Ensemble wave forecasting over typhoon period

Yang-Ming Fan
Coastal Ocean Monitoring Center
National Cheng Kung University
Tainan, Taiwan
ymfan@mail.ncku.edu.tw

Jia-Ming Chen
Coastal Ocean Monitoring Center
National Cheng Kung University
Tainan, Taiwan

Shunqi Pan
School of Engineering
Cardiff University
Cardiff, UK

Chia Chuen Kao
Department of Hydraulic and Ocean Engineering
National Cheng Kung University
Tainan, Taiwan

***Abstract*—The purpose of this study is to quantitatively assess the effect of uncertainties on the wave forecasts using the ensemble approach. The ensemble method is an effective approach to assess the effect of the model uncertainty by producing not only one, but several forecasts. The ensemble wave modelling system was applied to the Taiwan sea area, especially for typhoon wave. There are four different operational atmospheric models that provide predictions of wind at 10 m height above sea surface. The simulated wave of WAVEWATCH III drove from NCEP, JMA, NFS, and WRF wind fields. From the simulated wave heights of all ensemble members, it can be clearly seen that the uncertainties from the atmospheric predictions have significantly affected the predicted hydrodynamic results. A further ensemble statistics, including the ensemble mean, and mean ± standard deviation. The measurement outcome scatters in between wave forecasting of mean + standard deviation and mean - standard deviation, which proves that the ensemble forecasting is able to reasonably predict typhoon waves. Therefore, the accuracy of the predictions of waves can be significantly improved by using ensemble approach closer to the observed wave measurement.**

Keywords—ensemble statistics; typhoon wave

I. INTRODUCTION

The capability of monitoring and predicting the marine environment leads to a more sustainable development of coastal and offshore regions. In recent years, operational marine environment condition has been considered a necessity given its essential role in solving economic, environmental and social problems. Since there is a strong connectivity between the ocean and atmosphere, thus marine forecasting is usually limited by atmospheric predictability in forecasting horizon and accuracy.

Coastal areas such as the Taiwanese water are characterized by a lot of user pressure of uses brought about by human activities and infrastructures. In this area waves are highly variable and have a significant impact on such activities. For this reason, wave prediction and evolution is of great importance for the design and management of such coastal areas and the mitigation of typhoon damages.

It has long been accepted that running an ensemble of numerical forecasts from slightly perturbed initial conditions can have a beneficial impact on the skill of the forecast by means of ensemble averaging [1]. Beyond providing a better estimate of the first moment of possible future states, the ensemble members also offer the possibility of estimating higher moments such as the forecast spread, which can be used as an indicator of expected skill, and, ultimately, the full probability distribution. Theoretically, the probability of future states can also be computed through the Liouville equations [2] if the initial probability distribution is assumed to be known. However, computational and other problems make the use of these equations unfeasible for numerical prediction in the foreseeable future. The only current practical solution to estimating forecast probabilities is through ensemble forecasting.

At the European Centre for Medium-Range Weather Forecasts (ECMWF), a combination of total energy based singular vectors are used to sample analysis uncertainty for initial ensemble perturbations [3, 4]. At the National Centers for Environmental Prediction (NCEP, formerly known as the National Meteorological Center), the bred vectors, which represent a nonlinear extension of the Lyapunov vectors (the fastest growing perturbations on the attractor) are used for the same purpose [5]. In yet another approach, Houtekamer et al. use multiple analysis cycles (with perturbed observational data and different model formulations) for generating initial ensemble perturbations [6].

The purpose of this study is to quantitatively assess the effect of uncertainties on the typhoon wave forecasts using the ensemble approach. The ensemble method is an effective approach to assess the effect of the model uncertainty by producing not only one, but several forecasts. Each forecast used different model physics with the aim of sampling the range of forecast results that are consistent with the uncertainties in the model and observations [7].

The present study was supported by National Science Council grant NSC Project No. is NSC 98-2923-I-006-001-MY4.

II. ENSEMBLE MEAN AND ENSEMBLE STANDARD DEVIATION

As numerical forecasting system is a non-linear calculated process, it could be led to huge difference in forecasting results even slight change of system. However, there are many uncertainties exist in the forecasting system, for instance, the initial data error and model deficiencies, etc., all of which might cause changes in forecasting results. Traditional numerical forecasting system is deterministic model to get the deterministic answers. It can not grasp the uncertainty of forecasting process, and also can not provide the uncertain information. Therefore, it is difficult to grasp all possible change of ocean by using deterministic model.

