Upgrade of JMA's Storm Surge Prediction for the WMO Storm Surge Watch Scheme (SSWS) in 2022

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1. Introduction

Since 2011, the Japan Meteorological Agency (JMA) has operated an Asia-area model for the provision of real-time storm surge prediction information to the Economic and Social Commission for Asia and the Pacific (ESCAP) and World Meteorological Organization (WMO) Typhoon Committee Members within the framework of the WMO Storm Surge Watch Scheme (SSWS, Hasegawa et al. 2012). The Agency began providing storm surge time-series charts for selected locations in 2012, and the model used for this has been upgraded several times since then. Its forecast domain was extended in 2013, and provision of storm surge predictions for non-tropical-cyclone situations associated with winter monsoons and synoptic eddies was begun in January 2016. Multi-scenario prediction was also introduced in June 2016 to support the provision of even more useful risk management information (Hasegawa et al. 2017).

As multi-scenario prediction (previously with six scenarios) was technically limited in the representation of uncertainties associated with atmospheric forcing, more ensemble members and probabilistic forecasting were required for greater efficiency in risk management. Against this background, a storm surge ensemble prediction system with 52 ensemble members was introduced in August 2022, and the storm surge model was upgraded to incorporate the finite volume method (FVM) with an unstructured triangular grid to reduce computational consumption. JMA also (1) increased the grid resolution around coastal regions from 2 minutes (approx. 4 km) to 1.5 km, (2) extended the forecast period from 72 to 132 hours, (3) expanded the model domain to cover most of the Regional Specialized Meteorological Centre (RSMC) Tokyo's area of responsibility, and (4) improved the parametric TC model (typhoon bogus). Section 2 below details the model upgrades, Section 3 presents the new SSWS forecast products, Section 4 describes model performance, and Section 5 provides a summary.

2. Model

Table 1 compares the specifications of the previous model and the 2022 upgraded version. This section details the changes.

2.1 Governing equations

Table 1. Previous and new storm surge model specifications

	Previous	New
Model	Two-dimensional linear	Two-dimensional non-linear
Grid	Lat-lon Arakawa-C grid	Unstructured Arakawa-B grid
Region	0 – 46ºN, 95 – 160ºE	0 – 50ºN, 95 – 180ºE
Resolution	2-minute mesh (– 3.7 km)	1.5 – 50 km
Time step	8 seconds	4 seconds
Forecast period	72 hours	132 hours
Cycle	4/day (every 6 hours)	4/day (every 6 hours)
Initial times	00, 06, 12, 18 UTC	00, 06, 12, 18 UTC
Members	No tropical cyclone: 1 member (GSM) Tropical cyclone: 6 members (GSM + GEPS 5 members with typhoon bogus)	No tropical cyclone: 1 member (GSM) Tropical cyclone: 52 members (GSM + GEPS 51 members with typhoon bogus)
Atmospheric forcing	GSM* (0.25 x 0.2º) GEPS** (0.5625 x 0.5625º)	GSM (– 20 km[1]) GEPS (– 27 km)
Typhoon forcing (bogus)	● Pressure: Fujita's formula ● Inflow angle: 30º ● Velocity for asymmetry	● Pressure: Fujita's formula ● Inflow angle: 30º ● Velocity for asymmetry ● Directional land roughness parameterization (Westerink et al., 2008)

*GSM: JMA Global Spectral Model; **GEPS: JMA Global Ensemble Prediction System

The new model solves the following two-dimensional non-linear shallow water equations driven by meteorological fields. These are composed of vertically integrated momentum elements in two horizontal directions,

$$\frac{\partial U}{\partial t} + \frac{1}{r\cos\varphi}\left(\frac{\partial u^2 H}{\partial \lambda} + \frac{\partial uvH\cos\varphi}{\partial \varphi}\right) - fvH - \frac{uvH}{r}\tan\varphi = -\frac{gH}{r\cos\varphi}\frac{\partial(\zeta - \zeta_0)}{\partial \lambda} + \frac{\tau_{s\lambda}}{\rho_w} - \frac{\tau_{b\lambda}}{\rho_w} \quad (1)$$

$$\frac{\partial V}{\partial t} + \frac{1}{r\cos\varphi}\left(\frac{\partial uvH}{\partial \lambda} + \frac{\partial v^2 H\cos\varphi}{\partial \varphi}\right) + fuH + \frac{u^2 H}{r}\tan\varphi = -\frac{gH}{r}\frac{\partial(\zeta - \zeta_0)}{\partial \varphi} + \frac{\tau_{s\varphi}}{\rho_w} - \frac{\tau_{b\varphi}}{\rho_w} \quad (2)$$

and the following continuity equation is also used,

[1] The 20 km GSM resolution was introduced with the new storm surge model in August 2022, and was increased to 13 km in March 2023.

$$\frac{\partial \zeta}{\partial t}+\frac{1}{r\cos\varphi}\left(\frac{\partial uH}{\partial \lambda}+\frac{\partial v\,H\cos\varphi}{\partial \varphi}\right)=0 \tag{3}$$

where, u and v are current velocity components in the λ- (zonal) and φ- (meridional) directions. U and V are water mass fluxes defined as:

$$U \equiv \int_{-H_0}^{\zeta} udz \tag{4}$$

$$V \equiv \int_{-H_0}^{\zeta} vdz \tag{5}$$

f is the Coriolis parameter, g is gravity acceleration, r is the earth's radius, H is total water depth, ζ is surface elevation, ζ_0 is the inverse barometer effect converted into equivalent water column height, ρ_{w} is the density of water, $\tau_{\mathrm{s\lambda}}$ and $\tau_{\mathrm{s\varphi}}$ are the λ- and φ-components of wind stress on the sea surface, respectively, $\tau_{\mathrm{b\lambda}}$ and $\tau_{\mathrm{b\varphi}}$ are the λ- and φ-components of bottom friction stress, respectively, and H_0 is water depth.

