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ENSEMBLE PREDICTION OF OCEAN WAVES AT NCEP

H. S. Chen
NOAA/NWS/NCEP
email: hsuan.chen@noaa.gov

Abstract

According to Lorenz (1963), an atmosphere prediction system is unstable, sensitively dependent on the initial conditions. The system is chaotic and has a finite limit of predictability. On the contrary, we found that an ocean wave model using the action balance equation as the governing equation is stable and insensitive to the initial conditions. Nevertheless, the ocean wave model still has a finite limit of predictability, due to uncertainty of the forcing wind fields, not due to its insensitivity of the initial conditions. Hence, it is impossible to use the model for long-range prediction of ocean waves. An ensemble ocean wave prediction system is thus developed for extending long-range prediction.

Development and evaluation of the ensemble global ocean wave forecast system (EGOWaFS) at NCEP (National Centers for Environmental Prediction) is briefly described. Currently, the EGOWaFS consists of the NOAA WaveWatch III (NWW3) wave model, an ensemble of 11 different Global Forecast System (GFS) wind fields and an initial wave field. The initial wave field adopts the same one used in the operationally deterministic NWW3. Eleven individual wave fields are generated using the NWW3 subject to the forcing of the 11 different wind fields respectively. Ensemble mean, spread and probability with various thresholds are then calculated from the ensemble of these wave and sea surface wind predictions. Buoy data in the months of May through July 2004 are used for wind and wave comparison between the operationally deterministic and the ensemble. Bias, root mean square error (RMSE) and correlation of the ensemble mean of winds and waves are very close to those of the operationally deterministic respectively; the differences are minute. Trends of the ensemble spreads are well correlated to their corresponding RMSE. A storm event on June 03, 2004 at Buoy 46006 indicates that the wind and wave predictions of the EGOWaFS, realized by the ensemble of wind and wave predictions of each member, are indeed more reliable and realistic than those of the operationally deterministic. Currently, the EGOWaFS is still under an extensive study. It has run in operational mode since March 2006. Its prediction products of waves and surface winds are post at the website and ftp-site,
http://www.emc.ncep.noaa.gov/projects/wd21hc/ensemb/web/html/.
ftp://polar.ncep.noaa.gov/pub/waves/egowafs_fd

Key word: Predictability, Ensemble and deterministic forecast, Ocean waves

1. Introduction

It is well recognized that wave characteristics of the sea states, such as wave heights, wave periods, wave steepness, etc, are the critical factors needed to be considered in ship navigation, marine farming, sea rescue, harbor management, ocean engineering practice, ocean scientific research, just to name a few. Consequently, we need accurate wave predictions. Recent wave predictions are based on a single, deterministic solution of the action balance equation forced by the prediction wind fields. Because these prediction wind fields always contain a certain level of uncertainty, which we will explain later, accordingly, a deterministic wave prediction contains some uncertainty. We hope that, through the ensemble procedure, the level of the uncertainty for a given prediction can be properly conveyed making the wave prediction more realistic and reliable.

The mission of NOAA/NCEP/EMC (Environmental Modeling Center) is to improve numerical weather, marine and climate predictions through a broad program of research in data assimilation and modeling. At NCEP, an ensemble prediction of the atmosphere has become operational since December 1992. Since then, extensive experiments in atmosphere indicate that the ensemble prediction is favored over the deterministic prediction, particularly for long-range predictions, because it can provide more realistic and reliable guidance for atmosphere prediction. This success of the ensemble prediction of the atmosphere kindles our interest in developing an ensemble for ocean wave prediction. An ensemble wave forecast system, the EGOWaFS, is thus developed and has run operationally since late March, 2006.

2. Lorenz's Equations and Predictability

To demonstrate the need of using ensemble prediction for atmosphere and wind waves, we start with the commonly used Lorenz's equations as an example to demonstrate chaos theory and predictability. The Lorenz's equations (Lorenz, 1963) are,

$$\begin{aligned} \dot{x} &= \sigma\,(-x + y) \\ \dot{y} &= \gamma\, x - y - x\,z \\ \dot{z} &= x\,y - \beta\, z \end{aligned} \tag{1}$$