Ensemble forecasting was developed to compensate for the lack of deterministic forecasting through a set of equally distributed scenarios and get a series of answers. The ensemble mean has long been accepted that running an ensemble of numerical forecasts from slightly perturbed initial conditions can have a beneficial impact on the skill of the forecast [8]. In this study, the ensemble mean was chosen to assess the ensemble disagreement. The ensemble mean is obtained by averaging all ensemble forecasts. This has the effect of filtering out features of the forecast that are less predictable. These features might differ in position, intensity and even presence among the members. The averaging retains those features that show agreement among the members of the ensemble. The averaging technique works best some days into the forecasts when the evolution of the perturbations is dominantly non-linear. During the initial phase, when the evolution of the perturbations has a strong linear element, the ensemble average is almost identical to the control because of the "mirrored" perturbations. In order to know the ensemble mean is reasonable or not, ensemble standard deviation was calculated the difference between ensemble mean and true value. The formula of ensemble standard deviation is as follows:

$$s=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2} \qquad (1)$$

where x_i is the model results at each time; $\bar{x}$ is the mean of sampling the range of observations; n is the number of values x of model results.

III. MULTI-MODEL ENSEMBLE WAVE MODELLING SYSTEM

A. *WAVEWATCH III wave modelling*

WAVEWATCH III [8, 9, 10] is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model [11, 12]. It is a further development of the model WAVEWATCH, as developed at Delft University of Technology [13, 14] and WAVEWATCH II, developed at NASA, Goddard Space Flight Center [15]. WAVEWATCH III, however, differs from its predecessors in many important points such as the governing equations, the model structure, the numerical methods and the physical parameterizations. Furthermore, with model version 3.14, WAVEWATCH III is evolving from a wave model into a wave modeling framework, which allows for easy development of additional physical and numerical approaches to wave modelling.

The ensemble wave modelling System consists of the WAVEWATCH III wave model and an ensemble of four different wind fields. Four individual wave fields are generated using the WAVEWATCH III subject to the forcing of the four different wind fields respectively. The framework shows in Fig. 1. Ensemble mean and standard deviation with various thresholds are then calculated from the ensemble of these wave predictions.

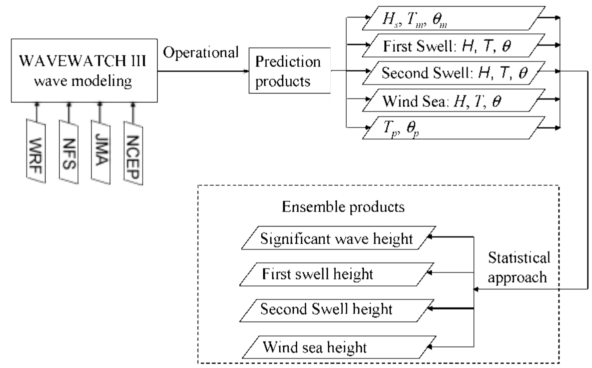

Fig. 1. Framework of the ensemble forecasting system

B. *Descriptions of the simulation region*

The interesting area of this study is in the Taiwan sea area. In order to get detailed wave information in this region and to effectively simulate the wave field, the simulated area shown in Fig. 2. The domain of the model covers from 99°E to 155°E and from 1°N to 41°N with a 0.5° grid resolution at one-hourly degree in both latitude and longitude. The bathymetry data WAVEWATCH III model runs were forced by operational 1-hourly wind fields with a 0.5 degree resolution in longitude and latitude, provided by the NCEP (National Centers for Environmental Prediction), JMA (Japan Meteorological Agency), NFS (Non-hydrostatic Forecast System), and WRF (Weather Research and Forecasting) models. The fields were linearly interpolated in space and time.

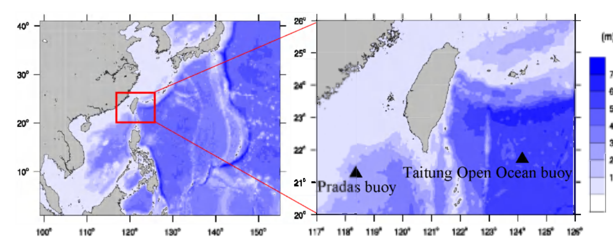

Fig. 2. The simulated domain of the model and corresponding data buoy station. Triangles show buoy locations.

C. *Observational data*

To verify the model predictions, field measurements of waves at two locations in the Taiwan sea area are used in this study, including Taitung Open Ocean buoy (21.75°N, 124.12°E) where the water depth is reached about 5000 meter; and the Pradas buoy (21.05° N, 118.75°E) where the water depth is reached about 2600 meter, locations of which are shown in Fig. 2. The pitch and role buoy is developed, manufactured and operated by the Coastal Ocean Monitoring Center (COMC) of National Cheng Kung University, assigned and supported by the CWB. The report directional wave spectra every hourly with the Fast Fourier Transform (FFT) is used to obtain the full two dimensional wave spectrum [16]. Details on data capturing, quality control and archiving can be found in Doong et al [17].

IV. METEOROLOGICAL DATA

A. *Meteorological models*

There are four different operational atmospheric models that provide predictions of wind at 10 m height above sea surface. These models have been widely used in operational forecasting, therefore only brief description to each model is given here.