In the 2022 update, the model was changed from a linear to a non-linear by adding advection terms, and its equations were extended to incorporate spherical effects. The model includes wind setup due to strong wind and inverse barometer effects associated with pressure drops, but does not incorporate schemes for wave setup, coastal inundation and sea level changes associated with other factors such as sea temperature.

JMA also reviewed drag coefficient formulation and adopted a parabolic model of drag coefficients (Peng and Li, 2015):

$$C_{\mathrm{d}}=\begin{cases}[3.146-0.00188\times(W-33)^2]\times10^{-3} & (W<60\ \ m/s)\\ \left[1.5+0.2755\times e^{-0.3685(W-60)}\right]\times10^{-3} & (W\geq 60\ \ m/s)\end{cases} \tag{6}$$

Here, W is surface wind speed. The drag coefficient thus increases with this value up to a maximum and decreases thereafter.

2.2 Unstructured grid and finite volume method

JMA spent several years planning the introduction of the storm surge ensemble prediction system and increased grid resolution. As a first step, a new storm surge model with lower computer resource consumption was required. Accordingly, the new model incorporates the finite volume method (FVM) for discretization in an unstructured grid system, with domain division into triangles of arbitrary sizes and shapes. This enables simulation of storm surges in coastal areas and open seas with fine and coarse resolution and the generation of topography-fitting meshes, making it efficient in storm surge prediction.

The equations are solved via numerical integration using the FVM. A staggered Arakawa-B approach (Arakawa and Lamb 1977) is adopted for the grid system, with current velocities (represented by vectors) located at triangle centroids and scalar surface elevations located at triangle vertices. The triangles represent vector control volumes, and scalar control volumes are defined by connecting triangle centroids and edge midpoints (Figure 1). These arrangements are also used in ocean circulation models such as the Finite Volume Community Ocean Model (FVCOM) (Chen et al. 2013) and the Finite-volume Sea Ice Ocean Model (FESOM2) (Danilov et al. 2017).

To suppress sub-grid scale noise and ensure numerical stability, the bi-harmonic filter (Danilov et al. 2017) also used in FESOM2 was introduced in place of viscosity terms.

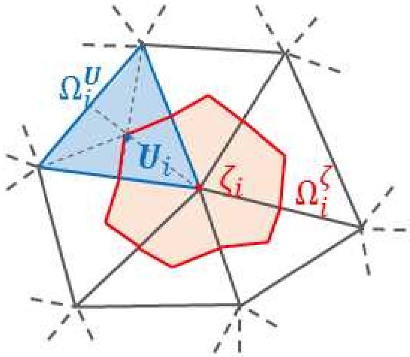

Figure 1. Locations of current velocity and surface elevation, with control volume $\boldsymbol{U}_i$ and ζ_i indicating the current velocity vector and surface elevation, respectively. The blue triangle and red polygon indicate the vector control volume ($\Omega_i^{\boldsymbol{U}}$) and the scalar control volume (Ω_i^{ζ}), respectively.

JIGSAW (Engwirda 2017) was adopted as an unstructured mesh-generating tool for its comparably high quality, efficiency and usability. Figure 2 compares unstructured grids around Japan's western Kyushu region with a previous structured latitude-longitude grid. Related storm surge calculation allows fine-resolution grids in coastal areas and coarse grids offshore simultaneously. The upgrade to an unstructured model system reduces the number of grid boxes by a factor to around 1/30 of the high-resolution structured latitude-longitude system, thereby reducing computational consumption.

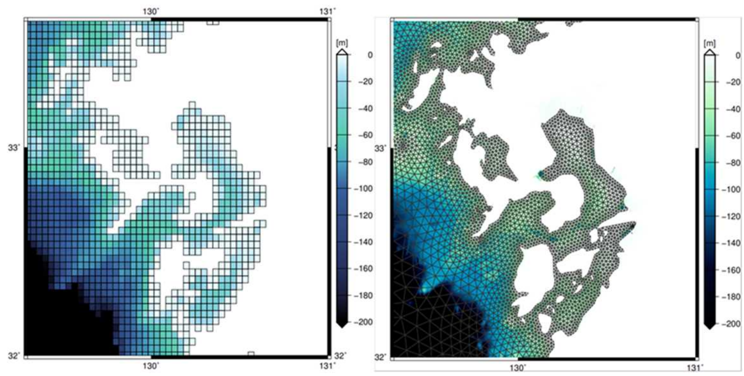

Figure 2. Unstructured grids around Japan's western Kyushu region

Left: previous storm surge model topography; right: new-model topography and grids

2.3 Typhoon bogus enhancement

A simple parametric tropical cyclone (TC) model with typhoon bogus and atmospheric model products are used for meteorological forcing (Section 5.5.2.4, JMA 2022). Storm surge model calculation requires atmospheric forcing covering the Asia region, but as the horizontal resolutions of the GSM and GEPS atmospheric models are insufficient to express tropical cyclone intensity, surface wind and pressure fields calculated from the typhoon bogus are planted into the atmospheric fields they predict.