Equation (1) is a nonlinear dynamic system simplified from the all-scale motions of the atmosphere of convective origin. (Saltzman 1962) It is described simply by three atmospheric variables $x(t)$, $y(t)$ and $z(t)$ with time being the only independent variable. The overhead dot in (1) stands for time derivative. And β, σ and γ are three constants which surely determine behavior of the system. The solution can be obtained through integrating (1) in time. With a particular choice of values for the three constants, $\beta = 83$, $\sigma = 10$ and $\gamma = 28$ (Lorenz, 1963), the solutions are unstable, sensitively dependent on the initial conditions, and become chaotic and unpredictable, an outcome so-called 'the butterfly effect'. Because the system is unstable, it is a finite limit of predictability. An example is illustrated in Figure 1, where three solutions with three slightly different initial values around $x(0) = 1$, $y(0) = 0$ and $z(0) = 0$ are shown. Figure 1 shows that, with a slight perturbation in the initial condition, the solutions agree quite well to each other only in the initial short-range period (short-range prediction), but after that period the solutions become uncorrelated and unpredictable. This makes long-range prediction unreliable except an exact initial condition is available. This prediction system of the atmosphere is defined to be unstable and is unpredictable for long-range prediction. To alleviate this shortcoming, an ensemble prediction is utilized to minimize the effect of the error generated by uncertainty of the initial conditions. This ensemble procedure is supposed to filter out some of chaotic components and to produce a more realistic and reliable prediction.

Conversely, the solutions of (1) can be stable, insensitively dependent on the initial conditions: e.g. if we choose $\beta = 83$, $\sigma = 10$ and $\gamma = 20$, three solutions with three different initial conditions, $(1.0,0,0)$, (5.0,0,0) and (0.1,0,0) respectively are shown in Figure 2. It shows that the solutions subject to small perturbation in the initial conditions are all sufficiently close to each other for all times. The system is defined to be stable and is infinitely predictable An ocean wind wave prediction model is stable as we will see later.

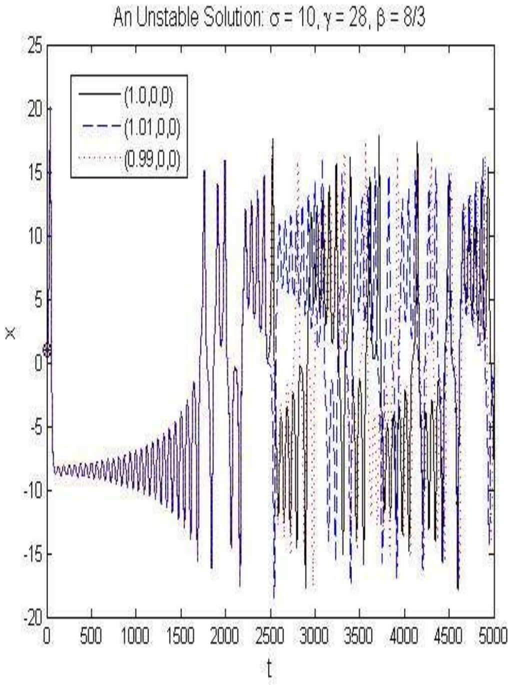

Figure 1. An unstable system.

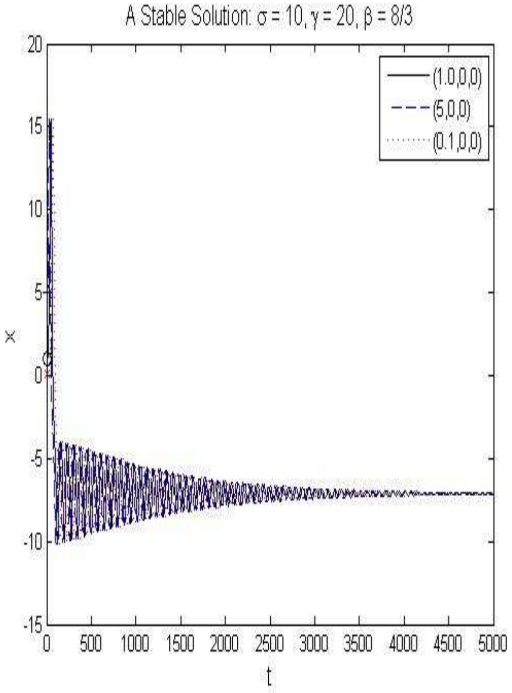

Figure 2. A stable system.

