NCEP-FNMOC Joint WAVEWATCH III Ensemble Forecasting System

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Introduction

The US National Centers for Environmental Prediction (NCEP/NOAA) and Fleet Numerical Meteorology and Oceanography Center (FNMOC) run a joint WAVEWATCH III ensemble consisting of 40 members (20 members each), forced by each center's atmospheric ensemble. An Ensemble Forecast System (EFS) is a stochastic numerical weather prediction (NWP) system whereby multiple forecasts, each perturbed from the control analysis, are run in parallel. These perturbed runs are known as "members." Combining the results of an EFS run allow for the calculation of a mean forecast which is generally more accurate than the forecast from the control analysis. In addition, probabilities of events and measures of confidence in the meteorological prediction (spread, reliability, sharpness) can be calculated. The joint wave ensemble runs on a 1 degree spherical grid, with sub-grid scale obstructions, producing 16 day forecasts. The initial conditions of the wave model members are not perturbed, as in the atmospheric ensembles. Rather the variability of each ensemble member comes from the variability inherent in the wind forcing from the atmospheric ensembles.

NOGAPS Ensemble Forecast System

FNMOC currently runs the Navy Operational Global Atmospheric Prediction System (NOGAPS) in an EFS environment (NOGAPS EFS). The initial conditions for the NOGAPS are produced by the Navy Atmospheric Variational Data Assimilation System-Accelerated Representer, a 4-dimensional variational data assimilation system. The spectral analysis produced by this system is used for the T319L42 control (deterministic) NOGAPS forecast, and is also truncated to T239 for the EFS. The perturbed initial conditions for NOGAPS EFS use the Ensemble Transform (ET) technique described by Mclay, et al. (2010).

The ET perturbations are computed over 9 latitude bands. The perturbations are updated every 6 hours though complete forecasts are made only every 12 hours (00Z and 12Z). The NOGAPS EFS consists of 80 NOGAPS perturbed members at T119L30 resolution run for 6-hour forecasts (used to produce the perturbations for the next cycle); 20 of these members continue the forecast out to 16 days. The same 20 members are used for update cycles and full forecasts for one day, then rotated to another group of 20 members for the next day (member

1 to 20, 21 to 40, 41 to 60, 61 to 80). Output from the model runs are one-degree by one-degree spherical gridded data. For production of probabilities and other statistics, the members also include one-degree grids from the deterministic NOGAPS 42-level T319 forecast and the T319L42 forecast lagged by 12 hours, for a total of 22 members. 20 FNMOC WW3 EFS members are forced by the 20 NOGAPS EFS forecast members.

NCEP Global Ensemble Ocean Wave Forecast System

NOAA/NCEP first implemented wind-wave ensemble forecast system in 2004 (Chen, 2006), consisting of a 10-member ensemble, forced with atmospheric data from NOAA/NCEP's Global Ensemble Forecast System (GEFS: Toth et al., 1997), plus a deterministic run forced with NOAA/NCEP Global Forecast System atmospheric data. This first system was upgraded in 2008 to its current configuration, consisting of a 20-member ensemble, forced with GEFS winds, plus one control run with deterministic GFS winds. The current configuration of the wave ensemble system at NOAA/NCEP is as follows:

- A global spherical grid with 1 x 1 spatial resolution extending from 78S to 78N, and sub-grid obstacles (identical to the FNMOC wave ensembles grids).
- One control run forced with GFS atmospheric data.
- 20 members forced with GEFS data, with bias-corrected 10-m winds.
- Four cycles per day (0, 6, 12 and 18Z), with forecast horizon of 10 days.

Ensemble members in the NOAA/NCEP system are initialized with spectral data from the 6h output of that same member in a previous run cycle. This ensures that the development history of swells be maintained within each ensemble member. A validation study of the NOAA/NCEP wave ensemble system is provided in Cao et al. (2007).

Joint NCEP-FNMOC WW3 Ensemble Products

Combined NCEP/FNMOC WW3 EFS products are currently being produced independently at FNMOC and at NOAA/NCEP, with each Center tailoring products for their customers.

At FNMOC, the combined products are currently being distributed via the Navy Enterprise Oceanographic Portal. Examples of the graphical FNMOC WW3 EFS products are the mean significant wave height and potential error shown in Figure 1a. The mean is simply the average of all 40 WW3 members and the potential error is defined as one standard deviation. Figures 1b show the probability of the significant wave height exceeding 12 ft. Probabilities are the percentage of members greater than the specified threshold. In this example Typhoon Maon produced large waves south of Japan on July 18, 2011.

At NOAA/NCEP, the product is made available to the general public under the name Combined NCEP/FNMOC Wave Ensembles Product. Products consist of 10-day forecasts of significant wave heights for each of the 41 (40 ensemble members plus NCEP control run) combined ensemble members and the ensemble-mean significant wave height, the combined ensemble spread and probabilities of significant wave height exceedence at 8 levels (1m, 2m, 3m, 4m, 5.5m, 7m and 9m). Figure 2a, b, c provides examples of graphical outputs from the NOAA/NCEP's Combined NCEP/FNMOC Wave Ensembles Product.

Verification using Altimeter Data

Monthly performance statistics are produced using significant wave height measurement from the JASON, JASON2, and ENVISAT altimeter measurements. The advantage of using altimeter measurement, as opposed to buoy measurements, for wave model verification is the global data coverage of the altimeter tracks. Figure 3 shows the scatter plot for the analysis time of the ensemble means, during March 2011. In addition to the raw data pairs, the observations are also binned for every meter and the mean and error are plotted. The NCEP WW3 ensemble has a slightly positive bias over the 1 to 9 meter range of wave height, while the FNMOC ensemble has a slightly negative bias over the same range of wave heights, although both ensembles have a negative bias at the 9 to 10 meter wave height range.

Figure 4 is a display of the NCEP, FNMOC and combined ensemble bias and RMSE as a function of forecast time for March 2011. The FNMOC ensemble mean has a small negative bias, while the NCEP ensemble mean has a small positive bias throughout the 10 day forecast range. As expected, the combined ensemble bias is near zero. The RMS error of the NCEP, FNMOC and combined ensembles increases with forecast time from about 0.5 meters at 00 hours to 1.2 meters at time 240 hours. The combined ensemble has a smaller RMSE error then the individual ensembles. The FNMOC and NCEP deterministic model RMSE are also plotted on Figure 5. The deterministic models have a smaller RMSE from the analysis to about forecast time 96, after which the ensemble means have a smaller RMSE.

