THE DEVELOPMENT OF JMA WAVE DATA ASSIMILATION SYSTEM

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1. INTRODUCTION

The Japan Meteorological Agency (JMA) has been operating numerical wave models since 1977. JMA now operates two wave models: the Global Wave Model (GWM) and the Coastal Wave Model (CWM) as listed in table 1. The current wave models are the third generation wave model MRI-III, which was developed in Meteorological Research Institute of JMA (Ueno and Kohno, 2004). It has been used operationally since May 30th, 2007 (Tauchi et al., 2007), with some minor updates on July 3rd, 2008 and April 1st 2011.

JMA also quasi-operates Shallow-water Wave Model (SWM) for several bays in Japan. This model has high resolution of 1 minute and is able to simulate detailed wave conditions. The model was based on WAM and developed in the National Institute for Land and Infrastructure Management, as a cooperative work between JMA and the Water and Disaster Management Bureau of MILT (the Ministry of Land, Infrastructure, Transportation, and Tourism). The main purpose is to provide the wave run-up height information to the river control managers of MILT.

JMA is going to replace its super computer system, Numerical Analysis and Prediction System (NAPS). Along with this replacement, some plans are considered to develop wave models and storm surge models. For example, 1) incorporation of wave data assimilation to wave models, 2) stochastic wave information by ensemble forecasts, 3) extension of areas of SWM, 4) inclusion of shallow water effect to the JMA wave models, and 5) issuing some information on dangerous area for voyaging and estimation of beach influence by high waves, by making use of wave spectra.

According to the result of the wave-verification project of JCOMM, the accuracy of JMA global model is not good especially at early forecast times. The main reason is that wave observations are not incorporated in the JMA operational wave models, although the problem also seems to be arose by the numerical weather model (the Global Spectrum Model; GSM), since the accuracy of surface winds at initial is not so good.

Therefore, a wave data assimilation scheme is eagerly expected and has been developed. It is a following development after the JMA Objective Wave Analysis System (OWAS), which had been developed for the previous years. The newly developed assimilation scheme showed good impacts on prediction accuracy, and is going to be put into operation.

Outline of this scheme and performance is explained. In this paper, assimilation scheme in detail is introduced in the next section. In section 3, the results and performances of the assimilation are described. Some comments are described in section 4 and end with summary in section 5.

2. NUMERICAL METHODS

2.1 The Assimilation scheme

The outline of JMA wave data assimilation system is explained. JMA developed the Objective Wave Analysis System (OWAS) and this system has been operationally used since December 1st, 2009. The OWAS modifies wave model GPVs (significant wave heights) by observed data via the optimum interpolation (OI) method. The OWAS refers various data: significant wave heights measured by the radar altimeter of orbital satellites, in situ wave data such as moored / drifting buoys, coastal wave recorders, and wave reports by ships. The outline of the OWAS was described in table 2.

Since the OWAS results are supposed as the most accurate wave field available, initial condition is modified so as to fit with those analyses. In our assimilation system, observed wave data are not directly used, but are used in objective analysis, and then the analyzed results are referred in assimilation. However, the OWAS only analyzes significant wave heights, not wave spectrum, and some way to rectify wave spectra from wave height information is necessary. Of course it needs many assumptions. In

Table 1. The outline of JMA operational wave model.

	Global Wave Model (GWM)	Coastal Wave Model (CWM)
Model type	MRI-III (Third generation wave model)	
Domain	global area 75°S~75°N, 180°W~0°~180°E (cyclic)	sea around Japan 20°N~50°N, 120°E~150°E
grids	720×301	601×601
grid interval	0.5° × 0.5°	0.05° × 0.05°
wave spectrum components	900 components (25 in frequency × 36 in direction) frequency：0.0375~0.3Hz；logarithmically divided direction：10 degree interval	
forcing	Global Spectral Model GSM（20km grid） winds within typhoons are modified by ideal gradient winds（~ 72 hours）	
forecast time (12UTC) (00/06/18UTC)	 216 hours 84 hours	 84hours 84 hours

