Recent upgrades of operational storm surge models in Japan Meteorological Agency

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Japan Meteorological Agency

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Introduction

- Japan Meteorological Agency (JMA) operates two types of regional storm surge model covering the coastal area of Japan and Asia.

- Both models were based on multi-scenario predictions only for six typhoon tracks and could not provide probabilistic forecast products before 2022.

  critical to capture the risk of storm surges within sufficient lead time.

- JMA newly introduced storm surge ensemble prediction systems (EPSs) and started providing probabilistic forecast products from August 2022.

Specification

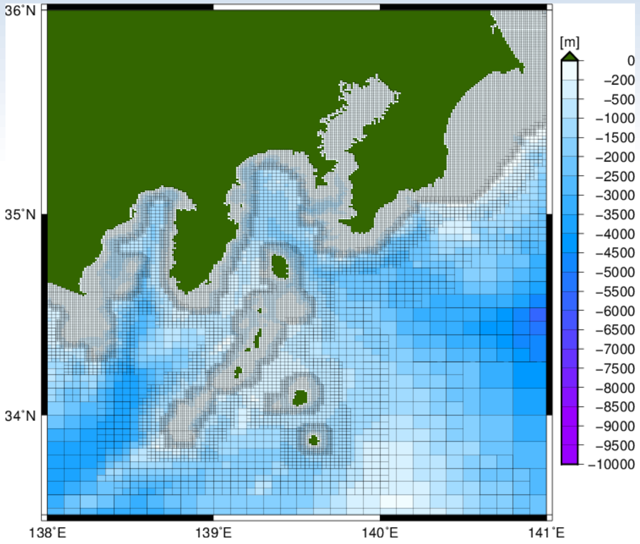
Model	Two-dimensional nonlinear model
Model domain	20°N - 50°N, 117.4°E - 150°E
Grid resolution	1km ～ 16km (Adaptive Mesh Refinement)
Forecast period	78 hours (00, 12UTC) 39 hours (03, 06, 09, 15, 18, 21UTC)
Atmospheric forcing	JMA Meso-Scale Model (MSM, resolution ~ 5km) Typhoon bogusing
Member	No-typhoon case: 1 member (MSM) Typhoon case: 6 members (MSM + typhoon bogusing)
Purpose of operation	Issuing of storm surge advisories/warnings in the Japan area

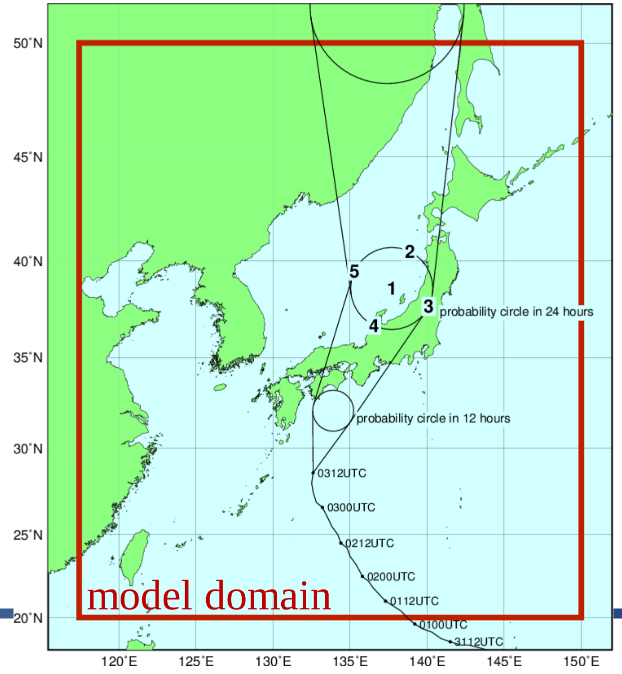
✓ If one or more typhoons exist near the coastal area of Japan, additional model runs are executed for five hypothetical tracks to consider typhoon forecast errors.

- Five tracks are prescribed at the center and four points on the probability circles.
- Storm surges are calculated by implanting typhoon bogusing into each track.

→ Six scenarios are considered.

Example of a grid around Japan's Kanto area



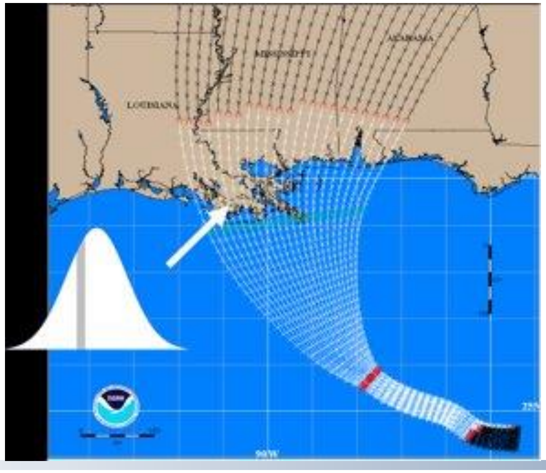


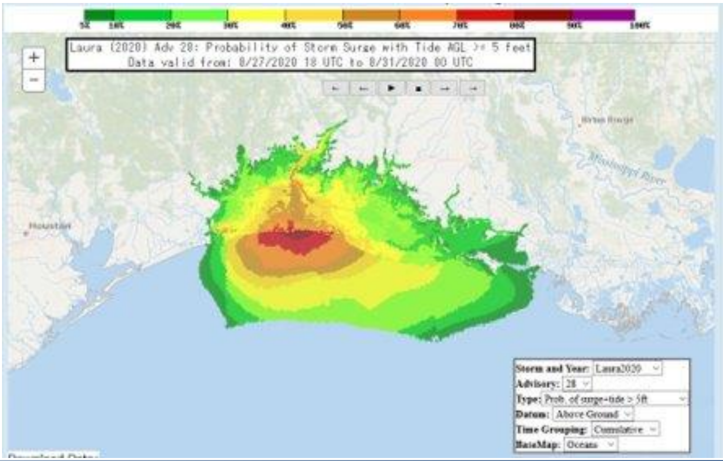
Probabilistic Forecast System (PFS)

- Six scenarios are insufficient to consider typhoon forecast errors and capture potential storm surges.

  → A probabilistic approach is suitable for storm surge forecast with a lead time of 3-5 days.

- JMA newly introduced the Japan-area storm surge probabilistic forecast system (PFS).
  - The concept is based on the P-Surge model operated by NOAA/NHC
  - This system consists of an ensemble of the Japan-area model runs.





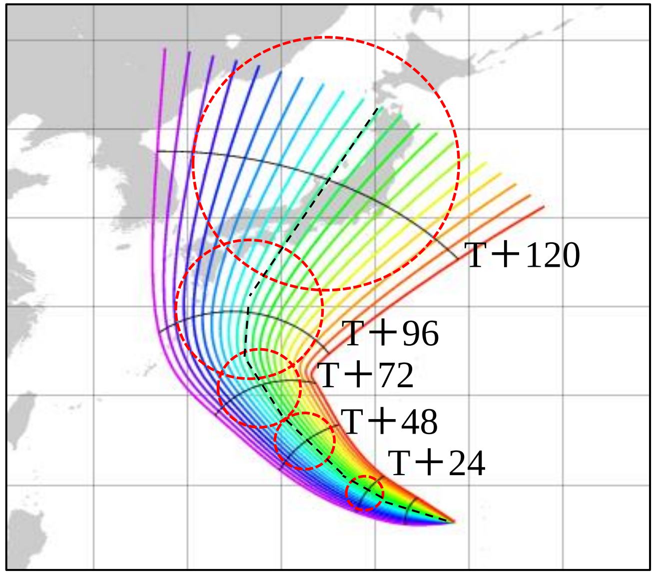
https://slosh.nws.noaa.gov/psurge2.0/index.php

Japan area

Method of PFS

- Create 21 cross-track members by shifting an official predicted track.
  - The whole tracks cover 70% probability circle + margin region.
  - The distance between members is the same. = inside of 1.25 × radius of 70% probability circle
  - For each track, storm surges are calculated up to 132-h by implanting typhoon bogusing.

