ESTIMATION OF PROBABLE MAXIMUM SIGNIFICANT WAVE HEIGHT IN THE SEA AREAS AROUND JAPAN BASED ON SIMULATIONS OF TYPHOON- AND DEPRESSION (STORM)-GENERATED WAVES

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1. INTRODUCTION

As a design significant wave height of maritime facility, the *R*-year return significant wave height has been usually used in recent years, which is estimated on the basis of extreme value analysis using extreme value data of significant wave height hindcasts or measurements over several decades. But significant waves exceeding such a prescribed return wave height may still occur and then detailed investigations on the validity of the return wave height may then lead to re-setting of the design significant wave height itself. On the contrary, a proper estimation of the probable maximum significant wave height (i.e., the most likely maximum that can ever occur, PMSWH), which may occur in a specified sea area, may provide valuable information for ensuring maritime facilities to the maximum degree and for taking countermeasures against wave-caused disasters.

Regarding the probable maximum values of extreme events in nature, a very rough estimation of the probable maximum wind speed generated by a typhoon is made by Takahashi (1961) using the Bernoulli theorem and also a probable maximum precipitation has been evaluated in various ways in the field of hydrology, for example by Hansen (1987). As for the probable maximum significant wave height (PMSWH) of ocean waves, a rough value in the case of typhoons or hurricanes can be evaluated using the Ijima et al. (1968) relation or the Young (1988) relation respectively and a very rough estimation of the limiting value of a storm-caused PMSWH such as in typhoons and extra-tropical cyclones (depressions) may be obtained using the Pierson-Moskowitz (P-M) spectrum or the SMB method-based relation. But the condition of storms to be assumed in a reasonable estimation of PMSWH is not clear at all.

In recent years, estimation of the PMSWH associated with an assumed depression has been conducted in the Southern North Sea by Holthuijsen et al. (1994) and in the Northern North Sea by Reistad et al. (2005) using a state of-the-art (third generation) wave model such as either WAVEWATCH II or WAM Cycle 4. A problem in these studies may be a probabilistic uncertainty (reasonability) related to a possibility of occurrence of an assumed stormy condition.

This paper presents an estimate of probable maximum significant wave height (PMSWH) generated by typhoons and extra-tropical cyclones (depressions) in the Northwestern Pacific Ocean and in the Japan Sea. Typhoons and depressions are generated over a period of 100,000 years using a Monte-Carlo simulation model, and the wind and wave computations are conducted for each of a large number of selected intense typhoons and depressions.

2. METHOD FOR ESTIMATING PROBABLE MAXIMUM SIGNIFICANT WAVE HEIGHT

2.1 *Constitution of System*

A system for estimating the PMSWH consists of ①a probabilistic generation model of typhoon parameters or depression parameters called a stochastic typhoon or depression model, ②a gradient wind-based wind model, ③a second generation wave model.

As for the stochastic typhoon model, an extended season-separated model by Nonaka et al. (2000) is applied. The model follows a space-time variation of 6 typhoon parameters such as the position of the center and the central pressure every 6 hours in each of the 4 seasons, in cases where the pressure distribution in a typhoon is approximated using an elliptical distribution. As for the stochastic depression model, a model developed by Yamaguchi and Hatada (1998) is employed. The model follows a space-time variation of 9 depression parameters every 6 hours, in cases where the pressure distribution is approximated using an elliptical distribution with a different radius length in each of the 4 axes.

One-hourly winds are estimated on the basis of the gradient wind-based model using one-hourly storm (typhoon or depression) parameters linearly interpolated from 6-hourly generated parameters. The wind model consists of a simple addition of pressure-dependent gradient wind components and storm movement-related wind components and a correction to sea surface winds at a height of 10 m by multiplication of a constant value of 0.6 in a typhoon case or a latitude-dependent value of around 0.6 in a depression case.

A deep water version of a shallow water wave model by Yamaguchi et al. (1984) is applied for one-hourly computations of waves in the Northwestern Pacific Ocean area with an 80 km grid distance or for half-hourly computations of waves in the Japan Sea area with a 40 km grid distance. In the latter case, the grid is rotated 45 degrees counterclockwise to the north-south direction in order to improve the resolution of coastal topography, as shown by an oblique rectangular frame in Figure 1 given below. For the computation of typhoon-generated waves, half-hourly directional spectra at each of the 5 grid points along the Korea-Tsushima Straits, which are estimated using the backward ray tracing model by Yamaguchi et al. (1987) on a 5 km-distance grid, are given as inflow boundary condition.

The 20 frequency data ranging from 0.036 to 0.5 Hz and the 19 direction data equally-divided with 20 degrees on the whole plain are used. A parametric open boundary condition is separately imposed for the typhoon or depression cases, excluding the above-mentioned case of typhoon-generated waves in the Japan Sea.

