



Maximum Potential Intensity of Typhoon as Information for Possible Natural Disaster

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The maximum potential intensities (MPIs, maximum wind speed in this study) of typhoons in western North Pacific for present-day and future climate were calculated. The present-day MPIs were calculated using JRA-25 and NCEP2 reanalysis data, and appeared to increase around the 1990s. The MPI using JRA-25 data was marginally higher than that using NCEP2 data. Six future MPIs were calculated using a numerical model with six different sea surface temperatures (SSTs) of CMIP3 models. The results were highly dependent on the SST, and the future climate experiment with the highest average MPI did not always show the highest MPI around Japan. We publicly opened our MPI maps on the internet via a database we developed, the typhoon disaster database. The number of people who access the database increased when a typhoon was approaching Japan, particularly when approaching densely populated regions. Increasing access to the database will lead to enhance people to access MPI maps. The information of MPI can raise disaster awareness and be useful in local disaster prevention practices.

Keywords: Typhoon disaster, Global warming, Maximum potential intensity, Numerical simulation, Disaster awareness.

1. Introduction

Worldwide, losses due to natural disasters have increased in recent years (Munch Re, 2006). The highest total event numbers, economic losses and insurance losses have been caused by typhoons, although earthquake and accompanying Tsunami events cause sometimes greater damage than typhoon events. A primary reason for the increase in typhoon disasters is the expanding human population in coastal regions, emphasized in reports by the United Nations Environment Programme (UNEP) and the Science Council of Japan (SCJ). The UNEP (2007) stated that the world population in coastal regions has recently increased and is predicted to reach six billion by 2025. Twenty six of the world's 33 megacities (those with a population of more than 10 million) are located in developing countries, and 21 of those

cities are in coastal areas. The average population density in coastal areas is now twice the global average population density. More than 100 million people live in areas that are no more than 1m above the sea level. The SCJ (2008) stated that the land–ocean margin (i.e., coastal regions) is the main area for human activity (i.e., production and consumption) and the primary source for food, minerals, water, and energy. The land–ocean margin is also where environmental problems and natural disasters often occur.

Additional important reason for the increase in typhoon disasters may be climate change such as global warming (IPCC, 2007a). Recently IPCC released the Summary for Policymakers of the Working Group 1 contribution to the IPCC Fifth Assessment Report (AR5) (IPCC, 2013). It stated that increases in intense tropical cyclone activity is low confidence in long term (centennial) change, but, those in tropical cyclone activity in the North Atlantic since the 1970 is virtually certain.

Variation in typhoons caused by climate change can especially influence coastal disasters such as storm surges, the most important factors being the strength, number, and path of typhoons. The strength of a typhoon (defined as the minimum central pressure or the maximum wind speed) is affected mainly by the sea surface temperature (SST), although additional factors such as heat storage in the oceanic mixing layer, moisture profiles in the atmosphere, and move speed of the typhoon are also important. It is generally thought that global warming will increase the strength and decrease the number of typhoons generated globally (e.g., McDonald *et al.*, 2005; Oouchi *et al.*, 2006). The path of typhoons under future global warming is difficult to project; however, the present-day precision of typhoon path prediction over the preceding few days has improved.

Global warming can intensify typhoon disasters because although the total number of typhoons decreases, the strength of individual typhoons increases. For example, projections indicate that global warming will increase monthly precipitation between June and October, when typhoons often hit Japan, but will not alter current precipitation between November and May, when typhoons rarely hit Japan (JMA, 2005). However, these results depend on numerical models and therefore are not definite projections. That is, most of the models show only the tendencies for the total number of typhoons to decrease, but there exist some models not showing this tendency. For example, a study shows decreasing extreme weather events, i.e., a reduction in Atlantic hurricanes under warming conditions in the late 21st century (Kuntson *et al.*, 2008).

However, from a disaster prevention viewpoint, it is important to prepare for the maximum potential increase in extreme weather events predicted by scientific research. This is also a lesson to be learned from the Great East Japan Earthquake disaster of March 11, 2011. Therefore, we have produced maps of Maximum Potential Intensities (MPIs) of typhoons under present-day and projected future climate conditions in order to provide the public with information on the potential for natural disasters. In section 2, the method used to calculate MPI for present-day

and projected future climate is explained. In section 3, characteristics of the MPI in western North Pacific are described. In section 4, the use of MPI for informing the public about potential natural disasters is discussed.