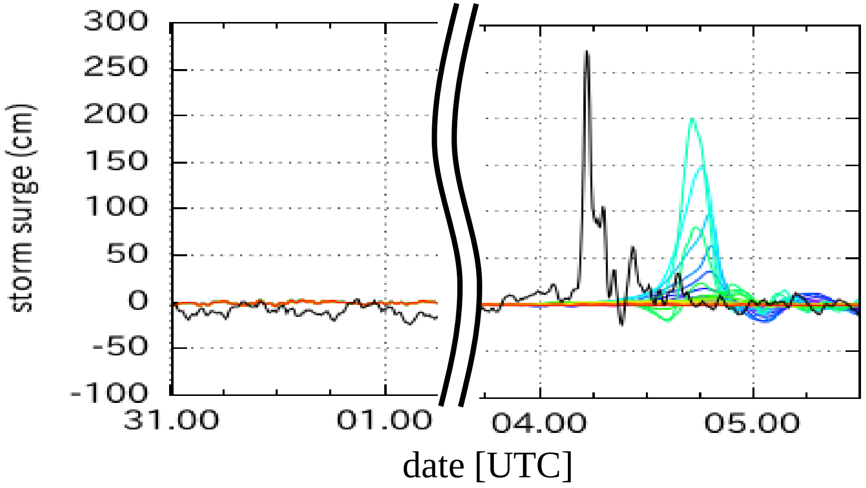
21 tracks for TY JEBI (31 Aug. 2018 00UTC Initial)



- ✓ Black dotted line: official predicted track
- ✓ Red dashed circles: 70% probability circle

Calculated 21 storm surges at Osaka (31 Aug. 2018 00UTC Initial)

- four days earlier of TY JEBI approaching



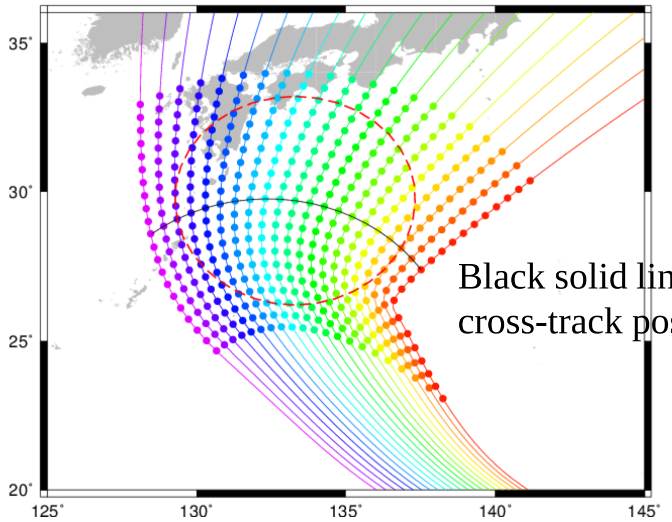
- ✓ Black solid line: observational data

- It is insufficient to consider only cross-track errors.
  - underestimate a maximum value
  - miss a timing of peak

Method of PFS

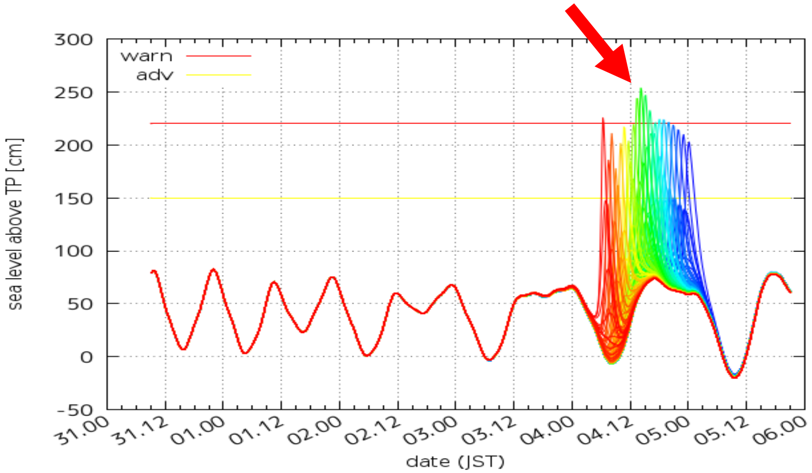
- Create along-track members by shifting the cross-track position in post-processing of calculations for cross-track direction.
  - This procedure corresponds to adding perturbations to moving velocity.
  - 10 members for forward/backward directions with the same distance (21×21 = 441 members in total).
  - Storm surges of along-track members are calculated by a time interpolation (No additional model runs).

441 members for TY JEBI (31 Aug. 2018 00UTC Initial)
Example for T+96



✓ Red dashed circles: 70% probability circle

Calculated 441 storm tides at Osaka (31 Aug. 2018 00UTC Initial)
- four days earlier of TY JEBI approaching



- The excess of warning criteria can be predicted in some members.
(Actually, the excess of warning criteria occurred at Osaka in 4 Sep. 05UTC)

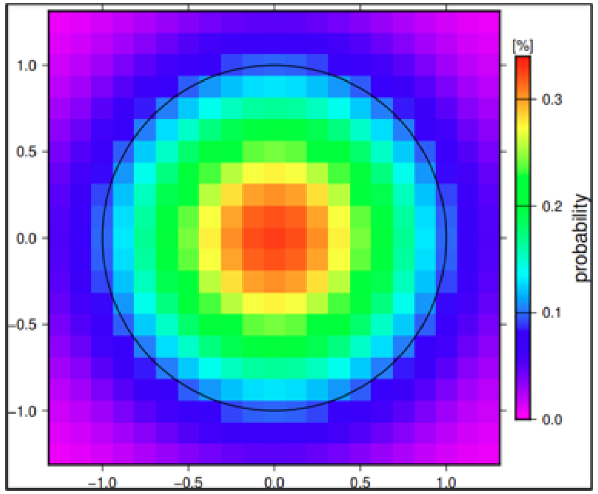
Probabilistic forecast products

Japan area

- ➢ Assign a probability to each member and calculate probabilistic quantities.
  - ・2D normal distribution is assumed as the cross- and along-track error distributions related to JMA's typhoon forecast. (consistent with Best Track Data of various typhoon)

2D normal distribution in the PFS

・Its origin is located at the center of typhoon.

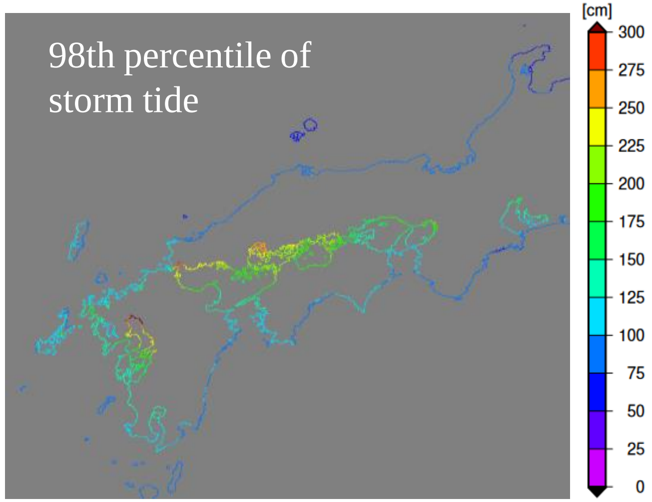


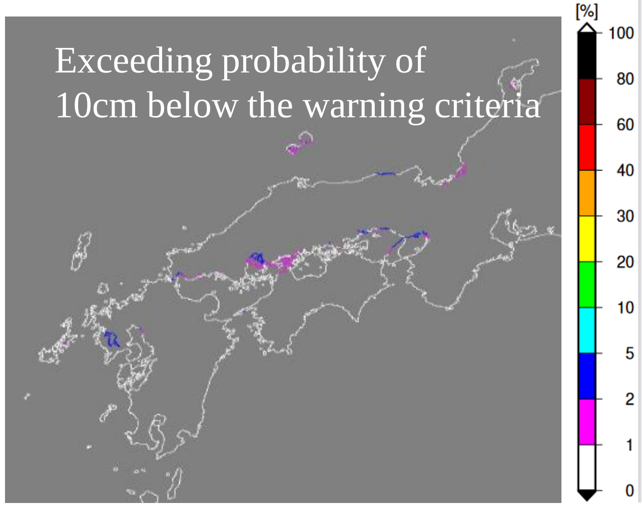
・Black solid line: probability circle.