2.2 *Extraction of Typhoons and Depressions for Wave Computations*

Figure 1 indicates an 80-km discretized modeling region for the probabilistic generation of typhoons or depressions. Using either of the Monte-Carlo simulation-based models, about 780,000 typhoons over 10,000 years are generated in the Northwestern Pacific Ocean area given in the left panel of the figure and about 3,800,000 depressions over 100,000 years are generated in another region of the Ocean given in the right panel of the figure. The regions overlap only for the area around Japan enclosed by the dotted line, because the generation areas of typhoons and depressions called cyclogeneses are different from each other.

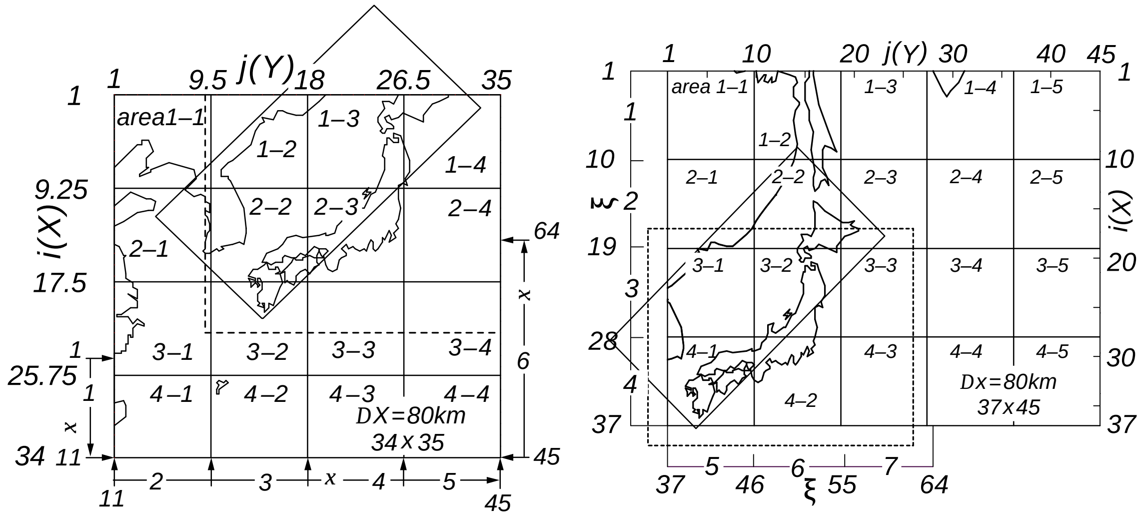

Figure 1. Modeling regions for the probabilistic generation of typhoon parameters or depression parameters.

The typhoons to be used in the wave computations are selected from a huge amount of typhoons generated according to the following criteria, in cases where the Northwestern Pacific Ocean area is divided into the 3 sub-regions ①southern area, ②central area, ③northern area, as shown in Figure 2. The selected typhoons are any of the

1) typhoons which pass through ①the southern area sustaining a central pressure lower than or equal to 910 hPa,
2) typhoons which pass through ②the central area sustaining a central pressure lower than or equal to 930 hPa,
3) typhoons which experience at least once a central pressure lower than or equal to 950 hPa in ③the northern area.

The total number of the typhoons selected over 100,000 years is 6084.

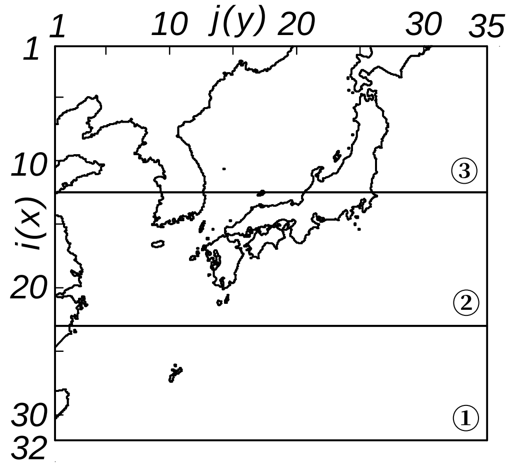

Figure 2. Sub-regions divided for extracting huge typhoons to be used in the wave computations.

Each depression for which the difference between the far-field pressure and the central pressure is greater than or equal to 90 hPa at least at one time in the modeling region shown in the right panel of Figure 1, is used in the wave computations. The total number of the depressions selected over 100,000 years is 37,042.

In the wave computations limited to the Japan Sea area, all typhoons passing through the Japan Sea sustaining a central pressure lower than or equal to 940 hPa and all depressions passing through the Japan Sea sustaining a pressure difference greater than or equal to 70 hPa are extracted. Total numbers over 100,000 years are 10,933 for the typhoons and 14,050 for the depressions respectively.