- NCEP model: The NCEP's Aviation (AVN) global gridded analysis datasets for the period from January, 2002 until the current day is adopted in this study. This dataset gives 6 hourly atmospheric variables with a resolution of 0.5 degree. It is a time limited model run produced to give global weather predictions for other clients that rely on data being available at a fixed time, especially important for applications such as aviation.
- JMA model: JMA is in collaboration to develop the model for the use of both climate simulations and weather predictions. The model is based on the global numerical weather prediction (NWP) model of JMA, upon which modifications and improvements have been implemented. The JMA GSM gives 6 hourly atmospheric variables with a resolution of 0.5 degree.
- NFS model: The NFS model has been the operational model at CWB (Central Weather Bureau) for regional analyses and forecasts since 2001 [18]. This model has three domains (D1, D2, and D3) with nested grids and the horizontal grid sizes are 45, 15, and 5 km, respectively. The NFS performs regional objective analysis twice a day (at 0000 and 1200 UTC) using the three-dimensional multivariate optimal-interpolation (OI) analysis scheme [19, 20] with the 12-h forecast from the previous run as the first guess. Subsequently, update cycle runs are executed every 12 hours with a forecast length of 72 hours [21, 22].
- WRF model: The community WRF modeling system is a mesoscale forecast and data assimilation system that is designed to advance the atmospheric research and operational prediction. It has been used in atmospheric researches including mesoscale convective system, tropical cyclone (TC), and large eddy studies. The WRF has also been used by several NWP centers in their daily operations to provide guidance for forecasters, e.g., National Centers for Environmental Predication, Air Force Weather Agency, and Korea Meteorological Administration. At Central Weather Bureau, the WRF model is in a process of checking out for operation.

B. *Quality of wind field*

The quality of wind fields is of paramount importance for a wave prediction system. Here presents a preliminary assessment of wind components from atmospheric models comparing with the corresponding data from buoy station. Since model grids do not match exactly with buoy station location, the comparison was performed using a bi-linear interpolation and the nearest grid points.

The qualitative differences between the modeled and observed wind speed at Taitung Open Ocean buoy (Fig. 3) are illustrated by the time series comparison. It is shown that the tendency of the time series for models is similar to the observations. But an interesting feature is that all models data present an underestimation of the wind speed. This is possibly needed higher resolution maybe a necessary, but not sufficient, condition to get an improvement in wind field quality. The statistical results in terms of the Bias, Root Mean Square Error (RMSE) and Scatter Index (SI) for four meteorological models of the modeled wind speed with buoy observations' are summarized in Table I. From this table the NCEP's predicted data show the lowest wind speeds than others.

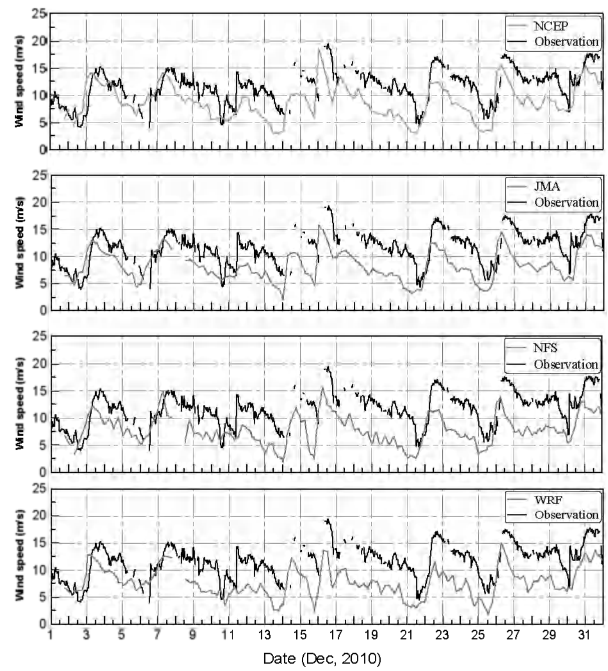

Fig. 3. Time series comparison of modeled and observed wind speed at Taitung Open Ocean buoy station. (see Fig. 2 for location).