2. Calculation of MPI for Present-Day and Future Climates

The MPI of tropical cyclones, including typhoons, is the upper (lower) bound of maximum wind speed (minimum central pressure) determined theoretically. The theoretical models to estimate the MPI in a thermodynamic environment were developed by Emanuel (1987) and Holland (1997).

Tsutsui (2010) investigated the changes in the MPI in tropical cyclones due to global warming in a region near Japan using the Holland's model (Holland, 1997). He used the Japanese 25-year Reanalysis data (JRA-25) (Onogi *et al.*, 2007) for present-day climate and the JRA-25 climatology with anomalies from Coupled Model Inter-comparison Project Phase 3 (CMIP3) (Meehl *et al.*, 2007) models for the future climate, and investigated the results from an ensemble average over multi-model data of CMIP3. Our study, on the other hand, employs Emanuel's model (Emanuel, 1987) and the results from an atmospheric general circulation model (AGCM) using SST anomalies from CMIP3 models as a part of the boundary conditions. Fudeyasu and Miyamoto (2013) noted that Holland's model does not include the effect of a dynamic process to be changed by the potential temperature and sea surface pressure under the tropical cyclone intensity. On the other hand, Emanuel's model well represents the upper bound of the tropical cyclone intensity, yet it may contain some important deficit (Bryan and Rotunno, 2009). We employed Emanuel's MPI in this study, although both methods have advantages and disadvantages.

Here we explain Emanuel's theory of MPI (Emanuel, 1987, 1995) and the calculation method of MPI for present-day and projected future climates, describing the data and numerical experiments required. According to Emanuel's method, the maximum potential wind speed of a typhoon can be derived from its thermodynamic efficiency as a Carnot cycle (e), the rate of input of heat energy into the typhoon (Q), and the rate of mechanical dissipation within the typhoon (D). It is explained as follows ($D = eQ$):

$$V_c^2 = C_k / C_d \times e \times (k_o - k_a), \quad (1)$$

where V_c is the maximum potential wind speed, C_k is the enthalpy transfer coefficient, C_d is the momentum transfer coefficient, e is the thermodynamic efficiency, k_o is the enthalpy of the sea surface, and k_a is the enthalpy of the atmosphere near the sea surface. The conversion from wind speed to pressure is done assuming cyclostrophic wind as follows:

$$P_c = P_{env} \times \exp(-V_c^2/RT_o), \quad (2)$$

where T_o is the SST, P_c is the minimum potential central pressure, P_{env} is the pressure in the surroundings, and R is the gas constant for air. We used maximum wind speed as the MPI in this study. The MPI of typhoons in both present-day and future climates (subject to global warming) can be estimated using this thermodynamic theory. To calculate MPI (the right-hand side of Eq. 1), the SST and the vertical temperature and moisture profiles in the atmosphere in present-day and future climates are required.

This study calculates the MPI for present-day climate from two reanalysis data (JRA-25 and NCEP2) described below. These reanalysis data are used as a proxy for observations. To investigate the response of MPI to different SST changes under future climate conditions, we conduct a present-day climate experiment and future climate experiments using the same AGCM. The model has its own bias. If the comparison is done between MPI for the future climate calculated from the model results and that for the present-day climate calculated from reanalysis data, the model bias affects the comparison result. Therefore, to reduce the bias effect, we investigate the differences between MPIs in both future climate experiments and present-day climate experiments using the same model.

Methods to calculate MPIs consists of three steps for (a) the MPI in the present-day climate, (b) the MPI in the present-day climate for comparison with the MPI in the future climate, and (c) the MPI in the future climate.

(a) MPI in the present-day climate

To calculate the MPI in the present-day climate, the SST and vertical temperature and moisture profiles in the atmosphere under the present-day climate conditions are required. Optimum Interpolation Sea Surface Temperature V2 (OISST2) data (Reynolds *et al.*, 2002) from NOAA was used as the SST. The JRA-25 reanalysis data (Onogi *et al.*, 2007) by CRIEPI and JMA and the National Centers for Environmental Prediction-Department of Energy Reanalysis 2 (NCEP2) by the NOAA-CIRES Climate Diagnostics Center (Kanamitsu *et al.*, 2002) were used as the vertical profile of temperature and moisture in the atmosphere. These values were averaged for time (monthly from 1986 to 2005) and space (2.5 degrees latitude and longitude). The vertical levels were 70, 100, 150, 200, 250, 300, 400, 500, 600, 700, 850, 925, and 1000 hPa. Moisture values at 70 hPa in JRA-25 data were set to 0 because the data contained values only above 100 hPa.

