Outline of the Storm Surge Prediction Model at the Japan Meteorological Agency

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Abstract

Japan has suffered many storm surge disasters in the past, especially those associated with tropical cyclones (TCs). To mitigate the effects of such disasters, the Japan Meteorological Agency (JMA), which is responsible for issuing storm surge warnings, operates a numerical storm surge model to provide the basis for warnings. The model runs eight times a day and provides 33-hour predictions of storm surges and sea levels for 290 points along the Japanese coastline. When a TC enters the vicinity of Japan, the model predicts multiple scenarios of storm surges with different meteorological forcing fields to take into account the uncertainty in TC track forecasts.

1. Introduction

Storm surges, especially those associated with tropical cyclones (TCs), represent a major marine hazard, and frequently result in the loss of life and property in many parts of the world. As an example, 1970's Cyclone Bhola killed more than 200,000 people in East Pakistan (now Bangladesh), and a 1991 cyclone killed 131,000 in Bangladesh. It should be noted that most of these casualties are attributed to storm surges caused by the TCs.

As Japan is located in a region of high TC activity, it often experiences storm surge disasters caused mainly by typhoons. In 1959, Typhoon Vera (T5915) hit the central part of Japan causing more than 5,000 fatalities, most of them related to a storm surge of 3.5 m in the Ise Bay area arising from the typhoon. Even more recently, Japanese society has suffered repeated storm surge disasters. In 1999, Typhoon Bart (T9918) caused severe storm surges in the western part of Japan, killing thirteen people, and in 2004 more than 30,000 houses were flooded by storm surges induced by Typhoon Chaba (T0416) in western Japan's Seto Inland Sea.

Accurate and timely forecasts and warnings are critical in mitigating the threat to life and property posed by such storm surges. The Japan Meteorological Agency (JMA), which is responsible for issuing storm surge warnings, has operated a numerical storm surge model since 1998 to provide basic information for use in warnings. In this paper, we give an outline and describe the specifications and performance of this storm surge model. As discussed below, the model computes only storm surges, but the issuance of storm surge warnings also requires the prediction of storm tides (i.e., the sum of the storm surge and the astronomical tide), meaning that astronomical tides must be calculated separately. However, this paper does not detail the method of astronomical tide prediction, as its focus is on the storm surge model.

2. Dynamics

Storm surges are mainly caused by the effects of wind setup due to strong onshore winds over the sea surface and the inverted barometer effect associated with pressure drops in low-pressure systems. To predict temporal and spatial sea level variations in response to such meteorological disturbances, JMA's storm surge model utilizes two-dimensional shallow water equations consisting of vertically integrated momentum equations in two horizontal directions:

$$\begin{aligned} \frac{\partial M}{\partial t} - fN &= -g(D+\zeta)\frac{\partial(\zeta-\zeta_0)}{\partial x} + \frac{\tau_{sx}}{\rho} - \frac{\tau_{bx}}{\rho} \\ \frac{\partial N}{\partial t} + fM &= -g(D+\zeta)\frac{\partial(\zeta-\zeta_0)}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{\tau_{by}}{\rho} \end{aligned} \tag{1}$$

and the continuity equation:

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial M}{\partial x} - \frac{\partial N}{\partial y} \tag{2}$$

where *M* and *N* are volume fluxes in the x- and y-directions, defined as:

$$\begin{aligned} M &= \int_{-D}^{\zeta} u\mathrm{dz} \\ N &= \int_{-D}^{\zeta} v\mathrm{dz} \end{aligned} \tag{3}$$

f is the Coriolis parameter; *g* is the gravity acceleration; *D* is the water depth below mean sea level; ζ is the surface elevation; ζ_0 is the inverted barometer effect converted into an equivalent water column height; ρ is the density of water; τ_{sx} and τ_{sy} are the x- and y-components of wind stress on the sea surface; and τ_{bx} and τ_{by} are the stress values of bottom friction. For computational efficiency, non-linear advection terms are omitted.

The equations are solved by numerical integration using an explicit finite difference method.

3. Meteorological forcing

A storm surge model requires fields of surface wind and atmospheric pressure as external forcing, and these fields – especially wind – have the greatest impact on the performance of storm surge prediction. In the operation of JMA's storm surge model, two kinds of meteorological forcing field are used; one is a simple parametric model of TC structure, and the other is the prediction of the operational JMA nonhydrostatic mesoscale model (referred to below as *MSM*) (Saito *et al.*, 2006).

The parametric TC model is introduced to take into account the errors of TC track forecasts and their influence on storm surge forecasting. Although the performance of TC forecasts has gradually improved, their mean position error remains around 100 km for 24-hour forecasts at present (JMA, 2008). This implies that there is a large spread of possible forecast values for surface wind and atmospheric pressure at a certain location, making accurate storm surge prediction difficult even for 24-hour forecasts. Figure 1 demonstrates how differences in the path of a TC change storm surge occurrence. If the typhoon veers left of the forecast track, a storm surge will occur in Osaka Bay (the western bay in the area shown in the figures) (Figure 1(b)), while a surge would occur in Ise Bay (the eastern bay in the figures) if the typhoon veers right (Figure 1(c)).