TABLE I. BIAS, RMSE AND SCATTER INDEX FOR THE FOUR METEOROLOGICAL MODELS IN WIND SPEED

Meteorological model	*BIAS*	*RMSE*	*SI*
NCEP	-.3.03	4.10	0.23
JMA	-3.44	4.32	0.22
NFS	-4.03	4.88	0.25
WRF	-4.12	4.87	0.22

V. Ensemble Predictions

In order to discuss the ensemble forecasting on typhoon wave, there are four different operational atmospheric models that provide predictions of wind at 10m height above sea surface to simulated wave of WAVEWATCH III drove from NCEP, JMA, NFS, and WRF wind model. Fig. 4~Fig. 6 show the track of typhoon Jelawat, typhoon Meari, and typhoon Nanmadol. Fig. 7, Fig. 9, and Fig. 11 show the simulated wave heights at Taitung open Ocean buoy station for four ensemble members during each typhoon events. Fig. 8, Fig. 10, and Fig. 12 show the simulated wave heights at Pratas buoy station for four ensemble members during each typhoon events. Blue dotted line mean simulate wave drove from NCEP wind model, Blue line mean simulate wave drove from JMA wind model, Green line mean simulate wave drove from WRF wind model, Green dotted line mean simulate wave drove from NFS wind model, Red dotted line means observed significant wave height. From this figure it can be clearly seen that the uncertainties from the atmospheric predictions have significantly affected the predicted hydrodynamic results.

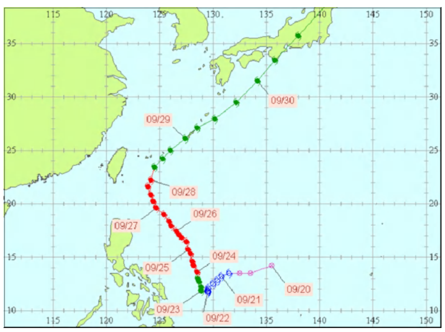

Fig. 4. Track of typhoon Jelawat in 2012

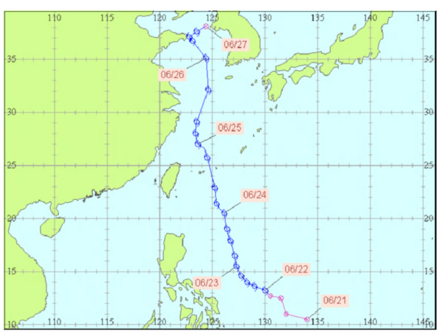

Fig. 5. Track of typhoon Meari in 2011

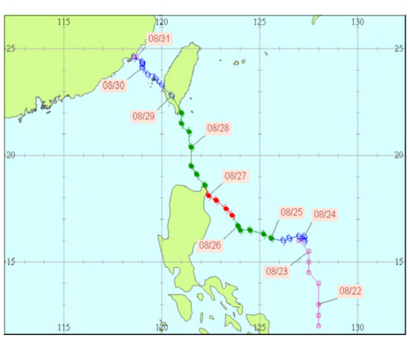

Fig. 6. Track of typhoon Nanmadol in 2011

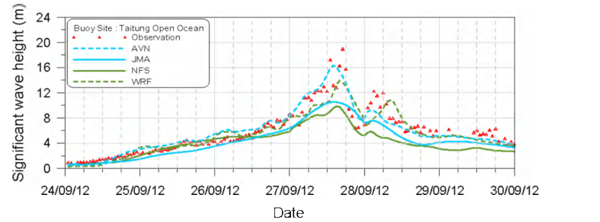

Fig. 7. The comparisons in time series of the significant wave height of ensemble members and observed data at Taitung open Ocean buoy station during typhoon Jelawat. (see Fig. 2 for location).

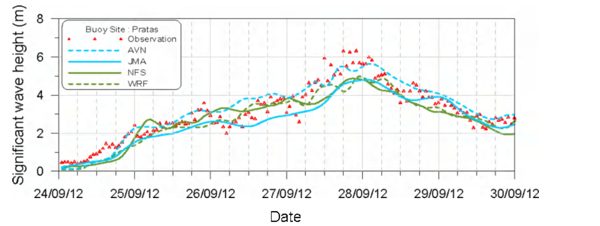

Fig. 8. The comparisons in time series of the significant wave height of ensemble members and observed data at Pratas buoy station during typhoon Jelawat. (see Fig. 2 for location).

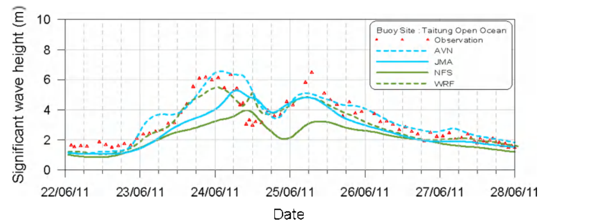

Fig. 9. The comparisons in time series of the significant wave height of ensemble members and observed data at Taitung open Ocean buoy station during typhoon Meari. (see Fig. 2 for location).

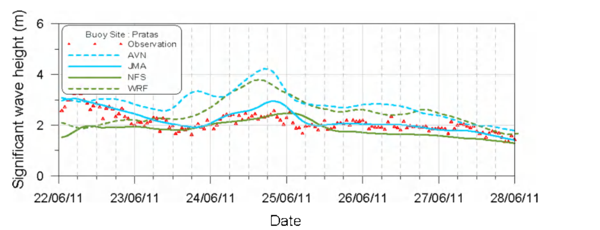

Fig. 10. The comparisons in time series of the significant wave height of ensemble members and observed data at Pratas buoy station during typhoon Meari. (see Fig. 2 for location).