In addition, wave computations are conducted for each of the 519 strong historical typhoons over the 58 years from 1948 to 2005 both in the Northwestern Pacific Ocean area and in the Japan Sea area. Also, the computations are carried out for each of the 148 historical depressions over the 20 years from 1979 to 1998 in the Northwestern Pacific Ocean area and then for each of the 194 historical depressions over the same period in the Japan Sea area. In the computations of typhoon-generated waves, the gradient wind-based model mentioned above is applied, and in the computations of depression-generated waves, 6-hourly ECMWF (European Centre for Medium range Weather Forecasts) analysis/reanalysis wind data with a space resolution of 1.125 degrees or 0.5625 degrees (after September 17, 1991) are provided. The time step of input wind data obtained through a linear interpolation is 1 hour on an 80-km discretized grid of the Northwestern Pacific Ocean area and 30 minutes on a 40-km discretized grid of the Japan Sea area. A bi-linear spatial interpolation is applied to the ECMWF wind data to obtain the wind data on these grids.

The maximum significant wave height at each of the grid points during a storm (typhoon or depression) is extracted from one-hourly wave height data during the storm in the Northwestern Pacific Ocean area or from half-hourly wave height data during the storm in the Japan Sea area. Then the first, second and third largest values of the storm (typhoon or depression)-generated maximum significant wave height data at each of the grid points are selected through a successive comparison of the storm-dependent maximum significant wave height data for each of more than several thousands of extraordinary huge storms generated over a period of 100,000 years. The first largest maximum significant wave height generated by a typhoon or a depression at each grid point is regarded as an estimate of the typhoon- or depression-generated probable maximum significant wave height (PMSWH) at that point. The same procedure is used for the historical storm-generated wave height data. In these historical storm cases, the term “the historical typhoon- or depression-generated largest significant wave height” is used.

3. PROBABLE MAXIMUM SIGNIFICANT WAVE HEIGHT IN THE NORTHWESTERN PACIFIC OCEAN

3.1 *Typhoon-Generated Probable Maximum Significant Wave Heightt (TG-PMSWH)*

Figure 3 shows the spatial distribution of the probable maximum significant wave height (TG-PMSWH), which is estimated through wave computations for typhoons generated over a period of 100,000 years using a Monte-Carlo simulation model. The wave height indicates 22 m in an extensive offshore area ranging from south to central Japan, and yields the highest value of 26 m in an offshore area of the Shikoku Island in Southwestern Japan. Also, it decreases to 18 m in the East China Sea, 18 m in an offshore area of Northeastern Japan and 14 m in an offshore area of Northern Japan.

In the Japan Sea, an area with 22 m significant wave height extends from the southwest part to the central part. This is due to the contingent passage of an exceptionally intense typhoon associated with the central pressure of 900 hPa in the Japan Sea. Also, an excessive inflow of wave energy through the Korea-Tsushima Straits caused by the poor space resolution of 80 km may contribute to the appearance of the huge wave height, probably leading to an overestimated value. As the maximum difference between the first largest maximum significant wave height (TG-PMSWH) and the second largest one is about 5 m, the TG-PMSWH tends to be much bigger than the second largest maximum significant wave height.

Figure 4 shows the spatial distribution of the return year period *R* corresponding to the TG-PMSWH, which is estimated using the parent distribution of typhoon-generated annual maximum significant wave height obtained from a Monte-Carlo simulation over a period of 20,000 years by Yamaguchi et al. (2004). The return year period is generally estimated to be more than 100,000 years in most of the area. It may be said that an estimate of the TG-PMSWH is reasonable in the sense that its occurrence probability is very small (less than 10^{-5}).

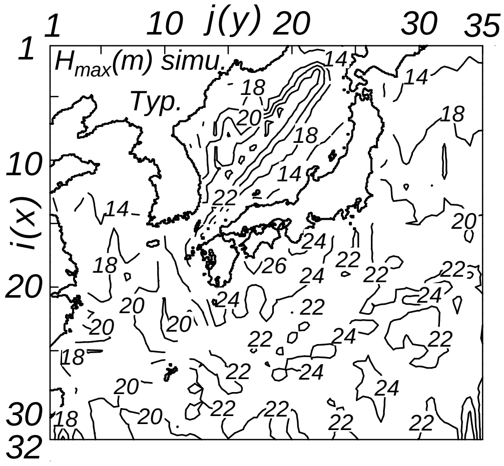

Figure 3. TG-PMSWH in the Northwestern Pacific Ocean.