The simple parametric TC model does not include wind speed reduction based on land surface friction. To address the previous model's tendency to overestimate negative and other storm surges in coastal areas, the upwind directional land roughness parameterization proposed by Westerink et al. (2008) was adopted to represent wind speed reduction in coastal areas.

2.4 Ensemble prediction

The previous storm surge model involved a multi-scenario prediction system, but its six members were insufficient to provide probabilistic forecast products such as ensemble spread and exceeding storm surge probability. In the 2022 update, the model was upgraded to enable storm surge ensemble prediction with 52 members using the GSM (deterministic) and GEPS (51 members) and provision of probabilistic forecast products with uncertainty information. Only deterministic products are provided in non-TC situations (Section 3).

2.5 Other upgrades

Introduction of the unstructured-grid FVM model increased the model resolution around coastal regions from 2 minutes (approx. 4 km) to 1.5 km and expanded the model domain (Figure 3). The new model covers most of RSMC Tokyo's area of responsibility including the Marshall Islands, which were not covered by the previous model.

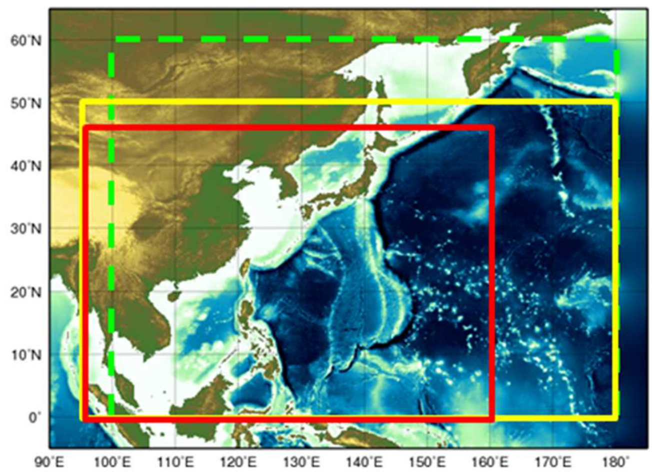

Figure 3. Model domains
Red frame: previous storm surge model domain; yellow frame: new domain; green frame: RSMC Tokyo's area of responsibility

The forecast period of the previous model was 72 hours (three days), but a longer lead time is required for better storm surge forecasting from a tropical cyclone-associated disaster mitigation perspective. The low number of scenarios in the previous multi-scenario prediction system did not allow products covering four or more days because it did not support quantitative evaluation of uncertainties, even though uncertainties generally increase with the forecast period. The 2022 introduction of the prediction system with 52 ensemble members allows quantitative evaluation of forecast uncertainty and extends the forecast period from 72 to 132 hours (5.5 days).

Figure 4 illustrates the generation of storm surge ensemble predictions. If no named tropical cyclone is present in the model domain, storm surge predictions are made four times a day based on GSM atmospheric fields. If one or more named tropical cyclones are present or expected within 24 hours, the storm surge model is run with GSM atmospheric fields for official deterministic forecasts of TCs and 51 ensemble members.

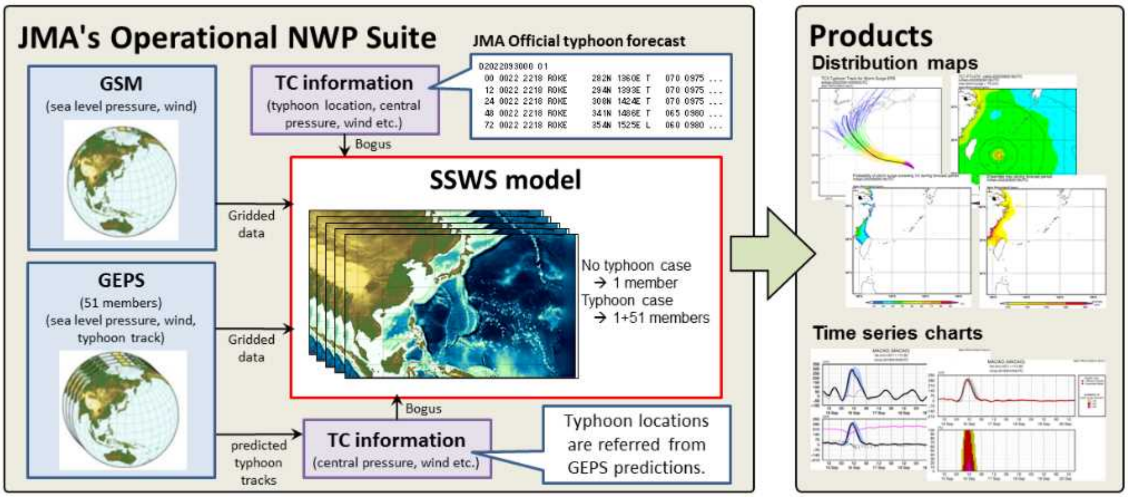

Figure 4. SSWS data flow

3. Storm surge forecast products

JMA began issuing storm surge distribution maps for Typhoon Committee Members via the Numerical Typhoon Prediction (NTP) website in 2011, and added storm surge time-series charts for selected locations in 2012. The charts include astronomical tides based on harmonic analysis for locations where sea level observation data are available. In 2019, the Agency began providing information on astronomical tides and storm tides for locations where harmonic constants of astronomical tides were not available from the database based on the Finite Element Solution tide model (FES2014[2],

[2] Produced by NOVELTIS, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), CLS Space Oceanography Division and Centre National d'Etudes Spatiales (CNES), and

Lyard et al. 2021) for ocean tide solution. Charts for 78 locations are provided (as of April 2023), and more will be added in response to Typhoon Committee Member requests.