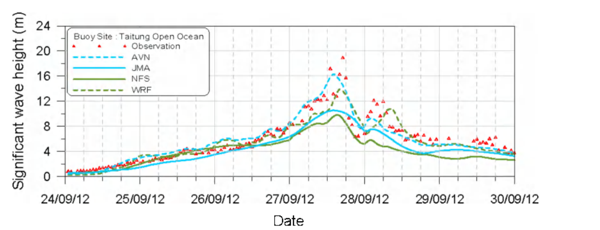

Fig. 11. The comparisons in time series of the significant wave height of ensemble members and observed data at Taitung open Ocean buoy station during typhoon Nanmadol. (see Fig. 2 for location).

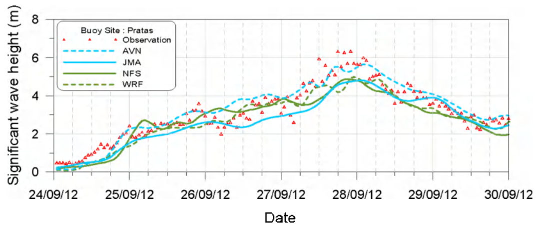

Fig. 12. The comparisons in time series of the significant wave height of ensemble members and observed data at Pratas buoy station during typhoon Nanmadol. (see Fig. 2 for location).

Fig. 13, Fig. 15, and Fig. 17 show the spatial distribution of ensemble mean on wave simulation during each typhoon events. The mean of significant wave height in the east is higher than other Taiwan sea area. Fig. 14, Fig. 16, and Fig. 18 are the spatial distribution of ensemble standard deviation on wave simulation during each typhoon events. They show that the biggest error is happened near Pacific ocean. Therefore, the ensemble forecasting on wave modelling has better model results in Taiwanese water than Pacific ocean. A further ensemble statistics, including the mean of ensemble mean, and mean ± standard deviation at each time, are shown in Fig. 19~Fig. 24. They show that the measurement outcome scatters in between wave forecasting of mean + standard deviation and mean - standard deviation, which proves that the ensemble forecasting is able to reasonably predict typhoon waves. The statistical results in terms of the Bias, Root Mean Square Error (RMSE), CR, and Scatter Index (SI) for three ensemble statistics of the modeled significant wave height with buoy observations' are summarized in Table II~Table IV.

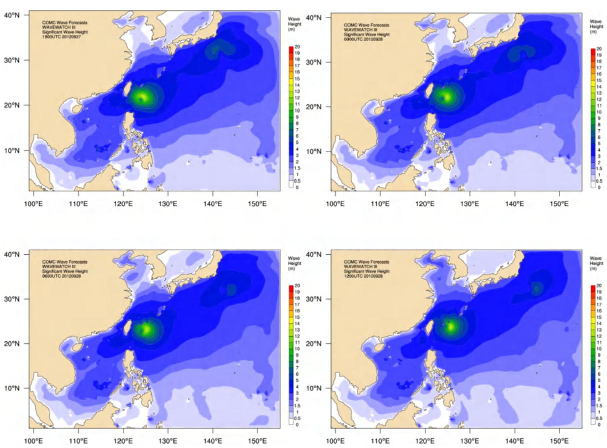

Fig. 13. The spatial distribution of ensemble mean on wave simulation during Typhoon Jelawat.

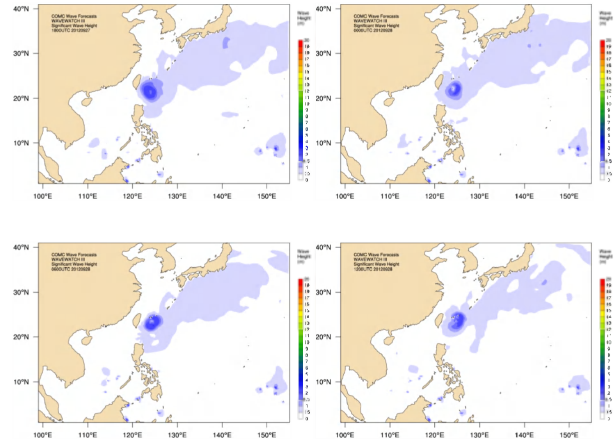

Fig. 14. The spatial distribution of ensemble standard derviation on wave simulation during Typhoon Jelawat.

