JMA's Wave Ensemble System and Related Development

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1. Introduction

Wind-generated waves associated with meteorological events such as tropical and extratropical cyclones can damage port facilities and capsize maritime vessels, as seen with the effects of Typhoon Faxai (1915) on the Tokyo Bay area in September 2019.

Against this background, JMA's third-generation ocean wave model MRI-III (operated within the Agency's deterministic Global Wave Model (GWM) and Coastal Wave Model (CWM)) provides wave forecast data to reduce the impact of disaster caused by wind-generated waves. As deterministic models are often characterized by significant and unpredictable uncertainty in medium-range and longer-term prediction, the Wave Ensemble System (WENS) with MRI-III was introduced in June 2016 to provide probabilistic wave prediction.

Here, WENS physics and specifications are described in Section 2, prediction accuracy is outlined in Section 3, and related online products are detailed in Section 4.

2. Numerical prediction modeling

2.1 Ocean wave model physics

As the 1 – 100-meter order of magnitude for ocean wavelengths is too small for individual wave resolution in numerical modeling, ocean wave models forecast wave energy density based on frequency and wave direction (referred to as the two-dimensional wave spectrum). MRI-III (Ueno 2004) employs the following energy balance equation:

$$\frac{\partial F}{\partial t} + \boldsymbol{\nabla} \cdot \left(\boldsymbol{C_g} F\right) + \frac{\partial}{\partial \theta}(\Omega F) = S_{in} + S_{nl} + S_{ds} + S_{btm}$$

where

$$\Omega = \frac{C_g}{C_p}\left(-\frac{\partial C_p}{\partial x}\cos\theta + \frac{\partial C_p}{\partial y}\sin\theta\right)$$

represents refraction in shallow water. $F(f, \theta, \boldsymbol{x}, t)$ is the two-dimensional wave spectrum, where f is frequency, θ is wave direction, $C_g(f, \theta, \boldsymbol{x})$ is group velocity, and $C_p(f, \boldsymbol{x})$ is phase speed. S_{in} is energy input from wind, S_{nl} is nonlinear energy transfer, S_{ds} is energy dissipation associated with wave breaking and other effects, and S_{btm} is energy loss associated with seabed friction. These source functions have previously been detailed by JMA (2022).

2.2 WENS characteristics

Table 1 shows the specifications of JMA's WENS operation for support in medium-range ocean wave forecasting with 51 members and no initial perturbation. All members start with the same initial wave spectrum. Surface wind fields as predicted by the Global Ensemble Prediction System (GEPS) are used for the 51 members.

Recent WENS updates have included the addition of shallow water effects (2020), horizontal resolution enhancement from 1.25 to 0.5 degrees (2020) and an ensemble member increase from 27 to 51 (2021).

Table 1. JMA Wave Ensemble System specifications

Model	MRI-III (third-generation wave model)
Area	Global (75°S-75°N)
Grid size	0.5°×0.5° (720×301)
Forecast length	264 hours
Ensemble size	51 members
Time step	10 minutes (advection term) 30 minutes (source term)
Spectral component	900 components 25 frequencies from 0.0375 to 0.3 Hz 36 directions
Initial condition	Data assimilation by Optimal Interpolation
Wind field	The Global Ensemble Prediction System (GEPS)

3. WENS performance

3.1 Ensemble mean verification

Figure 1 shows forecast accuracy comparison between ensemble mean and control run (CNTL) for significant wave height based on observation data from altimetry satellites as a base for verification. Mean errors and RMSEs are employed as forecast accuracy scores in the graphs. The overall bias of ensemble mean is negative and it is more accurate than CNTL, especially for prediction with lead times exceeding 72 hours.

Figure 2 shows maps of average significant wave heights from satellite observation and forecast accuracy scores for the ensemble mean of significant wave height in 24-hour forecasting. Forecast quality is generally high, but is low in some regions. Negative biases appear off the Philippines and in the North Atlantic, and positive biases are seen in the Southern Ocean. These biases are attributed to MRI-III errors.