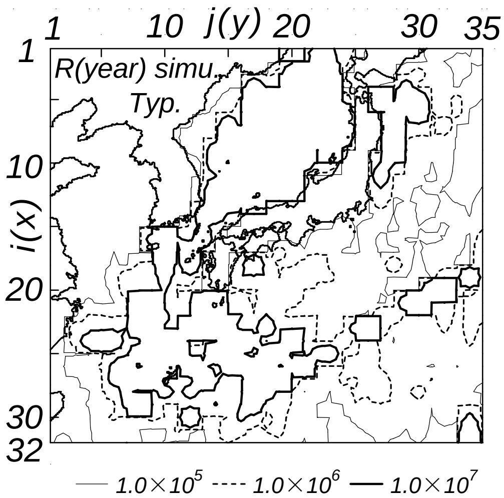

Figure 4. Return year period of TG-PMSWH in the Northwestern Pacific Ocean.

Figure 5 illustrates the spatial distribution of the largest significant wave height generated by the historical typhoons in the past 58 years from 1948 to 2005. The wave height ranges from 14 m to 20 m in the Northwestern Pacific Ocean and from 8 m to 12 m in the Japan Sea. These values are 10 m to 13 m lower than the TG-PMSWHs on the same area, although the spatial distributions resemble each other.

Figure 6 gives the 6-hourly track and central pressure of the typhoon that brings about a TG-PMSWH of 26 m in an offshore area of Southwestern Japan and Figure 7 indicates the spatial distribution of the maximum significant wave height generated by this typhoon. This typhoon proceeds from the south of Japan towards the north, maintaining a central pressure less than 880 hPa and reaching the Japan Sea with a central pressure of around 920 hPa. The maximum significant wave height exceeds 26 m in an offshore area of Southwestern Japan and an area with a 20 m height extends to the southern boundary.

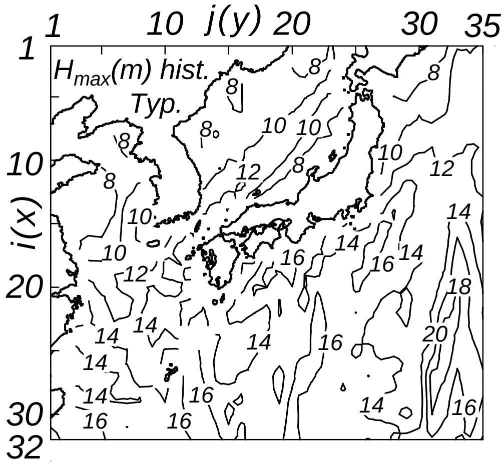

Figure 5. Historical typhoon-generated largest significant wave height in the Northwestern Pacific Ocean.

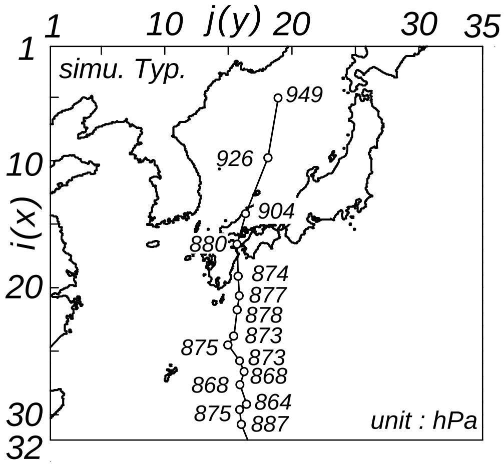

Figure 6. Track and central pressure of the typhoon which brings about PMSWH in an offshore area of Southwestern Japan.

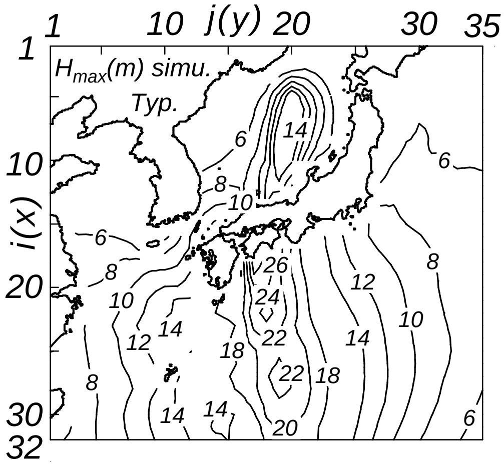

Figure 7. Maximum significant wave height associated with PMSWH-generated typhoon in an offshore area of Southwestern Japan.

The Ijima et al.(1968) expression yields an estimate for the maximum significant wave height of 27 m for a huge typhoon with a central pressure depression of Dp=140 hPa, a typhoon radius of r_0=140 km and a typhoon movement velocity of V=33 km/h. This height is comparable to the TG-PMSWH in an offshore area of Southwestern Japan. But it must be borne in mind that an estimate for the maximum significant wave height based on the Ijima et al.(1968) expression strongly depends on the typhoon movement velocity. For example, the maximum significant wave height is calculated as 37 m for V=55 km/h under the same conditions of Dp=140 hPa and r_0=140 km as before. Also, the P-M spectrum-based relation such as H_s=0.0246 U_{10}^2 give a significant wave height H_s of 39 m under a 10 m elevation wind speed U_{10} of 40 m/s and the SMB method-based relation in the infinite fetch-condition such as H_s=0.036U_{10}^2 yields an estimate of 49 m significant wave height for a wind speed of 40 m/s. These heights may be too big to occur in reality.

