THE NCEP–FNMOC COMBINED WAVE ENSEMBLE PRODUCT

Expanding Benefits of Interagency Probabilistic Forecasts to the Oceanic Environment

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The first multicenter collaborative ensemble to make probabilistic ocean wave forecasts—operational for two years now—performs better than the ensemble systems and deterministic forecasts of individual centers.

The U.S. National Centers for Environmental Prediction (NCEP) and the Fleet Numerical Meteorology and Oceanography Center (FNMOC) have joined forces to establish the first multicenter ensemble to provide probabilistic forecasts of wind-generated ocean waves. Results from the collaboration are expected to increase the accuracy of operational wind-wave forecasts, which have for many decades provided critical information to maximize safety and success of maritime and coastal activities. The NCEP–FNMOC multicenter wind-wave ensemble system (NFCENS) was made operational at NCEP on 1 November 2011. The next phase is an expansion that will provide opportunities for further collaboration with other operational centers in North America. By 2014, the current multimodel system will include data from a third wave ensemble system being developed at Environment Canada (EC).

The last decade witnessed the successful establishment of multicenter atmospheric model ensembles, a combination of results generated within a diverse set of ensemble systems, generally using different models, run independently at two or more collaborating operational centers. Early studies using global-scale models have shown that such systems, known by names as numerous as their sources of data (e.g., superensembles, multimodel ensembles, and multicenter ensembles), are a successful tool for extending the reliability of atmospheric models and the skill of their forecast products (e.g., Krishnamurti et al. 2000). The central idea behind such collaborative atmospheric ensemble systems is to combine the uncertainty associated with different models and perturbation methods, leading to an improvement in predictability. The increased predictability is made possible by an increased sampling, thereby accounting for atmospheric flow uncertainty (Candille 2009). Building on the benefits of global-scale ensembles, successful multimodel and multicenter systems have also been applied to medium-range weather forecasts (Park et al. 2008; Hagedorn et al. 2012), flood forecasting (Pappenberger et al.2008), and seasonal forecasting (Doblas-Reyes et al. 2005; Hagedorn et al. 2005). Such benefits of probabilistic forecasts based on super- and multicenter atmospheric ensembles are expected to be applicable to ocean circulation and wind-generated wave models alike and thus have the potential to produce significant improvements to the accuracy, relevance, and reliability of probabilistic predictions for the oceanic environment.

The establishment of the NFCENS multicenter wave ensemble follows the successful implementation of operational wave ensemble systems (WES) at the European Center for Medium-Range Weather Forecasts (ECMWF) in 1998 (Hoffschildt et al. 1999), at the U.S. National Weather Service (NWS) in 2005 (Chen 2006), at FNMOC in 2006, and at the Norwegian Meteorological Institute (NMI) in 2008. Benefits of these systems to marine forecasting applications have been shown in several studies. Hoffschildt et al. (1999) reported on the benefits of probabilistic forecasts from the ECMWF WES to ship routing. Other studies on benefits of the ECMWF WES were reported in Saetra and Bidlot (2004) and Carrasco et al. (2011). An early validation study of the NCEP WES, with discussions on future applications, is presented in Cao et al. (2007). Advantages of using the limited-area NMI WES for increasing predictability in targeted areas are presented in Carrasco and Saetra (2008). Recent studies have also investigated using WES to assess the impact of future climate change scenarios on extreme waves in the North Sea (Grabemann and Weisse 2008).

Other approaches toward improving the reliability and/or predictability of wave forecasts have also been described in recent studies. Durrant et al. (2009) applied the technique known as operational consensus forecast (OCF) to an ensemble of 10 deterministic wave model outputs, gathered from operational weather centers around the world. The OCF scheme employs bias correction and combines model data to provide improved forecasts in locations where recent data are available. Farina et al. (2005) presented an approach to reduce the computational costs of full wave model runs in a WES composed of linearized member approximations. The method helps reduce computation costs and/or allows for increased spatial resolution, but has a strong limitation since linearization eliminates its applicability to forecasting of swell systems. More recently, Pinson et al. (2012) demonstrated that the combination of model output and recent observations can be used to derive probabilistic forecasting of the wave energy flux.