(b) MPI in the present-day climate for comparison with MPI in the future climate

To calculate the MPI in the present-day climate for comparison with the MPI in the future climate, Extended Reconstructed Sea Surface Temperature V2 (ERSST2) data (Smith and Reynolds, 2004) from NOAA were used as the SST. These values were averaged monthly in terms of time (monthly from 1979 to 1998) and space (approximately 1.1 degrees latitude and longitude). The reason why OISST2 was

not used is because the present-day climate period in the experiment was set to 1979–1998, same as that set for the Atmospheric Model Intercomparison Project (AMIP), an integral part of CMIP3 (Gates, 1992). The period for ERSST2 was from 1854, which included the above period (1979–1998) and that for OISST2 was from 1981, which did not include it. The vertical temperature and moisture profiles in the atmosphere were calculated using Global Spectral Model 8911 (GSM8911) (Sugi *et al.*, 1990) under the above SST boundary conditions and with 348 ppm CO₂. The calculation was conducted for 11 years. The averaged summer and autumn (July–October) data from year 2 to year 11 were used to calculate MPI for the present-day climate projection. GSM8911 is a global spectral model with T106 horizontal resolution (approximately 1.1 degrees) and 21 vertical levels, and uses a modified Arakawa Schubert scheme (Kuma, 1996). The simulated climate with T42 version of GSM8911 is reported by Sugi *et al.* (1995a, b). Generally, the model simulates large-scale feature of the climate reasonably well, though the model tends to underestimate precipitation over western North Pacific in the summer season.

(c) MPI in the future climate

To calculate the MPI in the future climate, ERSST2 with anomalies from six CMIP3 models were used. The six CMIP3 models are listed in Table 1 which includes the institution, the country, the horizontal resolution, the number of vertical levels and the references. These six SSTs were chosen to allow for various temperature rise widths in summer and autumn (July–October) in the western North Pacific (Figure 1 and Table 2). The anomalies are the difference between monthly averaged CMIP3 SSTs from 2080 to 2099 in an SERS A1B scenario (one of the future climate projection experiments that assumes balanced energy generation between fossil

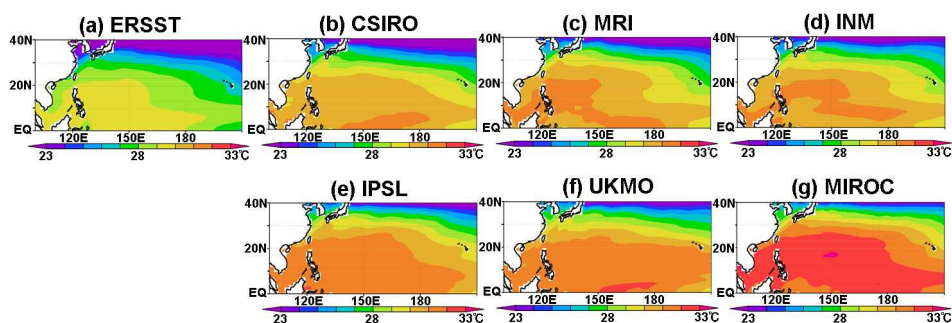


Figure 1 (a) Climatological SST (ERSST2) averaged in summer and autumn (July–October) from 1979 to 1998 and SST for six future experiments: (b) CSIRO-Mk3.0, (c) MRI-CGCM2.3.2, (d) INM-CM3.0, (e) IPSL-CM4, (f) UKMO-HadGEM1, and (g) MIROC3.2 (hires). SST for future climate experiments is calculated by adding climatological ERSST2 to the difference between SST averaged monthly in summer and autumn (July–October) from 2080 to 2099 in A1B scenario (projection experiments of future climate) of IPCC and SST averaged monthly in summer and autumn (July–October) from 1979 to 1998 in 20C3M (replication experiments for present-day climate) for each future experiment. The unit is °C.

Table 1 CMIP3 models of which SST were used in this study. The resolutions of atmospheric models are described by the horizontal resolution and the number of vertical levels. The horizontal resolutions are described by grid spacing (latitude x longitude) for a grid model or truncated wave number for a spectral model. The approximate grid spacing for spectral models of T42, T63 and T106 are 2.8°x2.8°, 1.9°x1.9° and 1.1°x 1.1°, respectively.