In association with the storm surge model upgrades, JMA updated its storm surge products for Typhoon Committee Members, replacing surge distribution maps for six scenarios with three-hourly probability maps including data such as ensemble mean, maximum and spread, third quartile and exceeding probability (Figure 5). Distribution maps for deterministic forecasts and ensemble maxima among all ensemble members during the forecast period continue to be provided. Time-series plume diagrams (equivalent to the previous time-series charts), boxplot diagrams and exceeding probability bar graphs are also produced (Figure 6) for risk management with appropriate lead times.

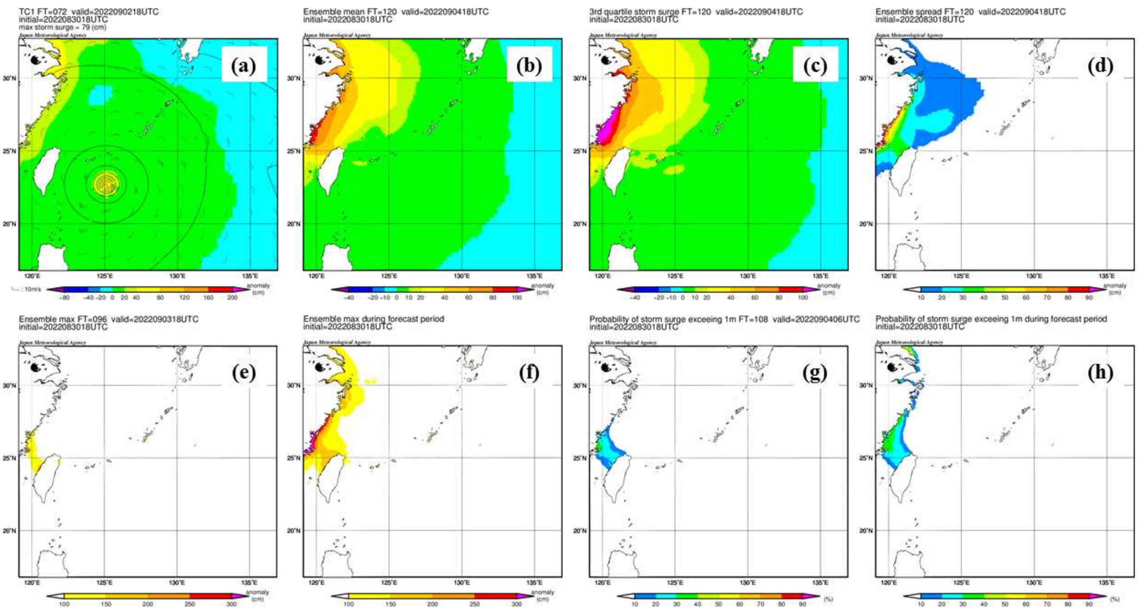

Figure 5. Distribution maps

(a) Storm surge for deterministic forecast, (b) ensemble mean for storm surges, (c) third quartile for storm surges, (d) ensemble spread for storm surges, (e) and (f) ensemble maximum storm surges, (g) and (h) probabilities of storm surge exceeding 1 meter. (a) – (d), (e) and (g) are three-hourly maps. (f) and (h) show maximum values for the forecast period.

distributed by AVISO with support from CNES (http://www.aviso.altimetry.fr/).

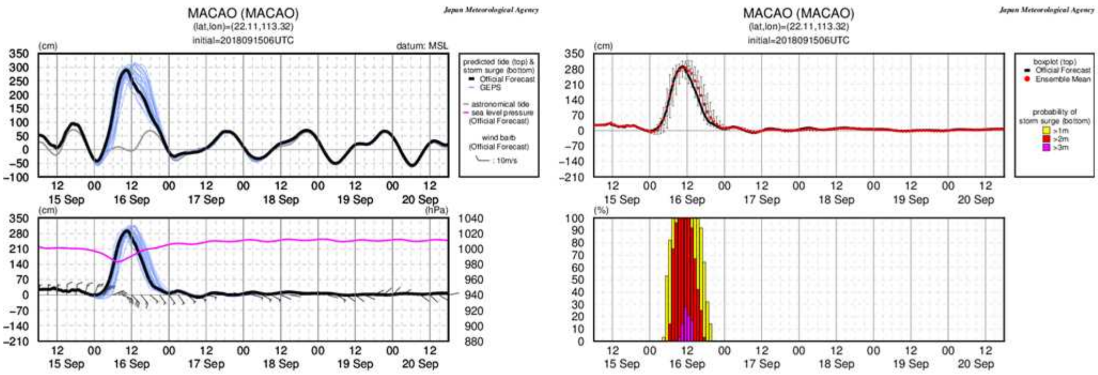

Figure 6. Time-series charts

Left: plume diagrams. Top: storm tides based on deterministic forecasting (black line), storm tides based on ensemble members (blue) and the astronomical tides (grey). Bottom: storm surges based on deterministic forecasting (black line) and on ensemble members (blue); magenta line: sea level pressure; wind barbs: surface wind.