3. Wind Wave Prediction Model

Almost all the current wind wave prediction models, including the NWW3, use the action balance equation as the governing equation (Komen, et al 1994),

$$\frac{\partial N}{\partial t} + \frac{1}{\cos\varphi}\frac{\partial(\dot{\varphi}\cos\varphi\, N)}{\partial\varphi} + \frac{\partial(\dot{\lambda}\, N)}{\partial\lambda} + \frac{\partial(\dot{\omega}\, N)}{\partial\omega} + \frac{\partial(\dot{\theta}\, N)}{\partial\theta} = S_{wind} + S_{dissip} + S_{nonlin} \tag{2}$$

where N is the action to be solved; $(\varphi \quad \lambda \quad \omega \quad \theta)$ are coordinates of latitude, longitude, wave radian frequency and wave direction respectively; and the source terms, $(S_{wind}, S_{dissip}, S_{nonlin})$, stand for wave generation, wave dissipation and wave-wave interaction respectively. An ocean wave prediction system consisting of (2) and a forcing wind field is a weakly nonlinear, highly dissipative dynamic system, in which the signature of the initial wave field fades away monotonically in a couple of the first prediction days and no butterfly effect is observed. A study of Chen, et al (2004) indicates that perturbation on the initial wave heights has little impact on the wave predictions except in the first 24 prediction hours and, most prominently, the wind forcing has the most impact throughout the prediction period. Similar conclusion is also made by Farina (2002) who studied the ensemble wave prediction through an initial wave spectrum perturbation.

For clarity, we schematize the atmosphere and ocean wave prediction dynamic systems in Figure 3. As we have mentioned before, an atmosphere prediction system is unstable and sensitive to the initial condition. Unfortunately, an accurate initial condition is not available for the atmosphere prediction system, because observation data as well as grid interpolations of a geographical distribution of the observational network always contain some errors, inevitably making the initial condition only a limit of accuracy and never exact. This inaccuracy of the initial conditions makes the wind fields predicted from an atmosphere prediction system always containing some degree of uncertainty, which in turn makes a single deterministic wave prediction unreliable and realistic, more so in long-range predictions. To improve this shortcoming, an ensemble procedure is used to minimize the errors generated from the uncertainty of the wind fields, making wave predictions more realistic and reliable. We would concentrate on variability of the wind forcing rather than on perturbations of the initial condition for the EGOWaFS.

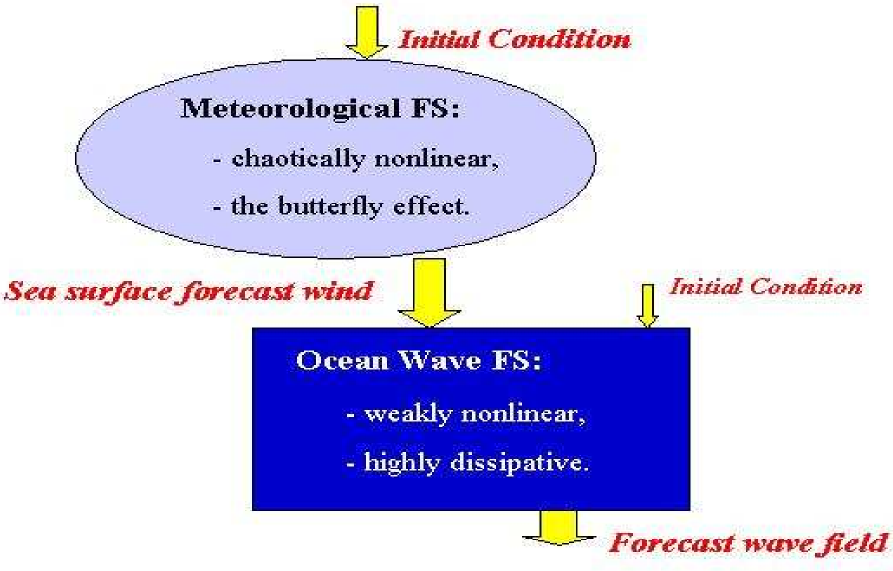

Fig. 3. A schema of the atmosphere and ocean wave prediction systems.