Figure 8 illustrates an example of a frequency spectrum corresponding to the huge significant wave height of 26 m. The spectrum is single-peaked and the estimated peak frequency is f_p=0.047 Hz, which is interpolated from fitting a parabolic curve to the discrete spectral densities at the frequency with largest spectral density and the two neighboring discrete frequencies. Since the ratio of the spectral density at the lowest frequency of

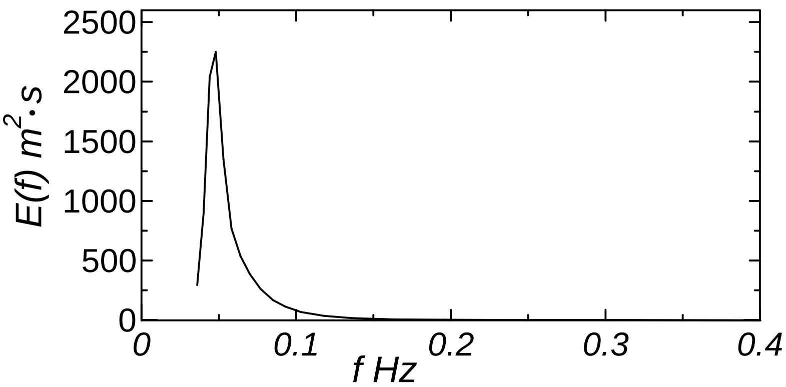

Figure 8. Frequency spectrum of huge waves with 26 m significant wave height.

f=0.036 Hz to the interpolated maximum spectral density at the peak frequency of f_p=0.047 Hz is 0.128, it may be said that a full spectral form of huge waves is substantially reproduced by the wave computation using a frequency resolution with the lowest frequency of 0.036 Hz, which is determined from the time-space restriction (the Courant condition) associated with a time step of 1 hour and a grid distance of 80 km.

3.2 *Depression-Generated Probable Maximum Significant Wave Height (DG-PMSWH)*

Figure 9 demonstrates the DG-PMSWH in the Northwestern Pacific Ocean. Since the cyclogeneses of depressions in the Ocean are located northerly from those of typhoons, the concerned area in Figure 9 is also shifted about 1,500 km northeasterly compared to that in Figure 3. The significant wave height decreases circularly from a highest value of 22–26 m in the eastern area. In an offshore area of Northern Japan, it becomes 18 m and in an offshore area of Southwestern Japan close to the cyclogeneses of depressions, it reduces to 10 m. In the Japan Sea, the significant wave height ranges from 14 m to 16 m and it is higher in the Japanese sea areas than in the continental sea areas.

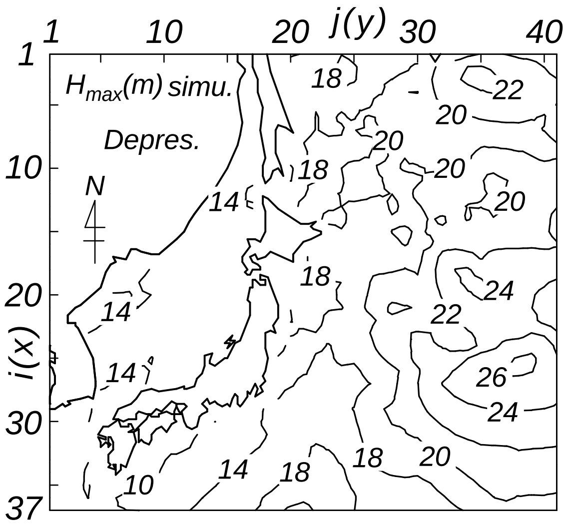

Figure 9. DG-PMSWH in the Northwester Pacific Ocean.

Figure 10 indicates the spatial distribution of the return year period of the DG-PMSWH, in cases where the parent distribution of the depression-generated annual maximum significant wave height is assumed to be the estimate which was analyzed using the simulation results over a period of 10,000 years by Yamaguchi et al.(2004). It can be seen from the figure that the return year period of the DG-PMSWH exceeds at least 10,000 years in most of the area and is greater than 100,000 years in an extended northeastern area associated with a huge significant wave height. The occurrence of the DG-PMSWH as well as the TG-PMSWH may be regarded as an extremely rare event.

Figure 11 shows the spatial distribution of the largest significant wave height generated by the historical depressions in the 20 years from 1979 to 1998. The shape of the significant wave height contour line is similar to that associated with the DG-PMSWH. The DG-PMSWH is 6 m to 10 m greater in the Pacific Ocean area and 6 m to 8 m greater in the Japan Sea, compared to the historical depression-generated largest significant wave height.