Upper right: boxplots for storm surge. Black line: storm surge based on deterministic forecasting; solid red line: storm surge based on ensemble means. Lower right: exceeding probability.

4. Model performance

4.1 Deterministic forecast verification

JMA has published results of storm surge model verification in its Annual Reports on Activities of RSMC Tokyo since 2015 (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/annualreport.html). Reports up to 2021 are based on the previous storm surge model. Here, verification results for deterministic forecasting based on the new model are outlined.

To evaluate the new model, storm surge forecast experiments were conducted for named TCs occurring from 2018 to 2020. The observation dataset (from eight storm surge watch scheme stations) used was from the University of Hawaii Sea Level Center (UHSLC) database website (http://uhslc.soest.hawaii.edu/data/?fd) .

Figure 7, showing scatter diagrams of modeled storm surges against observation data, indicates no strong tendencies. These results may be insufficient in evaluation of model accuracy for TCs because observation data are limited, and no remarkable storm surges were observed at most stations during the three-year period of coverage. Accordingly, additional verification was conducted using information from stations in Japan, where sufficient observation data are available and TCs frequently approached or made landfall during the period. Although the characteristics of model forecasts may vary by region, the previous and new storm surge models are considered to have comparable levels of accuracy for storm surge watch scheme stations.

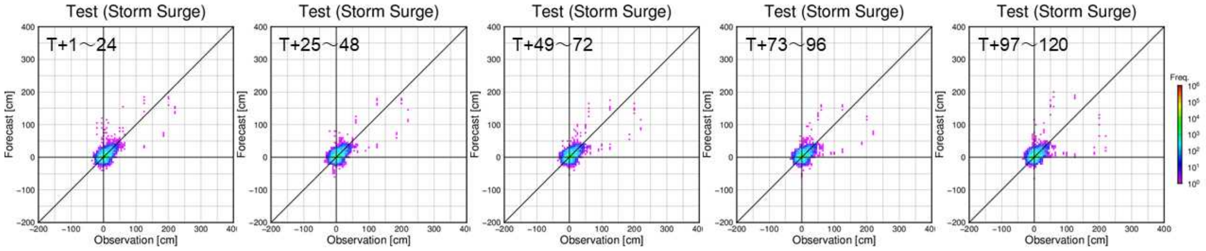

Figure 7. Scatter diagrams of modeled storm surges with the new model against SSWS station observation data

Figure 8 shows scatter diagrams of modeled storm surges against observation data from around 200 tide stations (operated by JMA, the Ports and Harbours Bureau, the Japan Coast Guard, and the Geospatial Information Authority of Japan) in Japan. The verification period is as per Figure 7, with TCs extracted. The top figures show the scatter diagrams calculated with the previous model, and the bottom figures show those calculated with the new model. Overestimation in the previous model (indicated by red circles) was mitigated in the new model. Naturally, the accuracy of both models degrades with longer forecast periods.

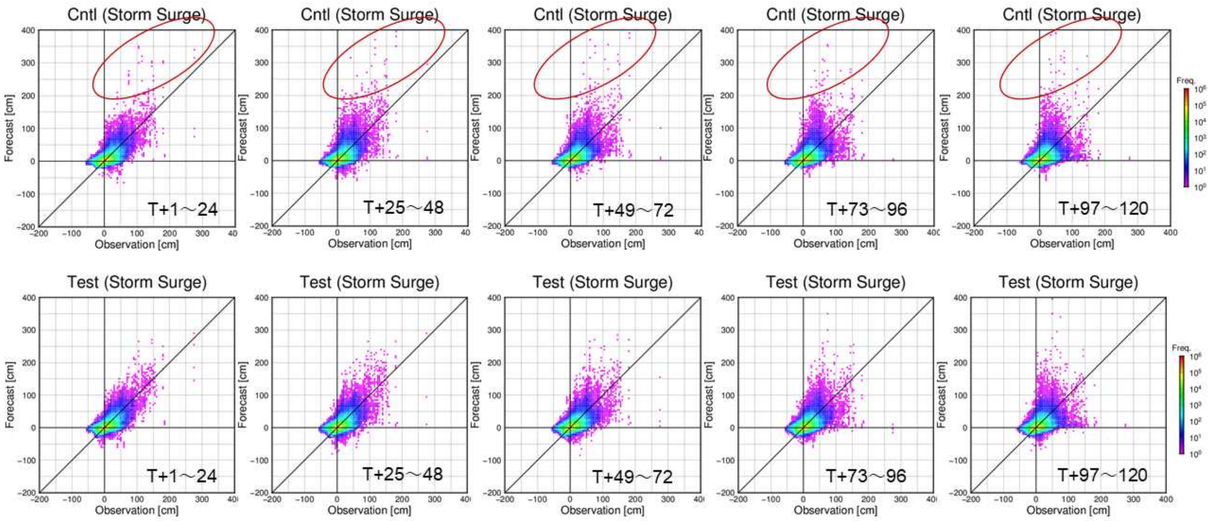

Figure 8. Scatter diagrams of modeled storm surges with the previous (top) and new (bottom) models against observation data for Japan

Figure 9, showing verification scores, indicates a clear reduction of overestimation for the false alarm ratio (FAR) and bias score (BS) in the new model. Probability of detection (POD) and threat score (TS) are also generally improved.