The operational implementation of the NFCENS system rides the wake of many of these recent developments and opens the opportunity of cooperation toward the establishment of new products, to the benefit of users of marine forecast data. During its first year of operations, the NFCENS products have broadened the user base of WES products as a consequence of its proven increased skill relative to the individual, originating WES products from NCEP and FNMOC. Despite its relatively low spatial resolution, the NFCENS has proven a useful tool to assist in forecasts of waves generated by hurricanes. These early benefits are described below, on the basis of validation studies made at FNMOC and NCEP as well as evaluations made at the National Oceanographic and Atmospheric Administration (NOAA)/NCEP/National Hurricane Center (NHC).

The NFCENS has been a first step toward the establishment of a North American Wave Ensemble System (NAWES), planned to become operational in 2014. NAWES will consist of an expansion of the NFCENS to include WES data from Environment Canada. In this framework of international cooperation, NAWES will be a natural extension of the North American Ensemble Forecast System (NAEFS), an atmospheric model ensemble system established in 2004 that currently integrates probabilistic forecasts from atmospheric ensemble data generated at NCEP, FNMOC, EC, and the National Meteorological Service of Mexico (NMSM). NAEFS is also a part of The Observing System Research and Predictability Experiment (THORPEX) of the Global Interactive Forecast System (GIFS).

These topics are discussed in more detail below. First, we provide a description of the NFCENS sources and its components. We then provide an overview of results indicating the individual performance of the two WES that currently make up the NFCENS, as well as of the resulting combined products. New research

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opportunities are presented, such as the development of higher-resolution, near-shore members via neural network approximation for the existing WES. Finally, we conclude by describing the basis for international cooperation established for expanding the NFCENS toward a NAWES and its integration within the NAEFS framework for data dissemination and distribution of probabilistic forecast products.

NFCENS SYSTEM COMPONENTS. The NFCENS combines significant wave height (Hs) forecasts from the FNMOC wave ensemble system (FNMOC-WES) and from the NCEP wave ensemble system (NCEP-WES). Both use the same version of the WAVEWATCH III model (Tolman 2008) and identical model options, geographical grids, and internal spectral grid settings. The shared geographical domain is represented in a single global spherical grid, with 1° × 1° spatial resolution, extending from 78°S to 78°N. The spectral grid consists of a discretized wave action density spectrum with 25 frequencies, ranging from 0.041 to 0.42 Hz with a 10% increment, and 24 directions with a 15° increment.

WAVEWATCH III computes the evolution of wave fields over space and time by solving the linear balance equation for the spectral wave action density. Wave generation by wind and decay by dissipative processes are estimated using the source terms proposed by Tolman and Chalikov (1996). Nonlinear wave–wave interactions are calculated using the discrete interactions approximations (DIA) of Hasselmann and Hasselmann (1985). Propagation is computed using a third-order accurate scheme (Leonard 1991). Subgrid-scale obstructions, such as islands and coastal features with dimensions on the order of 100 km or smaller, are included as described in Chawla and Tolman (2008). Near the coast, bottom friction is modeled using the Joint North Sea Wave Project (JONSWAP) parameterization (Hasselmann et al. 1973), as well as the depth-induced wave breaking parameterization of Battjes and Janssen (1978).

In the shared NCEP–FNMOC implementations, the WAVEWATCH III model computes wave growth using wind fields and air–sea temperature differences that can be provided at arbitrary and irregular intervals. The model systems also ingest ice concentrations that act as obstacles for wave generation and propagation whenever concentrations reach arbitrarily chosen levels. Forcing fields used at FNMOC and NCEP differ significantly. These are obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) Global Ensemble Forecast System (FNMOC-GEFS) at FNMOC and from the Global Ensemble Forecast System (NCEP-GEFS) at NCEP. Such fundamental distinctions in forcing data within NFCENS components are described in more detail next.

The FNMOC-WES. At FNMOC, the FNMOC-GEFS provides all forcing data used in its wave ensemble system (FNMOC-WES). The initial conditions for the FNMOC-GEFS are produced by the Navy Atmospheric Variational Data Assimilation System-Accelerated Representer, a four-dimensional variational data assimilation system (Xu et al. 2005). The 42-level, T319 spectral truncation analysis produced by this system is used for the T319L42 deterministic weather forecast, truncated to 42 levels at T159, and perturbed using the ensemble transform (ET) technique for the FNMOC-GEFS. Details of the system and procedures are provided in McLay et al. (2010).