Model	Institution, Country	Resolution	Reference
CSIRO-Mk3.0	CSIRO Atmospheric Research, Australia	T63, L18	Gordon <i>et al.</i> (2002)
INM-CM3.0	Institute for Numerical Mathematics, Russia	4°x5°, L21	Diansky and Volodin (2002)
MRI-CGCM2.3.2a	Meteorological Research Institute, Japan	T42, L30	Yukimoto <i>et al.</i> (2001)
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research / Met Office, UK	1.25°x1.875°, L38	Jones <i>et al.</i> (2004)
IPSL-CM4	Institut Pierre Simon Laplace, France	2.5°x3.75°, L19	Marti <i>et al.</i> (2005)
MIROC3.2 (hires)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	T106, L56	Hasumi <i>et al.</i> (2004)

and non-fossil fuel) and the monthly averaged CMIP3 SSTs from 1979 to 1998 in a 20C3M experiment (20th century experiments using historical green-house gas concentrations). Vertical temperature and moisture profiles in the atmosphere were calculated using GSM8911 under the above six SSTs boundary conditions with 659 ppm CO₂. All experiments were conducted for 11 years. The averaged summer

Table 2 Differences in sea surface temperature averages in western North Pacific (10° N–35° N, 120° E–180° E) and NINO3 region (5° S–5° N, 150° W–90° W) between the present-day climate experiment and six future climate experiments in summer and autumn (July–October). The unit is K.

Model	Western North Pacific	NINO3
CSIRO-Mk3.0	1.4	1.9
INM-CM3.0	1.9	2.0
MRI-CGCM2.3.2	1.9	1.8
UKMO-HadGEM1	2.4	2.6
IPSL-CM4	2.7	3.1
MIROC3.2(hires)	3.7	4.2

and autumn (July–October) data from year 2 to year 11 were used to calculate MPI for the future climate projection.

3. MPI characteristics in present-day and future climates of the western North Pacific

In this section, we explain the MPI characteristics in present-day and future climates, focusing on the western North Pacific, which strongly influences typhoon activity in Japan.

Figure 2 shows the MPI (maximum potential wind speed) in the western North Pacific in the present-day climate averaged every five years from 1986 to 2005, using JRA-25 and NCEP2 data. The MPI intensity calculated using JRA-25 data was slightly higher, especially at low latitudes, than that calculated using NCEP2 data. The MPI in the southern region of Japan (20°N – 32.5°N , 122.5°E – 145°E) increased from 1986–1990 to 1996–2000, but was almost the same during 1996–2000 and 2001–2005 time frames (Figure 3). The long term trend, however, is not clear from such short term data. The JRA-25 data is thought to have many advantages compared to other reanalysis data (Onogi *et al.*, 2007). The distribution and amount of predicted 6-h total precipitation is consistent with observations, especially in the tropics. Tropical cyclones are properly analyzed owing to the assimilation of wind profiles around tropical cyclones. As a consequence, the MPI at low latitudes using JRA-25 was the more realistic than when using NCEP2.

Figure 4 shows MPI (maximum potential wind speed) in the western North Pacific calculated from the present-day climate experiment and the six future climate experiments. MPI distribution from the present-day climate experiment was similar to that from JRA-25 data, but the MPI intensity from the present-day experiment was slightly weaker at low latitudes and around Japan than the MPI using JRA-25 data.

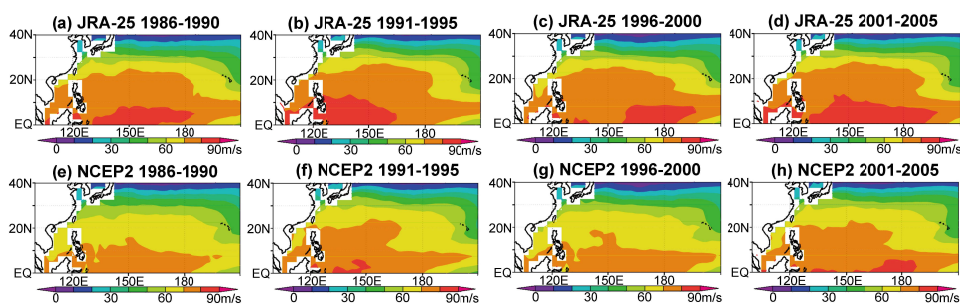


Figure 2 MPI (maximum potential wind-speed) in present-day climate averaged in summer and autumn (July–October) in every 5 years from 1986 to 2005 for (a)–(d) JRA-25 and (e)–(f) NCEP2. The unit is m/s.