	Shallow-water Wave Model （SWM）					
Model type	WAM base (Third generation wave model)					
Domain	Tokyo Bay 35.05°N~ 35.75°N, 139.55°E~ 140.15°E	Ise Bay 34.35°N~ 35.05°N, 136.45°E~ 137.45°E	Harima-Nada Osaka Bay 34.05°N~ 34.85°N, 134.15°E~ 135.45°E	Ariake Sea 32.45°N~ 33.25°N, 130.05°E~ 130.75°E	Sendai Bay 37.75°N~ 38.45°N, 140.90°E~ 141.50°E	Off Niigata 37.80°N~ 38.40°N, 138.35°E~ 139.25°E
grids	37×43	61×43	79×49	43×49	37×43	55×37
grid interval	1’ × 1’					
wave spectrum components	1260 components（35 in frequency×36 in direction） frequency： ：0.0418~1.1Hz；logarithmically divided direction：10 degree interval					
forcing	Meso-scale Model MSM（5km grid） winds within typhoons are modified by ideal gradient winds					
forecast time (03/09/15/21UTC)	33 hours					

our system, we adopted the following way.

1) Wave energy difference from observation

A wave height ratios *r* between a model GPV (the first guess) and analysis is calculated. This is a key value for rectification. This is a ratio of a significant wave height, there is no information on windsea or swell height difference. As the simplest way, we can homogeneously rectify the wave spectrum, just multiplying each spectrum component by this ratio. In our system, we tried to rectify widsea and swell respectively, by making use of knowledge on spectrum behaviors of windsea.

In fact, it requires some additional assumptions, a sincere way is to make use of wave spectrum observation by SAR etc, but those data are not available in JMA now.

2) Extraction of a windsea spectrum

First, we need to divide wave spectra to windsea and swell parts. There are many ways of division; we referred the way of the second generation (CH) wave model TOHOKU (Toba et al., 1985). The windsea spectrum component is defined by the model surface wind. We assume that windsea spectrum $F_{sea}(f,\theta)$ is defined as

$$F_{sea}(f_w,\theta); \quad f_w > \frac{f_{cr}}{\cos\theta} \quad \left(|\theta| < \frac{\pi}{2}\right) \tag{2.1}$$

The critical limit frequency f_{cr} is

$$f_{cr} = 0.75 \cdot f_p = 0.75 \cdot \frac{0.13g}{u_{10}} \tag{2.2}$$

Where f_p is the peak frequency of the PM spectrum, g is the acceleration of gravity, and u_{10} stands for surface wind. This scheme is also used in the JWA3G model (Suzuki and Isozaki, 1994) but the coefficient of critical frequency is 0.5. In our test, this value was turned out to tend to overestimate windsea area especially in the case of strong wind. The coefficient was determined to 0.75 empirically.

It could be preferable to use observed wind data. However, wind observation has been assimilated to numerical weather models. Moreover, model winds may be consistent to the estimated spectrum, that is windsea and swell and we use model winds.

3) Extraction of a swell spectrum

Next, swell spectrum part $F_{swl}(f,\theta)$ is defined. It is actually just the residues of $F_{sea}(f,\theta)$.

Table 2. Outline of JMA Objective Wave Analysis System (OWAS)

area	global area 75°S~75°N 180°W~0°~180°E (cyclic)
grids	720 × 301
grid interval	0.5° × 0.5°
the first guess	Global Wave Model GPV (6hours forecast) *Coastal wave Model GPVs are used in the sea around Japan
analyzing method	Optimum interpolation (OI) scheme
Observation data	Satellite (RA), buoy, ship, coastal recorders etc (Converted to 0.25 degree GPVs)
analysis time	4 times a day (00, 06, 12, and 18 UTC)

$$F_{swl}(f,\theta) = F(f,\theta) - F_{sea}(f,\theta) \tag{2.3}$$

Actually, plural swell may exit, but we do not consider swell component further and deal with them just as one swell.