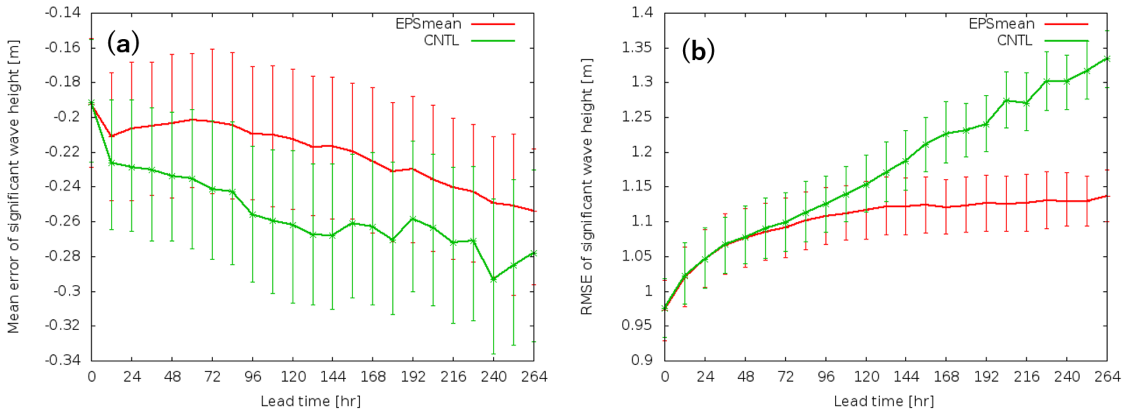

Figure 1. (a) Mean errors and (b) RMSEs for global significant wave height of ensemble mean (red) and control run (green) from June 2019 to March 2020.