The ET perturbations are computed over nine evenly spaced latitude bands extending from 90°S to 90°N. The perturbations are updated every 6 h, although complete forecasts are made only every 12 h (0000 and 1200 UTC). The FNMOC-GEFS consists of 80 NOGAPS perturbed members at T159L42 resolution, run for 6-h forecasts, used to produce the perturbations for the next cycle. Thereafter, 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, and then are rotated to another group of 20 members for the next day.

The FNMOC-WES is composed of 20 WAVEWATCH III members, forced by the 20 FNMOC-GEFS forecast members, so it also "cycles" through the 80 FNMOC-GEFS members every 2 days. The forcing data within the FNMOC-WES are ingested directly from output generated by the FNMOC-GEFS within a 1° × 1° spherical grid, at 6 h. Such forcing data consist of wind speeds and directions, air–sea temperature differences, and ice concentrations.

The NCEP-WES. The configuration of NCEP's wave ensemble system (NCEP-WES) follows closely the general structure of forcing fields generated using atmospheric data from NCEP's Global Ensemble Forecast System (NCEP-GEFS). When implemented in 1992, the NCEP-GEFS had 10 members run twice daily using the NCEP-GFS model data for integration, and the breeding vector (BV) technique (Toth and Kalnay 1993) to generate perturbed initial conditions. In 2005, the NCEP-GEFS was expanded to 20 members and extended to four daily cycles, out to 16 days. The perturbation cycle in the NCEP-GEFS uses

80 members that are rotated in groups of 20 at every 6-h forecast cycle.

In 2006, the BV method was upgraded with the use of ensemble transform and rescaling (BV-ETR), as described in Wei et al. (2008). A method for representing model-related uncertainty, the stochastic total tendency perturbation (STTP) scheme (Hou et al. 2011, manuscript submitted to *Tellus*) was introduced in early 2010. Currently, the NCEP-GEFS has a horizontal resolution of T254 (about 55 km on the equator) for 0–192 h and T190 for 192–384 h. The vertical dimension is resolved with 42 hybrid levels.

The NCEP-WES was implemented in 2004 (Chen 2006). Reflecting the then-operational NCEP-GEFS, it had 10 WAVEWATCH III model members and was run twice daily. The NCEP-WES also included a deterministic WAVEWATCH III run forced with data from NCEP's Global Forecast System. Upgrades to the NCEP-WES followed closely the upgrades to resolution, number of daily cycles, and forecast horizon that were applied to the NCEP-GEFS. The NCEP-WES was upgraded in 2008 to its current configuration, consisting of a 20-member ensemble forced with NCEP-GEFS bias-corrected wind data and one control run with deterministic GFS fields. Bias correction for the GEFS uses the decaying average method. Errors are calculated using forecast minus model analysis (Cui et al. 2006). The NCEP-WES runs four cycles per day. Although the NCEP-GEFS provides up to 16-day forecasts, NCEP's WES has a forecast horizon out to 10 days. The latter cutoff is legacy from a previous system. An extension of forecasts to 16 days is expected to be implemented in late 2013 or early 2014. A validation study of the NCEP WES is provided in Cao et al. (2007).

In both the FNMOC- and NCEP-WES systems, a full model cycle consists of a forecast run extending out to 10 days. Currently, the FNMOC-WES runs a "hindcast" phase, consisting of wind fields from the FNMOC-GEFS perturbation cycles. Because the divergence between atmospheric ensemble members is smaller during the perturbation cycles, running hindcast phases ensures that the development history of swells within a given WES member be maintained continuously within each member. This idea was initially introduced within the NCEP-WES, following a suggestion made by the NCEP-GEFS development group (Z. Toth 2005, personal communication). The hindcast phase is currently switched off in the NCEP-WES and will be reintroduced within the system in the near future.