Reliability and ROC diagrams

The reliability diagram shown in Figure 5 compares the frequency of the observational occurrence, in this case wave height exceeding 12 feet, to the predicted probability of the occurrence, for March 2011. The reliability of the ensembles to predict wave heights exceeding 12 feet are generally very good. The reliability falls off, however, at longer lead times and higher probabilities. The relative operating characteristics (ROC) diagram, for March 2011, is shown in Figure 6. The ROC diagram is a measure of the model skill to forecast an event, in this case waves exceeding 12 feet. It compares the hit rate to the false alarm rate. For a probabilistic forecasts ,the Probability of Detection (POD) and the False Alarm Rate (FAR) are calculated for each probability interval. The HR is the number of time the forecast probability fell in that bin and the event occurred . The FAR is the number of time a forecast was made for a probability bin and the event did not occur. (Mason, S.J. and Graham, N.E., 2002). Unlike the reliability diagram, points on the diagonal indicate the model has no skill. That is, the model is predicting equal number of false alarms as occurrences. As with the reliability diagram the model skill decreases with increasing lead times, but in general the combined ensemble is very skillful.

Ensemble Sensitivity

Efforts to train Navy forecasters to use ensemble guidance have indicated that in addition to the uncertainty information provided by the ensemble they would like information about why the uncertainty looks the way it does: ensemble sensitivity information. FNMOC is running an operational demonstration of ensemble sensitivity for significant wave heights in the Virginia Capes (VACAPES) operating area (OPAREA). Example products are shown in figure 7. Figure 7a is simply the ensemble mean (solid contours) and standard deviation (filled color contours) in the vicinity of the VACAPES (outlined in red). The user can drill down on locations to obtain an ensemble meteogram of significant wave height at a particular location. An example is shown in figure 7b where the time series for each ensemble member at a particular location is plotted in blue and the ensemble mean is plotted in black. Users can drill down further by clicking a forecast lead of interest. For example, imagine the user wants to know about why the spread at 48hrs looks the way it does. Clicking on 48hrs provides the top graphic in figure 7c.

Figure 7c provides the sensitivity of the 48hr waves at our selected location to the 500mb height field at hour 6 of the forecast. It communicates how deviations from the ensemble mean 500mb height field at hour six impact the waves at our point of interest at hour 48. The ensemble mean is plotted as solid black contours while the sensitivity is given as filled color contours. Warm colors indicate a positive sensitivity; ensemble members with 500mb height values greater than the mean at hour 6 tend to have significant wave height values greater than the mean at our point of interest at hour 48. Cool colors indicate a negative sensitivity; ensemble members with 500mb height values less than the mean at hour 6 tend to have significant wave height values greater than the mean at our point of interest at hour 48. The top panel of 7c indicates that ensemble members that have the storm positioned further to the south tend to have the lower wave heights at hour 48. Notice also that the more northerly positioned storms are associated with lower heights to the NW of the storm and a slight sharpening of the trough to the NE of the storm.

There are ensemble mean/spread, meteograms, and sensitivity graphics for NOGAPS, GFS, and combined NOGAP-GFS ensembles. The bottom panel of 7c plots the same information as the top panel but for the GFS. The north-south positioning of the storm has an impact on wave heights at hour 48 that is similar to the NOGAPS model, but the sensitivity to the heights to the NW of the storm are not evident. However, notice that the ensemble mean heights to the NW of the storm are lower than for the NOGAPS ensemble.

In addition to 500mb heights, the user can choose to look at sensitivities to low level vorticity, low level temperature, surface winds, upper level winds, and surface pressure. In addition to sensitivities at hour 6 of the forecast, the user can step forward in time to see how the sensitivity evolves. Navy forecasters have found these products to be useful for identifying areas were initializing the atmospheric model is likely to have the biggest impact on what they end up issuing as their wave forecast.

Discussion

NCEP and FNMOC have combined 20 member wave model ensemble from each center to create a 40 member combined wave model ensemble. Forecasting products include mean and variability of significant wave height and probability of significant wave height exceeding a specified threshold. Verification of the mean significant wave height using altimetry data shows that the combined ensemble is more skillful than that of the center's individual ensembles. Furthermore, the combined ensemble mean is more skillful then the deterministic wave model at lead times greater than 96 hours. Finally a case study is presented to illustrate the ensemble sensitivity between atmospheric and wave model forecasts.

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Mason, S.J. and Graham, N.E. (2002) Areas beneath the relative operating characteristics (ROC) and relative operating levels (ROL) curves: Statistical significance and interpretation. *Q.J.R. Meteorol. Soc.*, 128:2145–2166.

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Toth, Z., E. Kalnay, S. M. Tracton, R. Wobus and J. Irwin, 1997: A synoptic evaluation of the NCEP ensemble. Weather and Forecasting, 12, 140-

153.

