Ensemble Forecasting on Wave Modelling

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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. 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 ensemble statistics that the accuracy of the waves can be considerably improved by the ensemble mean + standard deviation.

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 (e.g., Leith, 1974). 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 (e.g., Ehrendorfer, 1994) 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 is used to sample analysis uncertainty for initial ensemble perturbations (Palmer et al., 1992; Molteni et al., 1996). At the National Centers for Environmental Prediction (NCEP, formerly known as the National Meteorological Centre), 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 (Toth and Kalnay, 1993). In yet another approach, Houtekamer et al. (1996) use multiple analysis cycles (with perturbed observational data and different model formulations) for generating initial ensemble perturbations.

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. 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. (Palmer, 2006)

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 (e.g., Leith 1974). 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:

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

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.

Ensemble Wave Modelling System

WAVEWATCH III wave modelling

WAVEWATCH III (Tolman 1997, 1999, 2009) is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model (WAMDIG 1988, Komen et al. 1994). It is a further development of the model WAVEWATCH, as developed at Delft University of Technology (Tolman 1989, 1991) and WAVEWATCH II, developed at NASA, Goddard Space Flight Center (e.g., Tolman 1992). 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 modelling 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.
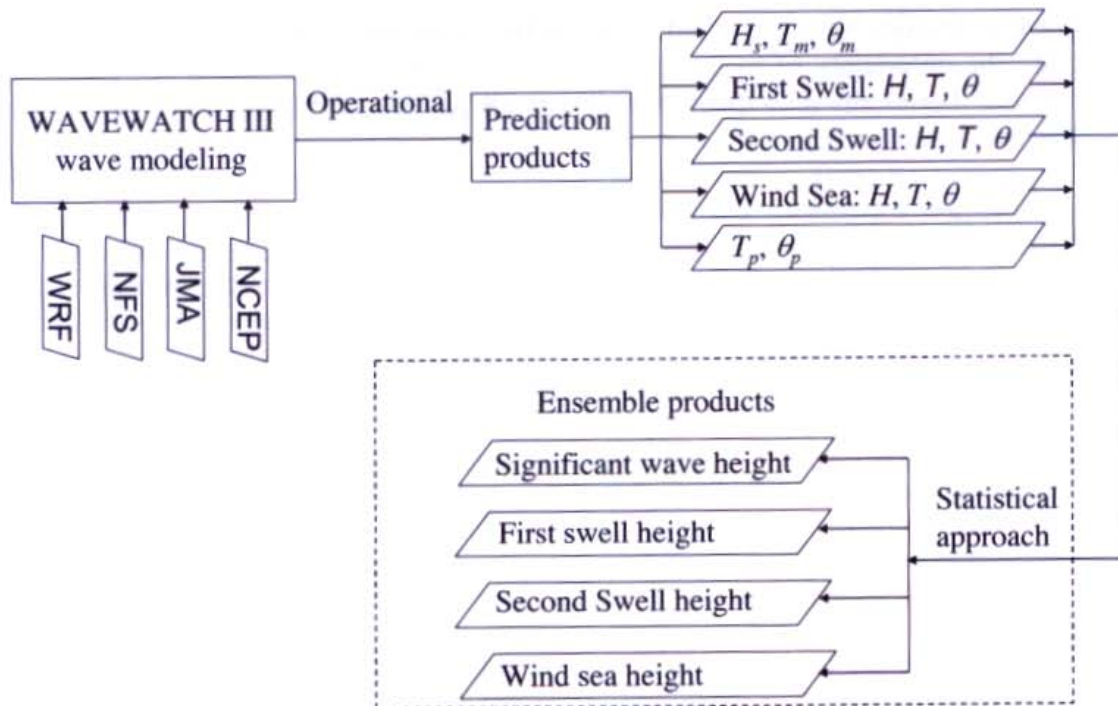
Fig. 1: Framework of the ensemble forecasting system

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.