4. EGOWaFS

Currently, the EGOWaFS consists of the NWW3 wave model, an ensemble of 11 different GFS wind fields and an initial wave field. The initial wave field adopts the same one used in the operational NWW3; i.e., the same initial wave field of the operationally deterministic is used at the initial time for all 11ensemble wave members. The NWW3 is a third generation wave model and is the current, operational wave model at NCEP. (Chen, et al 2003) Description of the NWW3 can be found in Tolman (1999). Out of these 11 wind members, one member is the operationally deterministic and the other 10 members are generated through introducing small, different perturbations to the initial atmospheric field using the breeding method. (Toth and Kalnay, 1993, 1997) This ensemble of the wind fields is operationally generated for up to 126 prediction hours at the 00, 06, 12 and 18Z run cycles. It has been extensively studied and is found to be more realistic and reliable than any one single wind field, as we can realize that one single prediction wind field is only one likely scenario of a good number of alternatives, not necessarily the most likely. In the EGOWaFS, we use each of the 11 wind fields as the wind forcing to individually run the NWW3 to generate one member of wave prediction. Thus, a total of 11 wave predictions are generated and they constitute an ensemble for further statistical analysis. Note also that, out of these 11 members of the wave predictions, one member is the control member, which we adopt the operationally deterministic wind and wave predictions and, therefore, no additional job runs for it are needed in the EGOWaFS. We also note that it requires a considerable of computer resource to run the EGOWaFS.

5. Results and Remarks

The wind and wave predictions of the 11 ensemble members can be used to contrive a deterministic and/or probabilistic prediction by applying various kinds of statistical processing. In this context, we study only the significant wave height, H_s, and the sea surface wind speed, U_{10}. We calculate the ensemble mean, the ensemble spread and the conditional probability. The ensemble mean is the average of the predictions of all 11 members. It is a smoothing of the prediction fields. The ensemble spread is calculated in the same way as the standard deviation in statistics. It can be related to the difference between the predictions of the members. Small spread indicates low prediction uncertainty and large spread high prediction uncertainty. The conditional probability is calculated with a designated threshold by assuming that each member has an equal likelihood. It can be understood like a probability density distribution.

Wind and wave data from about 30 buoys of deep water (mostly NOAA/NDBC buoys) in the months of May through July 2004 are treated as the accurate data for comparisons. Figure 4 shows the comparisons of bias, RMSE and correlation of U_{10} between the operationally deterministic and the ensemble mean. Figure 5 shows the corresponding comparisons of H_s. Figure 4 indicates that while the bias of the ensemble mean of U_{10} is slightly inferior to that of the operationally deterministic, its RMSE and correlation are slightly superior, particularly in the longer prediction hours. Note that the ensemble spread of U_{10} has a similar trend as the RMSE; the spread increases as the prediction hour increases. Figure 5 indicates that the bias and RMSE of the ensemble mean of H_s are slightly inferior to those of the operationally deterministic H_s, but their correlations are almost no difference. Also, the ensemble spread of H_s has a similar trend as the RMSE; the spread increases as the prediction hour increases. Figure 6 and 7 respectively show the U_{10} and H_s predictions of the 11 members, the ensemble mean and the observation data at Buoy 46006 in the storm event of June 03, 2004. Generally speaking, spread of the members becomes wider at a longer prediction hour. The ensemble means are slightly favored over the operationally deterministic U_{10} and H_s when comparing with the observation data. Table 1 shows the ensemble probability, the operationally deterministic and the observation data of U_{10} on Beaufort Wind Force Scale, and Table 2 shows those of H_s on the corresponding Beaufort Wave Height Scale. It indicates that, except the U_{10} at the 06, 54 and 72 prediction hour, the ensemble predictions of U_{10} and H_s hit and agree with all the observation data, while the operationally deterministic misses many.

Overall, the ensemble prediction is favored over the deterministic prediction. We admit this study up to now is far from completeness. A rigorous study is still underway and, hopefully, we can report more products and findings in the near future. We would like to mention that we have run the ensemble productions operationally since late March of 2006 and, recently, we have post the products at the website and ftp-site with the addresses given in the abstract. Figure 8 illustrates the example graphics of spaghetti, mean and spread and ensemble probability respectively.

