Development of Storm Surge Model in Japan Meteorological Agency

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Abstract

Japan Meteorological Agency (JMA) routinely operates two storm surge models. One is Japan area storm surge model which is used for mainly issuing storm surge warnings in domestic region. Another model, which is Asia area storm surge model, is operated for the purpose of providing real time storm surge infomation for Typhoon Committee members in the framework of the Storm Surge Watch Scheme (SSWS).

Calculations of the Asia area storm surge model are based on one scenario by Global Spectral Model (GSM). However, deterministic forecast is insufficient for risk management. Therefore, JMA plans to introduce multi-scenario predictions into the Asia area storm surge model. The scenarios are determined from JMA Typhoon Ensemble Prediction System (TEPS) with cluster analysis. The products are going to be issued in 2016.

JMA is also developing the next generations storm surge prediction system using Finite Element Method (FEM) model. Techniques to divide model region to finite elements and to make unstructured grids are established. JMA is operating the prototype FEM storm surge model for Asia area aiming for practical use in the next JMA super computer system (2018-).

1 Japan Area Storm Surge Model

Since Japan has suffered from many storm surge disasters over the years, accurate and timely forecasts and warnings are critical to mitigating the threat to life and property from such storm surges.

JMA, which is responsible for issuing storm surge warnings, has operated a numerical storm surge model since 1998 to provide basic information for the warnings.

Numerical storm surge prediction started in July 1998 only when a typhoon exists. The storm surge model has been modified in enlarging the model domain, prediction for the extratropical cyclone case, extending of forecast time and adding advection terms, etc. Since May 2010, for more detailed information and warnings, a new storm surge model with higher resolution (approximately 1 km mesh) and the gridded astronomical tide analysis method have been operated.

1.1 Dynamics

Storm surges are mainly caused by the effect of wind setup due to strong onshore winds on sea surface and inverse barometer effect associated with pressure drop in a low pressure system. The effect of wind setup is proportional to the square of wind speed and inversely proportional to water depth, and related with the coastal topography, that is, it is amplified in a bay opened against the wind.

The storm surge model operated in the JMA is almost the same as the one discribed in [6]. This model includes the ocean model and the part which makes the meteorological fields that drive the ocean model. To predict the temporal and spatial variations of sea level in response to such meteorological disturbances, the storm surge model utilizes two-dimensional shallow water equations. The shallow water equations consist of vertically integrated momentum equations in two horizontal directions:

$$\frac{\partial U}{\partial t}+u\frac{\partial U}{\partial x}+v\frac{\partial U}{\partial y}-fV=-g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial x}+\frac{\tau_{\mathrm{sx}}}{\rho_w}-\frac{\tau_{\mathrm{bx}}}{\rho_w} \quad (1)$$

$$\frac{\partial V}{\partial t}+u\frac{\partial V}{\partial x}+v\frac{\partial V}{\partial y}+fU=-g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial y}+\frac{\tau_{\mathrm{sy}}}{\rho_w}-\frac{\tau_{\mathrm{by}}}{\rho_w} \quad (2)$$

and the continuity equation:

$$\frac{\partial \eta}{\partial t}+\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \quad (3)$$

where U and V are volume fluxes in the x- and y-directions, defined as:

$$U \equiv \int_{-D}^{\eta} u\,dz \quad (4)$$

$$V \equiv \int_{-D}^{\eta} v\,dz \quad (5)$$

f is the Coriolis parameter; g is the gravity acceleration; D is the water depth below mean sea level; η is the surface elevation; η_0 is the inverse barometer effect converted into the equivalent water column height; ρ_w is the density of water; $\tau_{\rm sx}$ and $\tau_{\rm sy}$ are x- and y-components of wind stress on sea surface; and $\tau_{\rm bx}$ and $\tau_{\rm by}$ are stresses of bottom friction, respectively.

The equations are solved by numerical integration using an explicit finite difference method. Regarding grid system, the staggered (or Arakawa-C) grid [1] is adopted.