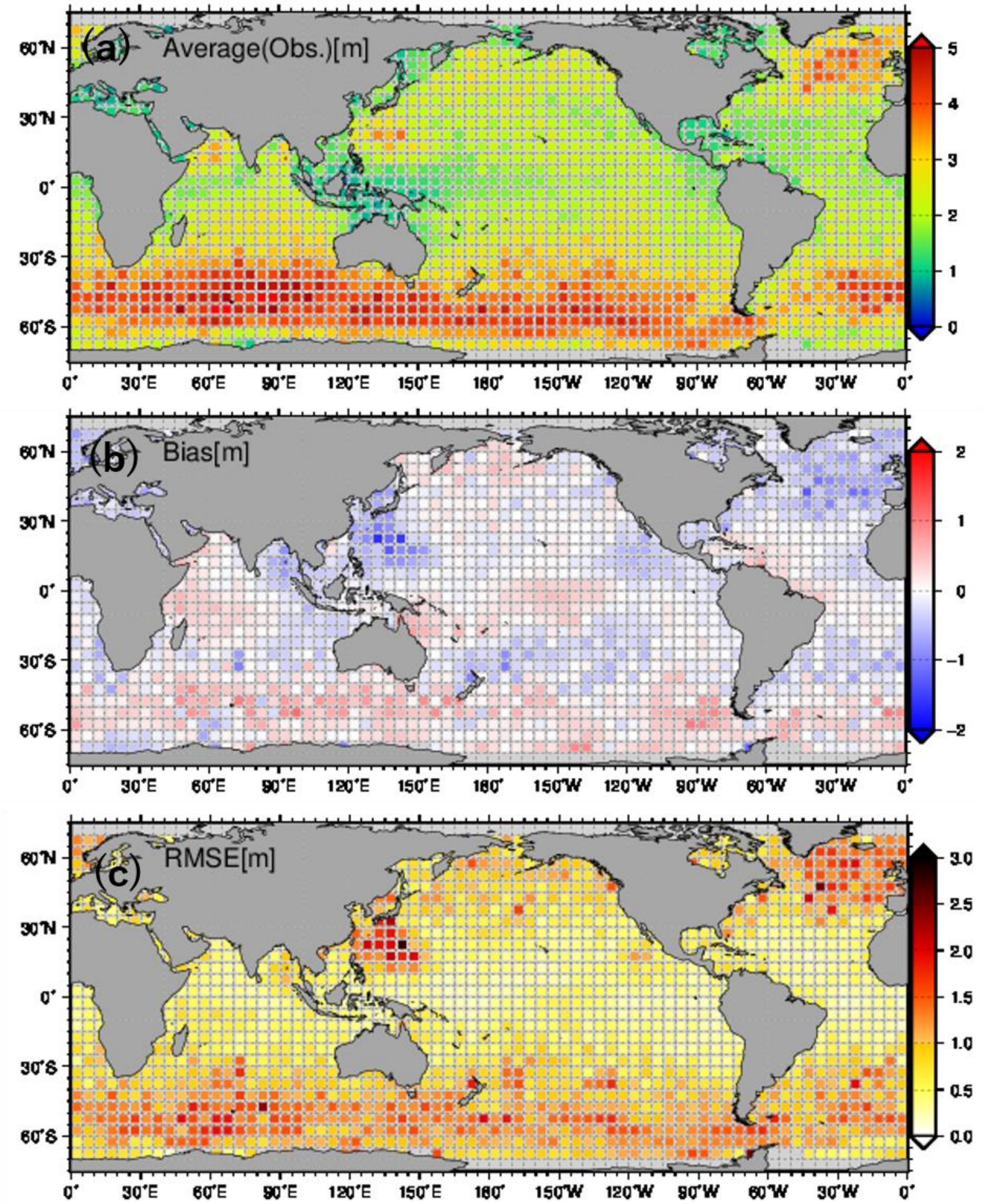

Figure 2. Horizontal distribution of (a) average significant wave heights calculated from satellite observations from June 2019 to March 2020; (b) mean errors and (c) RMSEs for the ensemble mean of significant wave height in 24-hour forecasting for the same period.

3.2 Probabilistic scores

Figure 3 shows reliability for significant wave height in 120-hour forecasts with probability divided into 51 ranges (the number