To take into account the influence of TC track uncertainty on the occurrence of storm surge, we conduct five runs of the storm surge model with five possible TC tracks. These five tracks are prescribed at the center and at four points on the probability circle within which a TC is forecast to exist with a probability of 70% (Figure 2), and are used to make meteorological fields with a parametric TC model. The simple parametric TC model used by Konishi (1995) based on Fujita's empirical formula (Fujita, 1952) is adopted. The radial pressure distribution of the simple parametric TC model is represented as follows:

$$P = P_\infty - \frac{P_\infty - P_c}{\sqrt{1+(r/r_0)^2}} \tag{4}$$

and is related to the gradient wind as follows:

$$-\frac{v^2}{r} - fv = -\frac{1}{\rho}\frac{\partial P}{\partial r} \tag{5}$$

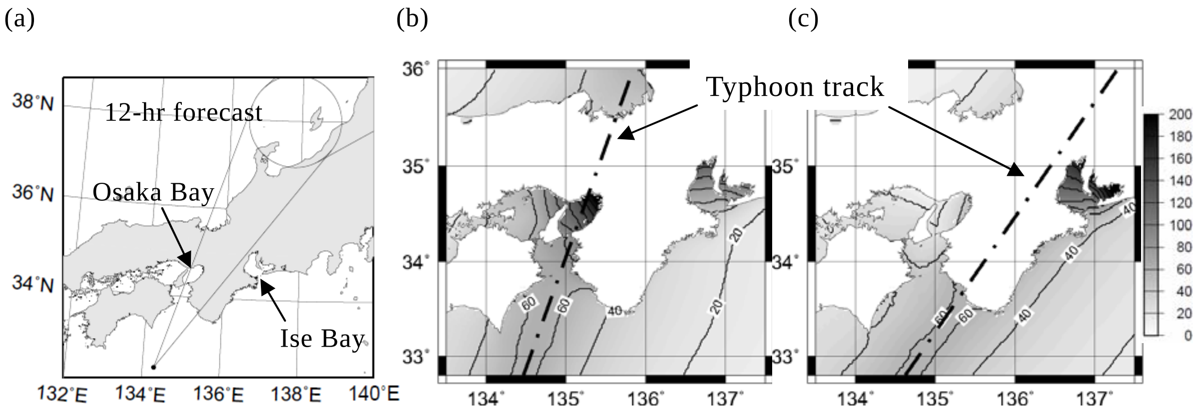

Figure 1 Maximum surge envelopes simulated with different typhoon tracks (unit: cm).
(a) The typhoon tracks used in the simulations (b) The case in which a typhoon takes the leftmost path
(c) As (b), but for the rightmost path.

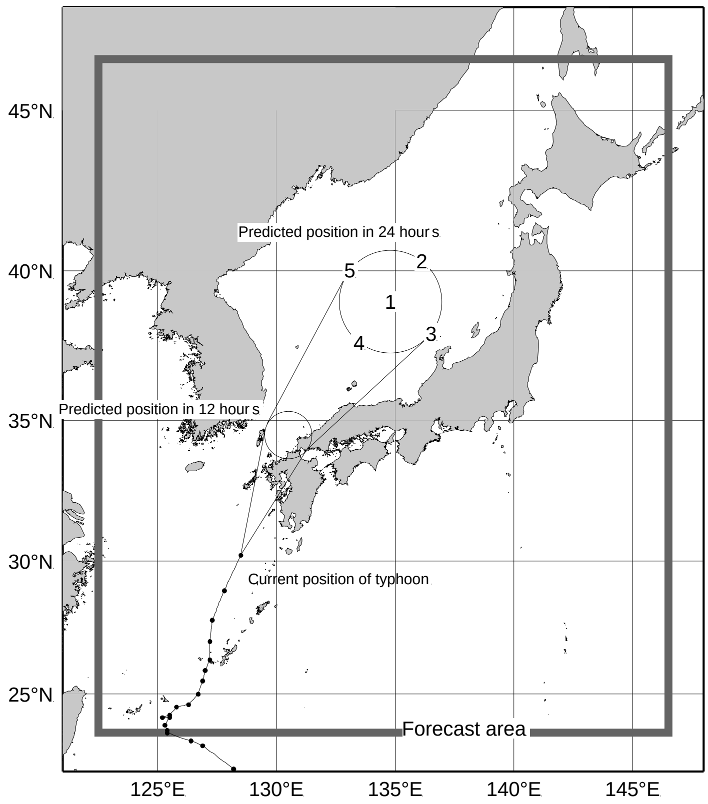

Figure 2　The model area and an example of a TC forecast track.
The circles represent areas into which the center of a TC will enter with 70% probability at each forecast time.　The numbers in and on the probability circle represent the TC tracks used in storm surge prediction. (1: center, 2: fastest, 3: rightmost, 4: slowest, 5: leftmost)

In Eqs. (4) and (5), P is the atmospheric pressure at distance r from the center of the TC, P_∞ is the atmospheric pressure at an infinitely distant point, P_c is the pressure at the TC center, r_0 is the scaling factor of the radial distribution of pressure, and v is the gradient wind speed.　The wind vectors are rotated inward 30 degrees to approximate the inflow in a TC.　For the asymmetry of the wind field in a TC, the moving velocity vector of the TC multiplied by a weight that decays exponentially with the distance from the TC center is added to the wind vector.　The resulting wind and pressure fields are applied to the storm surge model as external forcing.　These formulas diagnose wind and pressure fields at each point in time using the necessary input of forecast values as follows:

- The location (longitude and latitude) of the TC center
- The minimum pressure at the TC center
- The maximum sustained wind speed
- The radius of 50 kt wind speeds (if present)
- The radius of 1 000 hPa

These values are obtained from the tropical cyclone advisories issued by the RSMC Tokyo – Typhoon Center.