1.2 Meteorological Forcing

The fields of surface wind and atmospheric pressure predicted by the JMA Meso-Scale Model (MSM) are required as external forcing for the storm surge model. When a tropical cyclone (TC) exists around Japan, a simple parametric TC model is also used.

The simple parametric TC model (or referred to as bogus) is introduced in order to take into account the error of TC track forecast and its influence on storm surge forecasting. To consider 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 TC tracks are prescribed at the center and at four points on the forecast circle within which a TC is forecasted to exist with a probability of 70% (Figure 1):

1. Center track
2. Fastest track
3. Rightward biased track
4. Slowest track
5. Leftward biased track

and used to make meteorological fields with the parametric TC model.

The simple parametric TC model utilizes the Fujita's formula [4] that represents the radial pressure distribution in a TC:

$$P = P_\infty - \frac{P_\infty - P_c}{\sqrt{1 + (r/r_0)^2}} \quad (6)$$

and the gradient wind relation:

$$-\frac{v_g^2}{r} - f v_g = -\frac{1}{\rho}\frac{\partial P}{\partial r} \quad (7)$$

In Eq.6, P is an atmospheric pressure at distance r from the center of a TC, P_∞ is the atmospheric pressure at an infinitely distant point, P_c is the pressure at TC center and r_0 is the scaling factor of the radial distribution of the pressure. In Eq.7, ρ is the density of air, v_g is the gradient wind.

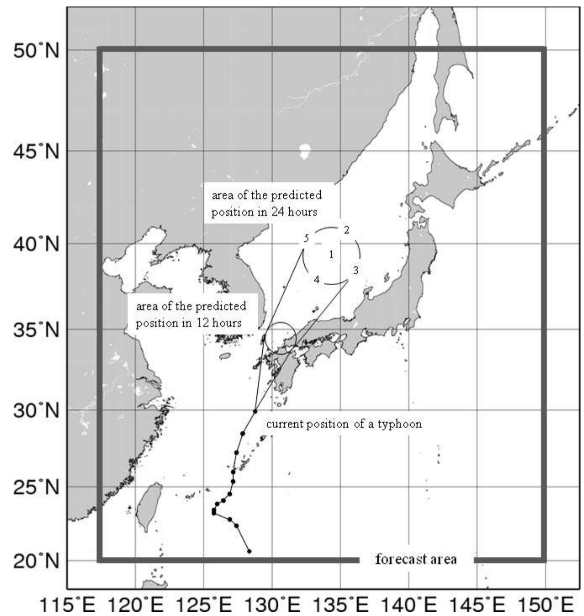

Figure 1: TC tracks of bogus and the domain of the Japan area storm surge model

To represent the asymmetry of wind field $\mathbf{w}$ in a TC, the moving velocity vector of the TC multiplied by a weight that decays exponentially with the distance from TC center is added to the gradient wind:

$$\mathbf{w} = C_1 \left\{ \mathbf{v_g} + \mathbf{C} \cdot \exp\left(-\pi \frac{r}{r_e}\right)\right\} \quad (8)$$

$\mathbf{C}$ is the the moving velocity vector of the TC, r_e is the coefficient of decay.

Analysis and forecast information on TC, such as center position, central pressure and maximum wind are applied to these formulas to synthesize the wind and pressure fields [7].

1.3 Specifications of the Model

Table 1.3 gives the specifications of the storm surge model. The finest horizontal resolution of the model is $45''$(lon) $\times$ $30''$(lat) (approximately 1km mesh). The model domain covers the entire Japan.

