CHAPTER 108

A Stochastic Typhoon Model and its Application to the Estimation of Extremes of Storm Surge and Wave Height

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Abstract

This paper presents a system for estimating extremes of storm surge height and wave height associated with typhoons, which consists of a Monte-Carlo simulation model for probabilistic generation of typhoon characteristics, termed a stochastic typhoon model, a parametric typhoon model for wind estimation, numerical models for the computation of storm surges or waves and an extreme analysis model for estimation of their return values. The system is applied to the estimation of 50 to 1000-year return values and their confidence intervals based on the computations over a period of 1000 years for storm surge heights in Ise Bay connecting to the Pacific Ocean, and for wave heights at some representative locations around the Pacific coast of Japan.

1. Introduction

Japanese coasts facing the Pacific Ocean and the East China Sea have frequently been hit by powerful typhoons and consequently have suffered severe damage by typhoon-generated storm surges and high waves. Design heights of sea water level and waves in the area are conventionally estimated based on statistical analysis of their extreme data hindcasted for typhoons which occurred in the past several decades. Extremes of typhoon-generated storm surges and waves are strongly dependent on the strength and track of a typhoon, because the severe wind

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area in a typhoon is limited, the radius being usually less than about 200 km and typhoon-generated winds greatly vary in space and time. Thus, the problem is whether the above-mentioned method could properly evaluate great variability of storm surge height and wave height associated with the contingency of typhoon characteristics. As an alternative and complemental method, this paper presents a system for estimating extremes of storm surge height and wave height around the concerned sea area, which consists of a stochastic typhoon model, a parametric typhoon model, numerical models for the computation of storm surges or waves and an extreme analysis model for the evaluation of their return values and confidence intervals.

2. Estimation System for Extremes of Storm Surge and Wave Height

(1) Stochastic typhoon model

Atmospheric pressure distribution in a typhoon is approximated with the Meyers formula such as

$$p=p_\infty - (p_\infty-p_c)\exp(-R/R_a)$$

$$R^2=(X-X_c)^2 + (Y-Y_c)^2 \qquad (1)$$

where p_c (hPa) is the central pressure, p_∞(=1013 hPa) the pressure of the far field, (X_c,Y_c) the position of the typhoon center in km unit and R_a (km) the typhoon radius. The stochastic typhoon model is a Monte-Carlo simulation model for probabilistic generation of typhoon parameters which are represented with the position of the typhoon center, the central pressure and the typhoon radius.

Data of typhoon parameters used in the modeling were gathered every 6 hours for 320 typhoons which passed through the Northwestern Pacific Ocean area during the period of 1951 to 1991 and had a central pressure of less than 980 hPa in the area, with 15 typhoons generated within the area being excluded in the modeling due to data scarcity. The data set consists of 7 parameters such as X_c, Y_c, p_c, their incremental change rates dX_c, dY_c, dp_c, and R_a. Fig. 1 shows the domain covered with the north latitude of about 23° to 44° and the east longitude of about 120° to 149°, which is divided into a grid system of 34 by 35 with a grid distance of 80 km.

The basic idea in the modeling is that each typhoon parameter may be represented by the sum of its mean value and the deviation from the mean value. Mean variation of each typhoon parameter along the boundary is approximated with use of a one-dimensional weighted spline function,

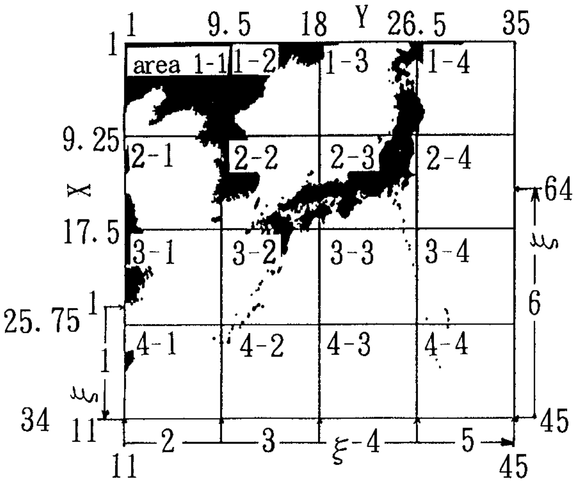

Fig. 1 The Pacific Ocean area where modeling of stochastic typhoons is made.

