by the following equation.

$$\phi'_{d4PDF} = \frac{\sigma_{obs}}{\sigma_{d4PDF}} \left( \phi_{d4PDF} - \overline{\phi_{d4PDF}} \right) + \overline{\phi_{obs}} \quad (1)$$

Here, the overbar means average value and the sigma means standard deviation. The shortage of observation data causes degrading of statistical value, and it would bring inadequate bias correction. Therefore, in this study, we used surrounding statistical value for calculation the bias correction instead of actual mean and standard deviation when the original observation data are few. As prior examination,



**Figure 4. Comparison of Joint PDF of central pressure of tropical cyclone at representative point in the South Pacific Ocean (S33-36 deg., E159-162 deg.). Left; previous GSTM, Nakajo et al., 2014. Right; new GSTM)**

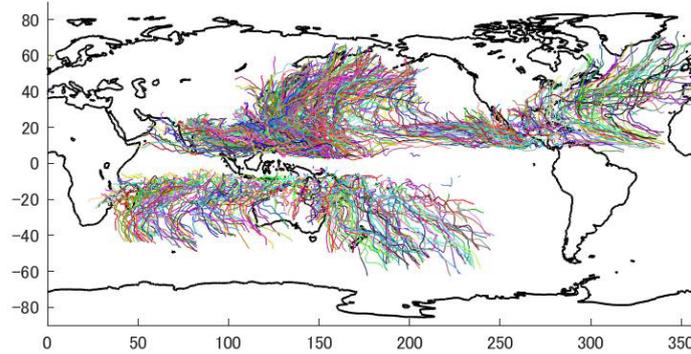


Figure 5. Tropical cyclone tracks calculated from 10-year simulation of new GSTM.

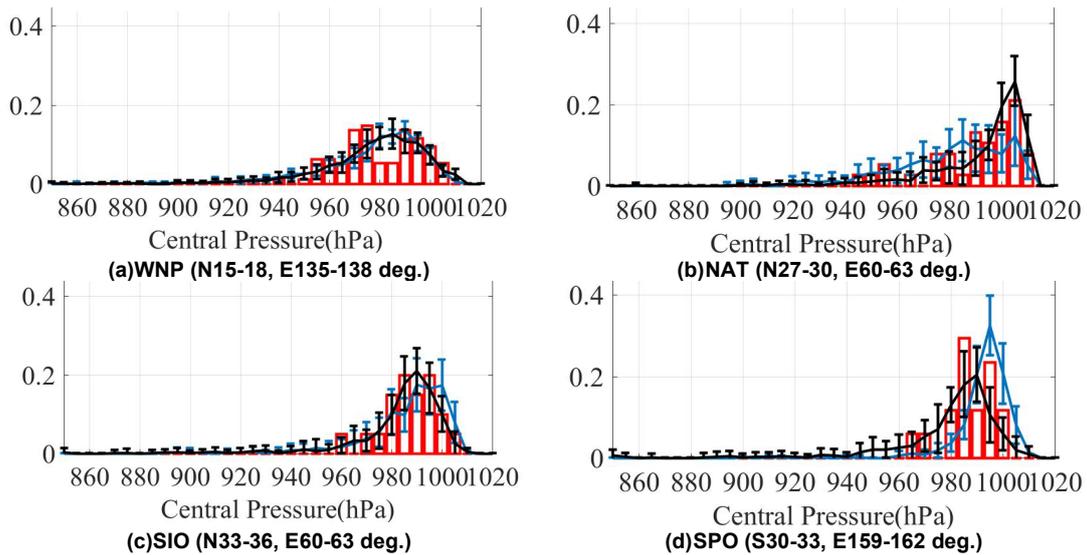


Figure 6. Probability distribution of central pressure at representative region. Red bar; observation, Blue line; previous GSTM, Nakajo et al., 2014. Black line; new GSTM

we confirmed the statistical values continuously vary in spatial.

#### Modified Joint PDF of Tropical Cyclone Development

Figure 4 shows an example of using d4PDF data in joint PDF. They show the statistical characteristics of intensification of tropical cyclone at certain region in the South Pacific Ocean (S33-36 degree., E159-162 degree). In both models, the peak of joint PDF is located positive area of change rate, and the location almost same. Therefore, we can find the major development trend of this region is decaying process in both models. This trend is reasonable because the latitude of this area is over 30 degree. The difference between two models is the extent of spread of joint PDF. This alteration would be caused by numerous sample data of the d4PDF. Besides, in new model, we also find the second peak in negative area of change rate. This means the possibility of tropical cyclone intensification. The difference of joint PDF between two models is quite significant in the low frequent area of tropical cyclone.

#### IMPROVED MODEL ACCURACY

The change of joint PDF is reflected to improvement of model accuracy. Figure 5 is tropical cyclone tracks calculated from new GSTM. Here only 10-years simulation results are shown. The synoptic track patterns of each basins are accord to that of observation. The accuracy of the frequency of tropical cyclone at each region is also good in new GSTM. For example, the distribution pattern of annual number of tropical cyclones passing each region is very similar pattern to that of observation. This is one of evidence of applicability of this model to risk assessment.

Figure 6 shows probability distributions of central pressure at representative regions. Blue lines are previous model results and black lines are new model. Red bars show observation data. We conducted 50-year simulation 20 times (therefore, total is one-thousand-year simulation) by each model. The error

bar shows deviation of 20 ensembles. In the South Pacific Ocean (d), the underestimation of intense tropical cyclone is improved by new model. This result agrees with alteration trend of modification of joint PDF shown in Figure 4. In the Western North Pacific (a), the difference between previous model and new model is not so large, and the model keeps good performance. In other basins, the improvement is significant, especially where the observation data are a few.