The surge model also uses wind and pressure fields predicted by MSM, which is a nonhydrostatic numerical weather prediction model with 5-km horizontal resolution. MSM runs eight times a day and provides 33-hour forecasts over the area of Japan. There are two reasons for using MSM fields in storm surge prediction. Firstly, these fields are used to predict storm surges caused by extratropical cyclones. When no TCs are present around Japan, the storm surge model predicts a single scenario using MSM prediction. Secondly, MSM generally gives more realistic wind and pressure fields than the parametric TC model when a TC is approaching the main islands of Japan. Complex meteorological processes such as extratropical transition, structural changes at the weakening stage and the effects of land topography mean that it is sometimes inappropriate to express the wind and pressure fields with the parametric TC model given by Eqs. (4) and (5). As described in Section 5, a comparative study confirmed that the use of MSM improves the accuracy of storm surge prediction, especially in short-range forecasting, because of its ability to reproduce realistic meteorological fields. JMA therefore started using MSM fields in operational storm surge prediction for TCs in September 2007.

4. Specifications and products of the model

Table 1 outlines the specifications of the storm surge model. Its horizontal resolution is one arc-minute in longitude and latitude, corresponding to an area of about 1.5 km by 1.9 km. The model area covers the whole of Japan (refer to Figure 2). The model runs eight times a day (i.e., every three hours) on JMA's high-performance computing system for numerical weather prediction, and provides 33-hour prediction of storm surges for about 290 locations along the Japanese coast.

Table 1 Specifications of the storm surge model

Area	23.5 – 46.5°N, 122.5 – 146.5°E
Grid resolution	1 arc-minute (1.5km in zonal direction, 1.9km in meridional direction)
Forecast range	33 hours
Initial time	00, 03, 06, 09, 12, 15, 18 and 21 UTC
Forecast members	6 members (in the case of tropical cyclones) 1 member (in the case of extratropical cyclones)

The model computes only storm surges, i.e., anomalies from the level of astronomical tides. However, storm tides (storm surges plus the astronomical tides) are also needed for the issuance of storm surge warnings. Astronomical tides are predicted using harmonic analysis of sea levels observed at tide stations beforehand. After the computation of the storm surge model, the level of the astronomical tide for each station is added to the predicted storm surge.

The model results are sent to local meteorological observatories that issue storm surge warnings to their individual areas of responsibility. These warnings include information on the period and water level of possible maximum surges in the area concerned, and are used by disaster prevention organizations for the implementation of countermeasures against disasters.

Provided with appropriate sets of meteorological forcing fields and bathymetric data, this model can also predict storm surges in other areas of the world. Appendix 1 presents an example of the model's application to storm surge events in Southeast Asia.

5. Performance of the model

In this section, we describe the performance of the storm surge model with two case studies and a comparative verification of surge prediction with two different forcing fields.

(a) (b)

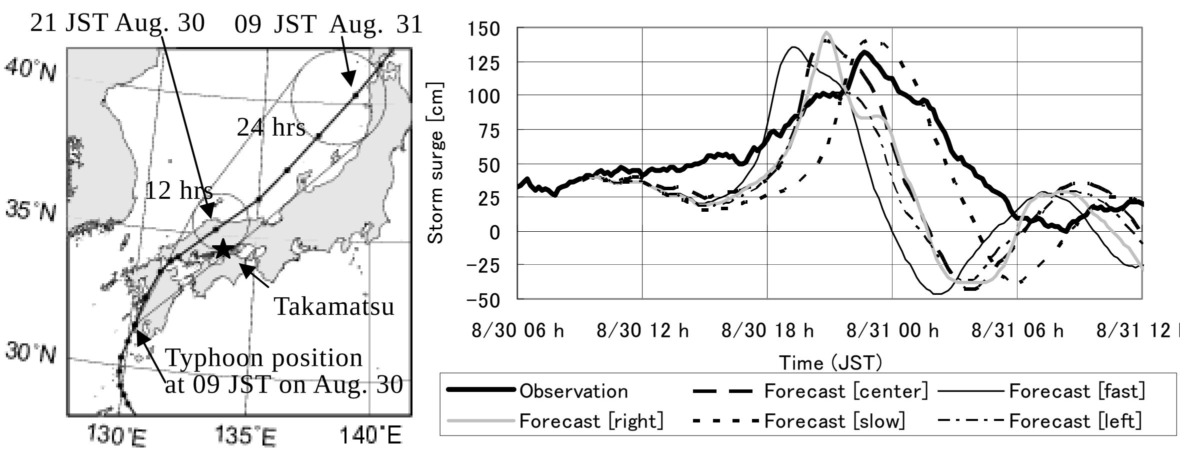

Figure 3 Track of Typhoon Chaba (T0416) and time series of a storm surge at Takamatsu.