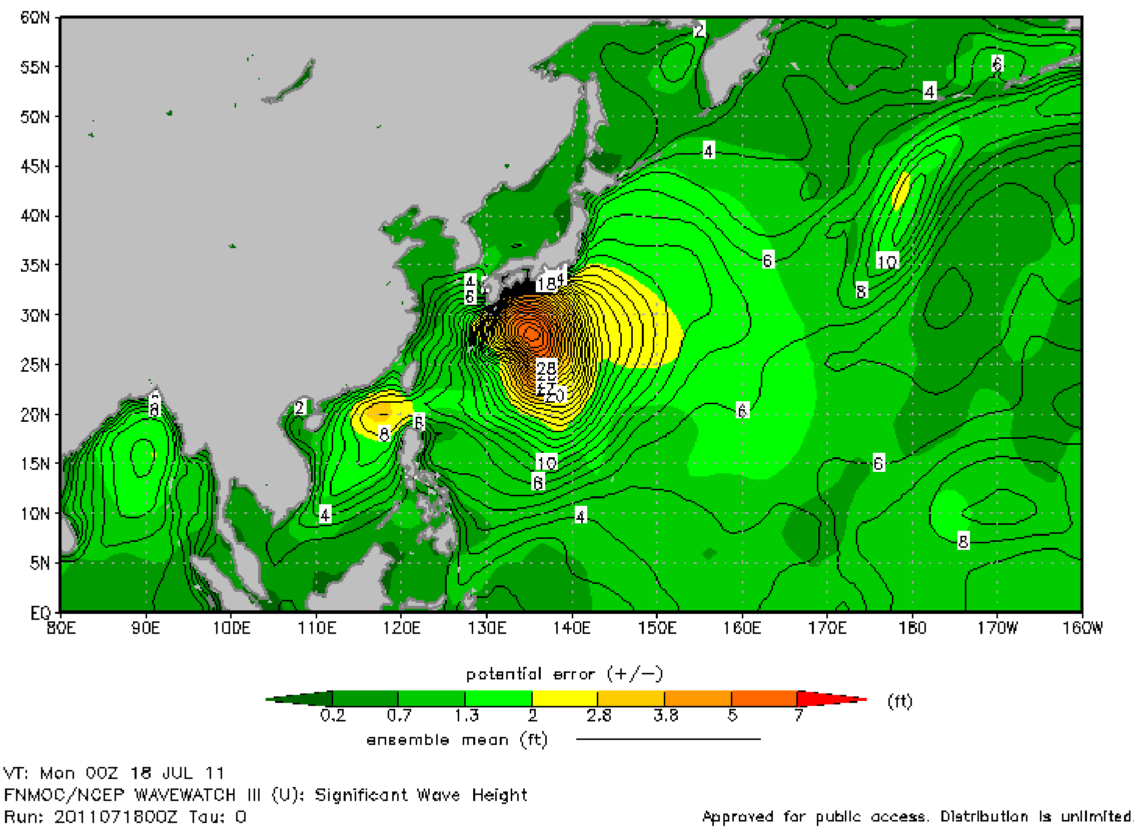


Figure 1a. Combined WW3 EFS mean significant wave height (contours in feet) and potential error (color shading) for July 18, 2011, 00GMT, Typhoon Maon. (FNMOC Product).

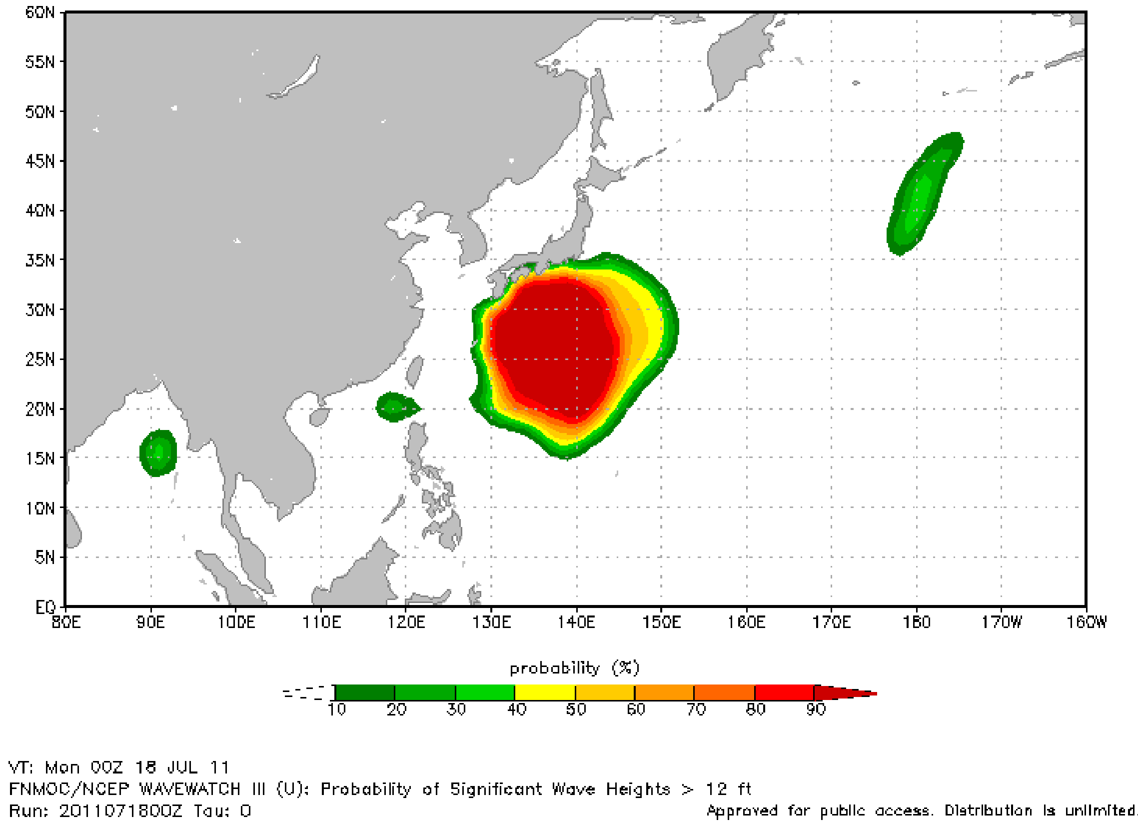


Figure 1b. Combined WW3 EFS Probability of significant wave heights exceeding 12 feet. (FNMOC Product) .

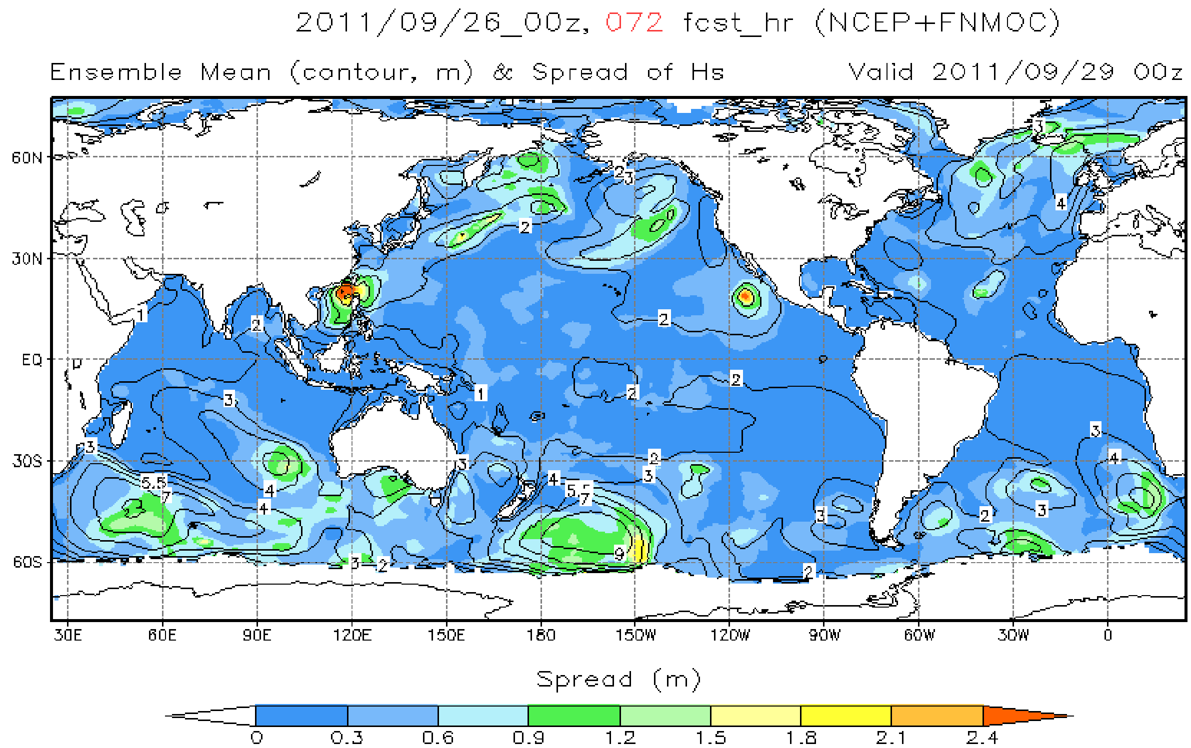


Figure 2a. Combined WW3 EFS: mean (contours in meters) and spread (color shading) from the global domain plot, at the 72h forecast range of 26 Sep 2011 00Z run. (NCEP Product).