and correlations between typhoon parameters in the area as well as those between incremental change rates of typhoon parameter are taken into account with use of linear regression equations. Deviations from averaged typhoon parameters along the boundary and in the area are represented with empirical probability distribution functions obtained by data analysis. In order to improve reproductiveness of the stochastic typhoon model, regression equations and empirical distribution functions are separately constructed at 6 sub-divided boundaries and in 16 sub-divided areas shown in Fig. 1.

Modeling of stochastic typhoon and Monte-Carlo simulation are conducted according to the following procedure.

(a) The annual occurrence rate of typhoons is fairly well approximated with the Poisson distribution for a mean value of 7.8, as shown in Fig. 2. So, it is determined with use of a computer-generated Poisson-type random number.

(b) The position where a typhoon generates is defined as the position where the typhoon crosses the boundary. Data of typhoon occurrence position and the other typhoon parameters are obtained from linear interpolation between the data before and after crossing the boundary. In order to describe the typhoon occurrence position on the boundary, a one-dimensional co-ordinate system ξ which is taken from the west boundary to the east boundary through the south boundary is introduced as indicated in Fig. 1. Fig. 3 shows the cumulative distribution of typhoon occurrence position. In the simulation, the occur-

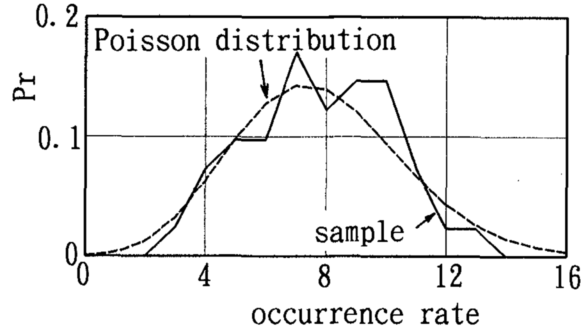

Fig. 2 Annual occurrence rate of typhoons and approximation with Poisson distribution.

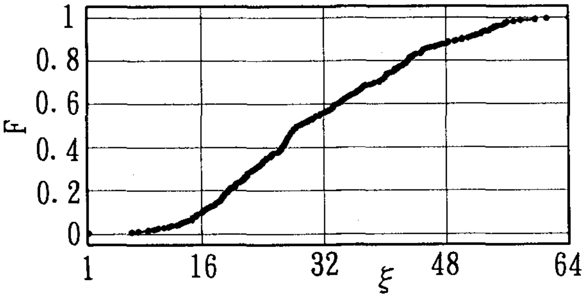

Fig. 3 Cumulative distribution of typhoon occurrence positions on the boundary.

rence position of a typhoon is obtained from the linear interpolation for cumulative distribution curve by giving a uniformly-distributed random number between 0 and 1 generated by computer.

(c) Mean variation of incremental change rate of typhoon position dX_{c0} along the boundary is approximated with a one-dimensional weighted spline function and then the deviation of individual data from the mean variation is separately expressed in the form of a cumulative distribution every sub-divided boundary. Fig. 4 illustrates the smoothing effect for scattered data by use of a one-dimensional spline function and an example of the cumulative distribution. Similar figures are prepared for the typhoon parameters such as dY_{c0}, p_{c0} and dp_{c0}.