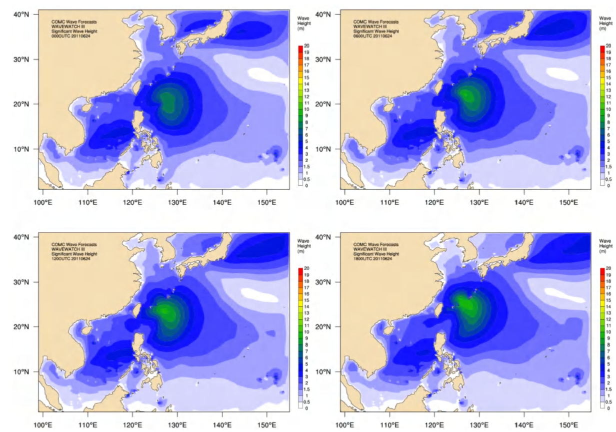

Fig. 15. The spatial distribution of ensemble mean on wave simulation during Typhoon Meari.

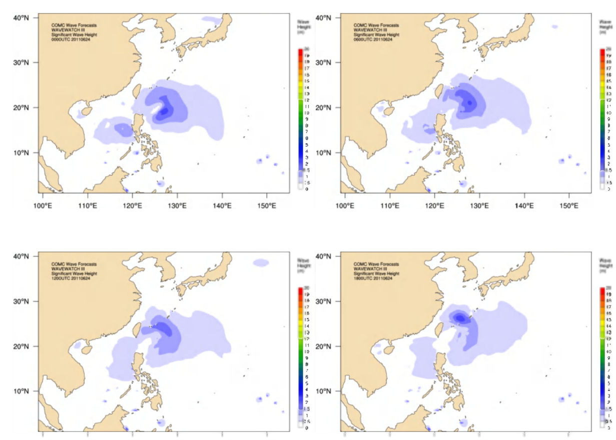

Fig. 16. The spatial distribution of ensemble standard derviation on wave simulation during Typhoon Meari.

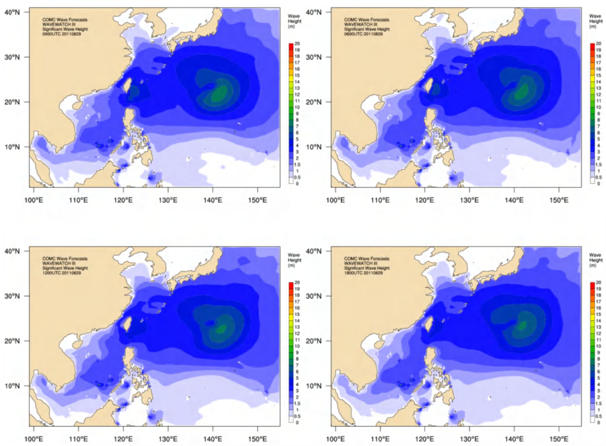

Fig. 17. The spatial distribution of ensemble mean on wave simulation during Typhoon Nanmadol.

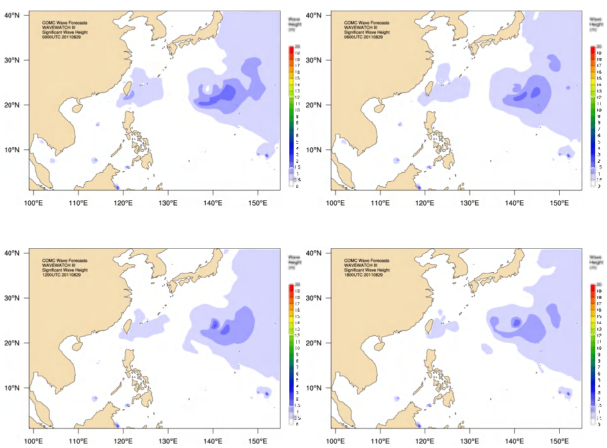

Fig. 18. The spatial distribution of ensemble standard derviation on wave simulation during Typhoon Nanmadol.

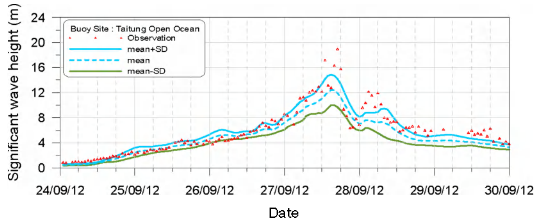

Fig. 19. Statistical analysis of ensemble results at Taitung open Ocean buoy station during typhoon Jelawat.

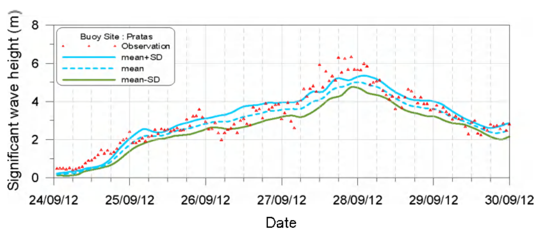

Fig. 20. Statistical analysis of ensemble results at Pratas buoy station during typhoon Jelawat.