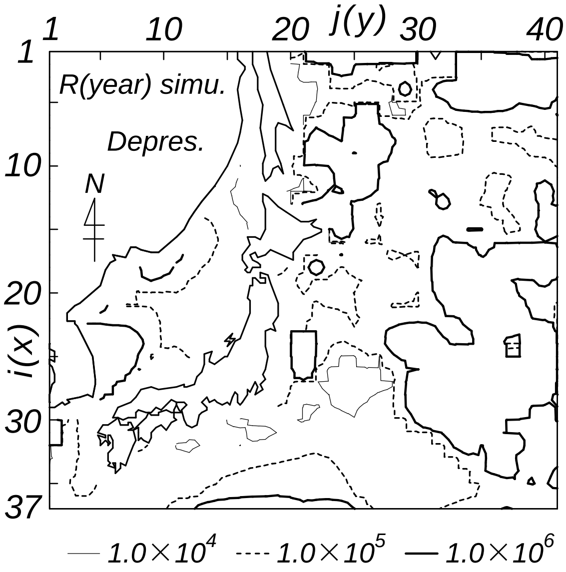

Figure 10. Return year period of DG-PMSWH in the Northwestern Pacific Ocean.

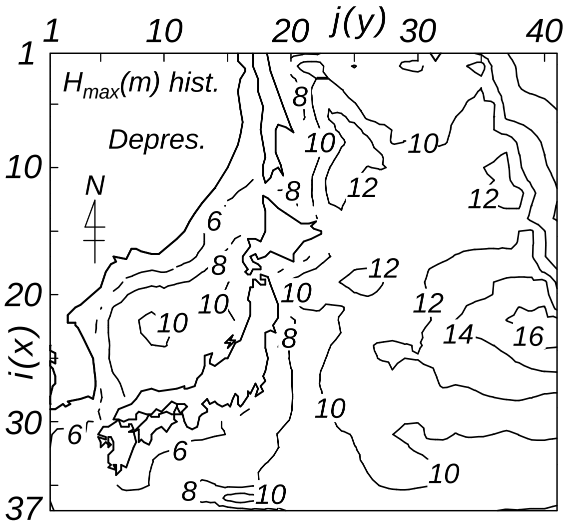

Figure 11. Historical depression-generated largest significant wave height in the Northwestern Pacific Ocean.

Figure 12 provides the 6-hourly variation of track, central pressure and difference between the far-field pressure and the central pressure for an extremely intense depression, which gives rise to a PMSWH of 26 m in the east area, and Figure 13 shows the maximum significant wave height distribution during this depression. The rapidly developing depression proceeds from the southwest of Japan toward the northeast and then attains extraordinary values such as a central pressure of 939 hPa and a pressure difference of 113 hPa in the east area. The significant wave height is greater in the right-hand area of the propagation direction than in the left-hand area and the largest value reaches 26 m.

Comparison between the TG-PMSWH in Figure 3 and the DG-PMSWH in Figure 9 reveals that the TG-PMSWH exceeds the DG-PMSWH over an extended area, whereas the DG-PMSWH is greater than or comparable to the DG-PMSWH in the area the north-east of Japan and in the Japanese area of the Japan Sea where the depression develops intensely.

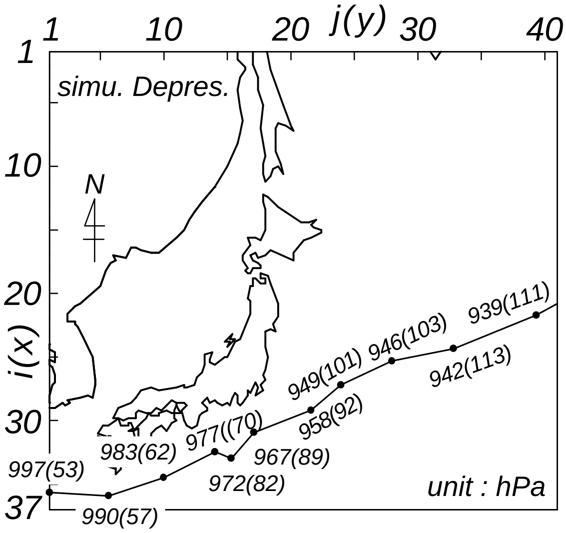

Figure 12. Track, central pressure and pressure difference of the exceptionally intense depression which produces PMSWH in the Northwestern Pacific Ocean.