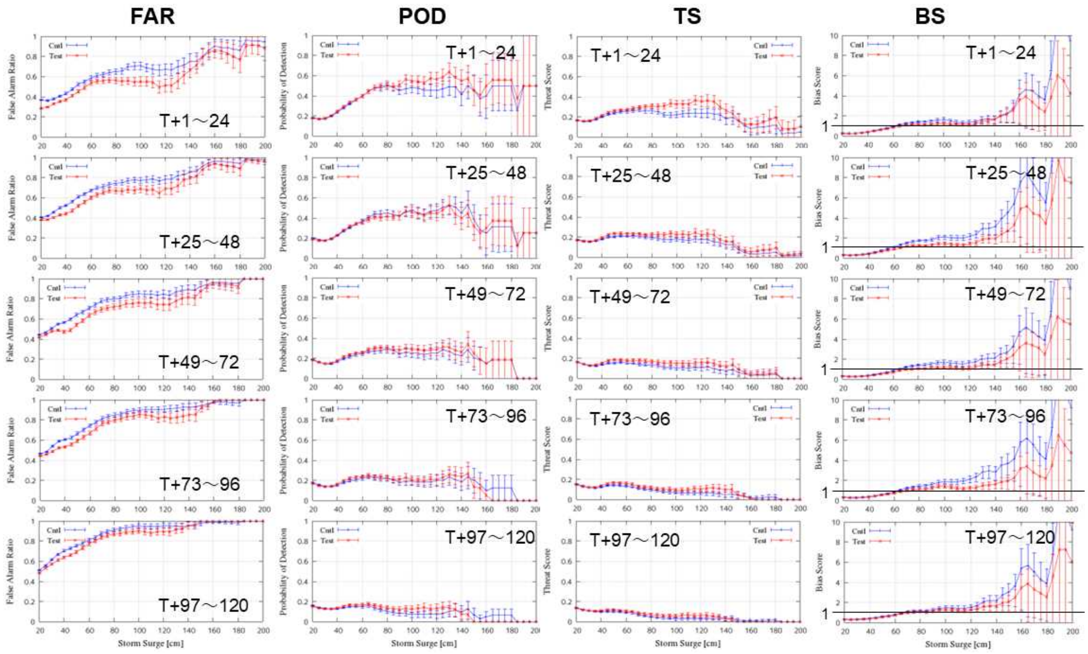

Figure 9. Verification scores for storm surges with the previous and new models against observation data for Japan

First column: false alarm ratio (FAR); second column: probability of detection (POD); third column: threat score (TS); fourth column: bias score (BS). Blue lines: previous-model verification scores; red lines: new-model verification scores; error bars: 95% confidence intervals.

4.2 Verification of ensemble prediction

Figure 10 shows ensemble prediction system threat scores with the new model for TCs in Japan, displaying each probability against a given threshold. The statistical period is as per deterministic forecast verification. It can be seen that threat scores generally peaked in the probability range from 20 to 40%. Although accuracy degrades with the forecast period, the system maintains largely level scores up to five days ahead.

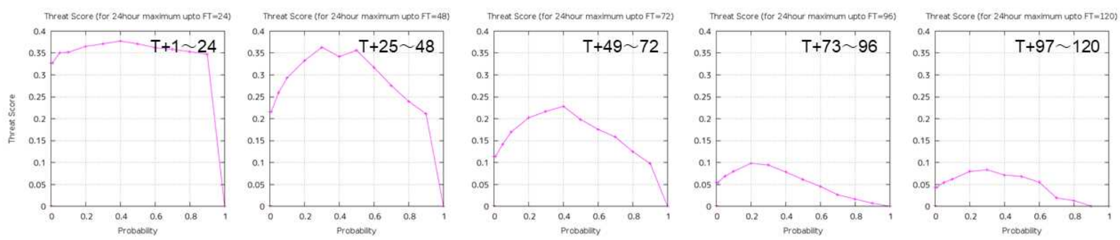

Figure 10. Threat scores of the ensemble prediction system for each probability against storm surges exceeding 100 cm

The statistical period is from 2018 to 2020. There were 27 ensemble members, corresponding to the number of 27 GEPS members during the period.

4.3 Case studies

Severe Tropical Storm Kompasu (T2118)

STS Kompasu moved westward over the South China Sea with a maximum wind speed of 30 m/s and a minimum pressure of 975 hPa in October 2021. Figure 11 shows the analysis track and six predicted tracks in the previous model and 52 predicted tracks (official and 51 ensemble members) of the new system covering the 48-hour period before the peak of a storm surge in Quarry Bay (Hong Kong, China). The tropical cyclone covered a large area, with 30-knot winds, causing storm surges along the southern coast of China. Both models underestimated the peak surge, but accuracy was slightly improved in the new one (Figure 12).