of WENS ensemble members). WENS exhibits very high forecast capacity for probability of wave heights over 3 m. However, the system over-forecasts for high probability of waves over 6 m due to WENS characteristics.

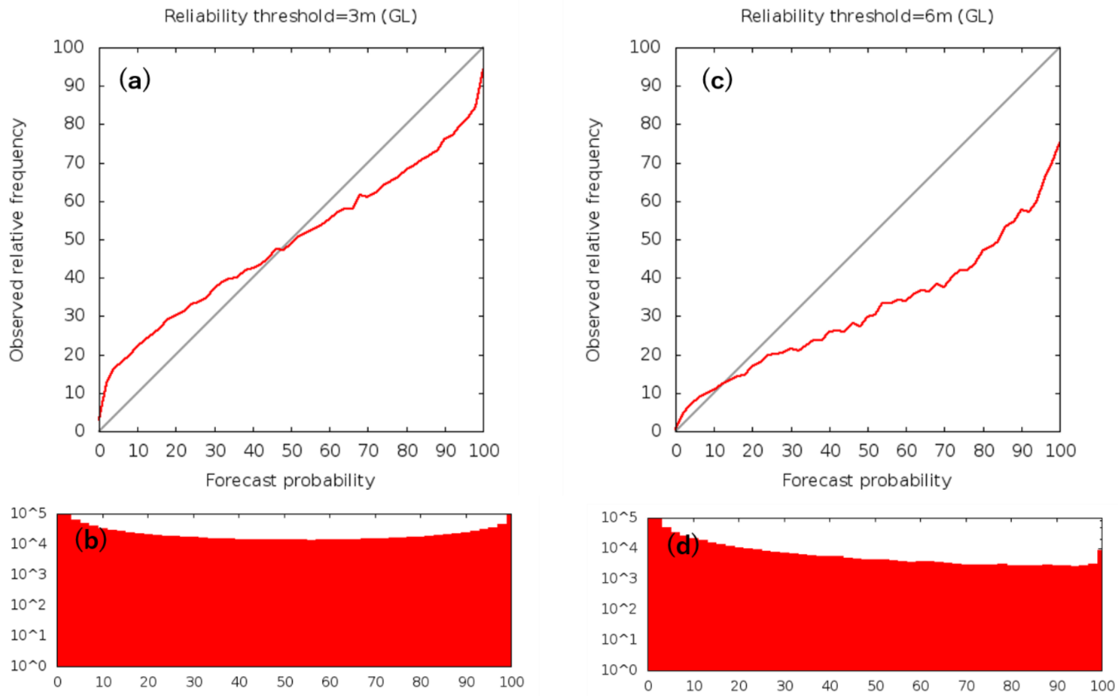

Figure 3. Reliability for significant wave height in 120-hour forecasting. (a) Reliability for prediction of waves over 3 m high; (b) number of observation data; (c) and (d): the same, but for over 6 m.