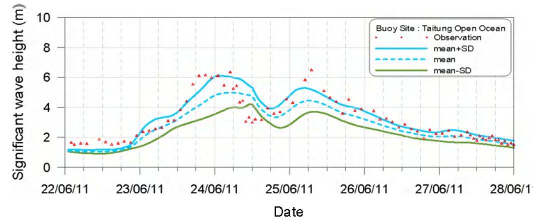

Fig. 21. Statistical analysis of ensemble results at Taitung open Ocean buoy station during typhoon Meari.

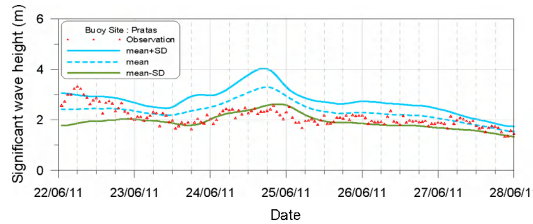

Fig. 22. Statistical analysis of ensemble results at Pratas buoy station during typhoon Meari.

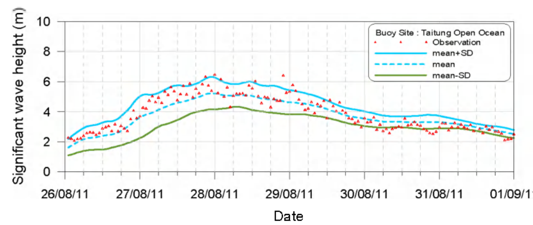

Fig. 23. Statistical analysis of ensemble results at Taitung open Ocean buoy station during typhoon Nanmadol.

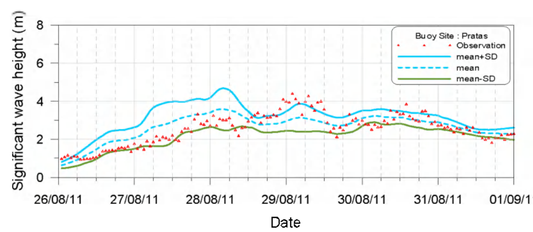

Fig. 24. Statistical analysis of ensemble results at Pratas buoy station during typhoon Nanmadol.

TABLE II. BIAS, RMSE AND SCATTER INDEX FOR THE THREE ENSEMBLE STATISTICS OF THE MODELED SIGNIFICANT WAVE HEIGHT WITH BUOY OBSERVATIONS' DURING TYPHOON JELAWAT.

Taitung Open Ocean				
	BIAS	***RMSE***	***CR***	***SI***
MEAN	0.04	0.67	0.85	0.17
MEAN-SD	-0.79	1.16	0.76	0.30
MEAN+SD	0.88	1.18	0.83	0.31
Prata				
MEAN	-0.22	0.51	0.96	0.16
MEAN-SD	-0.53	0.71	0.96	0.23
MEAN+SD	0.09	0.49	0.95	0.16

TABLE III. BIAS, RMSE AND SCATTER INDEX FOR THE THREE ENSEMBLE STATISTICS OF THE MODELED SIGNIFICANT WAVE HEIGHT WITH BUOY OBSERVATIONS' DURING TYPHOON MEARI.

Taitung Open Ocean				
	BIAS	*RMSE*	*CR*	*SI*
MEAN	-0.34	0.81	0.90	0.26
MEAN-SD	-0.83	1.18	0.86	0.37
MEAN+SD	0.14	0.75	0.91	0.24
Prata				
MEAN	0.24	0.45	0.59	0.21
MEAN-SD	-0.18	0.41	0.60	0.20
MEAN+SD	0.65	0.79	0.62	0.37

TABLE IV. BIAS, RMSE AND SCATTER INDEX FOR THE THREE ENSEMBLE STATISTICS OF THE MODELED SIGNIFICANT WAVE HEIGHT WITH BUOY OBSERVATIONS' DURING TYPHOON NANMADOL.

Taitung Open Ocean				
	BIAS	*RMSE*	*CR*	*SI*
MEAN	-0.13	0.50	0.92	0.13
MEAN-SD	-0.82	1.09	0.82	0.28
MEAN+SD	0.57	0.69	0.95	0.18
Prata				
MEAN	0.12	0.53	0.81	0.21
MEAN-SD	-0.39	0.62	0.83	0.24
MEAN+SD	0.64	0.92	0.76	0.36

VI. CONCLUSIONS AND OUTLOOKS

An operational ensemble forecasting on wave modelling has been successfully set up over Taiwan sea area, which used the state-of-the-art wave model, WAVEWATCH III. The WAVEWATCH III modelling is in a general good agreement with the measurements.

The measurement outcome scatters in between wave forecasting of mean + standard deviation and mean - standard deviation, which proves that the ensemble forecasting is able to reasonably predict typhoon waves. Therefore, the accuracy of the predictions of waves can be significantly improved by using ensemble approach closer to the observed wave measurement.