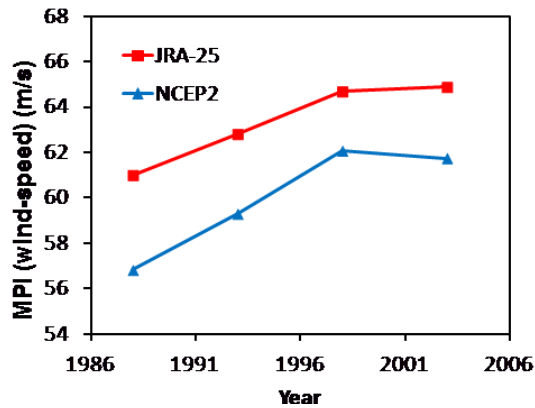


Figure 3 Five-year mean MPI (maximum potential wind-speed) in present-day climate averaged in summer and autumn (July–October) from 1986 to 2005 for southern Japan (20°N – 32.5°N , 122.5°E – 145°E). The unit is m/s.

MPI distribution in the six future climate experiments is mainly dependent on the SST distribution (Figure 1). For the western North Pacific region (10°N – 32.5°N , 122.5°E – 160°E), area averaged MPIs were the highest using the MIROC-hires SST experiment, followed by MRI, UKMO-HadGEM1, IPSL, INM, and CSIRO SST experiments (in descending order). For the south of Japan region (20°N – 32.5°N , 122.5°E – 145°E), where typhoon activity directly affects Japan, MPIs were the highest using the MRI SST experiment, followed by MIROC-hires, UKMO-HadGEM1, IPSL, INM, and CSIRO SST experiments (in descending order) (Table 3). That is, the future climate experiment with the highest MPI averaged over the western North Pacific region did not always produce the highest MPI around southern Japan. We speculate that this result is caused by the dependence of MPI on vertical temperature and moisture profiles in the atmosphere, in addition to SST. This

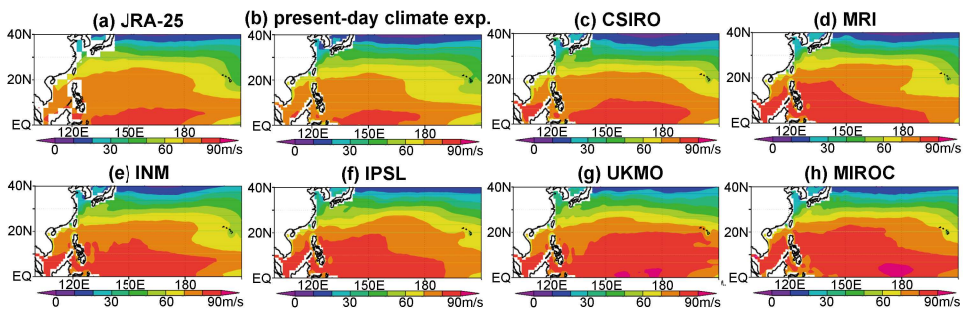


Figure 4 MPI (maximum potential wind-speed) averaged in summer and autumn (July–October) for (a) JRA-25; (b) present-day climate experiment and MPI (wind-speed) averaged in summer and autumn (July–October) for six future climate experiments: (c) CSIRO-Mk3.0, (d) MRI-CGCM2.3.2, (e) INM-CM3.0, (f) IPSL-CM4, (g) UKMO-HadGEM1, and (h) MIROC3.2 (hires). The unit is m/s.

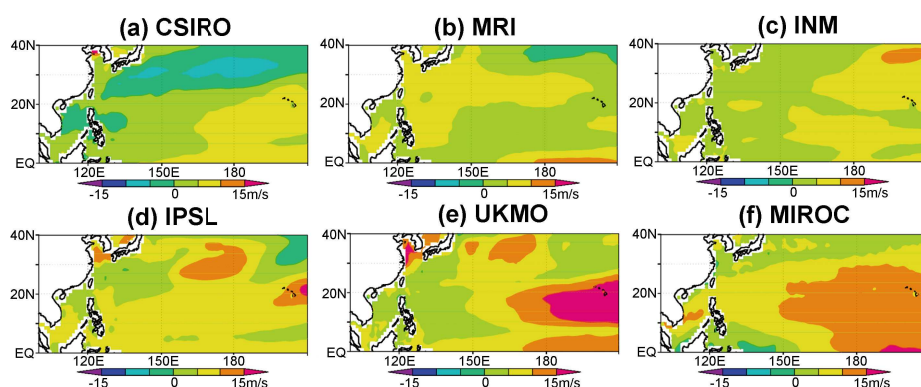


Figure 5 Differences between MPI (maximum potential wind-speed) averaged in summer and autumn (July–October) for the present-day climate experiment (Figure 4 (b)) and MPI (maximum potential wind-speed) averaged in summer and autumn (July–October) for six future climate experiments: (a) CSIRO-Mk3.0, (b) MRI-CGCM2.3.2, (c) INM-CM3.0, (d) IPSL-CM4, (e) UKMO-HadGEM1, and (f) MIROC3.2 (hires). The unit is m/s.