4 Products

WENS products are provided on the Numerical Typhoon Prediction (NTP) website of the RSMC Tokyo – Typhoon Center for ESCAP/WMO Typhoon Committee members and on the JMA website for the WMO Severe Weather Forecasting Programme (SWFP) (https://www.wis-jma.go.jp/swfdp/index.html), with significant wave height and peak wave period distribution charts of ensemble mean, probability and ensemble spread. Third quartile is available only for significant wave height distribution. Box plots and time-series representations of probability are also provided.

Figures 4-7 highlight Typhoon Surigae (2102) as an example of WENS products. Wave heights exceeding 6 m are predicted off the northeast coastal region of the Philippines with a probability of more than 60%. Figures 6 and 7 show the probability of swell with a period of over 12 seconds hitting the Philippine coast.

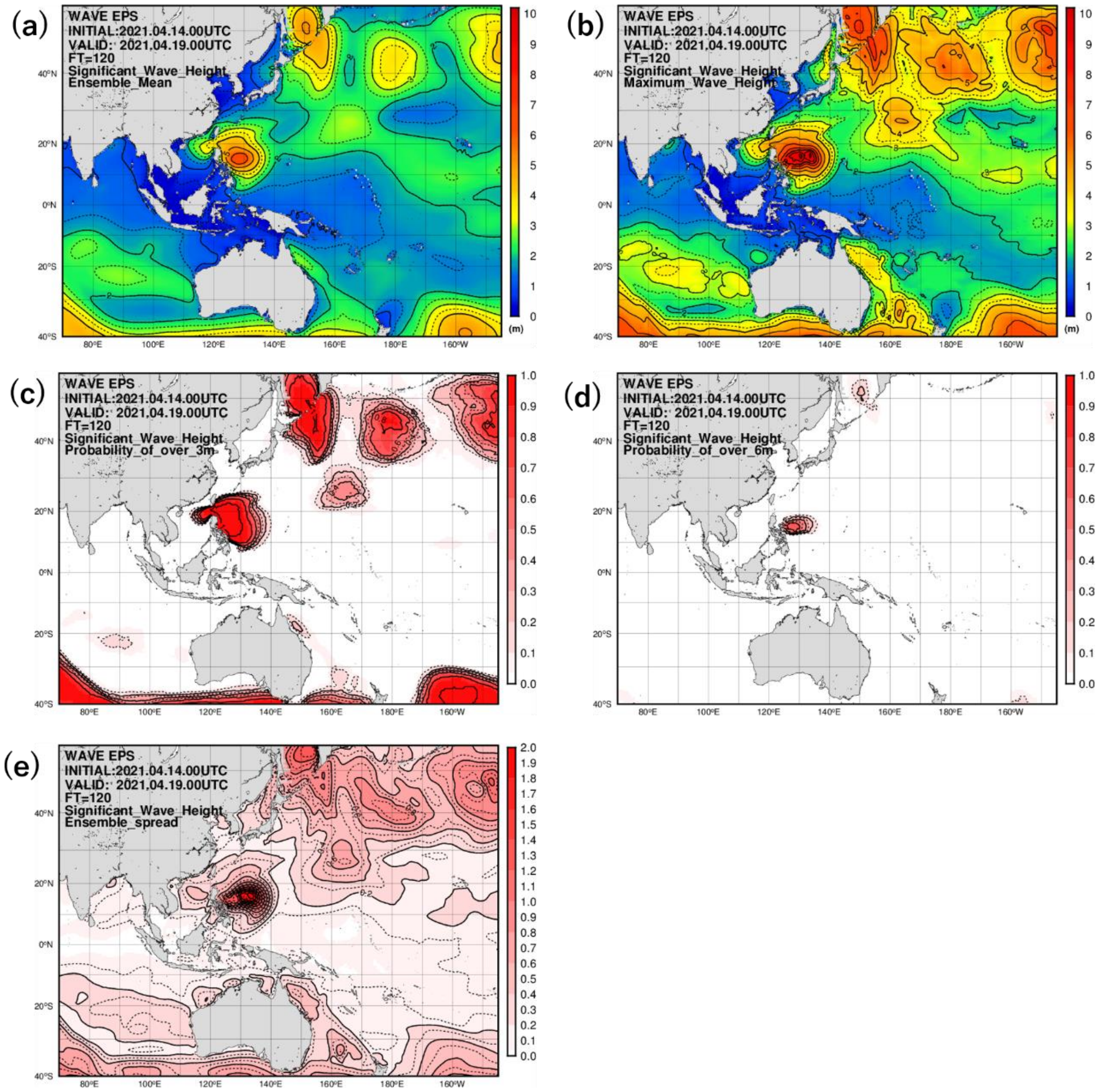

Figure 4. Statistical distribution of significant wave height in 120-hour prediction with an initial time of 00 UTC on 14 April 2021. (a) ensemble mean; (b) maximum; (c) probability of heights over 3 m; (d) probability of heights over 6 m; (e) ensemble spread.

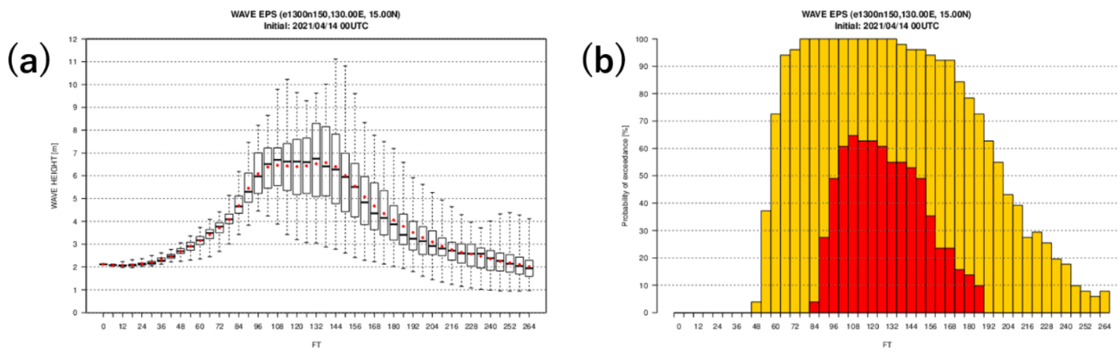

Figure 5. Time-series representations of significant wave height with an initial time of 00 UTC on 14 April 2021. (a) box plots; (b) probability off the northeastern coast of the Philippines. Yellow > 3 m; red > 6 m.