(a) The track of the typhoon. The thick line is the analyzed track, and the dots on the line show six-hourly positions. The two circles indicate the possible areas of the typhoon's center position with 70% probability for 12-hour and 24-hour forecasts.

(b) Observed and predicted storm surges for the Takamatsu tide station.
The five thin lines depict the time series predicted for the five different typhoon tracks.

Case study 1: Typhoon Chaba (T0416)

Figure 3 shows a time series of the storm surge at the Takamatsu tide station on August 30 – 31, 2004, when Typhoon Chaba (T0416) passed the western part of Japan. This typhoon caused storm surge disasters in coastal areas in the western part of Japan, particularly those surrounding the Seto Inland Sea. Figure 3 also shows the storm surge predictions initialized at 09 JST on August 30 about 12 hours before the peak surge occurred. In this prediction, only the parametric TC model fields were used as forcing. As described above, five forecast runs were carried out for the five different possible TC tracks, and the results are denoted by the five different lines in the figure. The heights of the forecast peak surges show close agreement with the observation results. Although the time of the predicted peak surge for the center track is slightly earlier than the observed value, this five-member ensemble predicted the probability of the time lag. Based on this model result, the Takamatsu Local Meteorological Observatory issued storm surge warnings about six hours before the sea level reached its maximum. This example can be considered to demonstrate the effectiveness of the model.

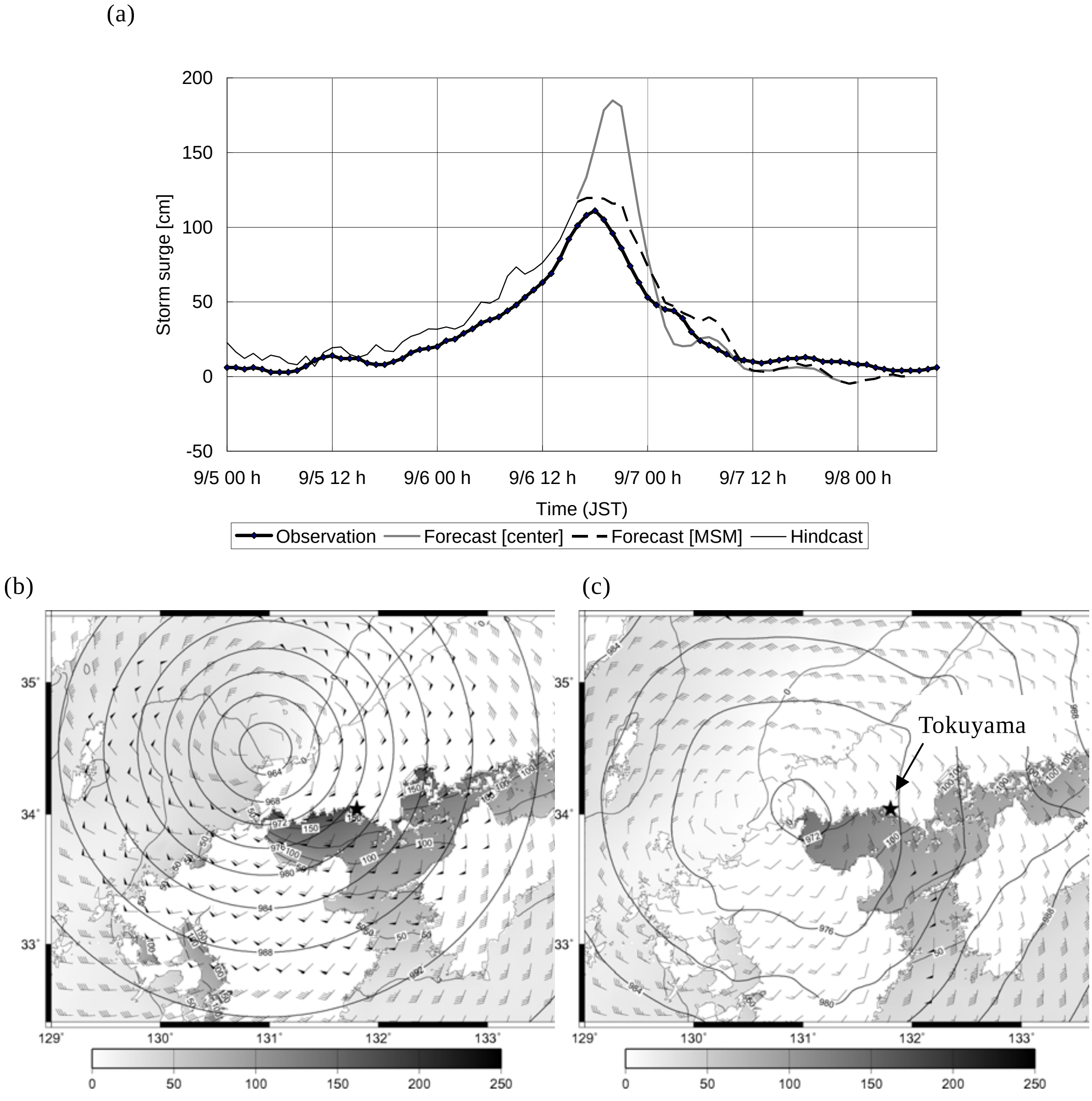

Figure 4 Storm surge of Typhoon Nabi (T0514).