・The horizontal and vertical axes are normalized by the radius of a probability circle.

Example of products in operation (31 Aug. 2018 00UTC Initial)

・four days earlier of TY JEBI approaching



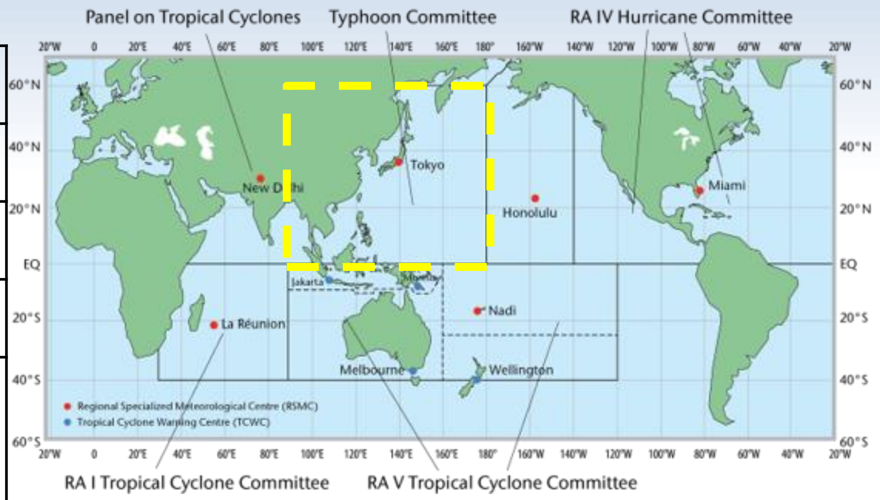


・The potential storm surge can be captured in the early stage of typhoon approaching.

→ lead to the early issue of storm surge advisories/warnings

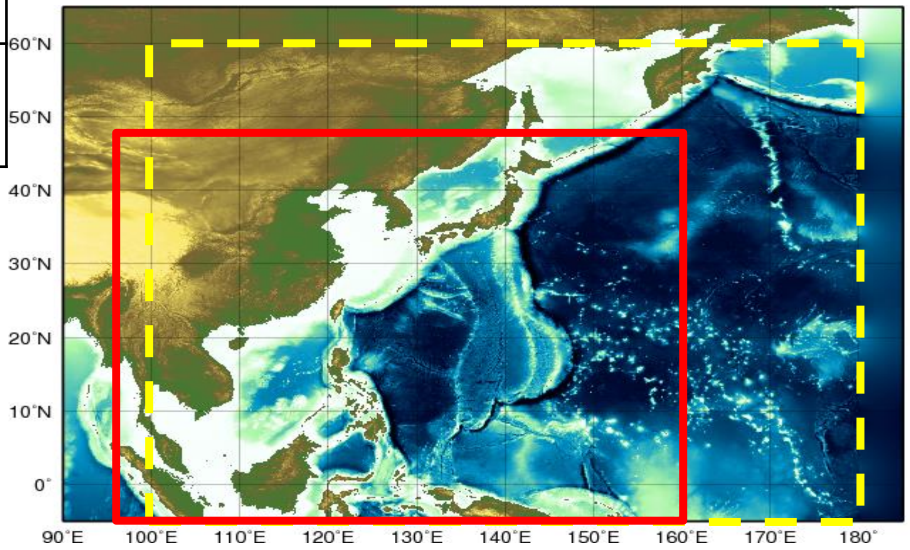
Specification of previous model

Model	Two-dimensional linear model
Model domain	0° - 46°N, 95°E - 160°E
Grid resolution	3.7km (Lat-Lon, Arakawa C-grid)
Forecast period	72 hours (00, 06, 12 18UTC)
Atmospheric forcing	JMA Global Spectral Model (GSM, resolution ~ 13km) JMA Global Ensemble Prediction System (GEPS, resolution ~ 27km) Typhoon bogusing
Member	No-typhoon case : 1 member (GSM) Typhoon case: 6 members (GSM + 5 members chosen from GEPS)
Purpose of operation	Provision of storm surge prediction products to Typhoon Committee Members in the framework of WMO Storm Surge Watch Scheme



The yellow box is the RSMC Tokyo's area of responsibility
https://community.wmo.int/latest-advisories-rsmcs-and-tcwcs

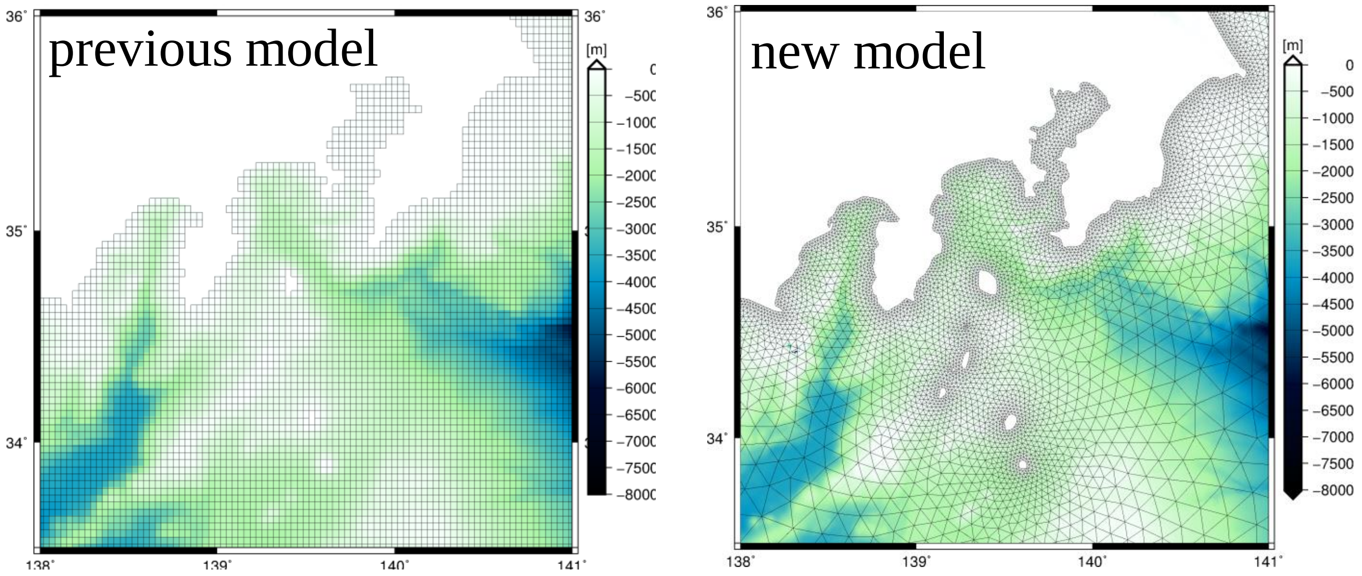
- To be improved
  - Grid resolution was low in the view of storm surge predictions.
  - Probabilistic forecast products could not be provided.
  - Model domain did not cover Marshall Islands.