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 (Brigham, 1988). Details on data capturing, quality control and archiving can be found in Doong et al. (2007).
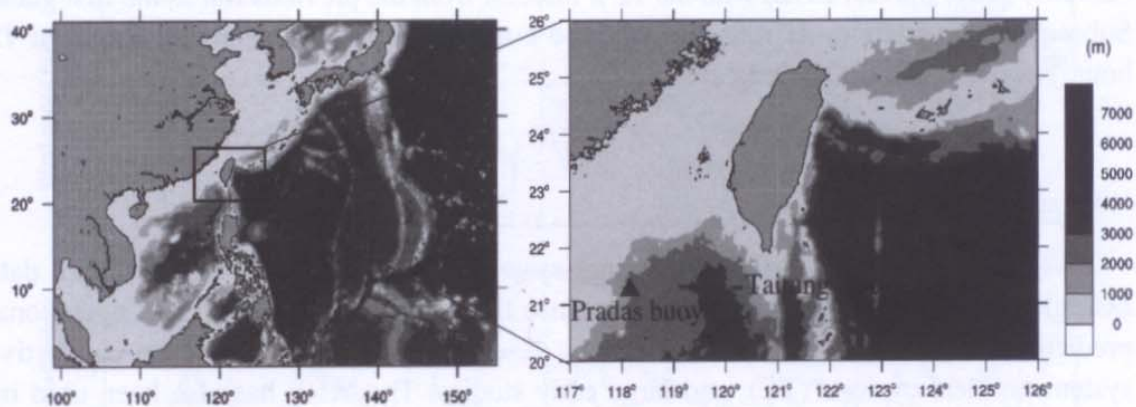
Fig. 2: The simulated domain of the model and corresponding data buoy station. Triangles show buoy locations.

Meteorological Data

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 (Hong, 2002). 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

(Lorenc, 1981; Barker, 1992) with the 12-h forecast from the previous run as the first guess. Subsequently, update cycle runs are executed every 12 hour with a forecast length of 72 hour (Leou and Liu, 2001; Seng et al., 2001).

WRF model

The community WRF modelling 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 centres in their daily operations to provide guidance for forecasters, e.g., National Centres 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.

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 modelled 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 modelled wind speed with buoy observations' are summarized in Table 1. From this table the NCEP's predicted data show the lowest wind speeds than others.

Table 1: Bias, RMSE and Scatter Index for the four meteorological models in wind speed.

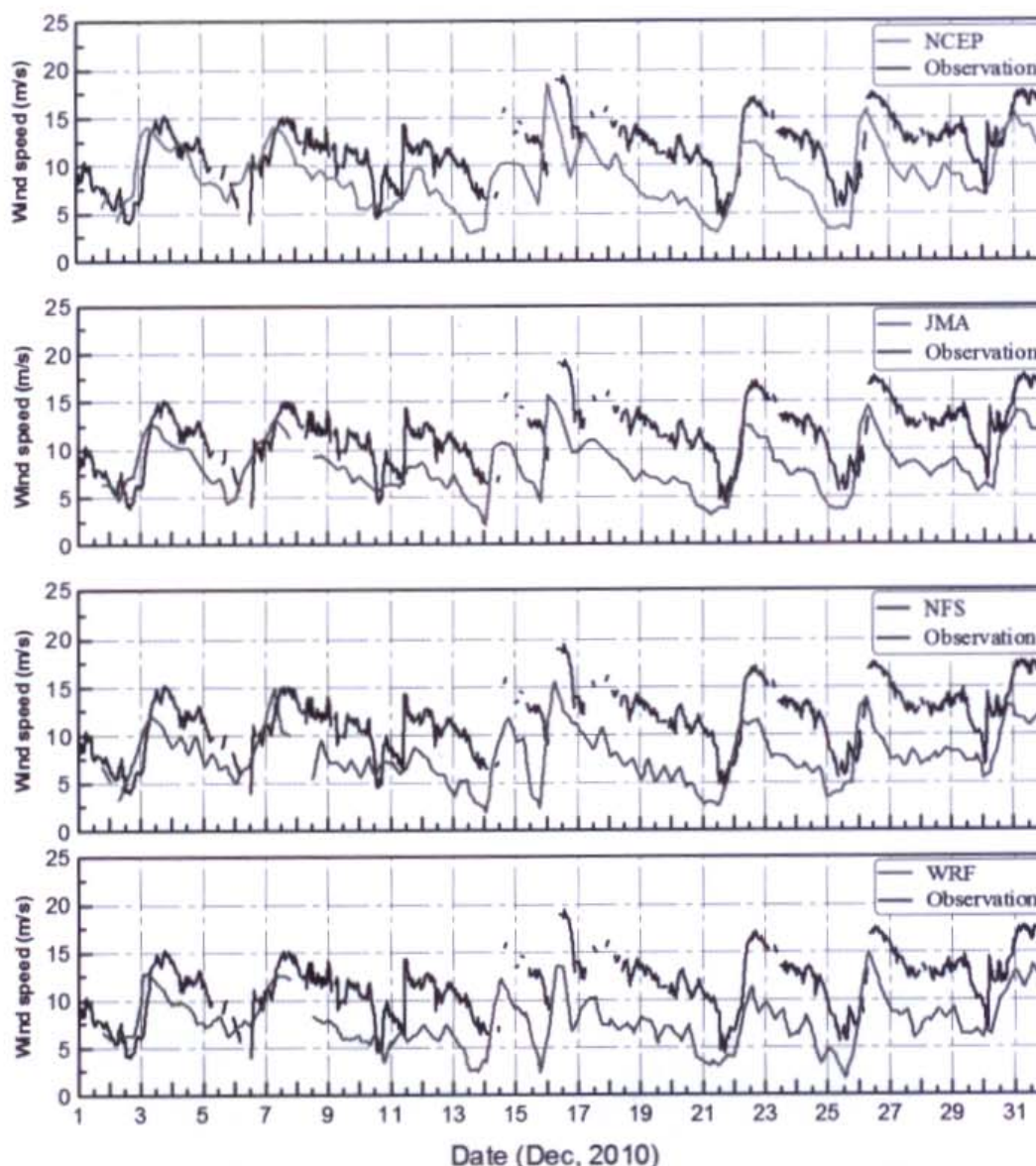| Meteorological model	Bias	RMSE	SI
NCEP	-3.03	4.10	0.23
JMA	-3.44	4.32	0.22
NFS	-4.03	4.88	0.25
WRF	-4.12	4.87	0.22