4) Modification

Let the total wave energy as E_{tot}, windsea energy E_{sea}, and swell energy E_{swl}, namely,

$$E_{tot} = E_{sea} + E_{swl}$$

The corrected values are expressed with prime (*)'. Previous to rectification, the each energy (E_{sea} and E_{swl}) are compared to check which one is dominant. The way of modification is slightly different in the case a. windsea dominant or b. swell dominant.

a. Windsea dominant case ($E_{sea} \geqq E_{swl}$)

The difference ratio r is used to rectify the windsea. However, we do not simply change the wave height energy H_{wsea}, instead, peak frequency f_p is changed. In windseas, wave heights and wave periods (frequency) have a strong relation, well-known as Toba's power law (Toba, 1972). Therefore, the difference of wave height can determine the corrected peak frequency f_p',

$$\left(\frac{f_p'}{f_p}\right)^3 = \left(\frac{H_{wsea}}{H_{wsea}'}\right)^2 = r^2 \tag{2.4}$$

We assume that windsea spectrum is expressed by the JONSWAP profile, and replace the windsea spectrum to the JONSWAP spectrum with peak frequency f_p'.

Since the modified total energy E_{tot}' is the product of r^2 and E_{tot}, the rectified energy E_{swl}'is determined as

$$E_{swl}' = E_{tot}' - E_{sea}' = r^2 E_{tot} - E_{sea}' \tag{2.5}$$

From this value, swell spectrum is rectified as

$$F_{swl}'(f,\theta)=\frac{E_{swl}'}{E_{swl}}F_{swl}(f,\theta) \quad (2.6)$$

b. Swell dominant case ($E_{sea} < E_{swl}$)

The swell spectrum is rectified with the difference ratio r.

$$\begin{aligned} F_{swl}'(f,\theta) &= r^2 F_{swl}(f,\theta) \\ &= \frac{E_{tot}'}{E_{tot}}F_{swl}(f,\theta) \end{aligned} \quad (2.7)$$

The windsea has the same difference ratio too. The spectrum is rectified with the same ratio, also considering of the Toba's power law.

However, the summation of the (temporary) estimated windsea energy E_{sea_tmp}' and E_{swl}' does not usually become same to E_{tot}'. Therefore, the windsea spectrum is further adjusted so as to the total wave energy becomes E_{tot}'.

$$F_{sea}'(f,\theta)=\frac{E_{tot}'-E_{swl}'}{E_{sea\_tmp}'}F_{sea\_tmp}'(f,\theta) \quad (2.8)$$

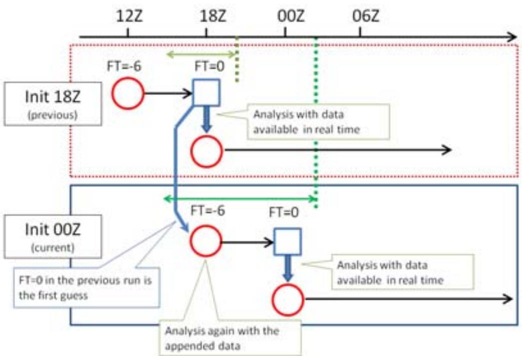

Figure 1 The schematic image of wave model analysis-forecast cycle.

2.2 The assimilation cycle

In JMA system, wave models run 6-hourly, and the OWAS also analyzes wave conditions 4 times a day. 6-hourly wave analyses are available. However, the OWAS only refers wave data which are available in real time base. There may be additional wave data in a few hours later. To make use of appended data for analyses too, the OWAS analyzes wave field again in the previous initial time and assimilation is carried out twice in one calculation: the previous initial time and current initial time. Longer hindcast might lead to better accuracy but it requires long computation. We only conduct assimilation twice in one model run. The wave model cycle and assimilation is illustrated in Figure 1.

3. RESULTS

The impact and performance of the assimilation system were verified with several calculations. We conducted several month-range calculations in different seasons. The results are shown in the following sub-sections.

3.1 Results of global calculations

Global calculations are most expected to be improved by assimilations. We conducted three cases: winter (January, 1- 31, 2010), summer (August, 1-20, 2009), and autumn (October, 1-31, 2009). The season name stands for the Northern Hemisphere (NH), but of course season is opposite in the Southern Hemisphere (SH). Since some input data were not available in the summer case, the period of calculation was shorter than other cases.