## EXAMPLE OF APPLICATION OF GSTM

### Frequency of Extreme Tropical Cyclone Event at Osaka, Japan

As an example of application of new GSTM, here we studied extreme tropical cyclone event around Osaka, Japan. The reference value of central pressure of this model tropical cyclone was set as 930 hPa. This value is equivalent to those of standard typhoons of disaster prevention planning in Japan, Vera (1959) and Nancy (1961). We conducted ten-thousand-year simulation and selected tropical cyclone track data passing through around Osaka from new GSTM result. Figure 7 shows tracks of candidate of these tropical cyclones.

From these data, we made the chart of empirical cumulative distribution function of central pressure when they approach to Osaka (Figure 8). From this figure, we can estimate the probability of strong tropical cyclone  $P$  by using following equation.

$$P(p < p_{ref}) = \frac{1}{CDF(p_{ref})} \quad (2)$$

Here,  $p$  is a central pressure and  $p_{ref}$  is a reference value.

The CDF of 930 hPa was estimated as 0.0235 from Figure 8, therefore, the probability of tropical cyclone stronger than 930 hPa is about 1/43. The return period of this event is almost 40 years, because the frequency of tropical cyclone around Osaka is about 1 per year. The damage of tropical cyclone disaster is also sensitive to its track, but here we did not consider the contribution of it.

### Frequency of Extreme Tropical Cyclone Event at the northeast coast of Australia

Another example of extreme tropical cyclone event we estimated is Mahina attacked the northeast Queensland coast in Australia in 1899. This is a famous tropical cyclone, and its central pressure is estimated the lowest record in Southern Hemisphere. However, the record is old, and the tropical cyclone brought severe damages, therefore estimated central pressure depends on the literature. For example, Whittingham (1958) estimated it was 914 hPa at landing from pressure gage record. However, Nott et al. (2014) concluded it might be 880 hPa based on the result of storm surge simulations.

Figure 9 shows empirical CDF of central pressure around landing area of Mahina. The probability of strong tropical cyclone (<880 hPa) could be estimated from this chart, and it is 1/1113. Then the frequency of tropical cyclone at target area is estimated about 0.33 per year. Therefore, if the central pressure estimated by Nott et al. (2014) was correct, the return period estimated from our statistical model is amazing about 3400 years. Even if the value was 914 hPa, the return period is estimated about

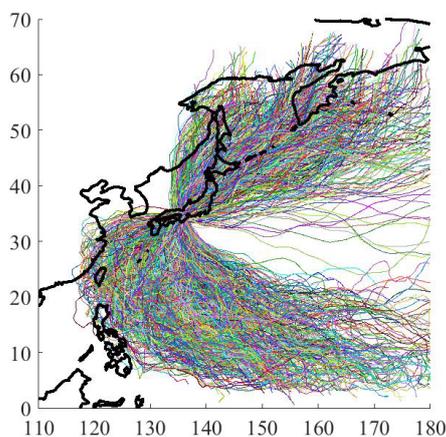


Figure 7. Tropical cyclone tracks approach to Osaka in 10,000 years.

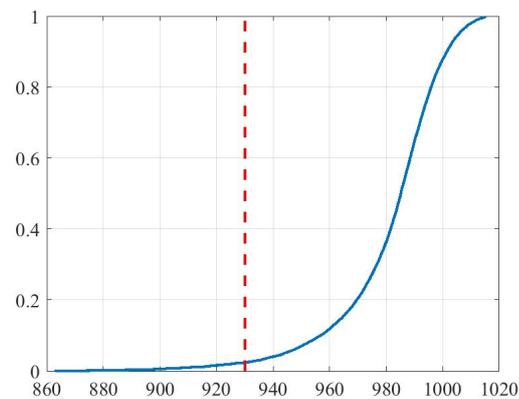
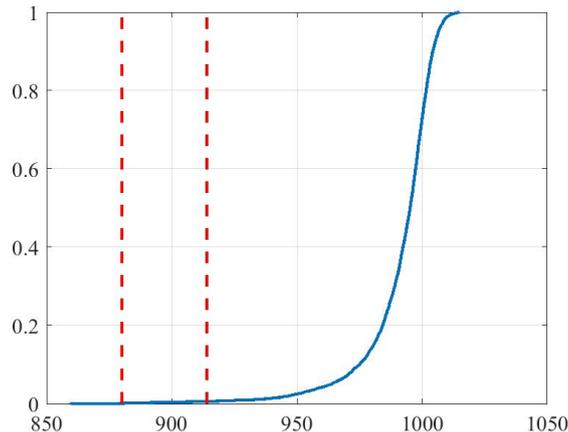


Figure 8. Empirical cumulative distribution function of central pressure around Osaka. Red line is standard tropical cyclone value of disaster prevention planning.



**Figure 9. Empirical cumulative distribution function of central pressure around landing point of Mahina (1899). Red lines are estimated central pressure 914 hPa (Whittingham, 1958) and 880 hPa (Nott et al., 2014).**

780 years. Therefore, it was quite long-term return period event.

## CONCLUSIONS

Improvement of GSTM by using large number ensemble GCM simulation results (d4PDF) was conducted and validated from comparison to observation data and previous model results. Model bias of d4PDF of central pressure, direction and frequency of tropical cyclone are non-negligible. Therefore, we modified them at each regional area in GSTM model calibration process.

The plenty of tropical cyclone samples improved model accuracy, especially at some basins, the South Pacific Ocean, the North Atlantic Ocean and the Indian Ocean, where observation data is limited. As an example of application, the frequencies of strong tropical cyclone events of two cases were estimated.

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