Model domain
RSMC Tokyo area

Unstructured grid

- ➢ JMA has constructed its own unstructured grid finite volume model.
  - ▪ The resolution in coastal areas has been increased from 3.7km to 1.5km.
  - ▪ The grid becomes coarse with distance from coastal line (maximally around 50km).



Comparison of grid around Japan's Kanto area

- ▪ JIGSAW (Engwirda, 2017) is used as a mesh-generating tool.

- ▪ The expression of complex topography and small islands has been largely improved.
- ▪ The whole grid points have been drastically reduced.
  → Computationally efficient
- ▪ The spherical non-linear 2D shallow water equation is solved by a finite volume method.

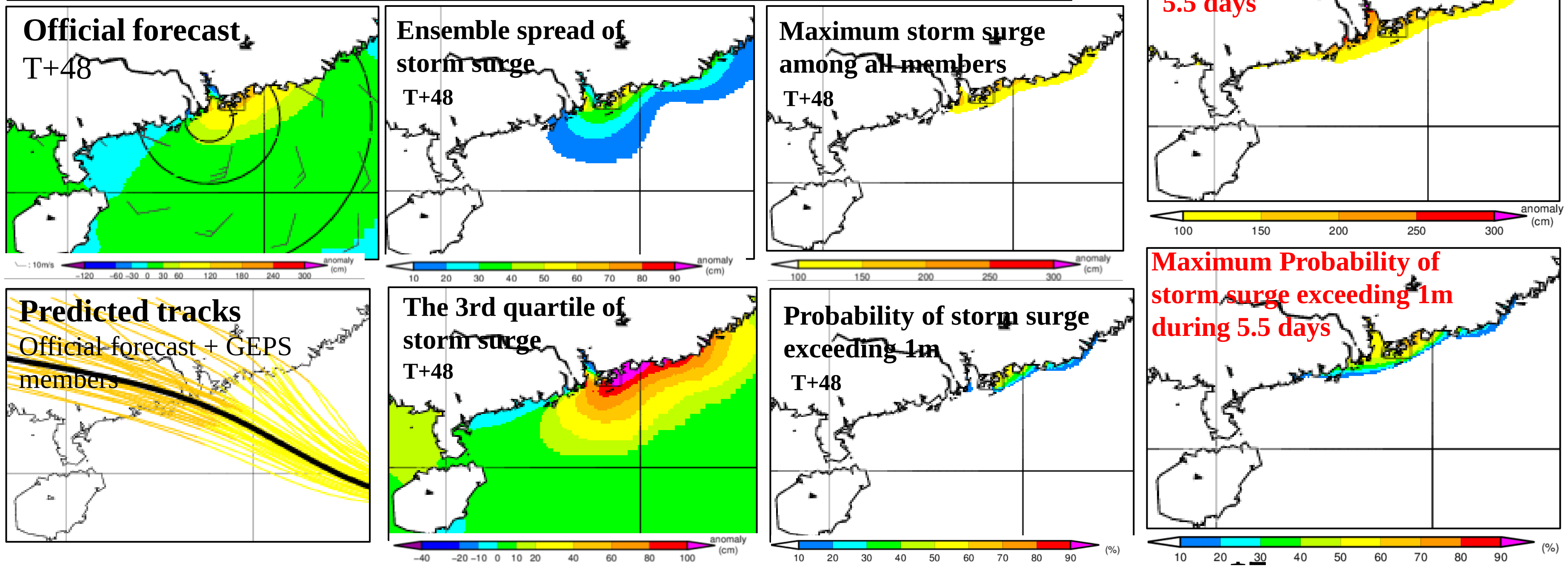
cf. FVCOM (Chen et al, 2013)
FESOM2 (Danilov et al, 2017)

Probabilistic forecast products

- The Asia-area EPS has been built by using GSM (1 member) and GEPS (51 members).
  - Products are provided to Typhoon Committee member countries.

Distribution maps

Example of the products for TY Ma-on (23 Aug. 2022 00UTC Initial)



Probabilistic forecast products

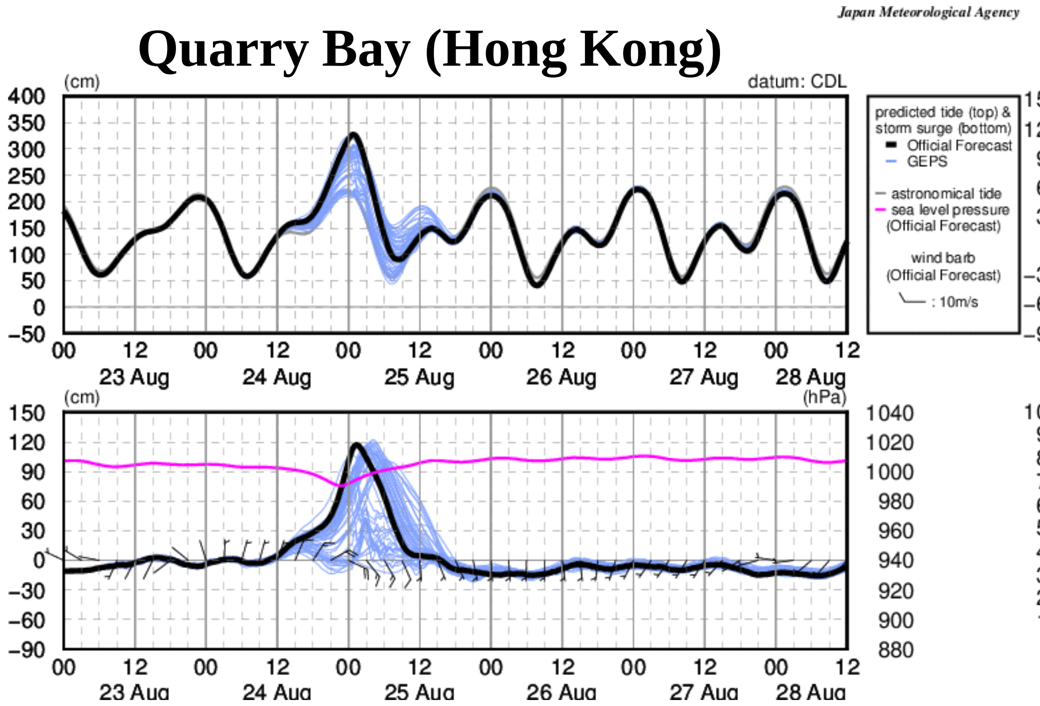
- ➢ The Asia-area EPS has been built by using GSM (1 member) and GEPS (51 members).
  - ▪ Products are provided to Typhoon Committee member countries.