Table 3 Differences in MPI (maximum potential wind-speed) average for each region between the present-day climate experiment and each future climate experiment in summer and autumn (July–October). The unit is m/s. The percentage change from the present-day climate experiment to each future climate experiment is in parenthesis.

	10°–32.5°N, 122.5°–160°E	20°–32.5°N, 122.5°–145°E
CSIRO SST Exp.–Present-day Exp.	-0.01 (-0.01)	-0.76 (-1.34)
INM SST Exp.–Present-day Exp.	3.58 (5.45)	3.09 (5.45)
MRI SST Exp.–Present-day Exp.	5.97 (9.07)	6.53 (11.50)
UKMO-HadGEM1 SST Exp.–Present-day Exp.	5.24 (7.98)	4.55 (8.02)
IPSL SST Exp.–Present-day Exp.	4.77 (7.25)	3.21 (5.66)
MIROC-hires SST Exp.–Present-day Exp.	7.70 (11.70)	5.78 (10.20)
Mean change among 6 experiments	4.54 (6.91)	3.73 (6.58)

was also evident in the MPI differences between MPIs from the six future climate experiments and that from present-day climate experiment (Figure 5).

4. Summary and Discussions

In this study, MPIs were calculated for present-day and future climates. Present-day MPIs calculated using JRA-25 and NCEP2 reanalysis data tended to increase, with the calculated MPIs using JRA-25 data slightly higher than those determined using NCEP2 data. All six future MPIs calculated using CMIP3 SST data also tended to increase, the extent to which was largely dependent on SST. The future climate experiment that generated the highest MPI averaged over the entire region did not always show the highest MPI for southern Japan.

How to let the public know and understand the information related to climate change and its effect such as MPI is a very difficult problem because it does not affect soon their daily life. In fact, even the concept of “probable precipitation,” often used in flood hazard maps, is not always accurately understood by the public (Fukuzono *et al.*, 2006, Shimokawa and Takeuchi, 2007). Proper understanding of such information by the public should be important in the choice of mitigation related to climate change by government (IPCC, 2007b). Therefore, we briefly discussed the use of MPIs as potential natural disaster information available to the public. We publicly opened our MPI maps on the internet via a database we developed, the typhoon disaster database (<http://ccwd05.bosai.go.jp/DTD/>). The number of people who access the database increased when a typhoon was approaching Japan, particularly when approaching densely populated regions. People who access the database do not always refer to the map; however, the number of people accessing the database is indicative of the number of people referring the map. However, it is uncertain whether the MPI concept is accurately understood by the public. Therefore, improving public understanding of MPI is crucial.

In addition, an important thing people want to know is whether the place where they live is under a threat. MPI can only provide information for a broad area because of resolution and accuracy limitations of the data and the numerical models used. In the future, we intend to add local information to MPI maps. The map of coastal disaster risk evaluation we previously developed (<http://engan.bosai.go.jp/engan/index.htm>) may be useful in this regard owing to its high-resolution topographic data and information on coastal disasters including typhoons.

In any case, people want to know whether a danger can approach the people themselves or not and have a tendency to take actively such information when there may be such danger. Therefore, the information of MPI can be provided effectively by integrating MPI map with people’s danger in the near future though the information of MPI itself is not related directly to people’s danger in the near future. Then, as one of such methods, as stated above, we publicly opened our MPI maps on the internet via the typhoon disaster database. Therefore, increasing access to the database will lead to enhance people to access MPI maps. From such a view point, we try to construct a system to search and display past typhoons with a path which is similar to the path of typhoon approaching Japan at present, i.e., information whether the typhoon can approach the place where the people live or not.

Information such as MPI cannot directly decrease disaster risk in high-risk regions. This is similar to risk reduction information about all natural disasters, not solely typhoon disasters but also floods and seismic disasters. However, such information can raise disaster awareness and incite the appropriate preparation. In this regard, it can be useful in local disaster prevention practices.

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