Fig. 3: Time series comparison of modelled and observed wind speed at Taitung Open Ocean buoy. (See Fig. 2 for location).

Ensemble Predictions

In order to discuss the ensemble forecasting, 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 shows the simulated wave heights at Pradas buoy station for four ensemble members. Real lines mean simulate wave drove from NCEP wind model, JMA wind model, and NFS wind model respectively, dotted line means simulate wave drove from NCEP wind model, circles means observed significant wave height and triangles means observed wind. From this figure it can be clearly seen that the uncertainties from the atmospheric predictions have significantly affected the predicted hydrodynamic results.
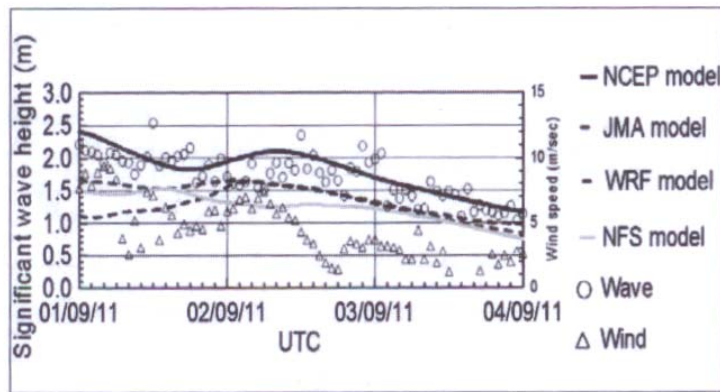
Fig. 4: The comparisons in time series of the significant wave height of ensemble members and observed data. (See Fig. 2 for location).