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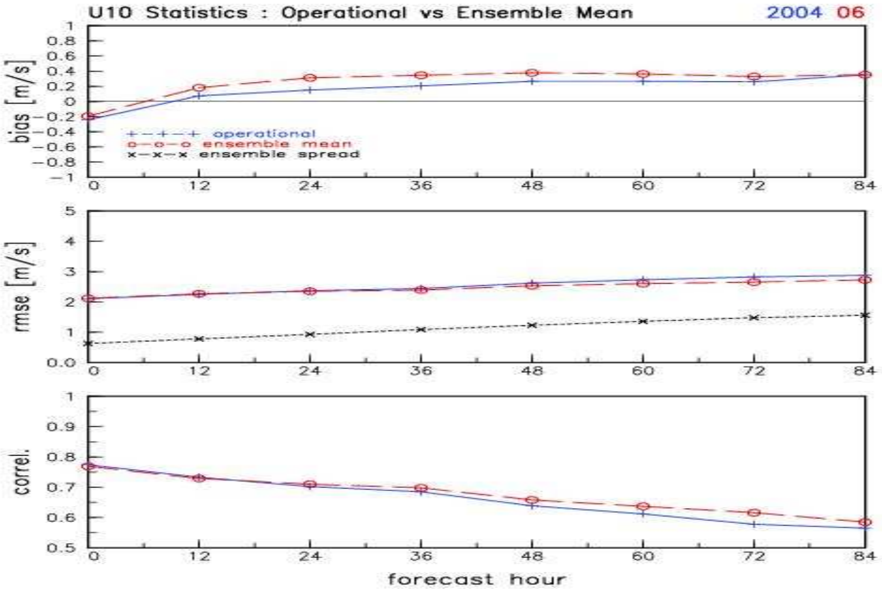


Fig.4. Statistics of deterministic (operational) vs ensemble mean U10.

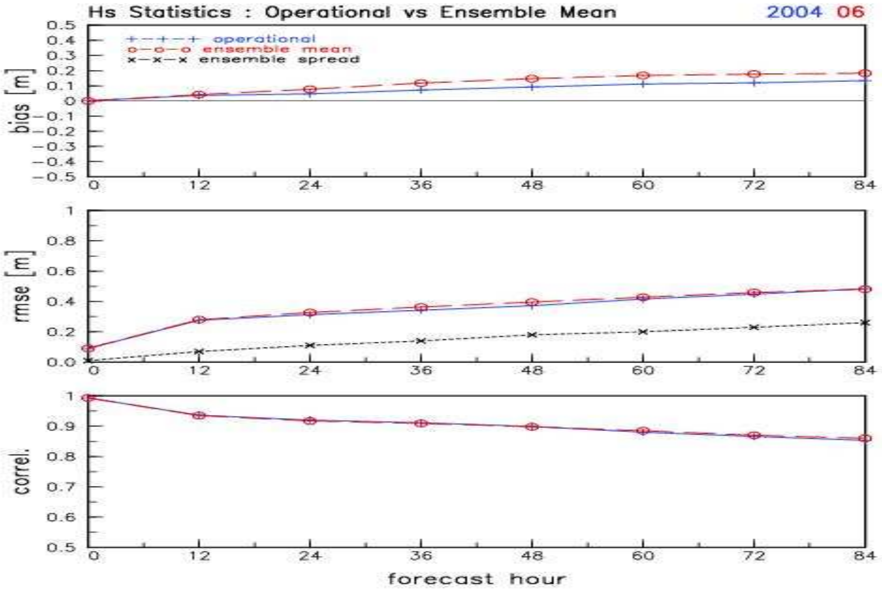


Fig.5. Statistics of deterministic (operational) vs ensemble mean Hs.

Number of data at each forecast hour > 1.1 k.

Green thin lines: 10 ensemble members,
Red dash line with + sign: control,
Blue line with + sign: ensemble mean,
Black dot with o sign: observation data.