In the formulation of typhoon radius, correlation with central pressure of the typhoon is taken into account using the regression equation such as

$$R_{a0}=a\cdot p_{c0}{}^{n} + b \qquad (2)$$

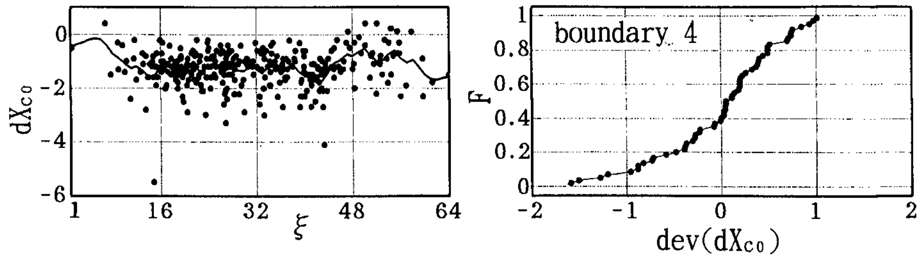

Fig. 4 Smoothing of dX_{c0} data along the boundary with spline function and cumulative distribution of deviation from mean variation.

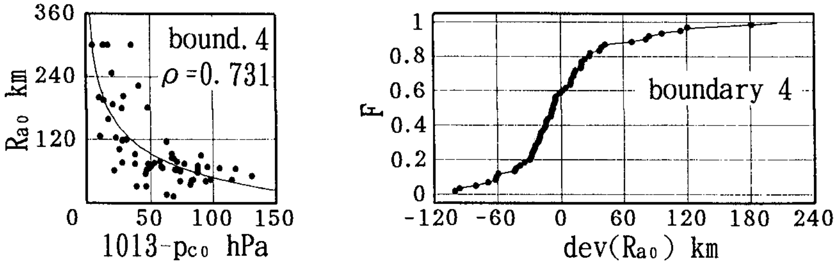

Fig. 5 Regression equation for R_{a0} and cumulative distribution of deviation from mean value in a sub-boundary.

where a, b and n are the coefficients to be determined by the least square method. Typhoon radius is expressed as the sum of mean value obtained from the above regression equation and its deviation from mean value for each sub-boundary. Fig. 5 indicates an example of the correlation diagram and the cumulative distribution.

Now typhoon parameters on the boundary X_{c0}, Y_{c0}, dX_{c0}, dY_{c0}, p_{c0}, dp_{c0} and R_{a0} can be successively simulated by using the regression equations and the cumulative distribution diagrams for each of which uniformly-distributed random number is given as input, and then position and central pressure of the typhoon at the next step can be determined from the relations such as

$$X_{c1}=X_{c0}+dX_{c0}, \quad Y_{c1}=Y_{c0}+dY_{c0}$$

$$p_{c1}=p_{c0}+dp_{c0} \tag{3}$$

Some restraint conditions are imposed on the generated typhoon parameters, and simulation is repeated until the conditions are satisfied.

(d) Regression equations are used to describe change of typhoon parameters every 6 hours associated with the typhoon movement in the simulation area. These are written as

$$X_{ci+1}=a\cdot X_{ci}+b,\quad Y_{ci+1}=c\cdot Y_{ci}+d$$

$$p_{ci+1}=e\cdot p_{ci}+f \tag{4}$$

where i is the time step and a to f are the regression coefficients to be determined by the least square method. Change of typhoon radius is formulated with the following multiple regression equation including the effect of central pressure of the typhoon.

$$R_{ai+1}=a\cdot R_{ai}+b\cdot p_{ci+1}+c \tag{5}$$

Variability of each typhoon parameter is taken into account with use of the cumulative distribution for the deviation from mean value obtained from the regression equation as before. Regression equations and cumulative distribution diagrams are separately constructed for 16 sub-areas shown in Fig. 1. Examples of the correlation diagram and the cumulative distribution of the deviation from mean value for X_c, and those for R_a in the sub-