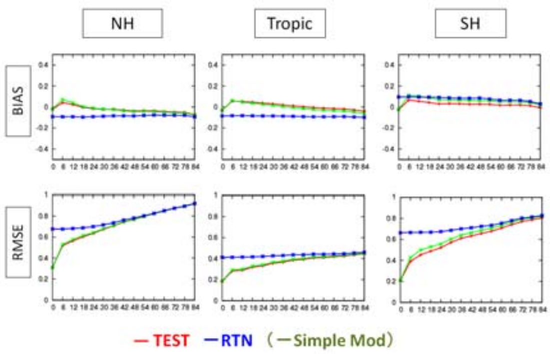

Figure 2 The statistical results (bias and RMSE) of winter case (Jan. 2010).

The TEST / RTN indicate assimilated / operational (non- assimilation) run. The Simple Mod indicates that spectrum was modified equally with the wave height ratio.

Figure 2 depicts the statistical results (bias and RSME) in the winter case. The values were calculated in NH, SH, and the tropics (20S ~ 20N). The decrease of RMSE by assimilation was 0.37m (NH), 0.23m (Tropics), and 0.45m (SH), respectively. However, the improvement became quickly small in the first 6 hours, and it gradually converged to the non-assimilated run. The effects of assimilation generally continued up to 72 hours.

In this case, high waves seldom generated in

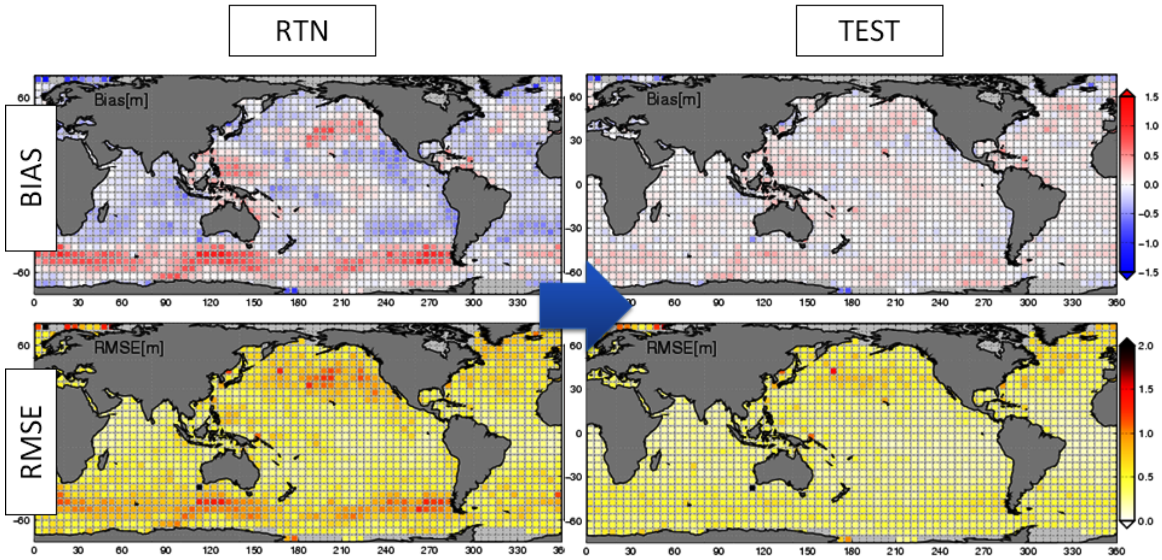

Figure 3 The horizontal distribution of BIAS and RMSE at 6 hours forecast in winter case (Jan. 2010).

the tropics and mean wave height was not high. Therefore, it would be reasonable that improvement of RSME was the smallest. In SH, RMSE improvement was remarkable. It may be because oceans cover the major part of SH and rectification was carried out in wide area. Especially, high waves always exist in high latitude zone in SH, large amounts of wave height might have been rectified.