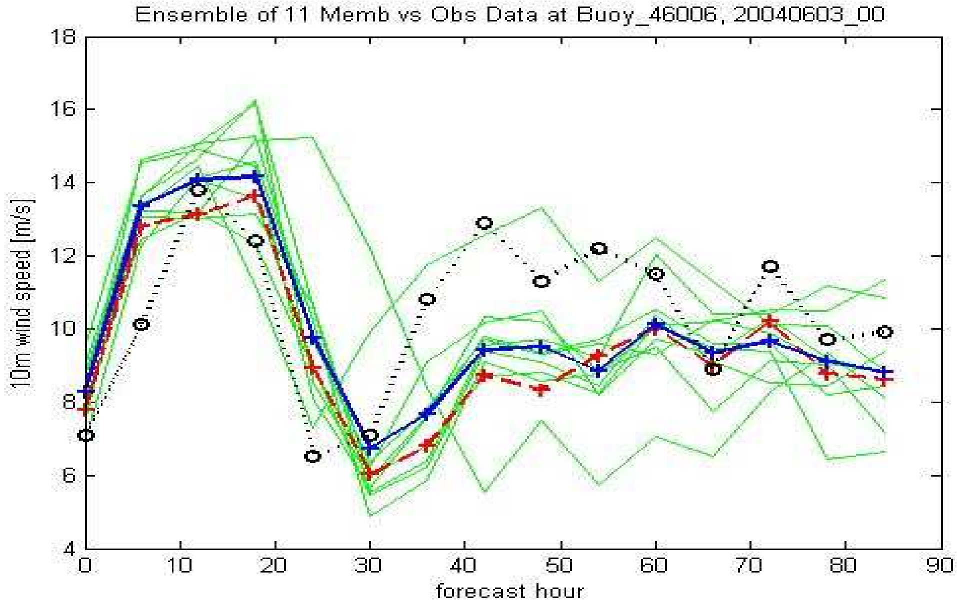


Fig. 6. U_{10} of 10 members, control, ensemble mean and data.

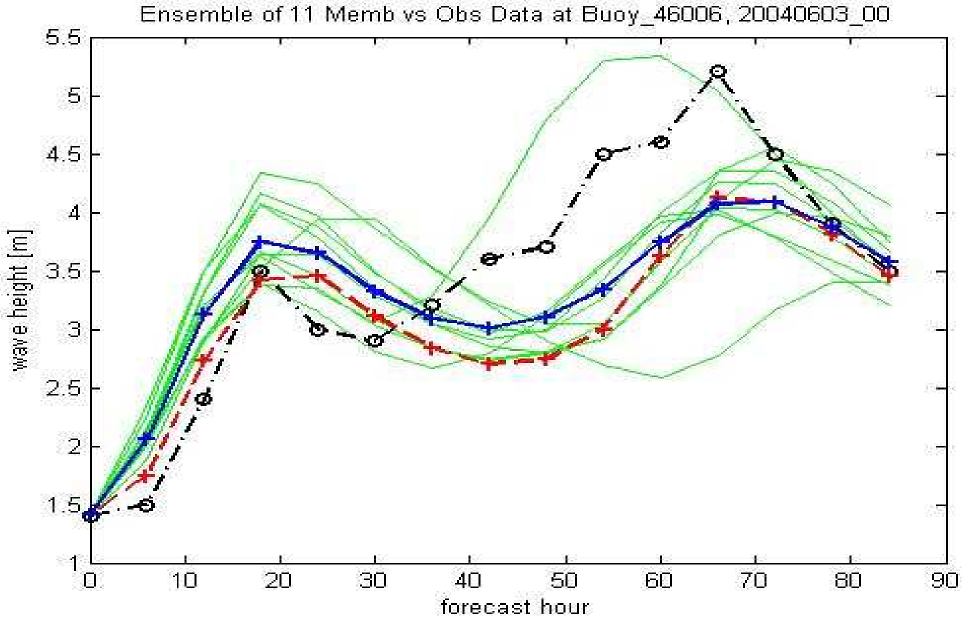
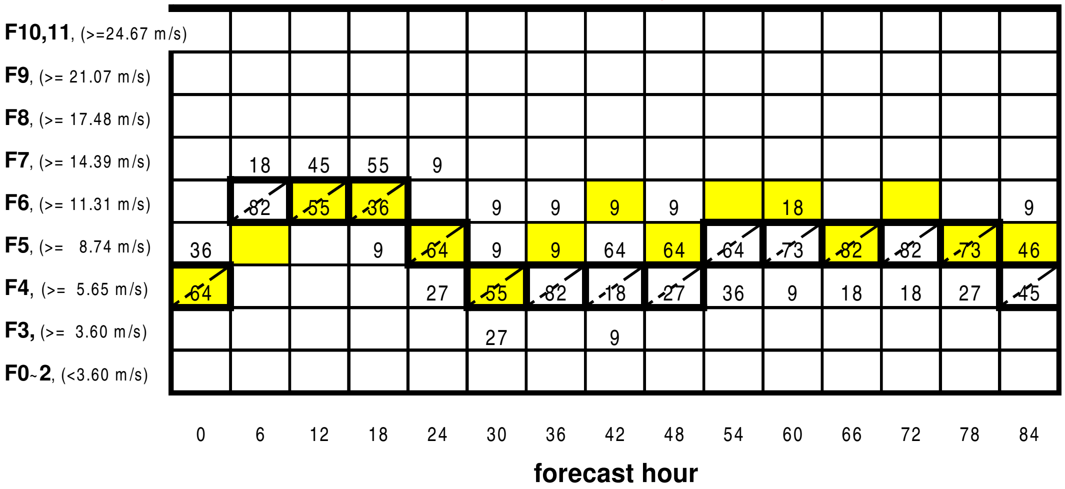


Fig. 7. H_s of 10 members, control, ensemble mean and data.