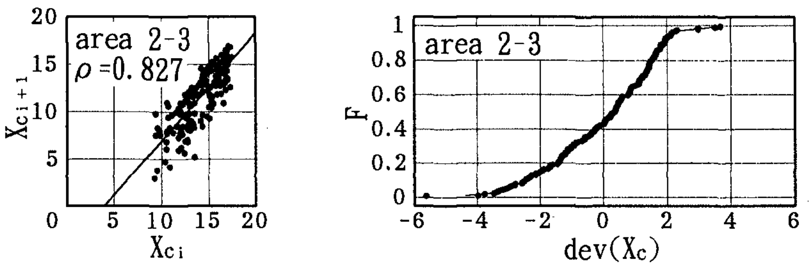

Fig. 6 Regression equation for X_c and cumulative distribution of deviation from mean value in a sub-area.

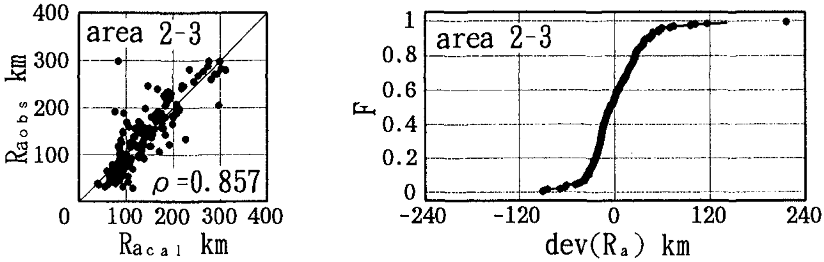

Fig. 7 Correlation diagram for R_a and cumulative distribution of deviation from mean value in a sub-area.

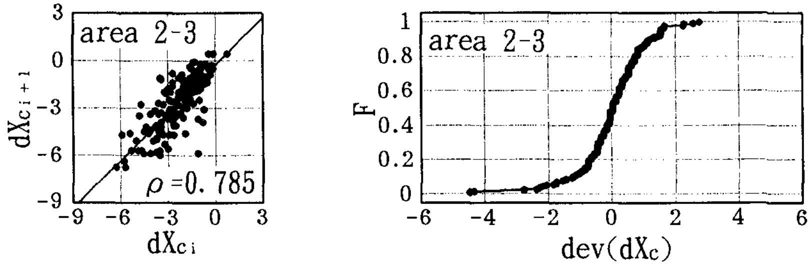

Fig. 8 Regression equation for dX_c and cumulative distribution of deviation from mean value in a sub-area.

area 2-3 are given in Fig. 6 and Fig. 7. Only eq.(5) is used to generate data of typhoon radius in the simulation area, because inclusion of the deviation gives rise to rapid and unnatural change of the typhoon radius with typhoon movement. Another reason is that correlation between data of typhoon radius and data calculated with eq. (5) is usually high to the extent that addition of the deviation is not required.

(e) Incremental change rates of the typhoon parameters dX_c, dY_c and dp_c are formulated in the same way as before. The regression equations are written as

$$dX_{ci}^{+}=a\cdot dX_{ci}^{-}+b,\quad dY_{ci}^{+}=c\cdot dY_{ci}^{-}+d$$

$$dp_{ci}^{+}=e\cdot dp_{ci}^{-}+f \tag{6}$$

where

$$dX_{ci}^{+}=X_{ci+1}-X_{ci},\quad dX_{ci}^{-}=X_{ci}-X_{ci-1}$$

$$dY_{ci}^{+}=Y_{ci+1}-Y_{ci},\quad dY_{ci}^{-}=Y_{ci}-Y_{ci-1}$$

$$dp_{ci}^{+}=p_{ci+1}-p_{ci},\quad dp_{ci}^{-}=p_{ci}-p_{ci-1} \tag{7}$$

Superscripts '+' and '-' mean change of typhoon parameter occurring from i step to i+1 step and from i-1 step to i step respectively. Both are defined at i step. Fig. 8 indicates the correlation diagram for dX_c and the cumulative distribution of the deviation from mean value based on the regression equation in the sub-area. Critical values of incremental change rates are used to restrict excess change over one time step of simulated typhoon parameters. Each critical value is calculated as the sum of the mean values obtained from the regression equation and deviation corresponding to 3 % or 97 % non-exceedance probability of the cumulative distribution. No restriction on typhoon radius is imposed because the regression equation gives high correlation with the original data of typhoon radius.