The green line indicates the simple modification in which wave spectra are corrected uniquely with the wave height ratio r. It shows that even simple modification worked well and led to good improvement. However, especially in SH, our scheme gave slightly better results and improvement was kept.

It is notable that non-assimilation case shows the flat bias, which means their wave fields could be physically natural and consistent. The bias quickly changes in assimilated runs, which could be a problem of spin up. In a sense, initial condition was artificially modified by assimilation, some inconsistency might be unavoidable.

Figure 3 depicts the horizontal distribution of bias and RMSE at 6 hours forecast. The map indicates that RMSE of the non-assimilated calculation was strongly dependent on bias and became worse in some areas, such as mid-latitude in SH and north-eastern Pacific. These biases were removed and became flat horizontally in the assimilated calculation and RSME decreased. In general accuracy of the assimilated model has less local dependency and became homogeneous.

The results of summer case (August in 2009) are depicted in Figure 4. August is winter in SH and waves are generally high. The impact of assimilation was large and the RMSE at initial decrease was as large as 0.59m in SH. It is ridiculous that some vibration is detected in both bias and RSME of the tropics, although the reason has not been cleared yet.

We got fair results in the October case too. Typhoons are often formed in October, and the swell fields by them were correctly rectified by the assimilation. However, such area is not so large in global scale and it usually continues only several days, assimilation impact was not so large. In fact, wave field by typhoons were sometimes not effectively rectified because of insufficient observation.

3.2 Results of regional calculations

We here show the assimilation impact in the seas around Japan by the Coastal Wave Model (CWM). Since the CWM requires more computer resources, we conducted only one case from 1 to 20 January 2010.

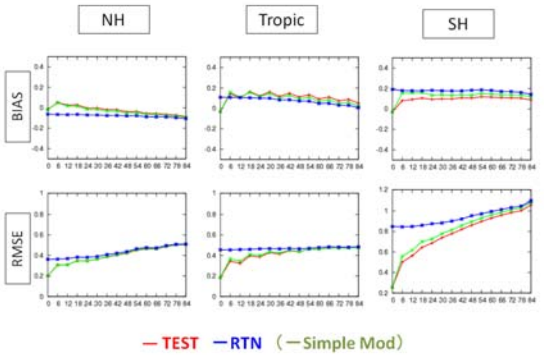

Figure 4 The statistical result of summer case (Aug. 2009) .
The caption is same as figure 2.

Figure 5 depicts the statistic results of regional calculation. The assimilation decreased RMSE by about 0.3m and the effect continued to 18 hours forecast. The impact tends to be small and quickly disappears compared to the global cases. As for bias, the assimilated run monotonously decreased as forecast time goes on. In winter, low bias is apparent in the JMA operational model. This low bias was clearly removed and the initial bias became near zero although it decreased too in later forecast.

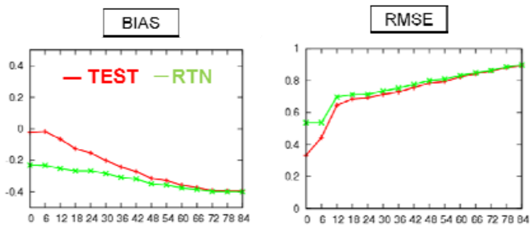

Figure 5 The statistical result of regional calculation (Jan. 2010) .
The caption is same as figure 2.

The horizontal impacts in 12 hours forecast are depicted in Figure 6. It is an example of 12 hours forecast wave heights in the Japan Sea at 00UTC on 9 of January. Wave heights became over 3m, which is larger than the wave advisory regulation, in the middle part of the Japan Sea. On the other hand, operational model underestimated and predicted wave heights below 3m. The assimilated model fairly predicted the wave heights over 3m. The distribution of 12 hours forecast by assimilated run was much alike to the analysis.

The wave heights were compared with observed values at Kyogamisaki, Fukuejima and Naha (the location is shown in Fig. 7). Figure 8 depicts the time sequences of wave heights at initial (FT=00) and 12 hours forecast (FT=12). In that period, strong monsoon blew in the East Asia, and several high wave events occurred.