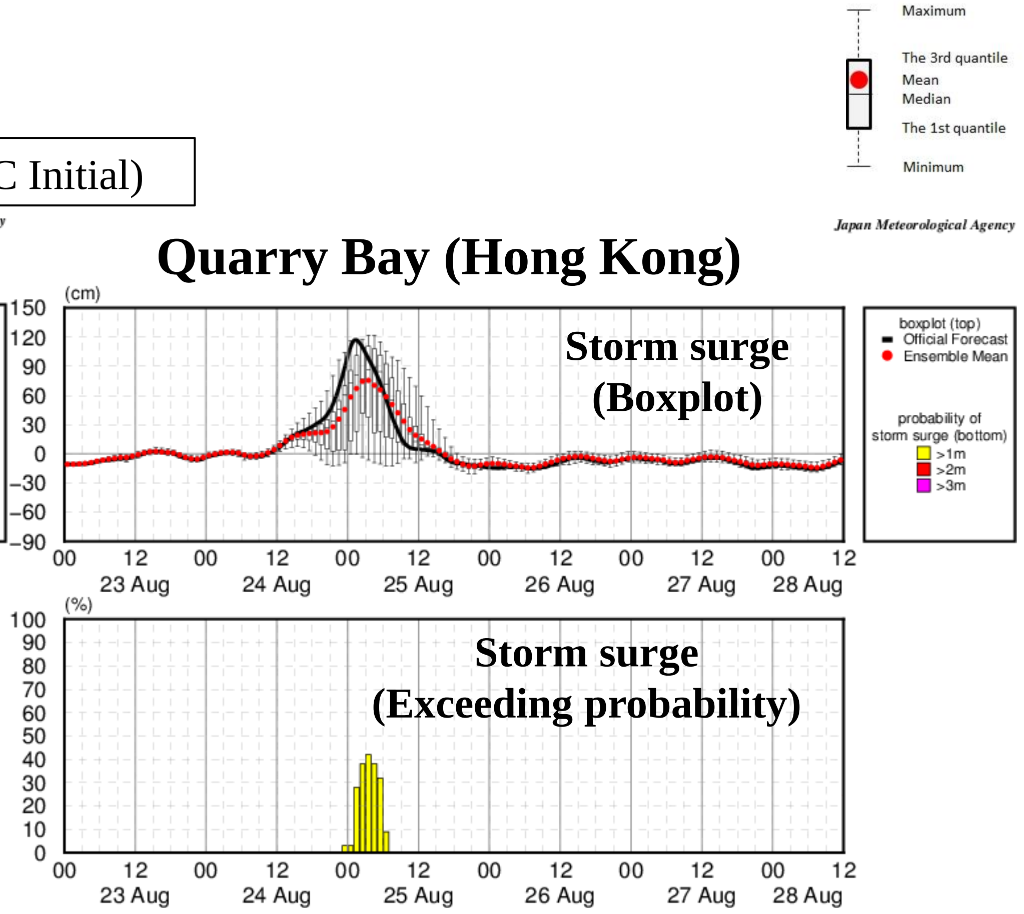
Time-series chart for selected locations

Example of the products for TY Ma-on (23 Aug. 2022 00UTC Initial)

Storm tide

Storm surge & Sea level pressure





Other upgrades

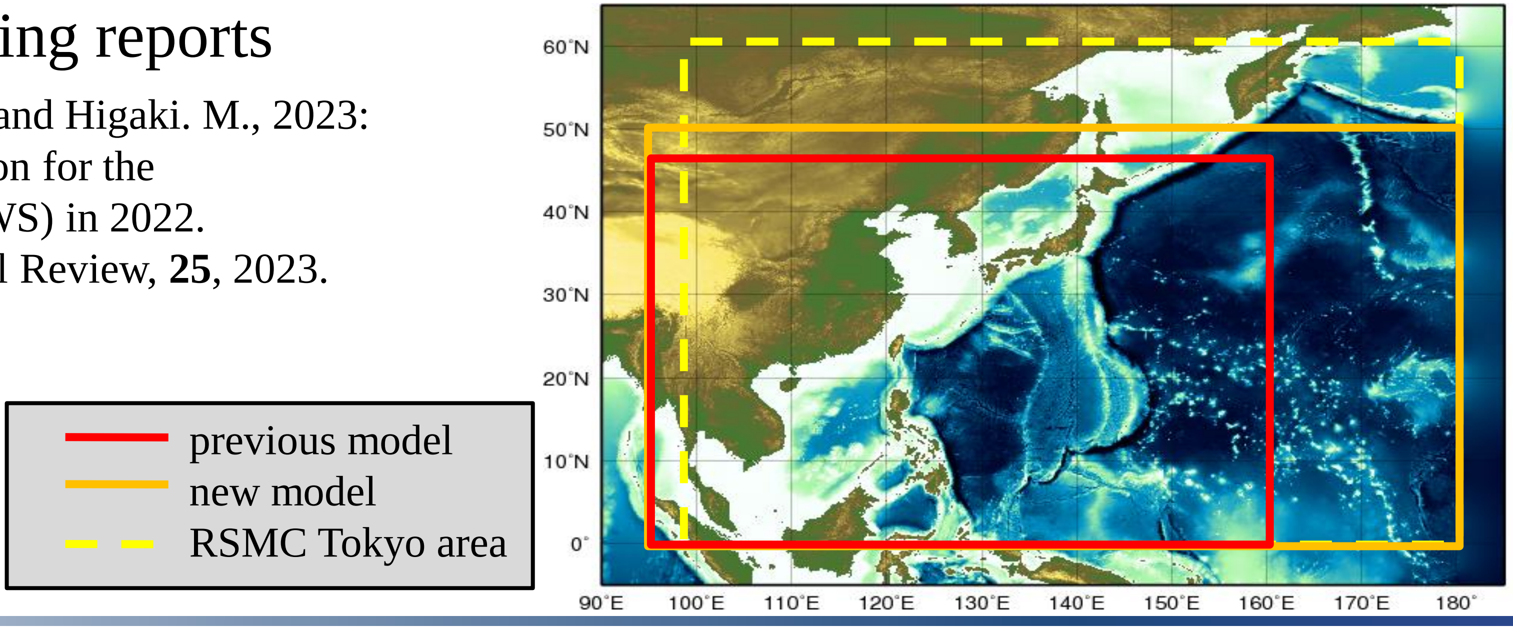
- Expansion of model domain
  - The new model can cover most of RSMC Tokyo area of responsibility (including Marshall Islands)

- Extension of forecast period from 72 to 132 hours
  - The new model yield more sufficient lead time for issuing warnings & evacuation

- For more detail, see the following reports
  - ✓ Hasegawa. H., Sugano. J., Fukuura. T. and Higaki. M., 2023: Upgrade of JMA's Storm Surge Prediction for the WMO Storm Surge Watch Scheme (SSWS) in 2022. RSMC Tokyo-Typhoon Center Technical Review, **25**, 2023.

  Download PDF

Comparison of the model domain



Summary

- JMA extensively upgraded two types of operational storm surge models in 2022.

- Japan area
  - JMA started operating Japan-area storm surge probabilistic forecast system (PFS) and providing probabilistic forecast products.
  - This system is effective to capture potential storm surges within sufficient lead time when typhoons are approaching.

- Asia area
  - JMA introduced an unstructured grid finite volume model and built ensemble prediction system and started providing probabilistic forecast products for Typhoon Committee Members.

Perspective

- Japan area
  - introduction of an unstructured grid finite volume model
  - improvement of typhoon bogusing by using a vortex relocation scheme
  - incorporation of a perturbation of typhoon strength to the PFS

- Asia area
  - improvement of typhoon bogusing by using a vortex relocation scheme

A vortex relocation scheme:

- Kurihara. Y., Bender. M. A. and Ross. R. J. Ross. 1993: An Initialization Scheme of Hurricane Models by Vortex Specification. *Mon. Wea. Rev.* **121** (7): 2030–45.
- Kurihara. Y. Bender. M. A., Tuleya. R. E. and Ross. J. R. 1995: Improvements in the GFDL Hurricane Prediction System. *Mon. Wea. Rev.* **123** (9): 2791–2801.

Backup

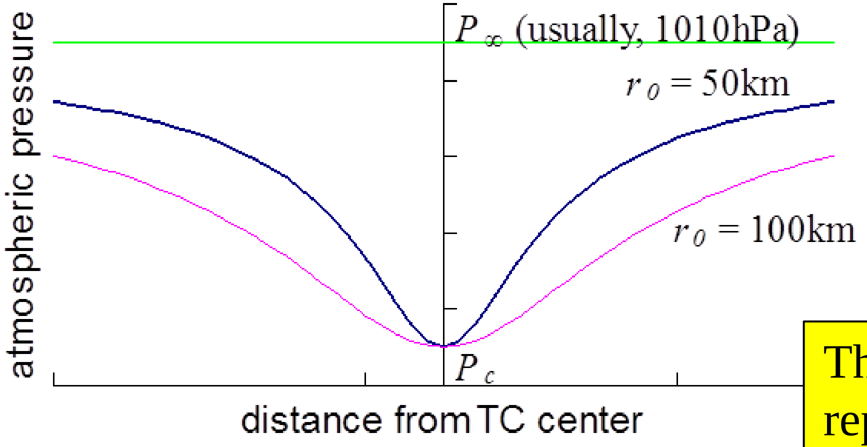
Typhoon bogusing

Bogus is simple parametric TC model. Radial pressure distribution is represented by Fujita's formula:

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

P: atmospheric pressure
P_∞: environmental pressure
P_c: central pressure
r: distance from center
r_0: scaling factor

r_0 decides sharpness of pressure distribution. r_0 is calculated from 30/50knot radius.