(f) Monte-Carlo simulation of typhoon parameters for a typhoon is continued until the typhoon center moves out of the simulation area or the center pressure rises more than 1008 hPa. Simulation is repeated by the annual occurrence rate of typhoons and then by the number of years arbitrarily given as input condition.

(2) Parametric typhoon model

The estimation of typhoon-generated winds relies on the application of a simple parametric model. The model computes the spatial distribution of wind speed and wind direction in a typhoon by composing axisymmetyrical gradient wind components and wind components related to the movement of the typhoon. Eq. (1) is assumed for the pressure distribution in a typhoon. Correction factor to wind speed at the height of 10 m is generally taken as 0.6, but some adjustment is made to improve the reproductiveness of storm surge computation.

(3) Storm surge model

Storm surge computation is based on a finite difference model for the vertically-integrated momentum and continuity equations, in which constant bottom friction factor and wind speed-dependent surface drag coefficient are used. Astronomical tides are not included in the storm surge computation because there is no way to determine phase relation between astronomical tides and storm surges associated with simulated typhoons. The domain of Ise Bay whose location is given in Fig. 9 is divided into a grid system of 38 by 34 with a grid size of 2.5 km. The time steps in wind and storm surge computations are 15 min and 45 s respectively. Although the topographical resolution is not sufficient for the storm surge computation in this area, the present grid system is necessary in order to save enormous computer processing time required for the computations of storm surges associated with more than 2300 typhoons.

(4) Wave model

Wave computation is performed with a shallow water wave model(Yamaguchi et al., 1987) which belongs to a decoupled propagation model, tracing the change of directional spectrum along a refracted ray of each component focused on a prescribed point. The usage of a nesting grid system with high topographical resolution results in a reasonable estimate of waves in coastal sea water. Fig. 9 shows a nesting grid system composed of the Northwestern Pacific Ocean area divided with a grid size of 5 km and a small sea area off Shikoku Island divided with a grid size of 0.5 km. The figure includes

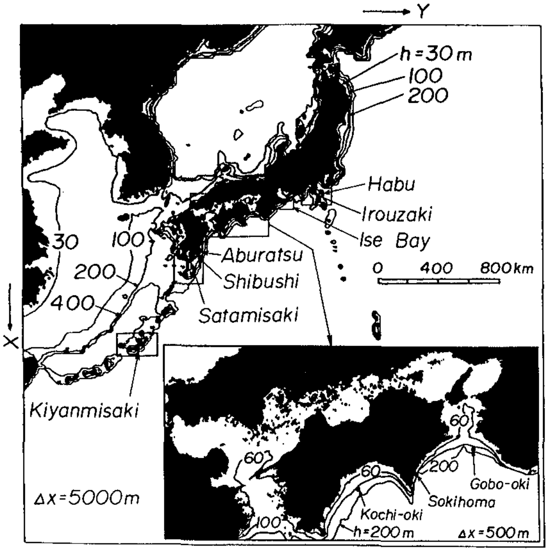

Fig. 9 Nesting grid used in wave computation, location of wave computation points and contour plot of water depth.

the location of Ise Bay where storm surge computation is conducted, the location of 9 wave computation points along the Pacific coast of Japan and contour plot of water depth. The numbers of frequency and direction data are 23 and 19 respectively, and the time step in wind and wave computations is 1 hour.