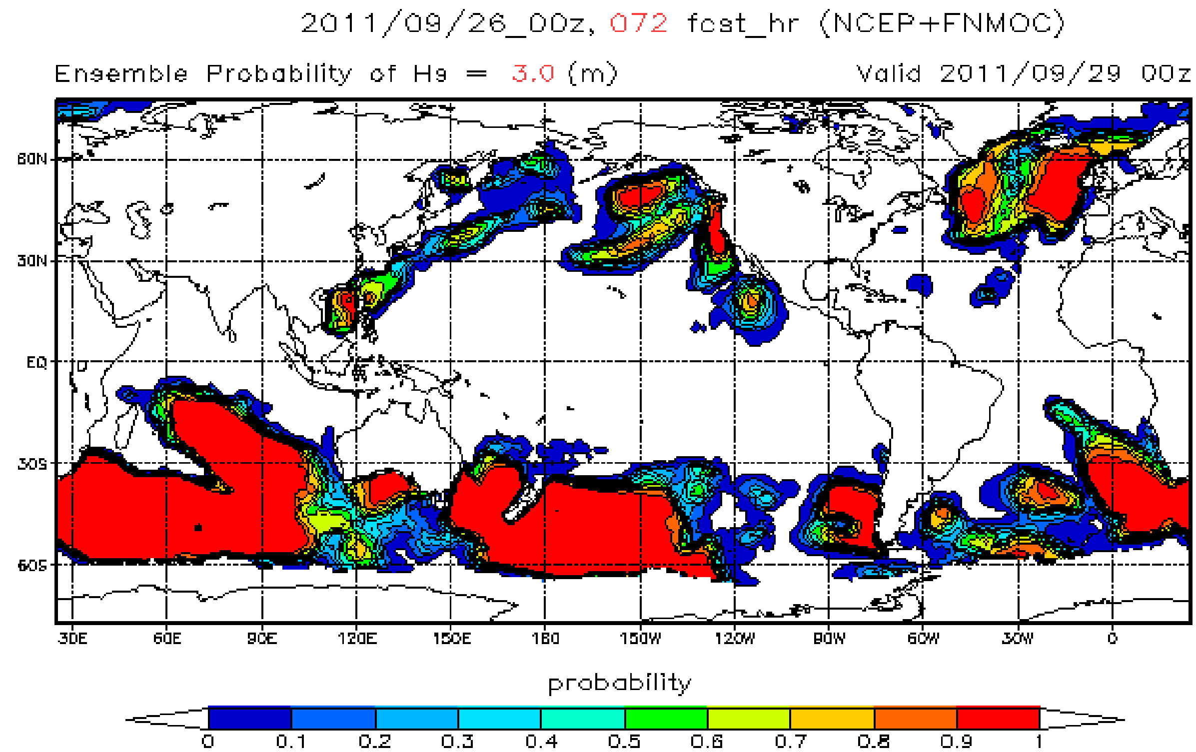


Figure 2b. Combined WW3 EFS: contours of probability of significant wave heights exceeding the 3m level, from the global domain plot, at the 72h forecast range of 26 Sep 2011 00Z run. (NCEP Product).

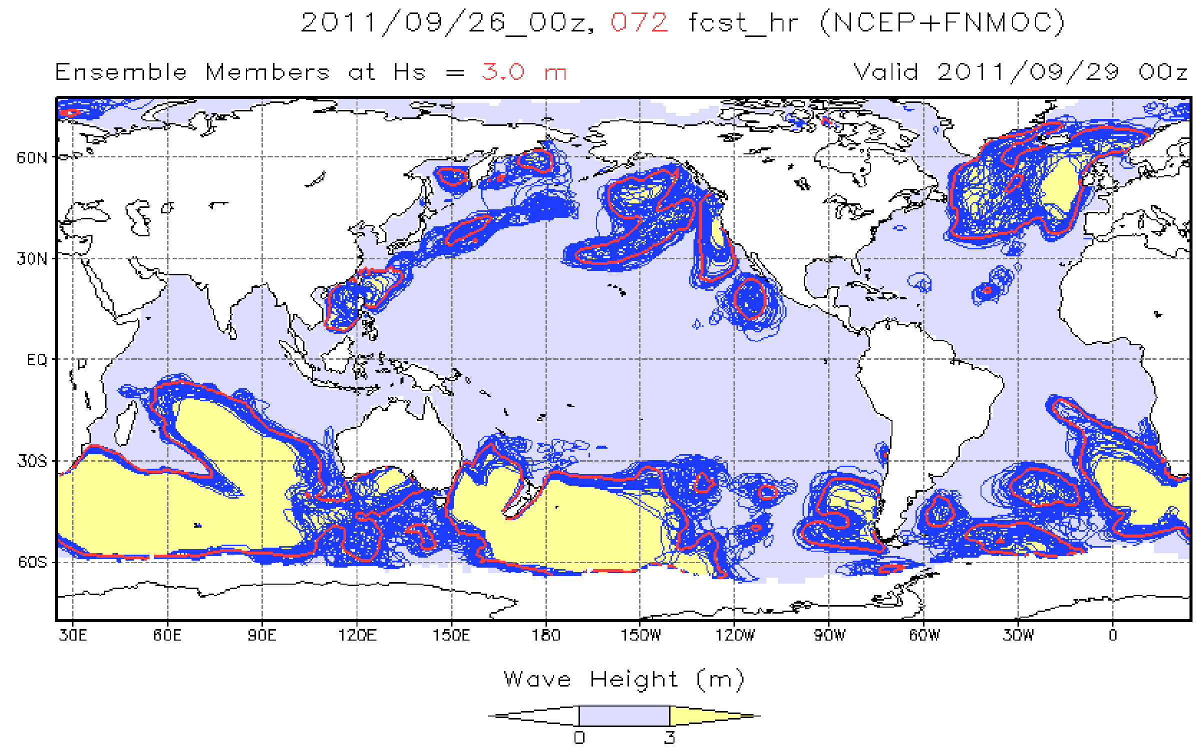


Figure 2c. Combined WW3 EFS: Contours of significant wave height (blue lines) at the 3m level from all the individual 41 wave ensemble members ("spaghetti" plot). Red lines indicate the ensemble mean contour at 3m. Yellow shaded areas indicate consensus between all members for wave heights larger than 3m. Global domain plot, at the 72h forecast range of 26 Sep 2011 00Z run. (NCEP Product).