The impact of assimilation seems not so large, but the wave heights by assimilated run become slightly closer to the observation. The improvement at initial would purely come from assimilation, while the 12 hours forecast may contain influence of model integration. The assimilated run predicted slightly better wave heights in 12 hours forecast too.

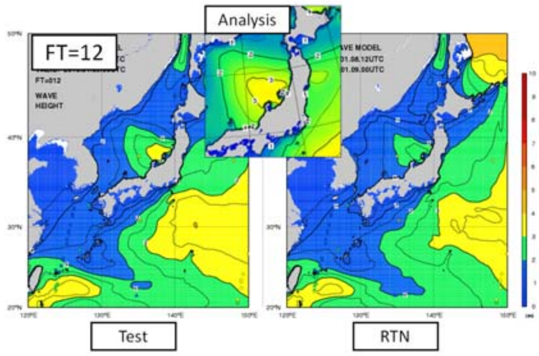

Figure 6 A example of 12 hours forecast wave (00UTC on 9 Jan. 2010) .
The central map indicates the analysis results.

4. DISCUSSIONS

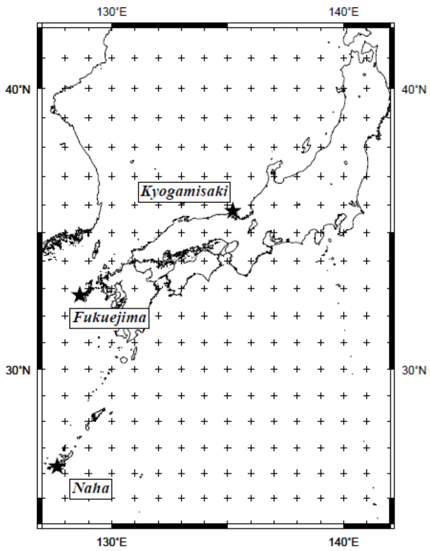

Figure 7 location of wave station.

4-1 persistency of the assimilation

In our test, assimilation surely improved accuracy in both calculations, but the impact of the global calculation was larger than the regional one. This may come from basically two reasons.

First, waves can endure and propagate as swell, the rectified information can be maintained widely in oceans. Since high swell can sometimes propagate for several days, the impact of corrected high swell could be kept both in time and space. In the regional case, swell easily dissipated by hitting beaches or propagating outside the region and impact disappears quickly.

Assimilation only rectifies initial condition and wave fields are supposed to be quickly adjusted to weather condition. However, assimilation impact could be sustained in some degree in oceans.

The other is that high waves may exist in global area and there is much possibility to rectify in quantity. If wave heights are not so high, modified values become small.

In a sense, large improvement indicates that predicted values contain large errors. As a matter of fact, JMA wave models tend to estimate delayed evolution of windsea and to overestimate saturated waves. The assimilation will support sufficient windsea growing and decrease higher waves.

4-2 some perspectives in operational system

JMA now issues 4 wave charts: AWPN, AWJP, FWPN, and FWJP. Two charts (AW…) are wave analyses charts and other two (FW…) are 24 hours forecast charts. The character “PN” indicates the charts are for North-Western Pacific, and “JP” indicates the charts are for seas around Japan. Analyses charts are currently produced by the OWAS and are issued twice a day. 24 hours forecast charts are still produced manually and are issued once a day.

According to the results, the 24 hours forecast has comparable accuracy with the manual wave charts. This means that we can produce wave forecast charts automatically based on the assimilated model GPVs. We have a plan to produce wave charts automatically.