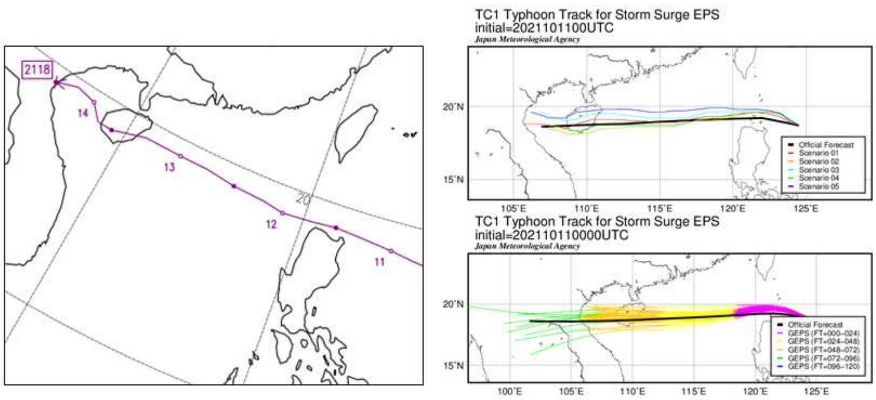

Figure 11. Analysis (left) and predicted tracks (right) for STS Kompasu

Colored lines (top right): 6 tracks from GEPS members; colored lines (bottom right): 51 tracks from GEPS members; black lines: RSMC Tokyo official forecast.

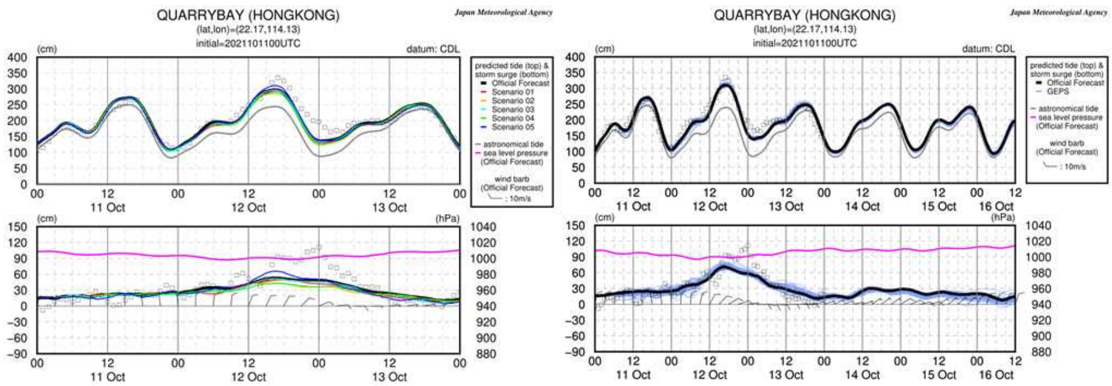

Figure 12. Storm surge predictions for Quarry Bay starting at 00 UTC on 11 Oct. 2021

Colored lines (top right): 6 tracks from GEPS members; colored lines (bottom right): 51 tracks from GEPS members; black lines: RSMC Tokyo official forecast. Left: previous model; right: new model (top: storm tide and astronomical tide; bottom: storm surge, sea level pressure and surface wind). Squares: tide station observation (https://www.ioc-sealevelmonitoring.org/station.php?code=quar).

Severe Tropical Storm Ma-on (T2209)

STS Ma-on passed northwest over the South China Sea with a maximum wind speed of 30 m/s and a minimum pressure of 985 hPa in August 2022. Figure 13 shows the analysis track and the 52 predicted tracks (official and 51 ensemble members) covering the 48 hours before the storm surge peak in Quarry Bay (Hong Kong, China). At this initial time, most predicted tracks were northward of the analysis track. The new system predicted a high probability of storm surges exceeding 1 meter high along the southern coast of China, and the ensemble spreads indicate high uncertainty around Quarry Bay (Figure 14), where the model predicted that the maximum probability of storm surge exceeding 1 meter in height was around 40% (Figure 15). The observed maximum storm surge in Quarry Bay actually did not exceed 1 meter, but the ensemble members generally captured the peak storm surge and tide well.

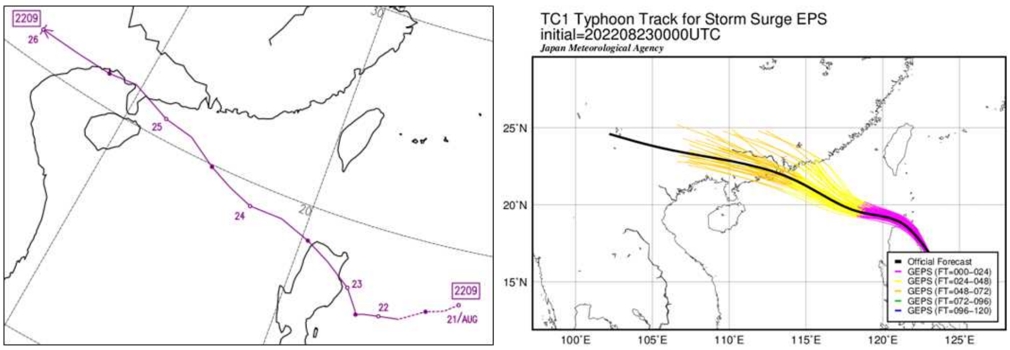

Figure 13. Analysis track (left) and predicted tracks (right) for STS Ma-on
Colored lines: 51 tracks from GEPS members; black line: official JMA forecast.