(a) Time series of observed and predicted storm surge data at the Tokuyama tide station.

(b) Predicted surge distribution valid for 21 JST, 6 September 2005 (unit: cm). The surge model is driven by the fields from the parametric TC model. The wind and pressure fields are also shown.

(c) As (b), but for prediction driven by MSM.

Case study 2: Typhoon Nabi (T0514)

In the above case, the model successfully predicted the magnitude and timing of the storm surge, but in other cases it sometimes overestimated storm surges when used with the parametric TC model, as illustrated here. Figure 4 presents the storm surge caused by Typhoon Nabi (T0514). The typhoon made landfall on Kyushu in the western part of Japan after 14 JST on 6 September 2005, inducing storm surges of around a meter in adjacent coastal areas. Figure 4(a) indicates that storm surge prediction with the parametric TC model overestimated by 80 cm. To study the cause of this error, we conducted a storm surge simulation driven by the meteorological fields predicted by MSM, and compared the results with those of the parametric TC model. The time series of the surge predicted with MSM shown in Figure 4(a) agrees closely with the observation. The difference in these two surge predictions can be attributed to the difference in the wind fields used. Around the time of the peak surges, the typhoon was in the weakening stage after landfall and the wind field was affected by the complex topography of the surrounding land areas (Figure 4(c)). However, as shown in Figure 4(b), the parametric TC model gives a wind field that is symmetrical and much stronger than that of MSM. This is because it does not take into consideration factors such as the effect of land topography on the wind field, mainly due to its simple algorithm. These results suggest that the parametric TC model may overestimate wind fields in coastal areas in the weakening stage of TCs, resulting in overestimated surge prediction.

Comparative verification

To examine the performance of the storm surge model, we conducted verification of the model results by comparing them with observed storm surges. In this verification, we examined the difference in the accuracy of the predicted surges driven by two different forcing fields (the parametric TC model and MSM), since the choice of forcing field affects the accuracy of surge prediction as shown in the above case study. These two sets of surge predictions are compared with hourly storm surge values observed at about 110 tide stations along the Japanese coast for all tropical cyclones that approached or hit Japan from 2004 to 2007. For surge prediction with the parametric TC model, only the results for central TC tracks are used among the five results corresponding to the five TC tracks.

Figure 5 shows scatter diagrams of the predicted surges against the observed values. The predicted values include all those for 1-hour through 33-hour forecast times. The figures show that the surge predictions driven by the parametric TC model sometimes exceed observed surges by over 100 cm (Figure 5(a)), while the error of surge predictions with MSM fields lies in the range of ±100 cm (Figure 5(b)). This suggests that surge prediction with MSM generally provides better prediction than with the parametric TC model.

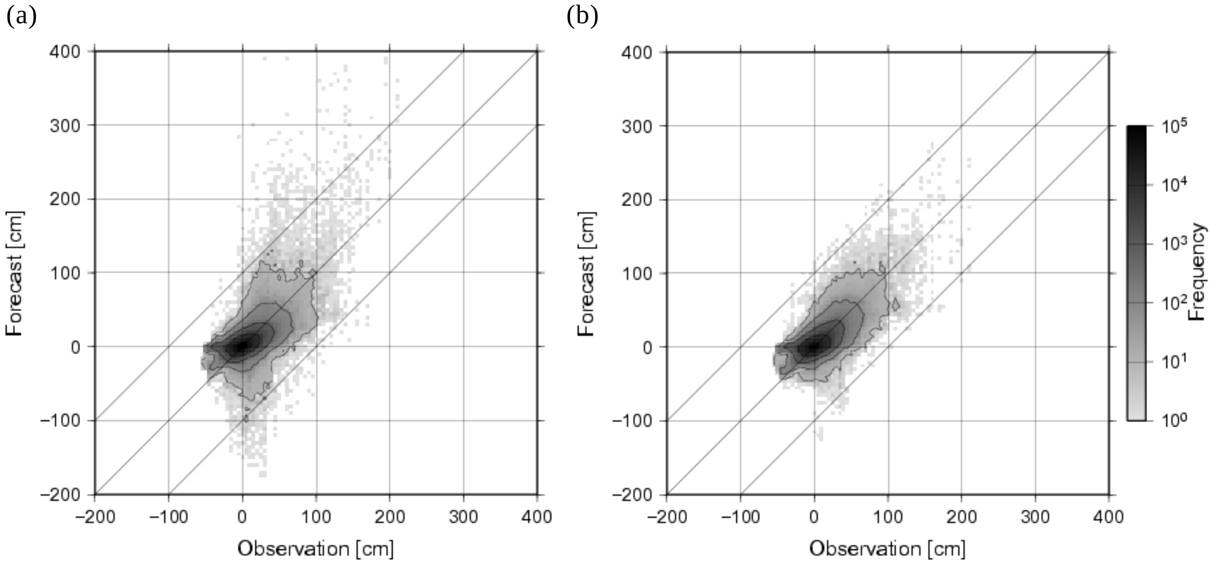

Figure 5　Scatter diagrams of predicted surges against the observed values.