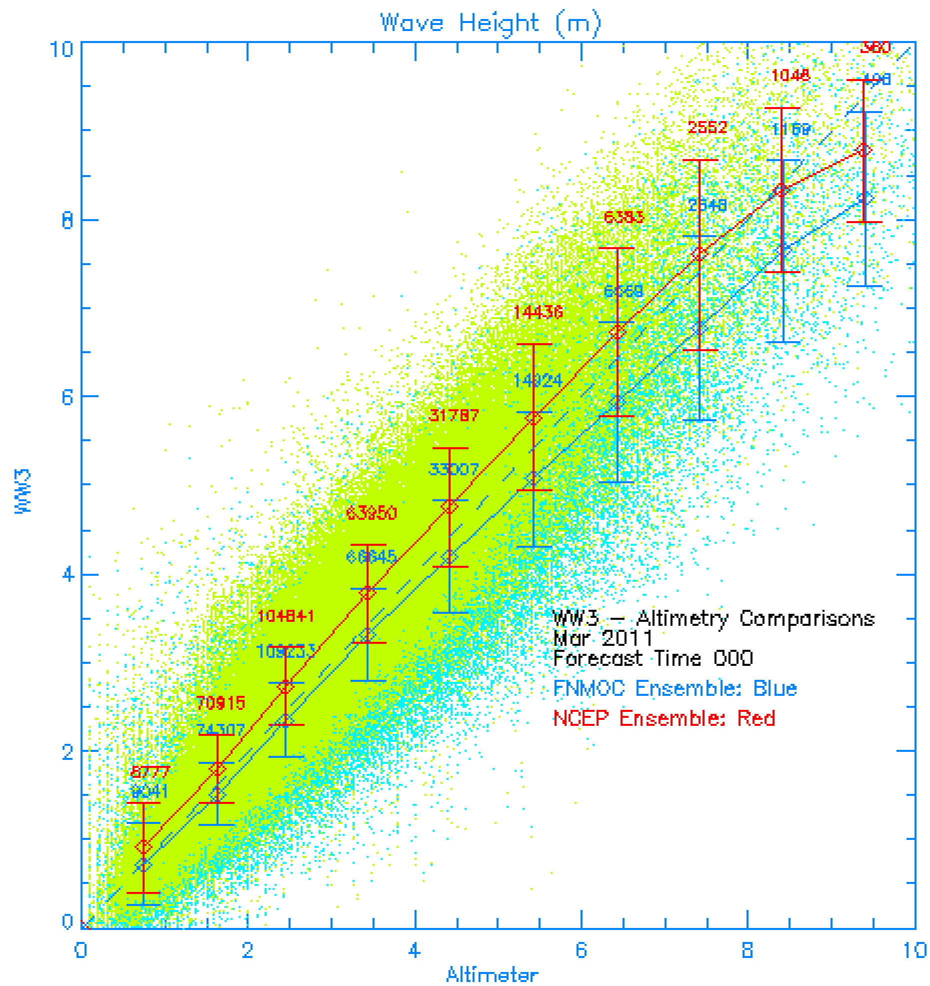


Figure 3. Scatter plot of NCEP and FNMOC WWW3 ensemble means as compared to altimeter measurements from JASON, JASON2 and ENVISAT, for forecast time 00. The data pairs are binned by wave height to produce mean and standard deviation as a function of wave height. Error bars represents 1 standard deviation