(5) Extreme analysis model

Return storm surge height and its standard deviation are evaluated applying the extreme analysis model based on the least square method (Goda, 1988) to data of its peak value during a typhoon. The optimum distribution is chosen among the Gumbel distribution and the Weibull distributions, shape parameters of which are 0.75, 1.0, 1.4, and 2.0, based on the largest correlation coefficient between the ordered data and its reduced variate.

Return wave height and its standard deviation are estimated with the extreme analysis model based on the PWM method (Yamaguchi et al., 1995), which was found from a numerical simulation study by the authors to be an excellent parameter estimation method. A sample of data is obtained from peak wave height during a typhoon in the case of simulated data and from typhoon-generated annual maximum wave height in the cases of observed and hindcasted data. Candidate distributions are the Gumbel and 3-parameter Weibull distributions, and choice of the optimum distribution is due to a criterion of the correlation coefficient. A jackknife method is applied to estimate the standard deviation of return wave height.

3. Reproductiveness of Stochastic Typhoon Model, Storm Surge Model and Wave Model

Table 1 shows an example of the comparison between mean values and standard deviations of simulated typhoon parameters and those of observed typhoon parameters for each sub-area, and Fig. 10 illustrates the courses and radius of simulated typhoons in a representative year.

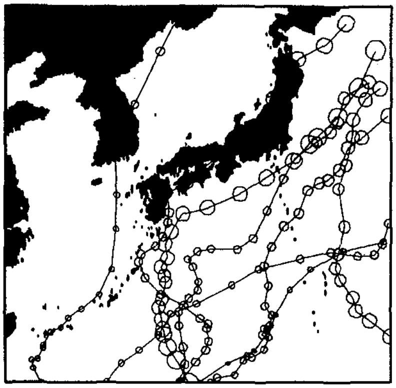

Fig. 10 Tracks and radius of simulated typhoons in a representative year.

Table 1 Comparison between simulation and observation for mean value and standard deviation of typhoon parameters.

typhoon parameters	area 2-3 mean	area 2-3 dev.
p_c obs.	981.0	14.8
(hPa) cal.	981.7	13.3
R_a obs.	139.0	72.1
(km) cal.	151.7	43.3
velocity obs.	42.6	20.9
(km/h) cal.	38.2	12.5
direction obs.	37.2	31.9
(°) cal.	35.5	27.7

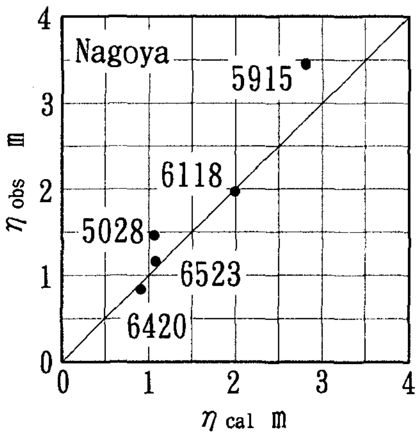

Fig. 11 Comparison of hindcast and observation for maximum storm surge height during a typhoon.

The stochastic typhoon model reasonably reproduces not only overall properties of typhoon characteristics but also their space-time variation associated with northward movement. It is natural that the model underestimates the standard deviation of typhoon radius because the effect of the deviation from mean value on the typhoon radius is neglected in the simulation.

Examples of the comparison between hindcasts and observations for typhoon-generated maximum storm surge height in Nagoya Harbor and for maximum significant wave height at 4 wave observation points are indicated in Fig. 11 and Fig. 12 respectively. Applicability of the storm surge model and wave model are verified by satisfactory agreement between computation and observation for many typhoon cases.