NFCENS products. The NCEP–FNMOC combined wave ensemble system (NFCENS) products are currently made available for two types of end users. Multicenter ensemble data generated at FNMOC for the Navy Enterprise Portal Oceanography (NEP-Oc) are restricted from the general public and made only accessible to Department of Defense personnel. At NOAA/NCEP, the product is made available to the general public through the NCEP Central Operations (NCO) ftp server (ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/wave/prod/) and the nonoperational Combined NCEP–FNMOC Wave Ensembles Product portal (http://polar.ncep.noaa.gov/waves/nfcens/). NFCENS data are routinely used by NWS forecasters as part of a suite of wave model guidance, which is made available to NWS forecasters within the NCEP Advanced Weather Interactive Processing System (NAWIPS).

An example of the graphical products channeled through the NEP-Oc is shown in Fig. 1, illustrating large waves generated by Typhoon Maon south of Japan, on 18 July 2011. The ensemble mean Hs and its spread (variability) are shown in Fig. 1. The mean is simply the average of all NFCENS members and the spread is defined as one standard deviation from the

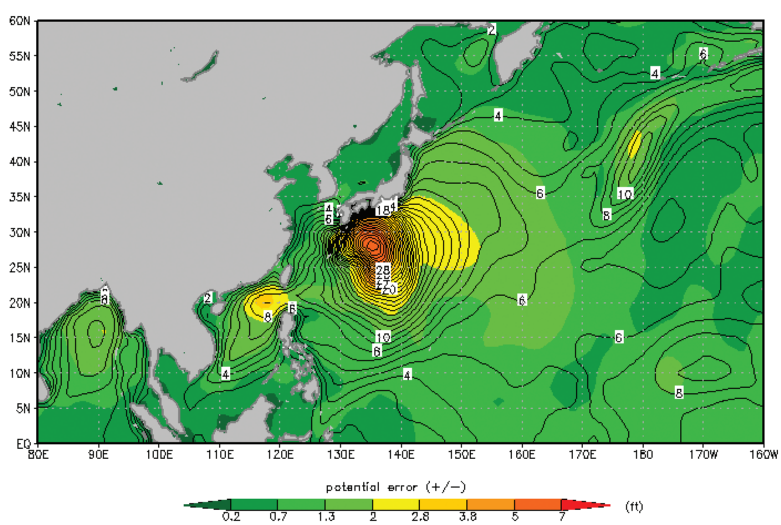

Fig. 1. Combined NFCENS mean significant wave height (contours in feet) and spread (color shading) for 0000 UTC 18 Jul 2011, Typhoon Maon. The image illustrates graphical output made available via the NEP-Oc portal, U.S. Navy.

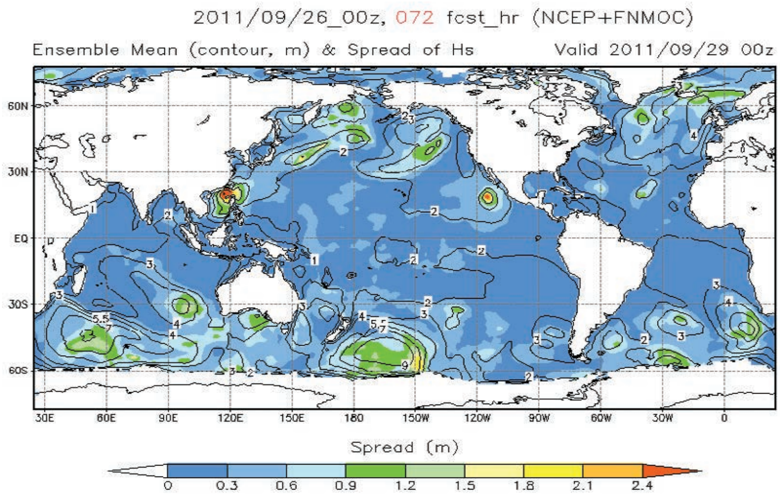

Fig. 2. Combined NFCENS: mean (contours in meters) and spread (color shading) from the global domain plot, at the 72-h forecast range of the 0000 UTC 26 Sep 2011 run. The image illustrates graphics made available publicly via NCEP's product web portals.

by the combined wave ensemble Hs product. More detailed analysis, beyond the scope of the present paper, will be the subject of other publications in the near future.