Table 1. Ensemble and NWW3 U_{10} forecasts and Observed Data in the Beaufort Scale.

numerics: ensemble forecast in percentage,
box with a diagonal: NWW3 forecast,
yellow box: observed data.

Ensemble U_{10} Forecasts at Buoy 46006 at 2004 06 03 00



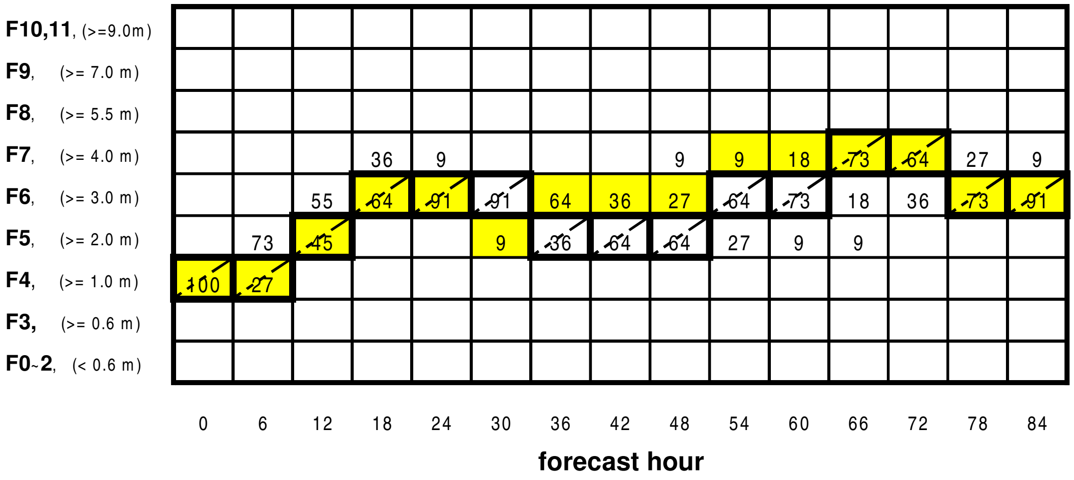
	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84
F10,11, (>=24.67 m/s)															
F9, (>= 21.07 m/s)															
F8, (>= 17.48 m/s)															
F7, (>= 14.39 m/s)		18	45	55	9										
F6, (>= 11.31 m/s)		⧄ 82	🟨 ⧄ 55	🟨 ⧄ 36		9	9	🟨 9	9	🟨	🟨 18		🟨		9
F5, (>= 8.74 m/s)	36	🟨		9	🟨 ⧄ 64	9	🟨 9	64	🟨 64	⧄ 64	⧄ 73	🟨 ⧄ 82	⧄ 82	🟨 ⧄ 73	🟨 46
F4, (>= 5.65 m/s)	🟨 ⧄ 64				27	🟨 ⧄ 55	⧄ 82	⧄ 18	⧄ 27	36	9	18	18	27	⧄ 45
F3, (>= 3.60 m/s)						27		9							
F0~2, (<3.60 m/s)															

forecast hour

Table 2. Ensemble and NWW3 H_s forecasts and Observed Data in the Beaufort Scale.

numerics: ensemble forecast in percentage,
box with a diagonal: NWW3 forecast,
yellow box: observed data.

Ensemble H_s Forecasts at Buoy 46006 at 2004 06 03 00



	0	6	12	18	24	30	36	42	48	54	60	66	72	78	84
F10,11, (>=9.0m)															
F9, (>= 7.0 m)															
F8, (>= 5.5 m)															
F7, (>= 4.0 m)				36	9				9	🟨 9	🟨 18	🟨 ⧄ 73	🟨 ⧄ 64	27	9
F6, (>= 3.0 m)			55	🟨 ⧄ 64	🟨 ⧄ 91	⧄ 91	🟨 64	🟨 36	🟨 27	⧄ 64	⧄ 73	18	36	🟨 ⧄ 73	🟨 ⧄ 91
F5, (>= 2.0 m)		73	🟨 ⧄ 45			🟨 9	⧄ 36	⧄ 64	⧄ 64	27	9	9			
F4, (>= 1.0 m)	🟨 ⧄ 100	🟨 ⧄ 27													
F3, (>= 0.6 m)															
F0~2, (< 0.6 m)															