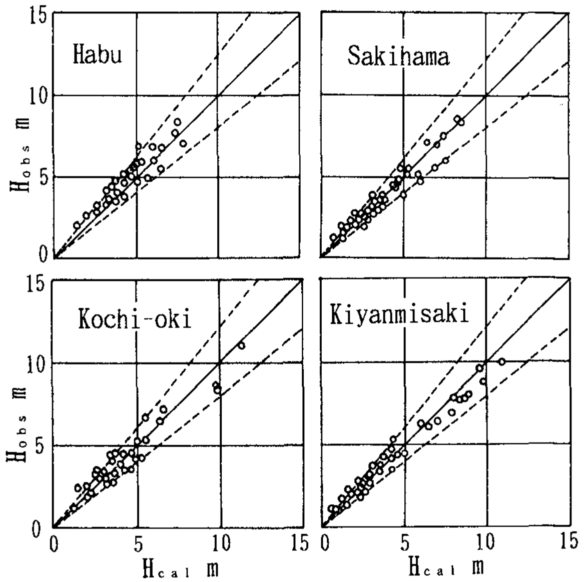

Fig. 12 Comparison of hindcast and observation for maximum wave height during a typhoon.

4. Estimation of Extremes of Storm Surge in Ise Bay

A Monte-Carlo simulation for the generation of typhoon parameters is carried out over a period of 1000 years. The number of typhoons generated is about 7800. The associated storm surges in Ise Bay are computed for 2347 influential typhoon cases.

Fig. 13 shows the relation between return storm surge height with standard deviation at Nagoya Harbor and return period, where they are estimated based on the simulated data and the observed data over a period of 42 years from 1950 to 1991. It should be noted that the standard deviation estimated using the observed data for a shorter period becomes increasingly larger than that based on the simulated data for a longer return period. It can be said that estimates of return storm surge heights for return periods of less than 100 years by this system are close to those evaluated from the observed data, and that even for longer return periods, the re-

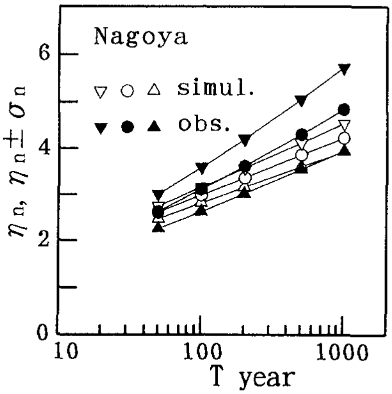

Fig. 13 Relation between return storm surge height with standard deviation and return period.

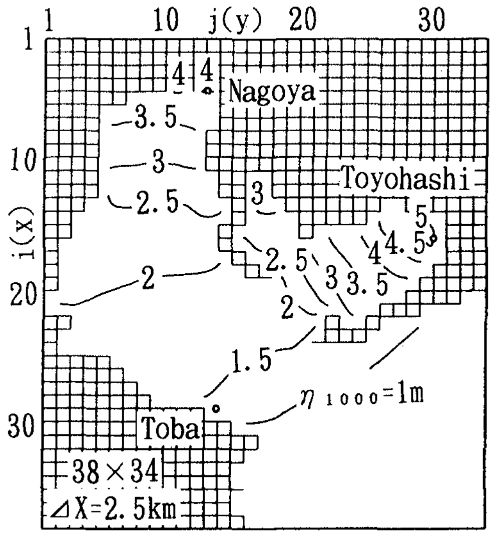

Fig. 14 Distribution of 1000-year return storm surge height in Ise Bay.

sults correspond well with each other, when their standard deviations are taken into account.

Spatial distribution of the 1000-year return storm surge height in Ise bay is given in Fig. 14, where the standard deviation ranges from 2.4 to 4.0 % of the return value and the maximum is 0.2 m. Return storm surge height rapidly increases from the entrance of the bay toward the inner most areas, in which case the maximum value exceeds 4 m at Nagoya Harbor and 5 m at Toyohashi point.

5. Estimation of Extremes of Wave height at the Pacific Coast of Japan

Two types of Monte-Carlo simulation are conducted. One is the simulation over a period of 1000 years as well as the case of storm surge computation, and the other is 100 times reiteration of the simulation over a period of 50 years. This is done for the purpose of directly computing standard deviation of each return wave height and investigating the applicability of a jackknife method to the evaluation of standard deviation based on the comparison between both estimates. Wave heights are calculated for about 3000 influential typhoon cases at 9 wave observation points indicated in Fig. 9.