Figure 3 shows the mean global bias of the individual WES from FNMOC and NCEP, as well as the NFCENS bias. Also shown are the biases of deterministic systems run at FNMOC and NCEP. Both the FNMOC deterministic and WES Hs products have a small negative bias that grows with forecast time, whereas the NCEP deterministic and WES Hs values have a small positive bias. As expected, the resultant NFCENS Hs bias approaches zero as the relative biases of the NCEP-WES and FNMOC-WES components cancel out. Figure 3 shows that, after combining components from these two WES, the resulting Hs product is nearly unbiased, also outperforming both deterministic runs, at all forecast times.

Root-mean-square errors (RMS) of WES and deterministic models are shown in Fig. 4. Both deterministic models provide Hs that have a smaller RMS relative to their respective, noncombined WES in the short range, up to the 72-h forecasts. Thereafter,

mean. Similar graphics are produced for probabilities of Hs exceeding 12, 18, and 24 ft. Probabilities are computed using the percentage of members greater than the specified threshold.

Similarly, output products made available at NOAA/NCEP consist of 10-day forecasts of Hs for each of the NFCENS members, the ensemble-mean Hs, the combined ensemble spread, and probabilities of Hs exceeding eight levels (1, 2, 3, 4, 5.5, 7, and 9 m). As in the NEP-Oc products, the mean and spread are simply the average and standard deviation of all NFCENS members. Figure 2 provides an example of graphical output from the NFCENS product.

PERFORMANCE OF INDIVIDUAL AND COMBINED WES. Altimeter measurements of Hs provide a vantage point from which a comparative performance assessment of ensemble forecasts from NCEP-WES, FNMOC-WES, and NFCENS can be made on a global scale. Presently, a 2-yr-long database (April 2010–March 2012) of along-track altimeter measurements of Hs made by *Jason-1*, *Jason-2*, and *Envisat* satellite missions is used. No bias corrections were applied to the observations from these satellites. However, the data were quality controlled for range, for consistency within Hs fields, and for possible effects of shallow water and sea ice. Data were, finally, averaged along track to match the resolution of the model. The altimeter data used provide independent measures of the system's skill, since they have not been assimilated in the model system. Below, a performance assessment is presented with the intention of providing a bird's-eye view of the benefits brought

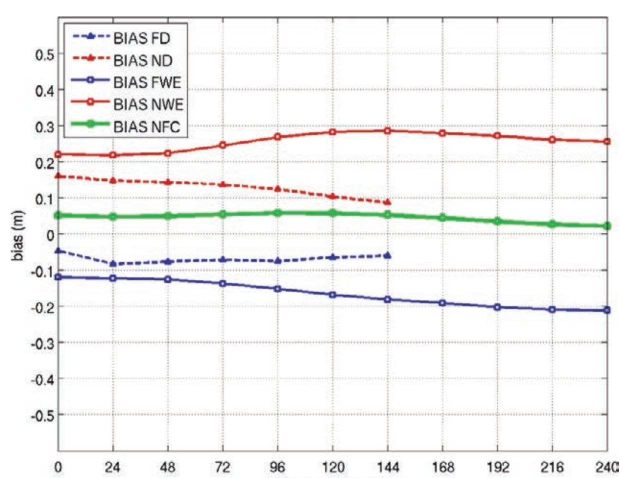

Fig. 3. Bias of modeled significant wave height Hs, relative to altimeter measurements of Hs. Shown curves are (i) bias of NCEP (ND) and FNMOC (FD) deterministic models and (ii) bias of NCEP (NWE), FNMOC (FWE), and NFCENS (NFC) ensemble systems. Forecast horizons range from 0 to 240 h, at 24-h intervals.