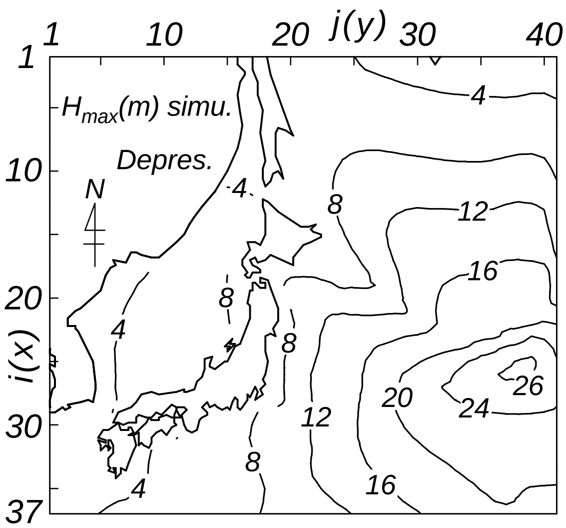

Figure 13. Maximum significant wave height generated by the exceptionally intense depression in the Northwestern Pacific Ocean.

4. PROBABLE MAXIMUM SIGNIFICANT WAVE HEIGHT IN THE JAPAN SEA

4.1 *Typhoon-Generated Probable Maximum Significant Wave Height (TG-PMSWH)*

Figure 14 indicates the spatial distribution of the TG-PMSWH. The significant wave height exceeds 20 m in the central area and reduces to 12 m elliptically toward the offshore areas off the continent and Japan. The typhoon which produces a significant wave height over 20 m in the central area yields significant wave heights of more than 22 m in almost the same area as in Figure 3. About 2 m reduction is realized in this area by both a usage of the 40-km grid accompanied by the rotation of the co-ordinate system and an introduction of wave energy flowing in from the Korea-Tsushima Straits in the wave computation. The power of the typhoon is extraordinarily intense. The largest PMSWH reduces to 18 m, if the PMSWH generated by this typhoon would be removed.

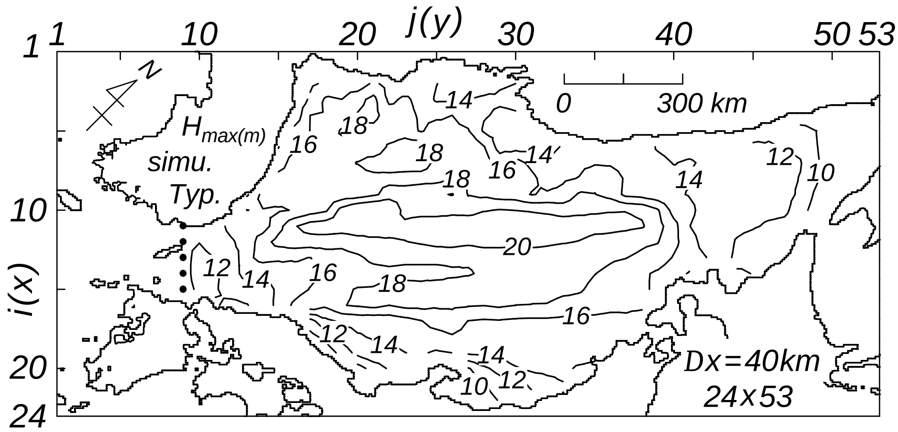

Figure 14. TG-PMSWH in the Japan Sea.

Figure 15 shows the horizontal distribution of the largest significant wave height generated by the historical typhoons for a year period of 58 years from 1948 to 2005. The TG-PMSWH is 7 m to 10 m greater than the historical typhoon-generated largest significant wave height, although their distributions resemble each other.

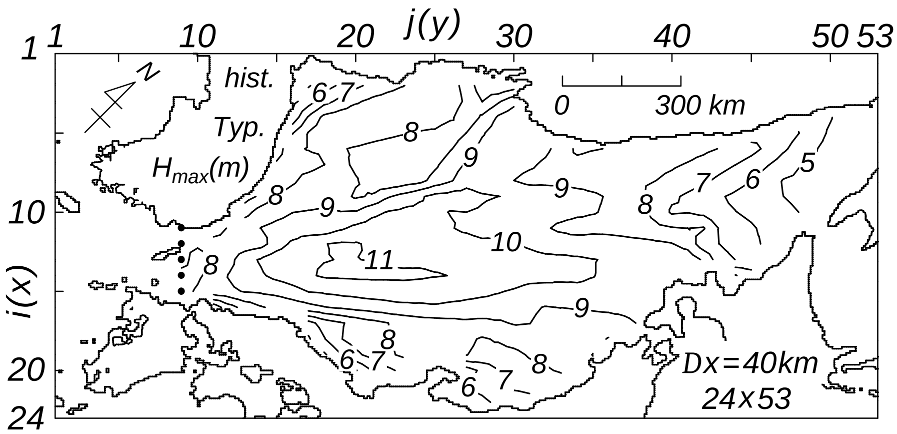

Figure 15. Historical typhoon-generated largest significant wave height in the Japan Sea.