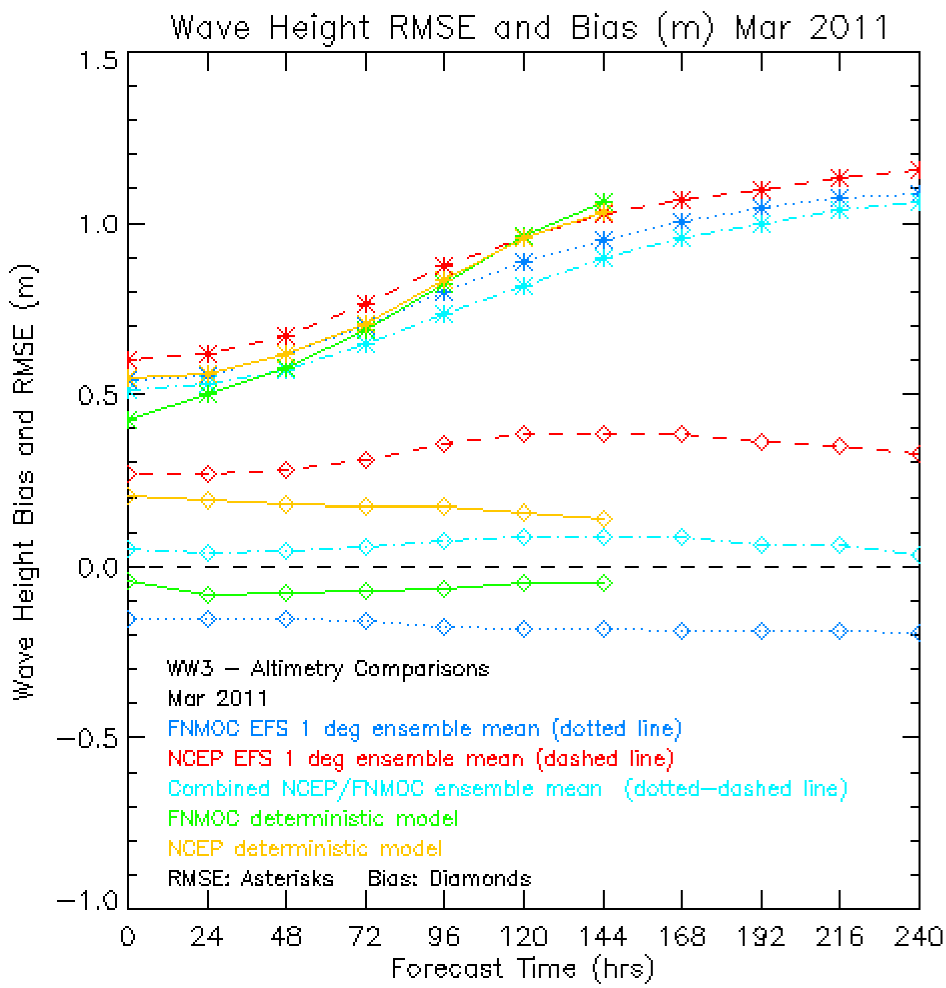
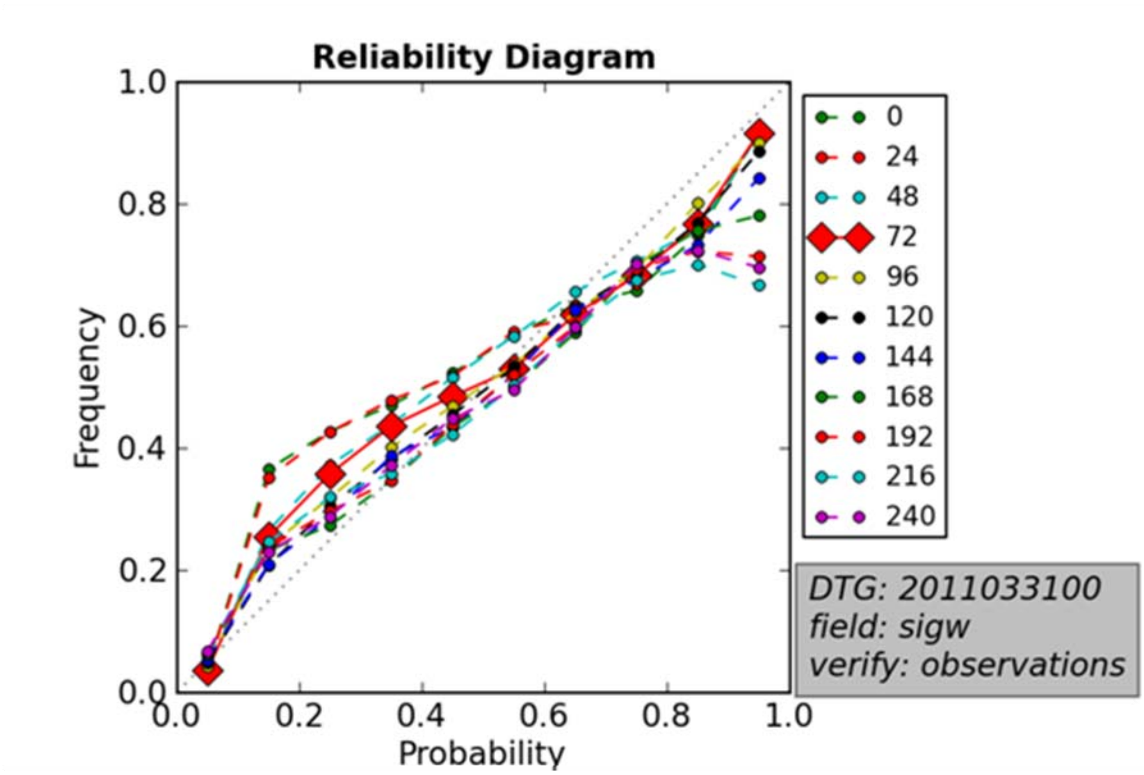


Figure 4. Bias and RMSE of Combined WW3 ensemble mean compared to altimeter observations, as a function of forecast time. Included are the scores for each center's contribution members for comparison. Also plotted are the NCEP and FNMOC deterministic model s bias and RMSE, for comparison.

Reliability Diagrams
WAVEWATCH III Wave Heights
Global, MAR 2011



wave height threshold = 12 ft

Figure 5. Reliability diagram from March 2011 for significant wave heights exceeding 12 feet, for combined NCEP-FNMOC WW3 ensemble.