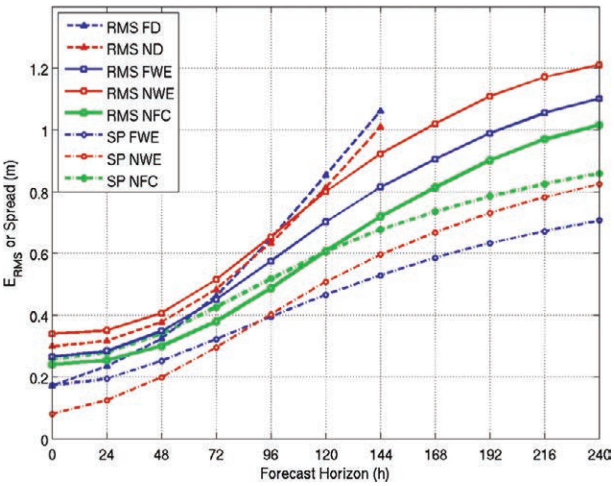

Fig. 4. Global RMS and ensemble spread (SP) of modeled significant wave height Hs, relative to altimeter measurements of Hs. Shown curves are (i) RMS of NCEP (ND: red stars) and FNMOC (FD: blue stars) deterministic models; (ii) RMS of NCEP (NWE: dashed red), FNMOC (FWE: dashed blue), and NFCENS (NFC: dashed green) ensemble systems; and (iii) SP from NCEP (NWE: solid red), FNMOC (FEW: solid blue), and NFCENC (NFC: solid green) ensemble systems. Forecast horizons range from 0 to 240 h, at 24-h intervals.

individual WES trend toward smaller RMS relative to both deterministic runs. Combined NFCENS Hs data outperform both NCEP's deterministic run and WES, as well as the FNMOC-WES, in all forecast times, and is only larger than the FNMOC deterministic run in the very short range (less than 36-h forecasts). This consistent reduction of total error is a welcome property of the multicenter ensemble Hs product.

Figure 4 also shows the mean global ensemble spread of the NFCENS and of its individual components. As demonstrated by Zhu (2005), an ideal ensemble forecast will be expected to have the same magnitude of spread as its RMS, at any given forecast time, to ensure that forecast uncertainty is fully represented. Both individual NFCENS components have spread values that are significantly smaller than their associated RMS, at all forecast times. The FNMOC-WES provides slightly better performance in the short-range forecast times, up to 72 h, whereas the NCEP-WES has a systematically small spread throughout the entire 10-day forecast range. Combining the two WES has led to a NFCENS Hs product that remediates this consistent underestimation of spread. As a matter of fact, RMS and spread of the NFCENS Hs are of nearly the same magnitude up to day 5, when the common trend of smaller spread relative to RMS seen in other ensemble systems is consistently established up to day 10. Still, compared to its individual WES components, the NFCENS Hs probabilistic forecasts are significantly more skillful.

The continuous ranked probability score (CRPS) is a useful verification tool for probabilistic forecasts (Hersbach 2000), providing a concise bird's-eye view of the reliability and resolution of an ensemble system. Since the CRPS reduces to the mean absolute error (MAE) of a deterministic forecast, it provides a consistent basis for comparing the reliabilities of deterministic and ensemble-based forecast systems. For both MAE and CRPS, smaller values mean higher reliability.

Figure 5 shows the CRPS and MAE of FNMOC and NCEP deterministic forecasts of Hs, as well as for their individual WES and the combined NFCENS Hs product. At all forecast times, both individual WES outperform their corresponding deterministic Hs forecasts—note that at 0 h, which is not formally a forecast, FNMOC has a more reliable nowcast than its WES product. In the short to medium forecast ranges, deterministic and probabilistic Hs forecasts issued at FNMOC have a better performance than those from NCEP. After 96 h, products from both centers have similar skill. As in the cases of other performance assessment statistics, the NFCENS multicenter ensemble consistently outperforms all other deterministic and probabilistic forecasts and nowcasts, providing a more reliable estimate of Hs at all forecast ranges.

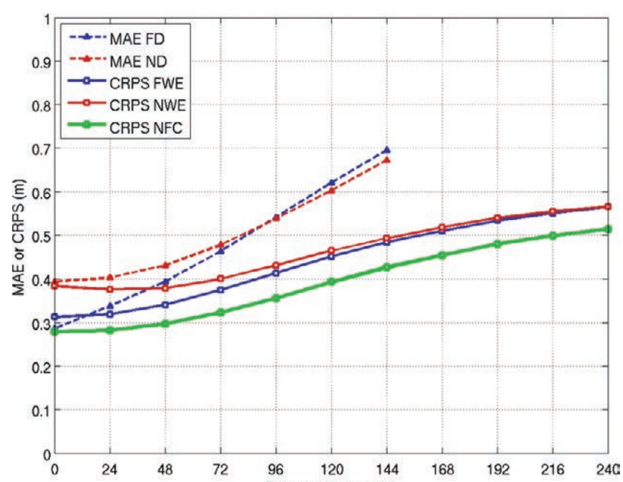

Fig. 5. CRPS and MAE of modeled significant wave heights Hs, relative to altimeter measurements of Hs. Shown curves are (i) MAE of NCEP (ND: red stars) and FNMOC (FD: blue stars) deterministic models and (ii) CRPS of NCEP (NWE: solid red), FNMOC (FWE: solid blue), and NFCENS (NFC: solid green) ensemble systems. Forecast horizons range from 0 to 240 h, at 24-h intervals.