ACKNOWLEDGMENT

The authors would like to thank the Central Weather Bureau for providing wind-field data and the observed wave data.

REFERENCES

[1] C. E. Leith, "Theoretical skill of Monte Carlo forecasts," Monthly Weather Review, 102, pp. 409–418, 1974.

[2] M. Ehrendorfer, "The Liouville equation and its potential usefulness for the prediction of forecast skill. Part I: Theory," Monthly Weather Review, 122, pp. 703–713, 1994.

[3] F. Molteni, R. Buizza, T. N. Palmer, and T. Petroliagis, "The ECMWF ensemble prediction system: Methodology and validation," Quarterly Journal of the Royal Meteorological Society, 122, pp. 73–119, 1996.

[4] T. N. Palmer, F. Molteni, R. Mureau, R. Buizza, P. Chapelet, and J. Tribbia, "Ensemble prediction," ECMWF Research Department Tech. Memo. 188, 45 p, 1992.

[5] Z. Toth, and E. Kalnay, "Ensemble forecasting at NMC: The generation of perturbations," Bulletin of the American Meteorological Society, 74, pp. 2317-2330, 1993.

[6] P.L. Houtekamer, L. Lefaivre, J. Derome, H. Ritchie, and H. L. Mitchell, "A system simulation approach to ensemble prediction," Monthly Weather Review, 124, pp. 1225-1242, 1996.

[7] T. N. Palmer, "Predictability of weather and climate: from theory to practice, Predictability of weather and climate," ed. Tim Palmer and Renate Hagedorn, Chapter 1, Cambridge: Cambridge University Press, 2006.

[8] H. L. Tolman, "User Manual and System Documentation of WAVEWATCH-III Version 1.15, " NOAA/NWS/NCEP/OMB Technical Note 151, 97 p, 1997.

[9] H. L. Tolman, "User Manual and System Documentation of WAVEWATCH-III Version 1.18, " NOAA/NWS/NCEP/OMB Technical Note 166, 110 p, 1999.

[10] H. L. Tolman, "User Manual and System Documentation of WAVEWATCH III Version 3.14, " NOAA/NWS/NCEP/OMB Technical Note 276, 194 p. + Appendices, 2009.

[11] G. J. Komen, L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P. E. A. M. Janssen, "Dynamics and Modelling of Ocean Waves, Cambridge University Press," 532 p, 1994.

[12] WAMDIG, "The WAM model–A Third Generation Ocean Wave Prediction Model," Journal of Physical Oceanography, 18, pp. 1775-1809, 1988.

[13] H. L. Tolman, "The Numerical Model WAVEWATCH: A Third Generation Model for the Hindcasting of Wind Waves on Tides in Shelf Seas, Communications on Hydraulic and Geotechnical Engineering," Delft University of Technology, ISSN 0169-6548, Rep. no. 89-2, 72 p, 1989.

[14] H. L. Tolman, "A Third-generation Model for Wind waves on Slowly Varying, Unsteady and Inhomogeneous Depths and Currents," Journal of Physical Oceanography, 21, pp. 782-797, 1991.

[15] H. L. Tolman, "Effects of Numerics on the Physics in a Third-generation Wind-wave Model," Journal of Physical Oceanography, 22, pp. 1095-1111, 1992.

[16] E. O. Brigham, "The Fast Fourier Transform and Its Applications," Prentiss Hall International, 448 p, 1988.

[17] D. J. Doong, S. H. Chen, C. C. Kao, and B. C. Lee, "Data Quality Check Procedures of an Operational Coastal Ocean Monitoring Network," Ocean Engineering, 34, pp. 234-246, 2007.

[18] J. S. Hong, "The evaluation of typhoon track and quantitative precipitation forecasts of CWB's NFS in 2001," Meteorological Bulletin, 44, pp. 41-53, 2002. (in Chinese)

[19] E. H. Barker, "Design of the Navy's multivariate optimum interpolation analysis system," Weather and Forecasting, 7, pp. 220-231, 1992.

[20] A. C. Lorenc, "A global three-dimensional multivariate statistical interpolation scheme," Monthly Weather Review, 109, pp. 701-721, 1981.

[21] T. M. Leou, and C. S. Liu, "A case analysis of NFS during SCSMEX," Proceeding, 2001 Conference on Weather Analysis and Forecasting, CWB, Taipei, Taiwan, pp. 161-165, 2001. (in Chinese)

[22] Y. F. Seng, S. C. Lin, T. M. Leou, S. C. Lin, and C. S. Liu, "Diagnostic evaluation on precipitation forecasts by the Central Weather Bureau's new generation regional forecast system (NFS)," Proceeding, 2001 Conference on Weather Analysis and Forecasting, CWB, Taipei, Taiwan, pp. 183-191, 2001. (in Chinese)