Since the storm surge is the shallow water long wave, its phase speed is proportional to the square root of water depth. It is inefficient to set all grids with the same resolution from a viewpoint of computer resources. Therefore, the adaptive mesh refinement [2] in which the mesh

Table 1: Specifications of the Japan area storm surge model

Model	2-dimensional model
Grid	Lat-Lon Arakawa-C grid
Region	20°N - 50°N, 117.5°E - 150°E
Resolution	approximately 1, 2, 4, 8, 16 km (Adaptive mesh)
Time step	4 seconds
Initial time	00, 03, 06, 09, 12, 15, 18, 21 (UTC)
Forecast time	39 hours
Member	TC case: 6 members (MSM+5 bogus) no TC case: 1 member (MSM)

is fine over the shallow water and coarse over the deep water is adopted. The resolution is varied for 5 levels (1, 2, 4, 8 and 16 km) with the water depth. This method makes the storm surge calculations more efficient than the normal lat-lon grid system.

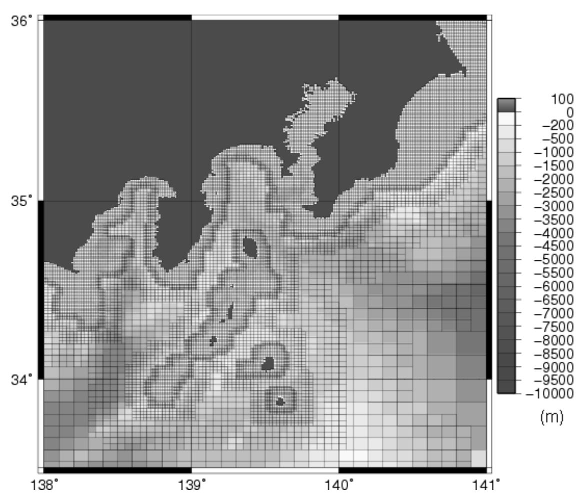

Figure 2: Horizontal grid system and water depth of the storm surge model (around Kanto region)

The storm surge model runs 8 times a day (every 3 hours) and calculates storm surge predictions up to 39 hours ahead. Initial values are generated by a previous calculation using the newest MSM prediction as the forcing (hindcast). Since the initial values are not so important as the one in atmospheric models, assimilation of observation data is not conducted.

The model computes only storm surges, i.e. anomalies from the level of astronomical tides. However, storm tides (storm surge plus astronomical tide) are also needed in issuing a storm surge warning. Astronomical tides are predicted by using harmonic analyses of sea level observations. The JMA developed the gridded astronomical tide method which calculates the astronomical tide even on the no-observation grid. After the computation of the storm surge model, the level of astronomical tide for the coastal area is added to the predicted storm surge.

Then the results are sent to Local Meteorological Observatories that issue storm surge warnings to their responsible areas.

1.4 Plans

Current five runs with possible TC tracks on the forecast circle don't always have the same possibilities. For valid information for risk management, probabilistic forecast being needed. JMA plans to introduce EPS into Japan Area Storm Surge Model based on Meso-scale EPS (MEPS) in the next JMA super computer system.

2 Asia Area Storm Surge Model

In recent years, heavy storm surge disasters occurred worldwide, such as the one in the coast of the Gulf of Mexico caused by Hurricane Katrina in 2005, the one in the coast of Bangladesh by Cyclone Sidr in 2007, the one in the coast of Myanmar by Cyclone Nargis in 2008, and the one in the coast of Philippines by Typhoon Haiyan in 2013. By these storm surges more than thousands of people suffered. The countermeasures for storm surges and inundation are crucial.

In response to a request by the WMO Executive Council (60th session, June 2008), WMO initiated the development of a regional SSWS in regions affected by tropical cyclones. In relation to the western North Pacific and the South China Sea, the ESCAP/WMO Typhoon Committee (41st session, January 2009) endorsed a commitment by the RSMC (Regional Specialized Meteorological Center) Tokyo - Typhoon Center to prepare storm surge forecasts with the aim of strengthening the storm surge warning capabilities of National Meteorological and Hydrological Services (NMHSs) in the region. JMA began development of a storm surge model for the Asia region in 2010, in collaboration with Typhoon Committee members who provide sea level observation and sea bathymetry data. Horizontal distribution maps of predicted storm surges and time series charts have been published on JMA's Numerical Typhoon Prediction website [5].