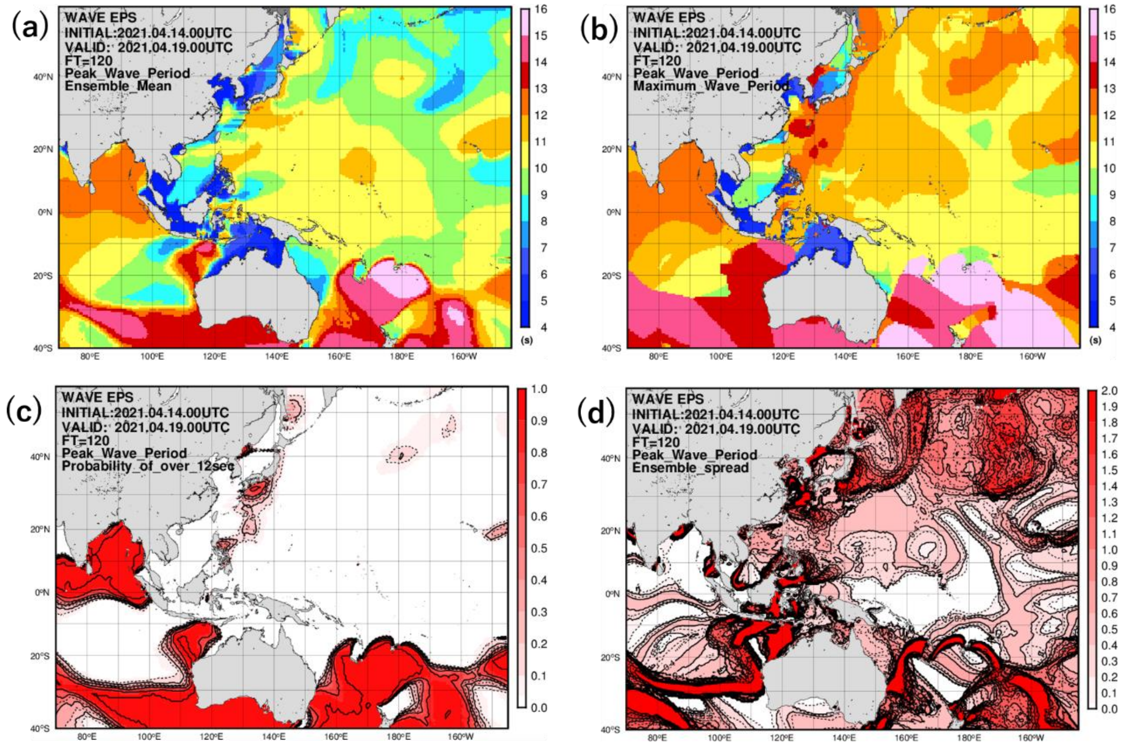

Figure 6. Statistical distribution of peak wave period in 120-hour prediction with an initial time of 00 UTC on 14 April 2021. (a) ensemble mean; (b) maximum; (c) probability of values over 12 seconds; (d) ensemble spread.

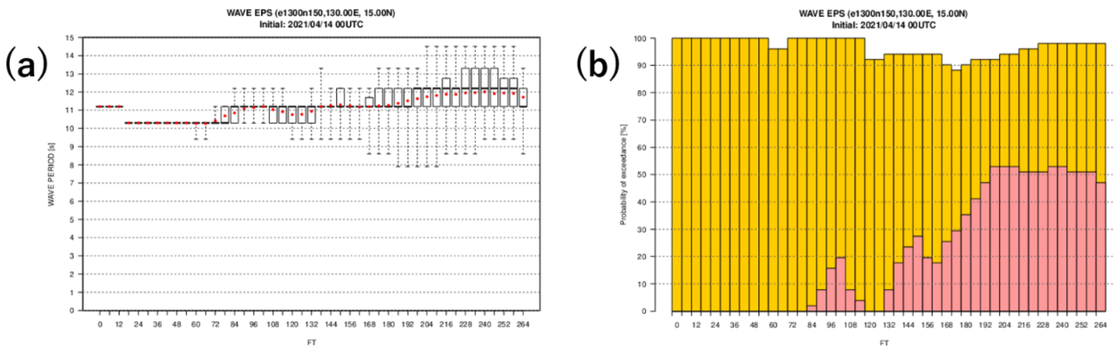

Figure 7. Time-series representation of peak wave period with an initial time of 00 UTC on 14 April 2021. (a) box plots; (b) probability off the northeastern coast of the Philippines. Yellow > 10 sec; pink > 12 sec.

5 Summary

This paper outlines the features and prediction accuracy of JMA's WENS operation for medium-range ocean wave forecasting and related online products for Typhoon Committee and SWFP members.

WENS is run twice a day with 51 members and a forecast range of 264 hours. A basic energy balance equation is applied, and a two-dimensional wave spectrum is used as a variable to forecast ocean wave fields. Results from the system are utilized for one-week ocean wave forecasting and issuance of related warnings.

The system is characterized by relatively high forecast accuracy, but also exhibits errors such as a negative bias in ensemble mean significant wave height for high-wave areas and over-forecasting of high-wave probability.

JMA plans to employ a multi-grid model for WENS to increase horizontal resolution for coastal regions and reduce calculation burdens.

References

JMA 2022: Outline of the operational numerical weather prediction at the Japan Meteorological Agency. Appendix to WMO Technical Progress Report on the Global Data-Processing and Forecasting System and Numerical Weather Prediction, 246pp, https://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2022-nwp/index.htm.

Ueno, K. 2004: The development of the third generation wave model MRI-III for operational use. *Proceedings of the 8th International Workshop on Wave Hindcasting and Forecasting*, North Shore, Oahu, Hawaii, 14–19 November 2004, G2, (http://www.waveworkshop.org).