(a) Predictions with parametric TC fields, (b) those with MSM.

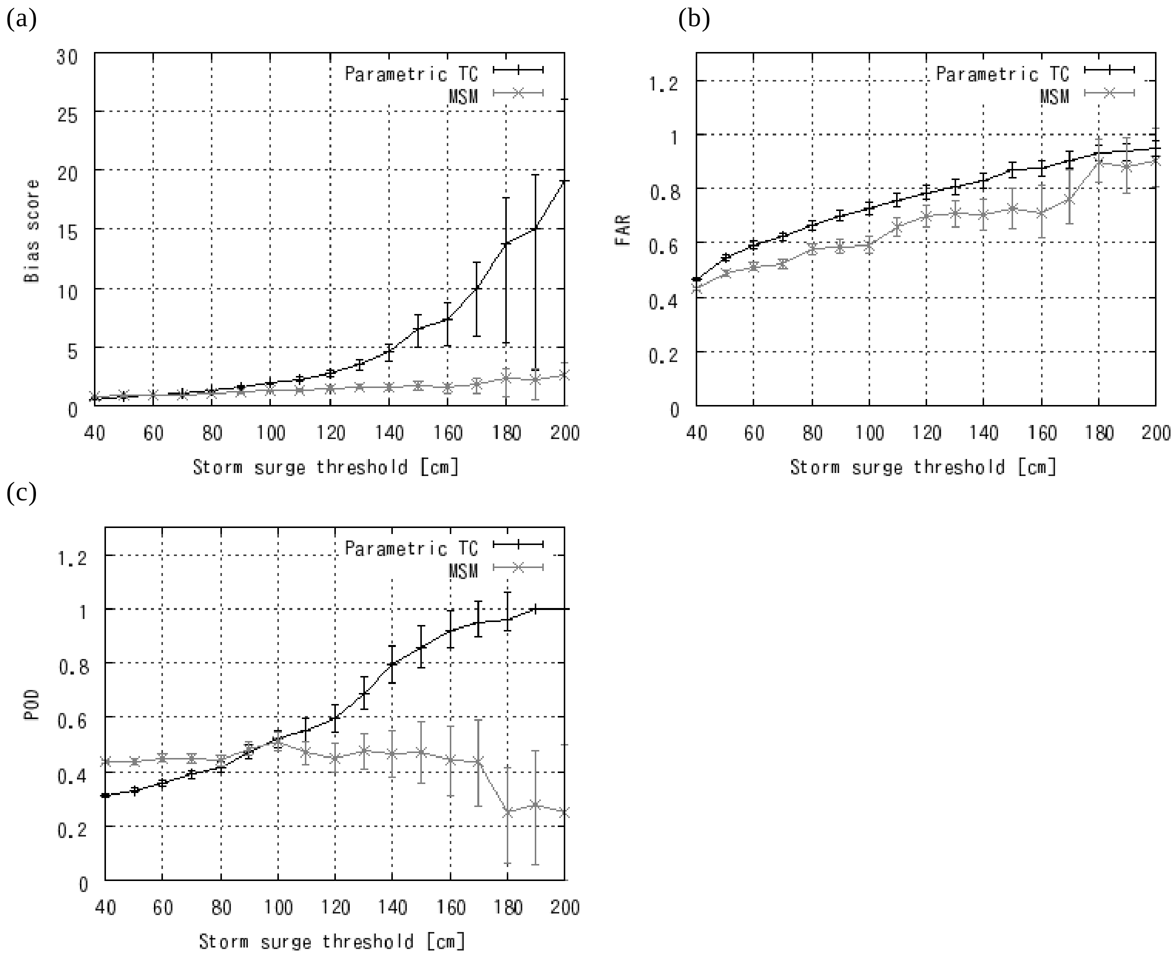

Figure 6　Verification scores.

(a) Bias score　(b) False alarm ratio (FAR)　(c) Probability of detection (POD).

To quantitatively evaluate the accuracy of the model, we also calculated verification scores; the bias score, the false alarm ratio (FAR) and the probability of detection (POD) (Figure 6). Refer to Appendix 2 for the definitions of these scores. The bias scores for the parametric TC model increase rapidly with the threshold, and those for storm surges of over one meter are much larger than one (the perfect score), while those of MSM are close to unity. The FAR scores increase with the threshold for both sets of predictions, but those for MSM are smaller than those of the parametric TC model. These two scores indicate that prediction with the parametric TC model has a tendency to overestimate, and that the use of MSM alleviates this tendency. On the other hand, for the threshold marking more than 100 cm, the POD of MSM is smaller than that for the parametric TC model, implying that prediction with MSM misses large storm surges more frequently than that with the parametric TC model. However, this is to be expected, since prediction with the parametric TC model has a tendency of overestimation as indicated by its large bias score.

In addition, to examine changes in accuracy with the forecast time, FAR and POD values for every six-hour period were calculated, and are shown in Figure 7. According to these figures, surge prediction with MSM gives better scores for short-range forecasts (FT=1 – 6), but its accuracy decreases with forecast time and approaches that of prediction with the parametric TC model after the 18-hour forecast point.

This comparative study suggests that the use of MSM will suppress the tendency of overestimation and improve the accuracy of short-range forecasting. Accordingly, we decided to use wind and pressure fields predicted by MSM as the forcing of the surge model as well as the parametric TC model, and have used this system since September 2007.