Fig. 5 shows the spatial distribution of ensemble mean on wave simulation. The mean of significant wave height over Taiwan sea area is about 1 meter. Fig. 6 is the spatial distribution of ensemble standard deviation on wave simulation. It shows that the biggest error is happened near Japan water. Therefore, the ensemble forecasting on wave modelling has better model results in Taiwanese water than Japanese waters. A further ensemble statistics, including the ensemble mean, and mean ± standard deviation, is shown in Fig. 7. It shows that the accuracy of the ensemble mean + standard deviation model has been significantly improved when the initial date is closer to the peak.
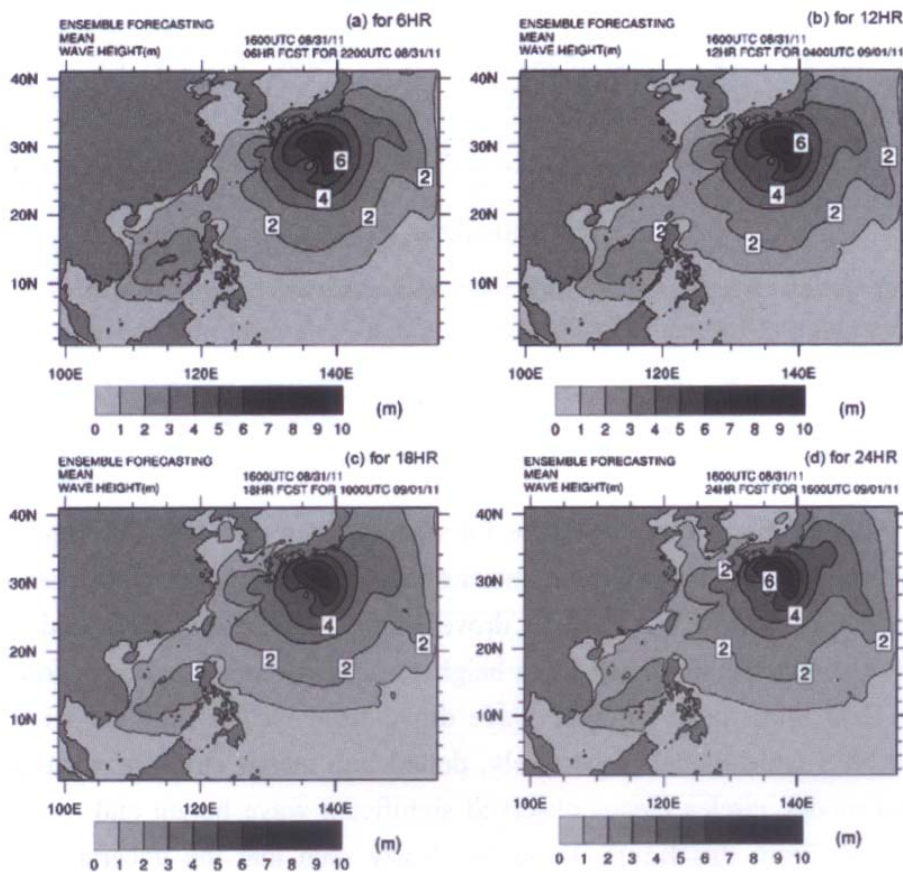

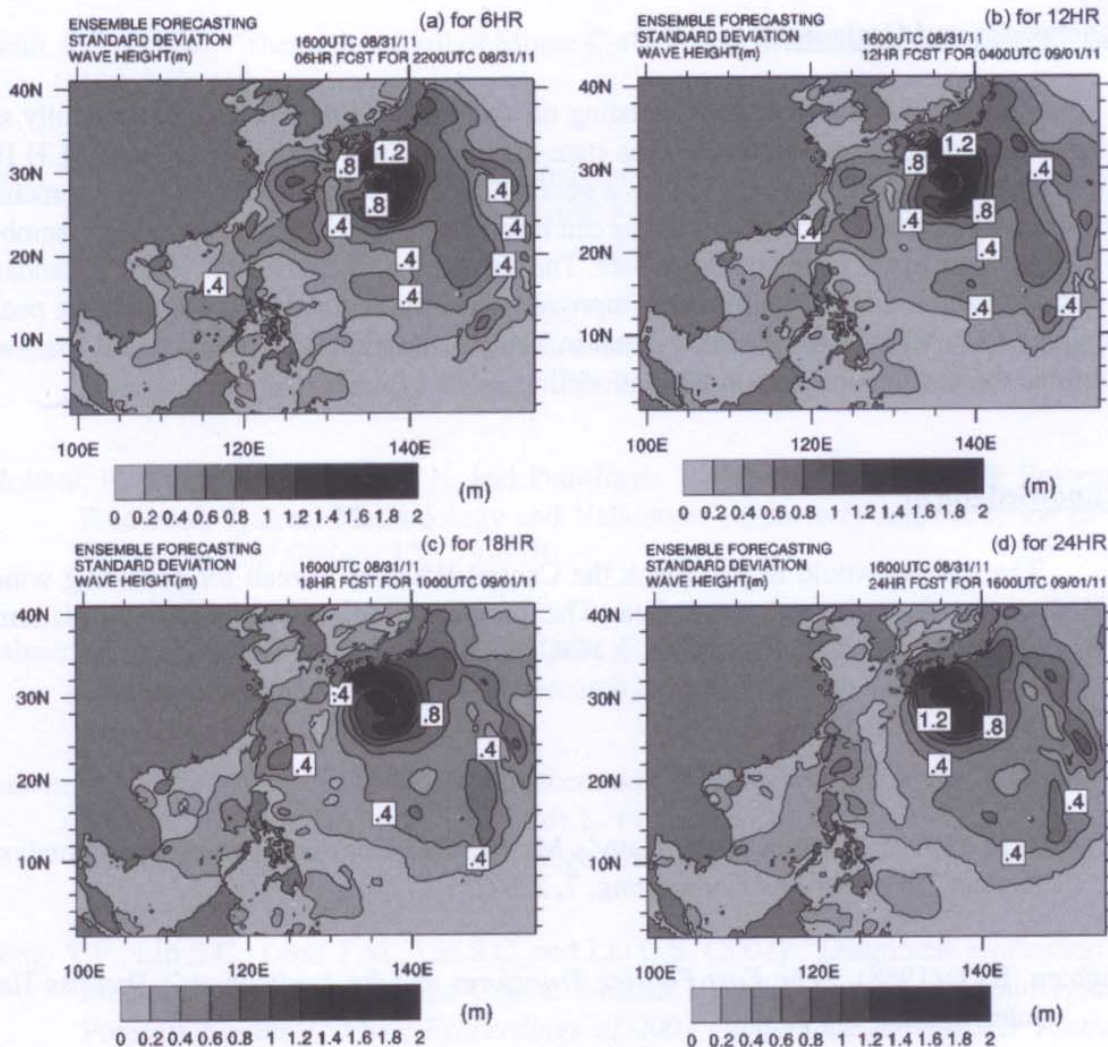**Fig. 5:** The spatial distribution of ensemble mean on wave simulation.