Fig. 15 illustrates the effect of the number of iterations on mean and standard deviation of return wave height, in which statistically stable results can be seen for more than 50 iterations. Table 2 is the results of extreme analysis, in which standard deviations with a jackknife method agree well with those by direct calculation.

Fig. 16 shows longshore variation of the 1000-year return wave height and its standard deviation (68 % confidence interval) estimated using two kinds of simulation data, hindcasted data and observed data. Wave hindcasting is conducted for more than 150 intense typhoons which occurred during 45 years from 1948 to 1992, and period of wave observation ranges from 10 years to 21 years up to 1993. The return wave heights estimated from 4 kinds of extreme wave height data are in general agreement in spite of a great difference between computation period and observation period, when their standard devi-

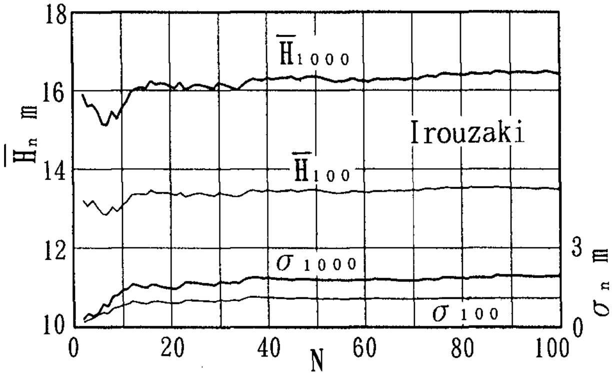

Fig. 15 Effect of iteration number of simulation on return wave height and standard deviation.

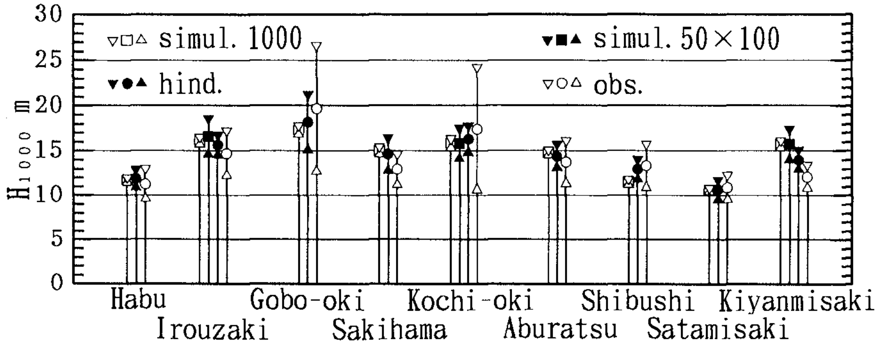

Fig. 16 Variation of 1000-year return wave height with standard deviation around the Pacific coast.

Table 2 Applicability of jackknife method in estimation of standard deviation.

location (depth m)	data	N_y (years)	$H_n \pm \sigma_n$ (m)	
			100 years	1000 years
Irouzaki (50)	simul.	50×100	13.5±1.1	16.6±2.0
	jack.		1.1	1.9
Kochi-oki (120)	simul.	50×100	12.9±1.0	15.8±1.7
	jack.		1.1	1.9
Kiyanmisaki (51)	simul.	50×100	13.2±1.0	15.7±1.7
	jack.		0.9	1.6

ations are taken into account, but the confidence intervals are much wider in the estimates based on observation data.

6. Conclusions

It should be emphasized that the system proposed in this study is very useful to estimate extremes of storm surge height and wave height for return periods of more than several hundred years and their confidence intervals around the Pacific coast and the East China Sea coast of Japan.

7. Acknowledgements

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