5. SUMMARY

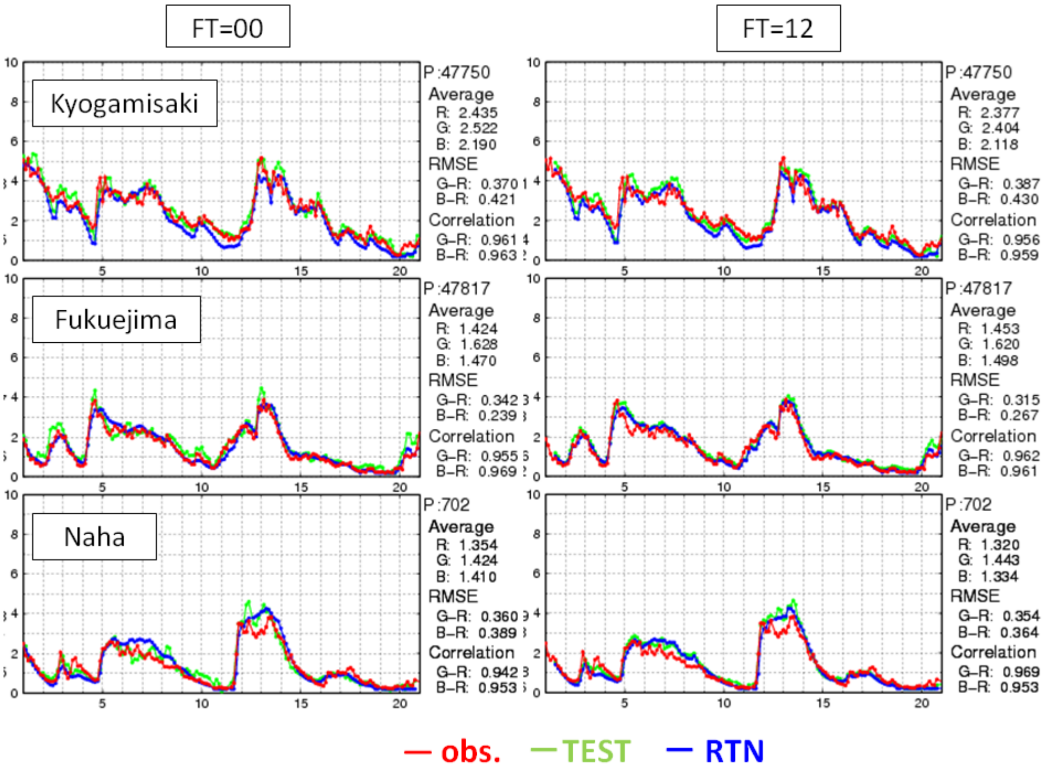

Figure 8. Time sequences of wave heights at Kyogamisaki, Fukuejima, and Naha.

Right graphs are initial and left graphs are 12 hours forecast.

A wave data assimilation system for JMA operational wave model has been developed. The outline of this system is as follows:

1) Wave data are not assimilated directly in this system. This system refers the analyzed wave heights of the JMA Objective Wave Analyses System (OWAS). The key factor to rectify is the ratio of wave heights between model products and the OWAS products.
2) In modification, windsea and swell parts are extracted and modified respectively. Windsea spectra are modified supposing the JONSWAP spectrum profile. The peak frequency is determined by considering Toba's power law. As for swell spectrum modification, we monotonously rectify their energy by the wave height difference.
3) The assimilation system showed good improvement of accuracy. In verification tests, assimilation system decreased RSME by about 0.2 to 0.6m. The effect of assimilation was maintained longer than a simple test of monotonous modification.
4) The assimilation impact is apparent in global calculation. The impact may be maintained by propagation of swell. Also, there is much possibility for large rectification because high waves usually exist in global area,.

The good impact of the wave data assimilation system was confirmed, this system is going to be launched to the operation in the next year, just after the replacement of the JMA super computer system NAPS. It is expected that this system much improve the prediction accuracy. However, we have further development plans.

The accuracy of 24 hours prediction of the assimilated model was satisfactory and is comparable to the current wave forecast chart manually made. We have a plan to develop a system to produce wave charts automatically.

This system uses results of the OWAS. The statistic RMSE of the OWAS is about 0.4m and it should be improved. We expect some spontaneous improvement by the introduction of the assimilation system because it will give better first guesses. Besides, we have a plan to further develop the OWAS, by introducing the 3D-VAR scheme instead of the OI scheme.

In the assimilation system, no observed wave spectrum is used. It is not convenient for JMA to refer observed wave spectrum in real time now, but that information is crucial, especially to modify model spectra in detail. We would like to consider a way to utilize wave spectrum observations.

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