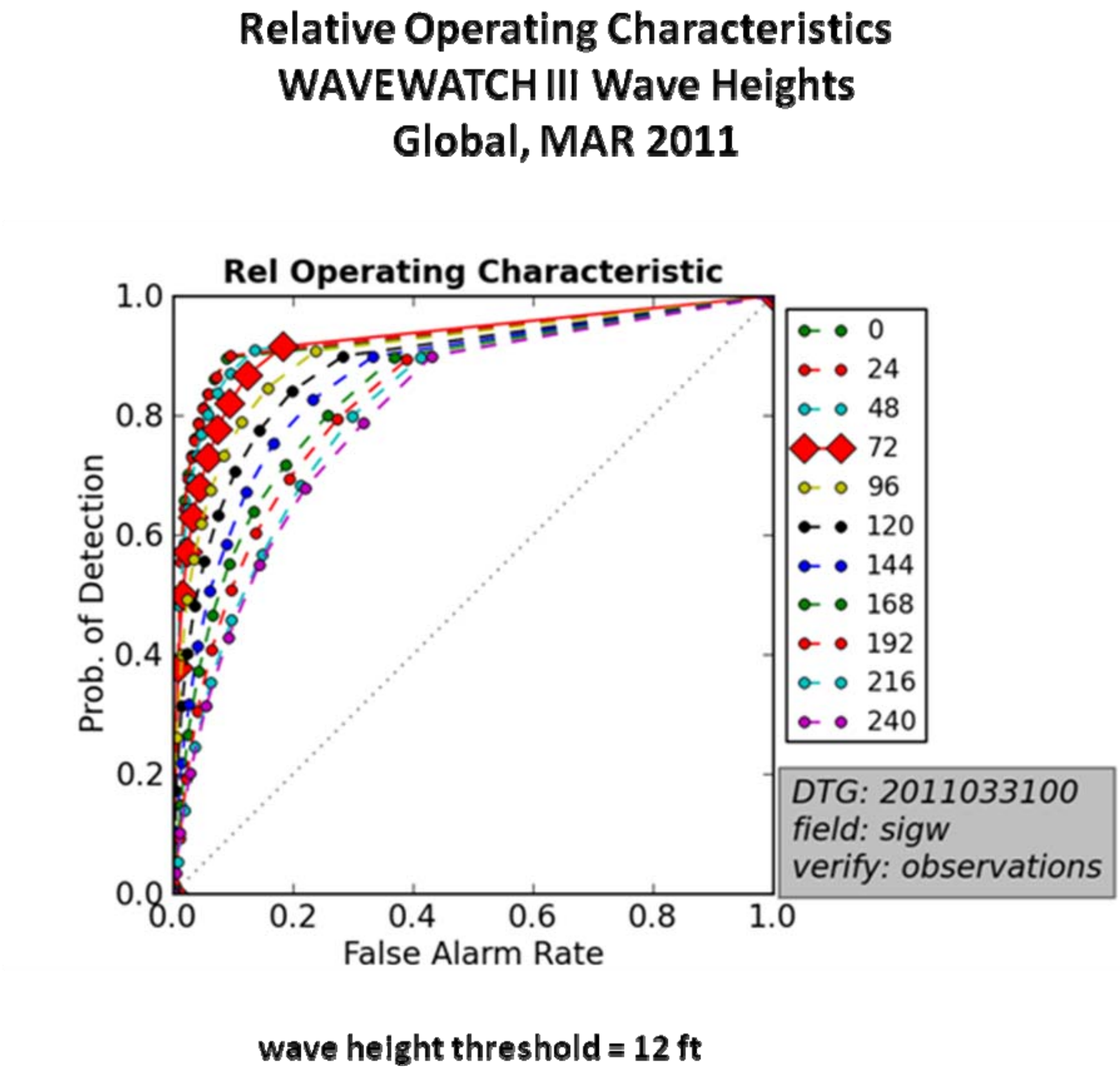


Figure 6. Relative Operating Characteristic (ROC) diagram for March, 2011, for combined NCEP-FNMOC WW3 ensemble.

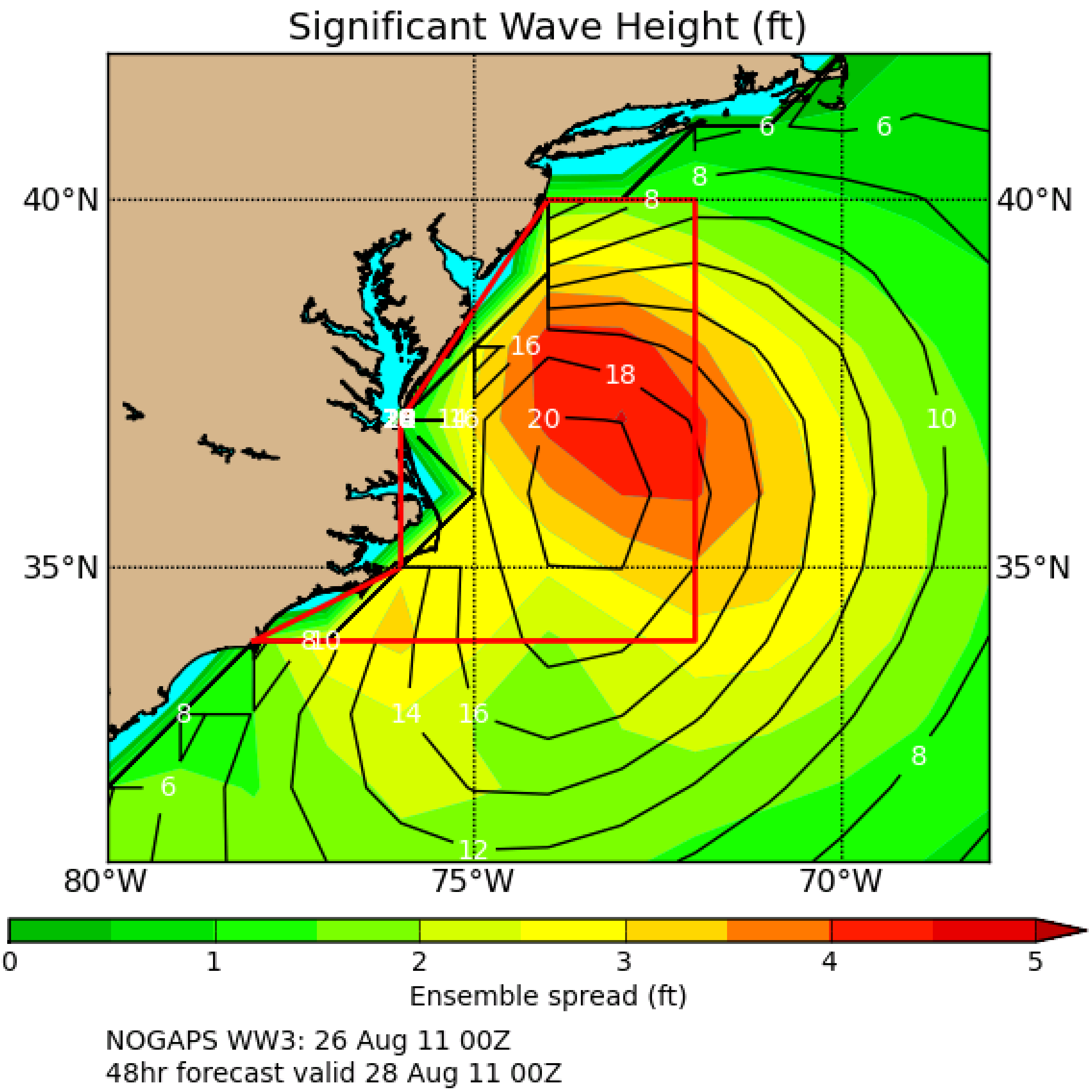


Figure 7a: Ensemble mean (solid contours in feet) and standard deviation (filled color contours) using the NOGAPS WW3 ensemble for significant wave heights associated with a 48hr forecast of Hurricane Irene.