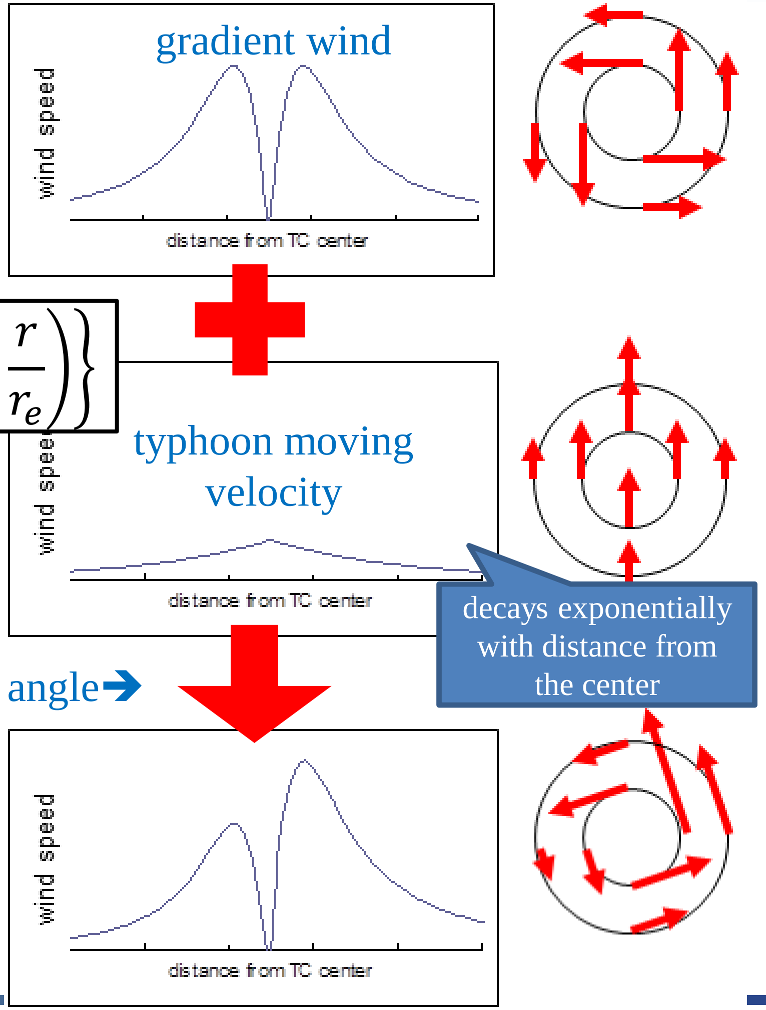
gradient wind relation:

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

f: coriolis force
ρ: density of air
v_g: gradient wind

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

$\boldsymbol{w}$: wind field
$\boldsymbol{C}$: TC velocity vector
r_e: coefficient of decay



inflow angle

This parametric TC model cannot represent wind speed reduction due to topography.

Typhoon bogusing

Common

- Upwind directional land roughness parameterization (Westerink *et al*, 2008) is adopted to represent the wind speed reduction in coastal areas.

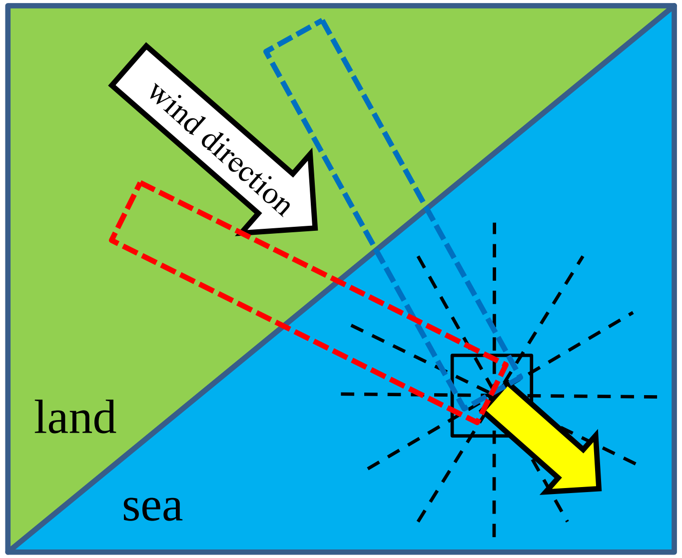
- Calculation of dumping coefficient

1. Calculate weighted average of roughness length of 30 km-upwind for 12-directions

$$\textit{Gaussian weight}: \ w(i) = \frac{1}{\sqrt{2\pi\sigma}} e^{[-d(i)^2/2\sigma^2]}$$

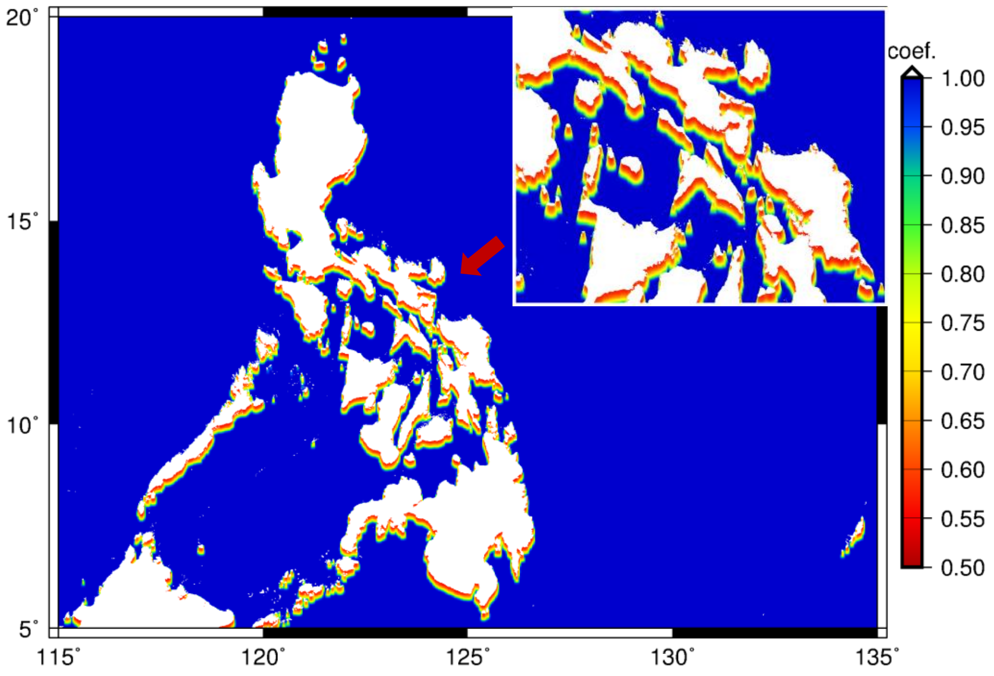
2. Interpolate directional land roughness to wind direction in a target grid
3. Calculate dumping coefficient from ratio between the interpolated land roughness and sea roughness

$$f_{\text{r-directional}-k} = \left(\frac{z_{0_{\text{marine}}}}{z'_{0_{\text{land-directional}-k}}} \right)^{0.0706}$$