2.1 Dynamics

The basic equations of the Asia area storm surge model are nearly the same as those of the Japan area storm surge model (Section 1) except that advection terms are omitted:

$$\frac{\partial U}{\partial t} - fV = -g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial x} + \frac{\tau_{\rm sx}}{\rho_w} - \frac{\tau_{\rm bx}}{\rho_w} \quad (9)$$

$$\frac{\partial V}{\partial t} + fU = -g(D+\eta)\frac{\partial(\eta-\eta_0)}{\partial y} + \frac{\tau_{\rm sy}}{\rho_w} - \frac{\tau_{\rm by}}{\rho_w} \quad (10)$$

and the continuity equation:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \quad (11)$$

Definitions of each variables and constants are the same as those of the Japan area storm surge model.

2.2 Data

The bathymetry data for the storm surge model is mainly made from the 2-minute Global Gridded Elevation Data (ETOPO2) of NGDC/NOAA (Figure 3). The bathymetry data was partly modified with local bathymetry data provided by the Typhoon Committee members, which enable more accurate forecast.

The astronomical tides are determined by harmonic analysis using the past tide observation data provided by the Typhoon Committee members.

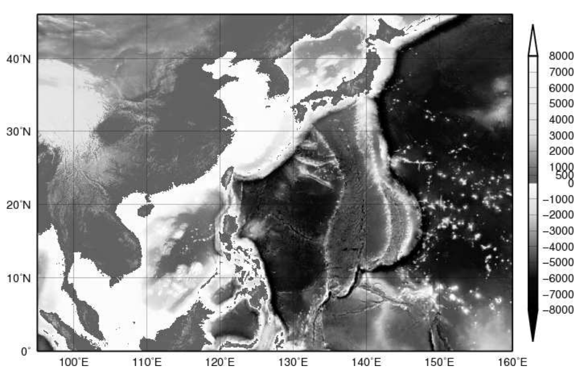

Figure 3: Model domain and topography of the Asia area storm surge model

2.3 Meteorological Forcing

In the operation of the Asia area storm surge model, two kinds of meteorological forcing field are used. One is a simple parametric TC model, and the other is the products of the JMA operational GSM. The simple parametric TC model of the Asia area storm surge model is the same one as of the Japan area storm surge model (Section 1).

2.4 Specifications of the Model

Table 2.4 shows the outline of the specifications of the Asia area storm surge model. The horizontal grid resolution is 2 minutes, corresponding to a distance of about 3.7 km. The model covers almost all areas in the RSMC Tokyo - Typhoon Center area of responsibility (Figure 3). It runs four times a day (every 6 hours), and calculates storm surge predictions up to 72 hours ahead. Each calculation takes about 10 minutes, and storm surge distribution maps are created using the results. When no typhoon is expected nor exist during the forecast time, the model calculates the hindcast only for the next run, and no distribution maps are produced.

The 3-hourly distribution maps of the whole domain and enlarged versions showing only the areas around typhoon are available up to 72 hours. The time series charts include predicted/astronomical tide, storm surge, sea level pressure and surface wind.

Table 2: Specifications of the Asia area storm surge model

Model	2-dimensional linear model
Grid	Lat-Lon Arakawa-C grid
Region	0° - 46°N, 95°E - 160°E
Resolution	2-minutes mesh (approximately 3.7 km mesh)
Time step	8 seconds
Initial time	00, 06, 12, 18 (UTC)
Forecast time	72 hours
Member	1 member

3 Multi-Scenario Predictions for SSWS

Calculations of the Asia area storm surge model are based on one scenario by GSM and bogus. However, deterministic forecast is insufficient for risk management. Therefore, JMA plans to introduce multi-scenario predictions into the Asia area storm surge model. The scenarios are determined from JMA Typhoon EPS with cluster analysis. The products are going to be issued in 2016.

3.1 JMA Typhoon EPS

Since February 2008, JMA has operated a TEPS as RSMC Tokyo in the framework of the WMO. The system employs a low-resolution version of GSM.