Fig. 6: The spatial distribution of ensemble standard deviation on wave simulation.
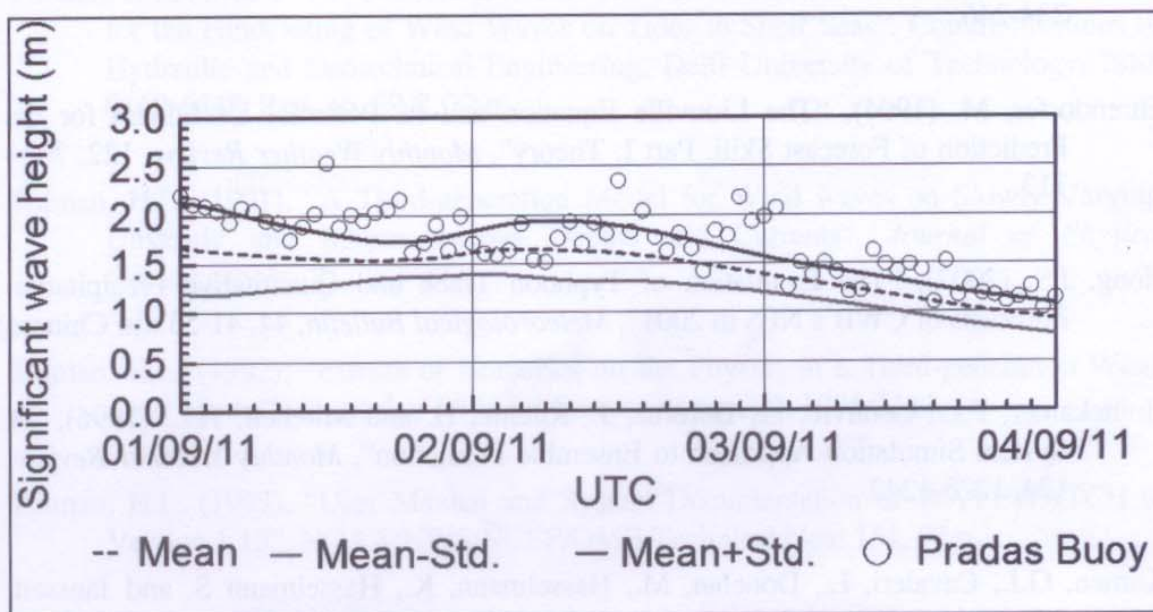

Fig. 7: Statistical analysis of ensemble results.

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 accuracy of the predictions of waves can be significantly improved by using ensemble approach closer to the observed wave data. The accuracy of the ensemble mean + standard deviation model has been significantly improved when the initial date is closer to the peak. As typhoon wave cause disaster every year in Taiwan, the follow-up research will focus on ensemble forecasting on typhoon wave modelling.

Acknowledgment

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