6. Summary and concluding remarks

This paper describes the major features of the operational storm surge prediction model at JMA. It is a two-dimensional model that runs eight times a day, providing 33-hour predictions of storm surges and sea levels for 290 points along the Japanese coast. The model results are used as the basis for storm surge warnings. One of its important features is that, when a TC is present around Japan, the model predicts multiple scenarios of storm surges with different meteorological forcing fields to allow for the uncertainty in TC track forecasts. A parametric TC model and JMA’s nonhydrostatic mesoscale model are used as the sources of meteorological forcing for the storm surge model.

The performance of the storm surge model was investigated through two case studies and a comparative verification. Although the parametric TC model is useful for creating an ensemble of meteorological forcing, it was found to sometimes overestimate wind speed in TCs, resulting in overestimation in storm surge prediction. The results of the verification suggest that the use of MSM prediction for surge model forcing suppresses the tendency for overestimation and improves the short-range prediction of storm surges.

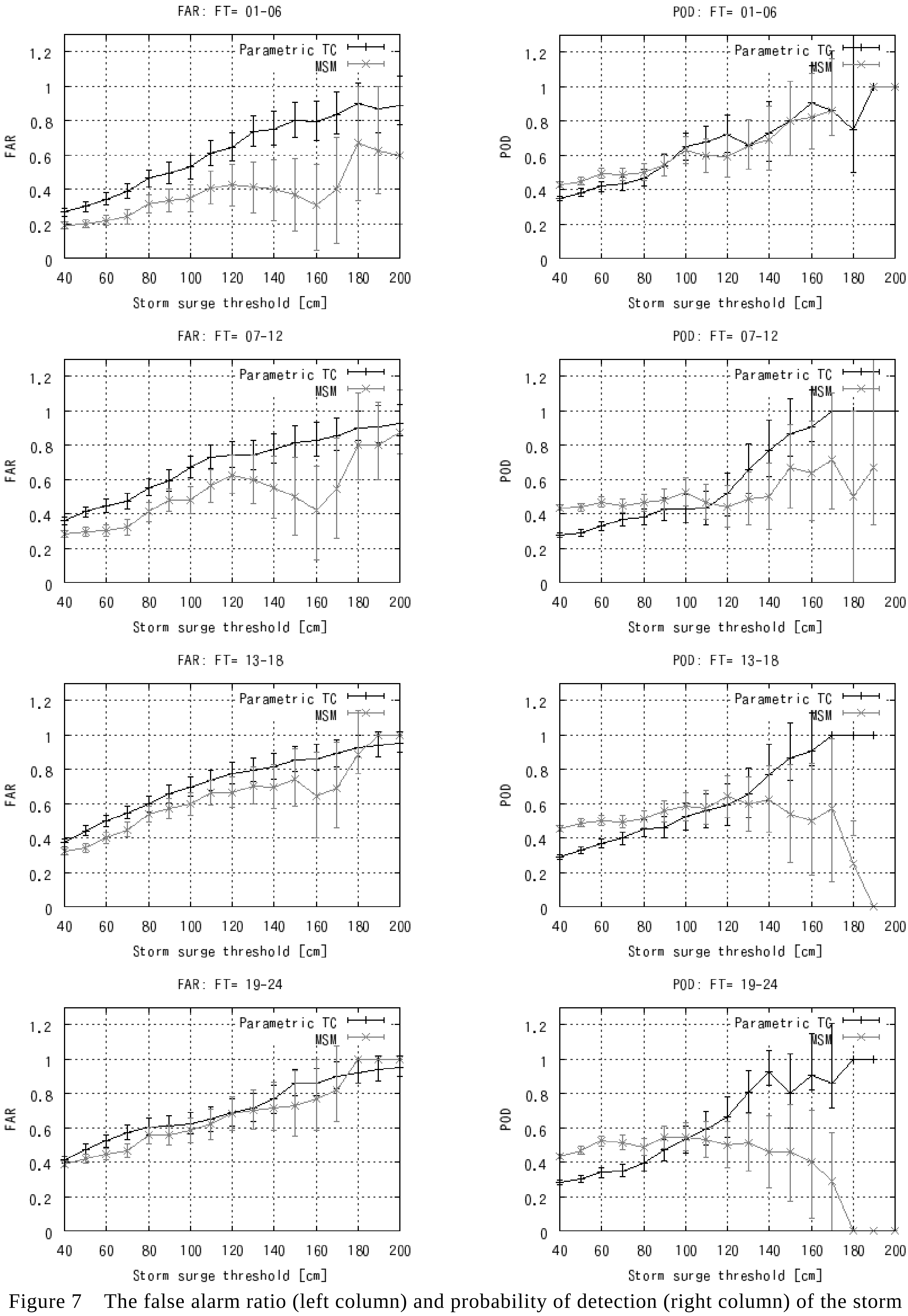

Figure 7　The false alarm ratio (left column) and probability of detection (right column) of the storm surge model for each six-hourly forecast period.

From top to bottom, scores for 1 – 6, 7 – 12, 13 – 18 and 19 – 24 hour forecasts, respectively.