Multi-scenario predictions for SSWS are based on TEPS which was upgraded in March 2014 [8]. A major TEPS upgrade in March 2014 included enhancement for the horizontal resolution of the EPS model and an increased ensemble size.

Table 3: Configurations of the current and previous TEPS

	Previous system	Current system
Ensemble size	11	25
Initial time	00, 06, 12, 18 (UTC)	
Forecast range	132 hours	
Resolution	TL319 (55 km)	TL479 (40 km)

3.2 Cluster Analysis

Current TEPS's ensemble size is 25 members. This number is too large for Asia area storm surge model from restriction of computer resources. Therefore, we should select some scenarios from whole members.

In our plan, cluster analysis (K-means method) is adopted to determine five scenarios:

$$\mathbf{C}_k = \frac{1}{N_k} \sum \mathbf{x}_i, (k = 1, \cdots, K) \quad (12)$$

$$\mathbf{x}_i = (lat_i, lon_i), (i = 1, \cdots, N) \quad (13)$$

where $\mathbf{C}_k$ is center of cluster and $\mathbf{x}_i$ is location of typhoon. In this case, $N = 25$, $K = 5$. Five scenarios should have appropriate variance with each other to cover representative scenarios (Figure 4). In the first step, initial clusters are given appropriate variance to a certain degree. Cluster analysis is executed iteratively until Clusters are fixed. In the last step, nearest members from each centers of cluster are adopted.

TEPS's resolution is too coarse to predict storm surge accurately. Therefore, the simple parametric TC model (bogus) is introduced to typhoon track of selected members.

3.3 Example of Calculation

Typhoon Haiyan hit and seriously damaged the Philippines in November 2013. Maximum wind speed was 65 [m/s], minimum pressure was 895 [hPa]. Approximately 5,000 peple died from storm surge. Maximum peak surge was estimated at about 5 [m] from field surveys.

Figure 5 - 7 are example of multi-scenario prediction for typhoon Haiyan. Figure 5 shows selected five typhoon tracks. Figure 6 shows timeseries chart in Tacloban (Philippines). The models predicted storm surge well though the model slightly underestimated peak surge. Figure 7 shows timeseries chart in Quynhon (Vietnam). Peak surge in the coast of Vietnam occured in the latter half of forecast time. The predicted peak surges are remarkably variant with each scenarios.

Multi-scenario prediction is valid for uncertain case in terms of risk management. JMA is going to start oper-

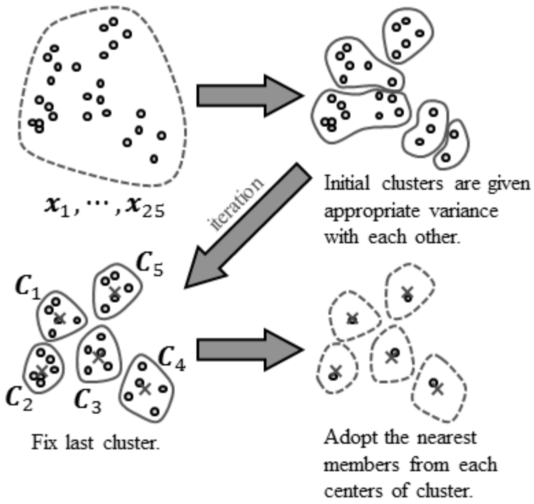

Figure 4: Method of scenario selection

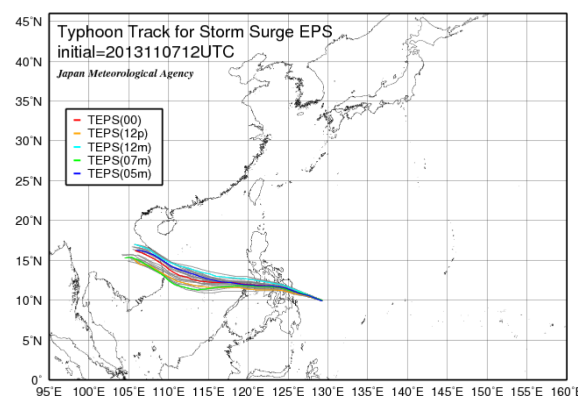

Figure 5: Typhoon tracks calculated by TEPS in Haiyan (2013)