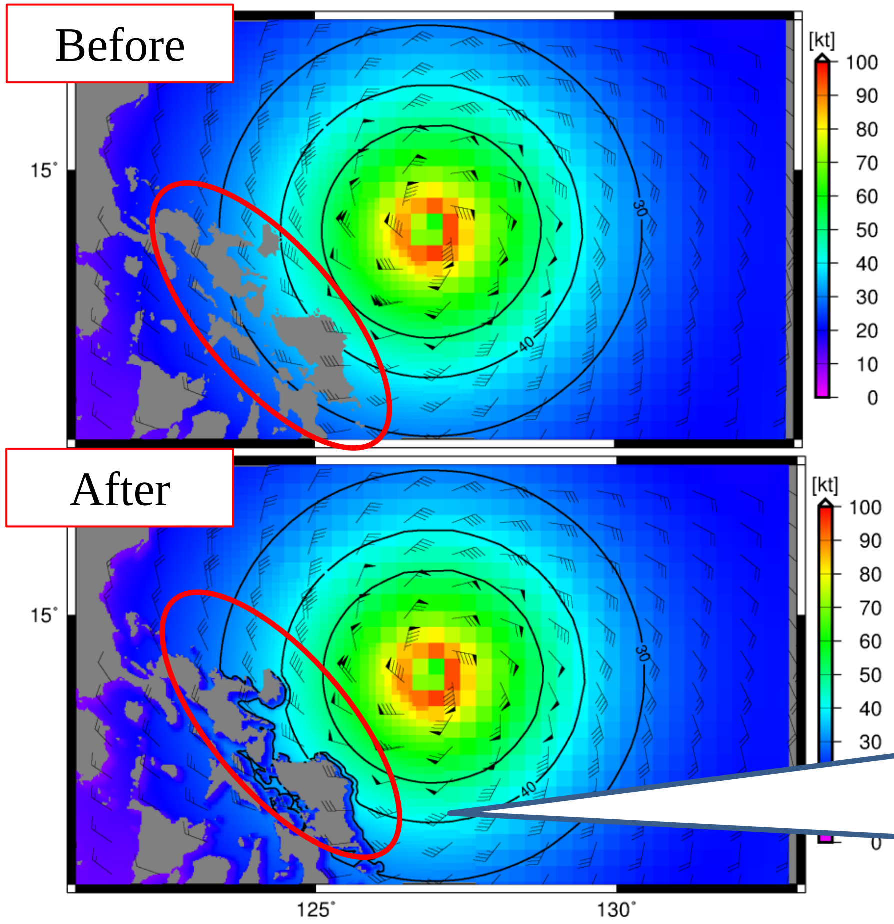


Typhoon bogusing

- Effect of upwind directional land roughness parameterization



Dumping coefficient against northern wind



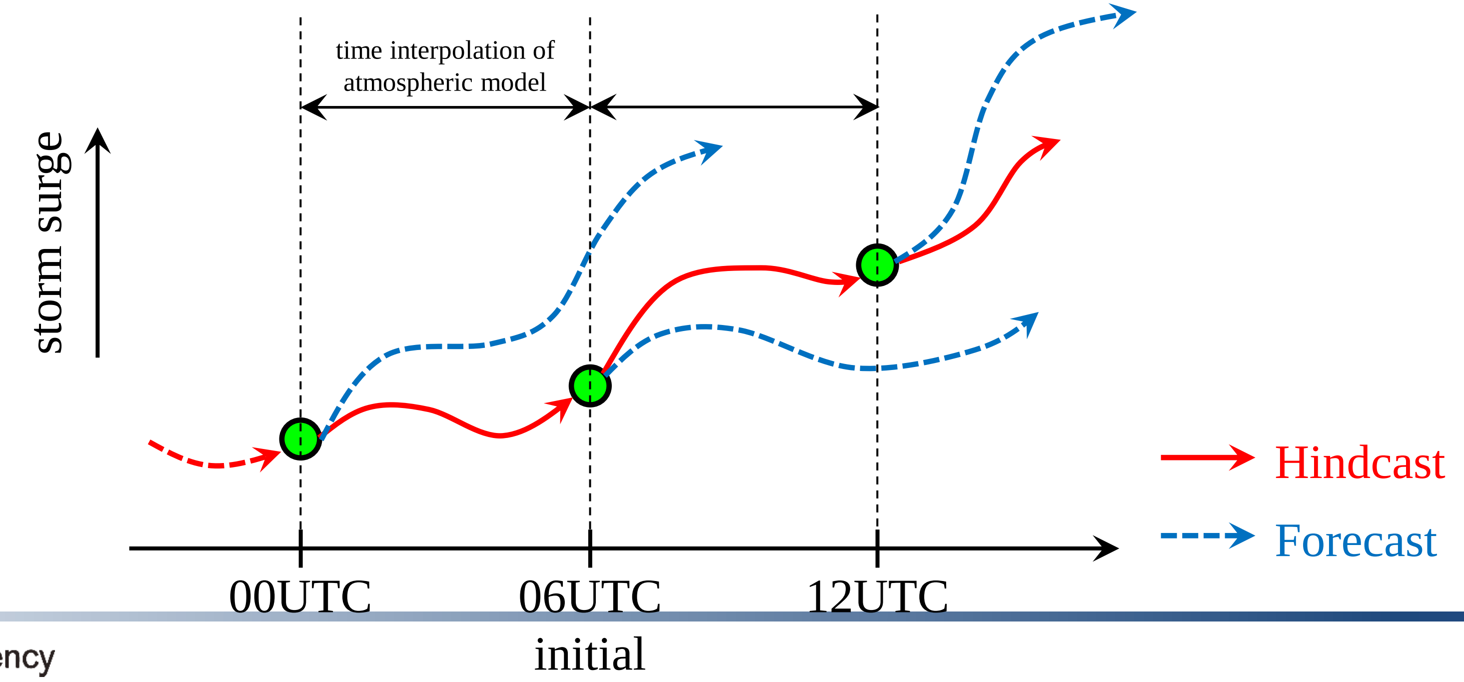
Ex.) TY Surigae
Colors and contours show wind speed.

Offshore winds are effectively dumped.

Initial condition

- Initial conditions are generated by “Hindcast”.
  - Initials of atmospheric model include analysis.
  - Storm surge model is driven by previous and current initials (analysis values) of atmospheric model (more accurate and continuous calculations).
  - No data assimilations

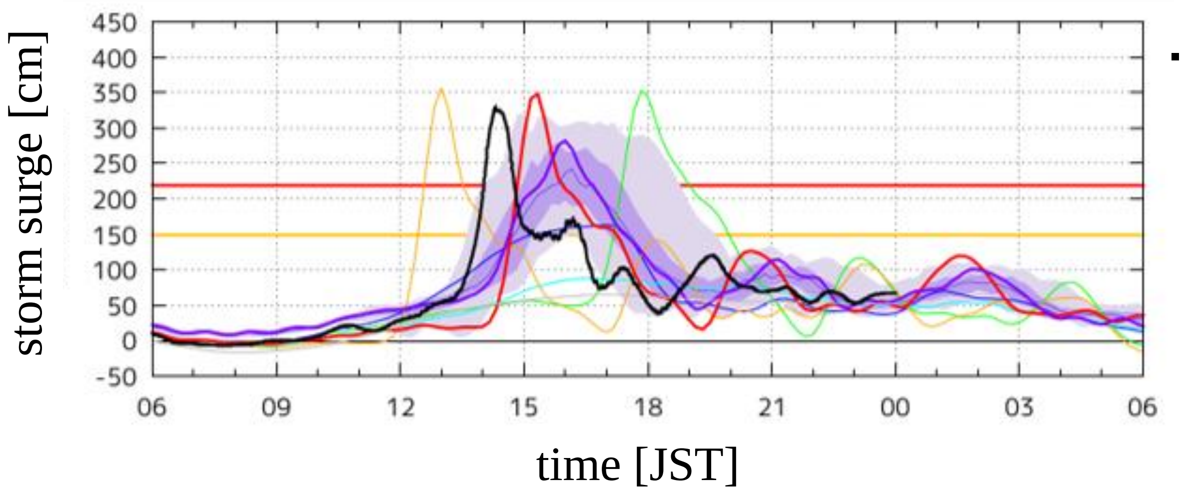
    Accuracy of the storm surge model largely depend on the accuracies of atmospheric model.