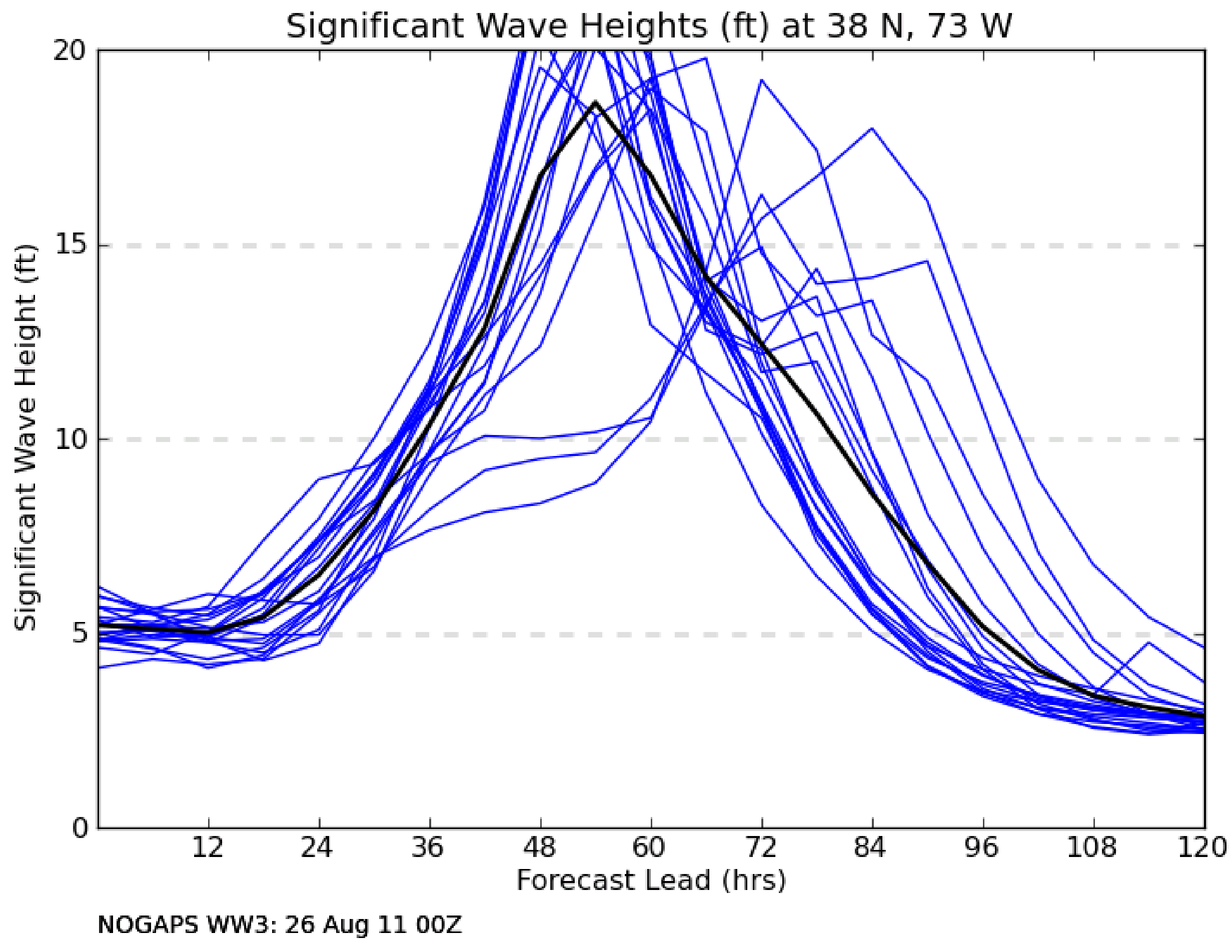


Figure 7b: Significant wave height for individual NOGAPS WW3 ensemble members at a location off the coast of Virginia.

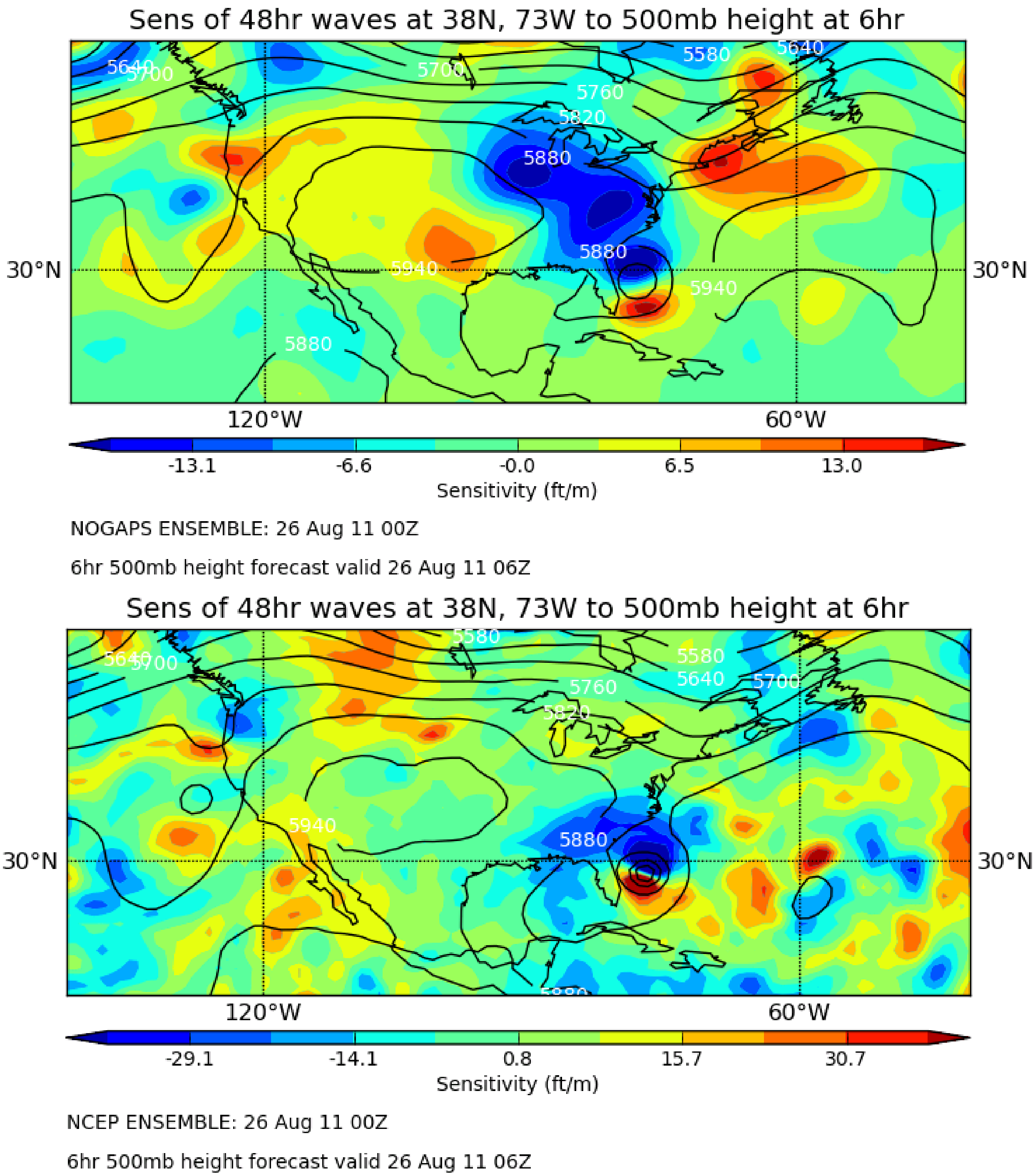


Figure 7c: Ensemble mean 500mb heights (solid contours) and sensitivity of the significant wave height at a point off the Virginia coast at 48hrs to the 500mb height field at hour 6 of the forecast (color fill), for NOGAPS EFS (top) and GEFS(bottom). The figure communicates how changes in 500mb at hour 6 of the forecast impact waves at our point of interest at hour 48 of the forecast. The top panel is the NOGAPS WW3 sensitivity and the bottom is the GFS WW3 sensitivity. Warm colors indicate positive sensitivity and cool colors indicate negative sensitivity.