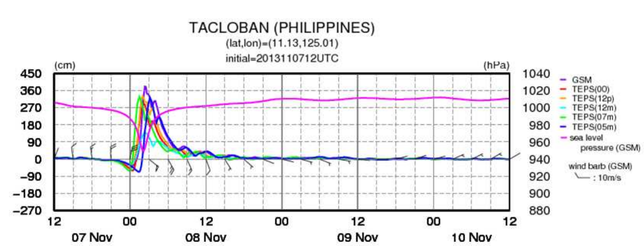

Figure 6: Timeseries chart in Tacloban (Philippines)

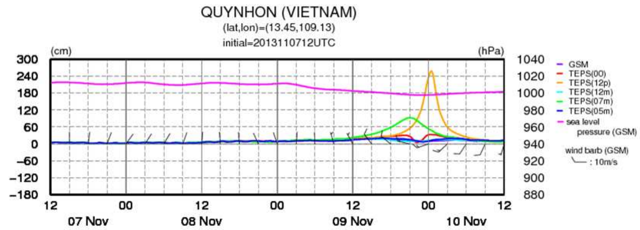

Figure 7: Timeseries chart in Quynhon (Vietnam)

ating multi-scenario system and its products are going to be issued from 2016. We compromise on the five scenario system in current JMA super computer system but some members are going to be added in order to introduce probabilistic forecast in the next super computer system.

4 Finite Element Method Model

FEM being focused on as a solution of storm surge predictions instead of Finite Difference Method. In FEM, model region is divided to finite elements and any forms of element are valid (unstructured grid). FEM is superior for dealing with complicated coastlines and is suitable for storm surge predictions. Aiming for practical use in the next super computer system (2018-), JMA is developing new storm surge prediction system using FEM model.

4.1 Generating Unstructured Grid

Techniques to divide model region to finite elements and to make unstructured grids are established. Delaunay triangulation [3] is adopted. Global Self-consistent Hierarchical High-resolution Geography (GSHHG) of NGDC/NOAA is used as coastline data. From restriction of computer resources, coastline data is modified to target resolution for operational use. Bathymetry data is made from the 1-minute Global Gridded Elevation Data (ETOPO1) of NGDC/NOAA.

5 Summary

JMA is responsible for issuing storm surge warnings in domestic region and providing real time storm surge information for Typhoon Committee members as RSMC Tokyo. For that purposes, JMA operates two storm surge models.

Improvement of storm surge models is required for better information. JMA is developing storm surge models for upgrading. JMA plans to introduce multi-scenario prediction in current super computer system and to introduce EPS and FEM model in the next system.

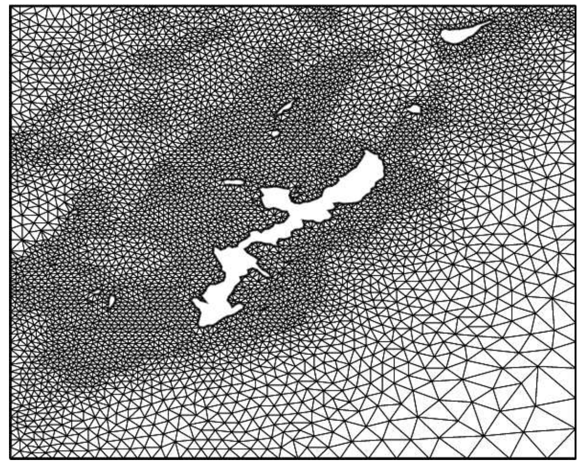

Figure 8: Unstructured grid around Okinawa area

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