Storm surge EPS based on MEPS

- JMA initially considered to introduce a storm surge EPS based on JMA Meso-scale EPS (MEPS).
  - ･MEPS is an ensemble run of JMA Meso-scale model (resolution: 5km, the number of members: 21)

- In the performance test of storm surge EPS based on the MEPS, it was found that the worst scenario can be missed when an ensemble spread of MEPS is small.

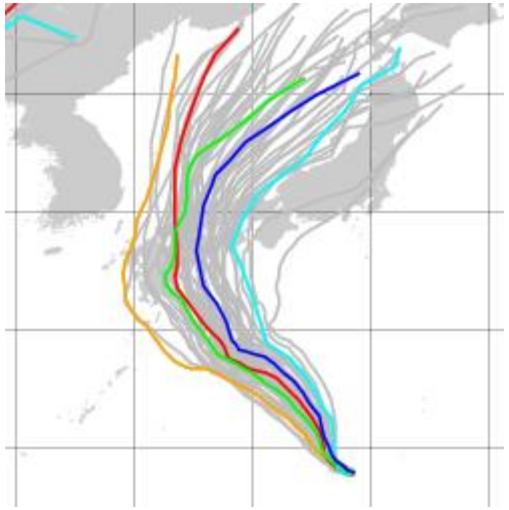


･Predicted storm surge at Osaka (03 Sep. 2018 06UTC Initial)
- ･Dark purple band: 1st - 3rd quatile
- ･Thin purple band: area between maximum and minimum value
- ･Purple line: ensemble mean
- ･Black line: observational data

Cluster analysis

- In the previous model, five members was extracted from GEPS by a cluster analysis.

- K-mean method
  - ･All members are classified into five clusters according to similarity of tracks.
  - ･The nearest members are chosen from each center of clusters.



K-means method

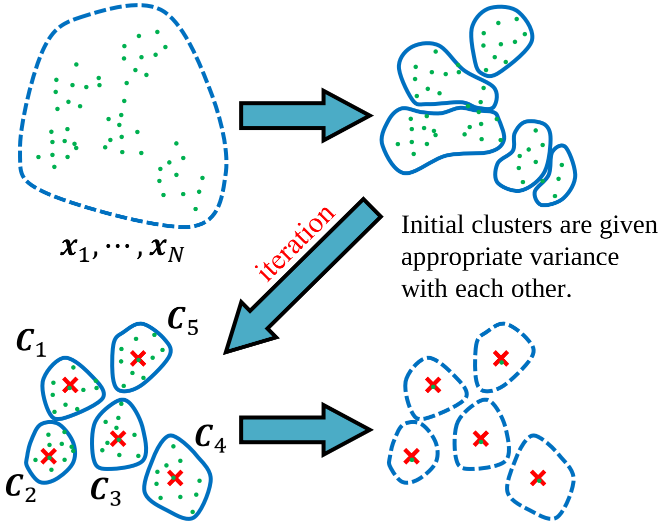
(N=51, K=5)

Center of typhoon:

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

Center of cluster:

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



- Example of TY Krosa
  Gray line: Tracks of GEPS for 51 menbers.
  Color line: Five members extracted by a cluster analysis

(Hasegawa, Kohno, Higaki and Itoh, 2017)

Finite volume model

cf. FVCOM (Chen et al, 2013), FESOM2 (Danilov et al, 2017)

➢ Solve 2d shallow water equation in spherical coordinate system

momentum equation

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

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

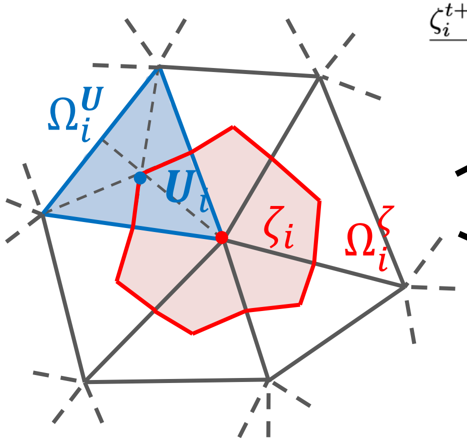
continuity equation

$$\frac{\partial\zeta}{\partial t}+\frac{1}{r\cos\varphi}\left(\frac{\partial uH}{\partial\lambda}+\frac{\partial vH\cos\varphi}{\partial\varphi}\right)=0$$

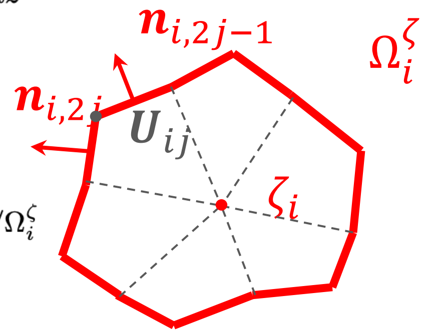
$$U\equiv\int_{-H_0}^{\zeta}u\,dz,\quad V\equiv\int_{-H_0}^{\zeta}v\,dz$$

➢ Arakawa B-grid configuration

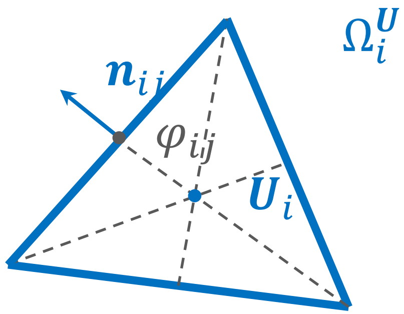
- current speed flux (vector)
  - placed at centroid of triangles
  - control volume is Ω_i^U
- sea-surface height (scalar)
  - placed at nodes
  - control volume is Ω_i^ζ



$$\frac{\zeta_i^{t+1}-\zeta_i^t}{\Delta t}=\sum_j^{jm}(\boldsymbol{n}_{i,2j-1}+\boldsymbol{n}_{i,2j})\boldsymbol{U}_{ij}^t/\Omega_i^\zeta$$



$$\frac{\boldsymbol{U}_i^{t+1}-\boldsymbol{U}_i^t}{\Delta t}=\sum_j^3\boldsymbol{n}_{ij}\varphi_{ij}^t/\Omega_i^U$$



Numerical scheme

- The following scheme is adopoted.
  - The Euler forward-backward scheme is adopted for a time integration.
  - The biharmonic filter is implemented to remove grid-scale noise.

    cf. FESOM2 (Danilov et al, 2017)
  - The implicit gravity-wave radiation condition is adopted for the open boundary condition.

    cf. Chapman, 1985
  - The first-order upwind differencing scheme is adopoted for an advection term.
  - A parabolic drag coefficient is chosen.

    cf. Peng & Li, 2015

Comparison of specification

	Previous model	New model
Model	two-dimensional linear model	two-dimensional nonlinear model
Grid	Lat-Lon, staggered grid (Arakawa C-Grid)	Unstructured (triangular) grid (Arakawa B-Grid)
Region	0 – 46ºN, 95ºE – 160ºE	0 – 50ºN, 95ºE – 180º
Resolution	2’ x 2’ (~3.7 km)	1.5 km~50 km
Forecast period	72 hours	132 hours
Initial time	00, 06, 12, 18 UTC	00, 06, 12, 18 UTC
Ensemble member	no-typhoon case: 1 member (GSM) typhoon case: 6 members (GSM + 5 members chosen from GEPS)	no-typhoon case: 1 member (GSM) typhoon case: 52 members (GSM + GEPS 51 members)
Atmospheric forcing	GSM (~27km) GEPS (~55km)	GSM (~20 km) GEPS (~27 km)

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