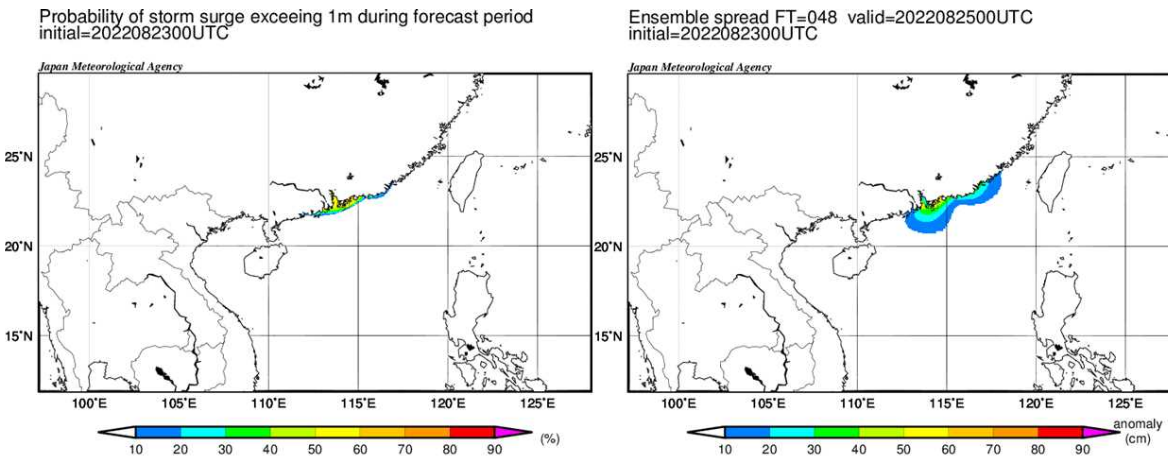

Figure 14. Probabilities of storm surges exceeding 1 meter in height during the forecast period (left) and ensemble spread (right) starting at 00 UTC on 23 Aug. 2021

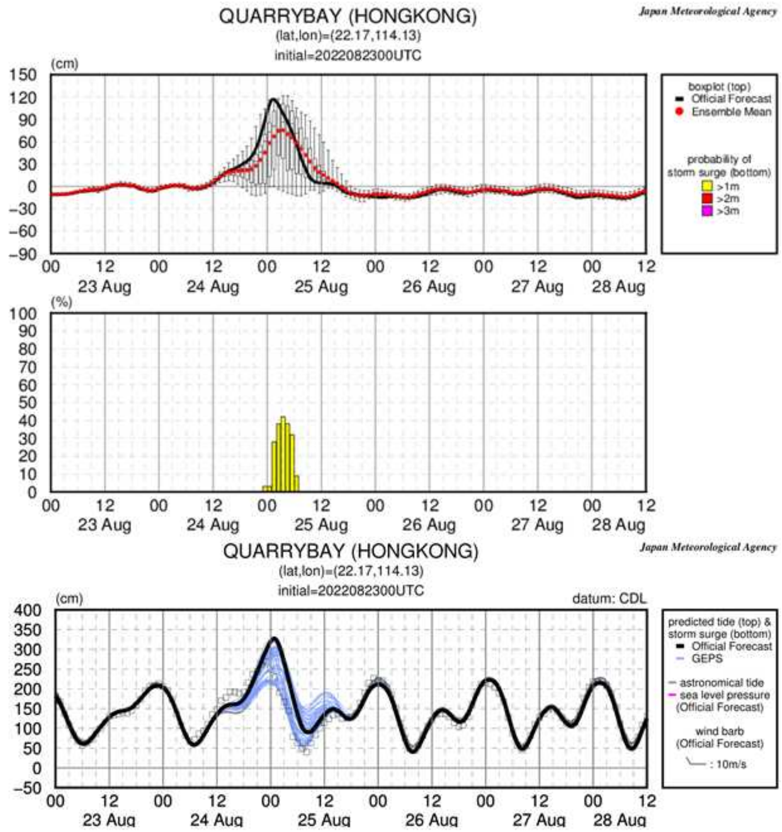

Figure 15. Time-series representation of storm-surge boxplots (top), storm surge probability bars (middle), and expected storm tide (bottom) for Quarry Bay starting at 00 UTC on 23 Aug. 2021. Squares (bottom): tide station observation (https://www.ioc-sealevelmonitoring.org/station.php?code=quar).

5. Summary

In August 2022, JMA upgraded its Asia area storm surge model and updated its graphical products for Typhoon Committee Members within the framework of the WMO SSWS as follows:

- Introduced an unstructured (triangular) FVM model
- Increased number of ensemble members (6 to 52)
- Increased grid resolution for coastal regions (2 minutes (approx. 4 km) to 1.5 km)
- Extended forecast period (72 to 132 hours)
- Expanded model domain to cover most of RSMC Tokyo's area of responsibility
- Improved typhoon bogus (parametric TC model)

The lower computational consumption of the unstructured FVM model in particular facilitated 52-member ensemble prediction and other work. This prediction system enables quantitative evaluation of prediction uncertainty, extended forecast periods and provision of probabilistic products.

In official RSMC Tokyo – Typhoon Center deterministic forecasting, the new model's accuracy is generally improved due to the increased grid resolution, the enhanced typhoon bogus and new drag coefficient formulations.

This higher accuracy and the provision of probability products with uncertainty information and sufficient lead times are expected to be highly useful in storm surge forecasting. The new model and related products will support effective disaster mitigation and risk management by Typhoon Committee Members.

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