forecast hour

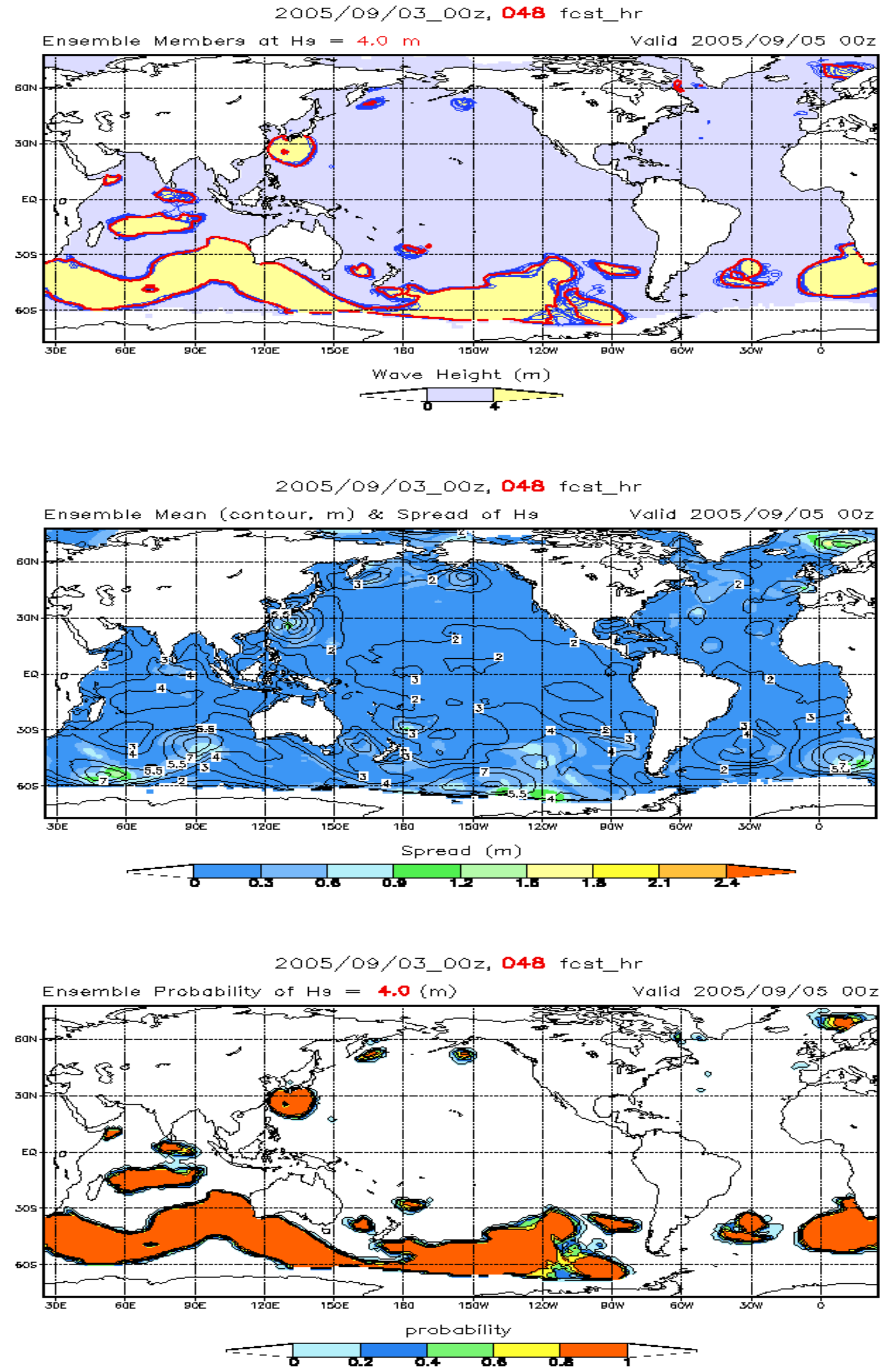


Fig. 8. Illustrated plots of spaghetti, mean and spread and probability of H_s.