4.2 *Depression-Generated Probable Maximum Significant Wave Height (DG-PMSWH)*

Figure 16 demonstrates the spatial distribution of the DG-PMSWH. In small areas close to the north and center of Japan, a significant wave height of 16 m appears and a significant wave height of 15 m covers extensive areas. These huge wave height areas are brought about by only 4 depressions with intensities comparable to those of intense typhoons with central pressures ranging from 940 hPa to 950 hPa and pressure differences ranging from 81 hPa to 96 hPa.

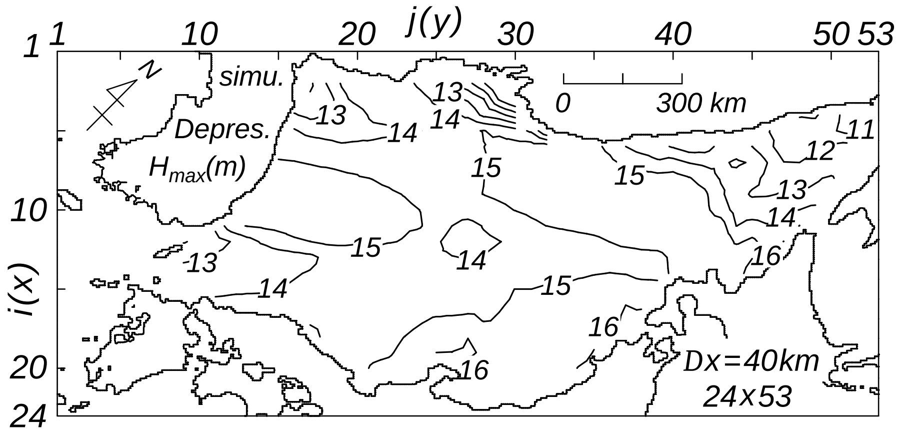

Figure 16. DG-PMSWH in the Japan Sea.

Figure 17 indicates the spatial distribution of the largest significant wave height generated by the historical depressions over the 20 years from 1979 to 1998. This distribution looks like that in Figure 16, but the DG-PMSWH is about 7 m greater than the largest significant wave height generated by the historical depressions at the maximum difference level.

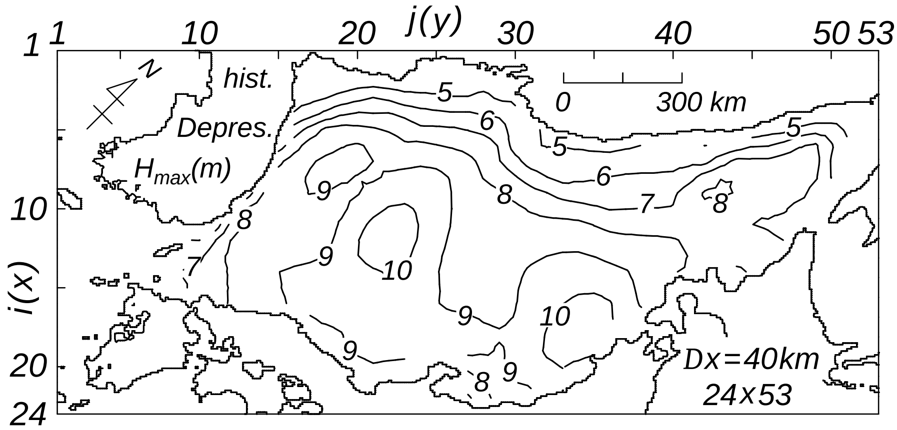

Figure 17. Historical depression-generated largest significant wave height in the Japan Sea.

A comparison between the TG-PMSWH and the DG-PMSWH in the Japan Sea suggests that the TG-PMSWH exceeds DG-PMSWH in almost the entire area, whereas the DG-PMSWH gives greater height than the TG-PMSWH along the extensive coastal areas of Japan and along the north coastal areas of Russia. In the Japan

Sea, an extremely intense typhoon incidentally maintains its power while progressing in a northeastern direction and happens to result in huge significant wave heights in the entire area. On the other hand, a depression strongly develops while advancing in an eastern direction and sometimes causes extraordinarily high waves along the coastal areas of Japan.

5. CONCLUSIONS

The main results in this study are summarized as follows.

1) The typhoon-generated probable maximum significant wave height (TG-PMSWH) exceeds 26 m in the sea area near Shikoku Island facing the Pacific Ocean.
2) The depression-generated probable maximum significant wave height (DG-PMSWH) is over 26 m in the eastern sea area far from Japan.
3) These PMSWHs are 10 m to 13 m greater than the largest significant wave heights generated by the historical typhoons and depressions of the recent decades.
4) The above-mentioned features regarding typhoon- and depression-generated PMSWHs can be seen in the Japan Sea.

6. ACKNOWLEDGEMENTS

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