As explained in Section 4, the model described in this paper calculates only storm surge components, but disaster mitigation activities also require astronomical tide prediction to forecast the total water level or storm tide. For this purpose, JMA carries out harmonic analysis of sea level data observed at tide stations for several to ten years, and calculates astronomical tides using the harmonic analysis results. This method gives pointwise astronomical tide predictions. In order to estimate astronomical tides at any given location without a tide station, JMA has been developing a data assimilation method to combine the information from observation data and an ocean tide model.

Storm surges are generally caused by wind setup and the inverted barometer effect. However, in addition to these effects, ocean waves also influence the occurrence of storm surges on coasts facing deep open seas; this effect is called *wave setup* (Longuet-Higgins and Stewart, 1964; Konishi, 1997). Since wave setup should also be predicted, but the current version of the JMA storm surge model does not consider it, a method to estimate its effects is now under development.

Lastly, the model computes water level changes at points in the sea, but the prediction of seawater inundation in coastal land areas remains beyond its scope.

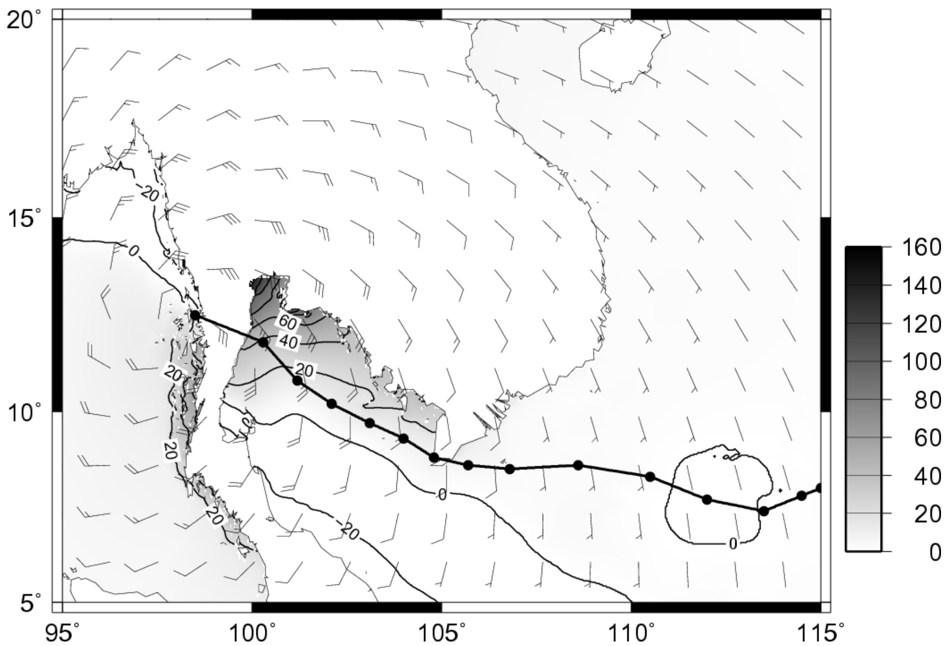

Figure A1 Modeled storm surge for the case of STS Linda (T9726).

The shaded areas show the modeled surge distribution for 00 UTC on 4 November 1997 (unit: cm).

The thick line represents the TC track, and the dots on the line depict the six-hourly positions.

Appendix 1　Application of the JMA storm surge model to storm surge events in Southeast Asia

Provided with appropriate sets of meteorological forcing fields and bathymetric data, this model can predict storm surges in countries other than Japan, and can be run on a PC if a modest model setting is chosen, such as a 2-arc-minute horizontal resolution and a 20°×20° model domain.　As mentioned in Section 3, the input data needed are the TC parameters when the parametric TC model is used to create the external forcing of the surge model.

As an example of the model's application to surge events in Southeast Asia, its results for the surge event associated with STS Linda (T9726) are presented in Figure A1.

Appendix 2　Definitions of verification scores

This appendix gives the definitions of the verification scores used in this paper, which are based on Jolliffe and Stephenson (2003).　All pairs of predicted and observed values are divided into four categories as shown in Table A1, and the frequencies of the four categories are used to calculate the verification scores.

Table A1　Contingency table

		Observed	
		Yes	No
Forecast	Yes	Hits	False alarms
	No	Misses	Correct negatives

(1) Bias score

The bias score is the ratio of the number of forecasts of occurrence to the number of actual occurrences.　Scores range from 0 to infinity, and the perfect score is 1.

$$BS = \frac{(\text{hits}) + (\text{false alarms})}{(\text{hits}) + (\text{misses})} \qquad \text{(A1)}$$

(2) Probability of detection (POD)

This quantity is defined by:

$$POD = \frac{(\text{hits})}{(\text{hits}) + (\text{misses})} \qquad \text{(A2)}$$

It represents the total number of correct event forecasts (hits) divided by the total number of events observed.　It ranges from 0 to 1, and the perfect score is 1.

(3) False alarm ratio (FAR)

FAR is defined by:

$$FAR = \frac{(\text{false alarms})}{(\text{hits}) + (\text{false alarms})} \qquad \text{(A3)}$$

It is the number of false alarms divided by the total number of event forecasts.　It can vary from 0 to 1.　A FAR value of zero represents perfect skill.

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