Case studies. Prior to the operational implementation of the NFCENS multicenter ensemble at NCEP, NOAA/NCEP/National Hurricane Center provided an operational evaluation of the NFCENS forecast products. NHC's marine forecasting responsibility extends across an expansive area that includes sectors of the North Atlantic, the eastern North Pacific, and the eastern South Pacific. For NHC's sea-state forecasts, there are two key Hs thresholds and associated products: seas 8 ft or higher that are identified in high-seas forecast products and 12-ft sea radii that are a component of the forecast/advisory products for tropical cyclones. NHC forecasters rely heavily on ensemble probabilities of Hs exceeding these two thresholds.

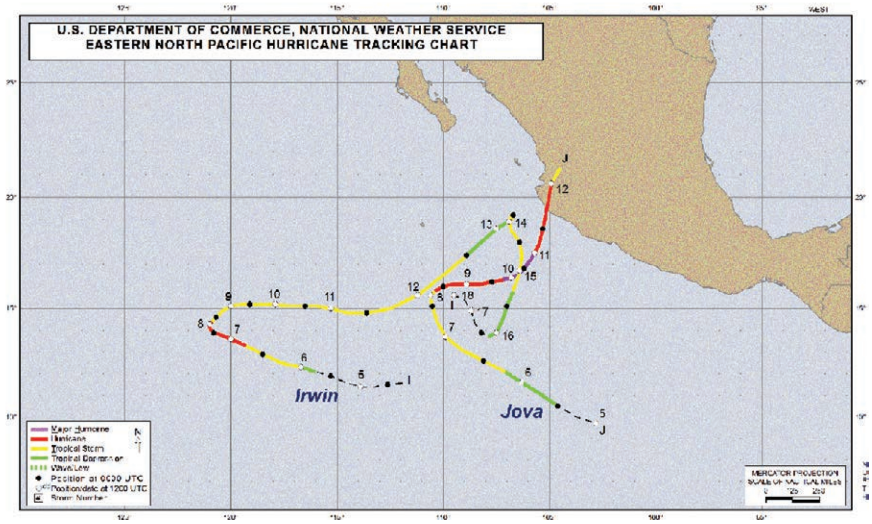

Fig. 6. National Hurricane Center best tracks for Hurricanes Irwin (6–16 Oct 2011) and Jova (6–12 Oct 2011).

The evaluation of the new NFCENS Hs products, undertaken in September and October 2011, provided an interesting opportunity to investigate the benefits of the combined ensembles product during the peak of the hurricane season. Assessments were made on the basis of case studies comparing the NCEP WES, the NFCENS, and observations, including cases involving challenging sea states generated by Hurricane Irwin and Tropical Storm Jova. A selection of three relevant cases is presented next. Figures used to illustrate the case studies reproduce the actual real-time, computer-based graphics display of wave data used by forecasters at NHC.

Hurricane Irwin and Tropical Storm Jova. Hurricane Irwin was a category 2 hurricane on the Saffir–Simpson wind scale that occupied the eastern North Pacific between 6 and 16 October 2011 (Berg 2012) at the same time that category 3 Hurricane Jova (6–12 October) was in the basin (Brennan 2012). Figure 6 shows the best tracks from both Irwin and Jova. The swell emanating from these tropical cyclones coincided with a long-period cross-equatorial swell event, making for a complicated swell field west-southwest of Mexico during this period.

Figure 7 shows the probability of Hs exceeding 8 ft from the 1200 UTC 12 October 2011 runs of the NCEP-WES and the NFCENS data at the 84-h forecast. Notice that the NCEP-WES showed little spread in the forecast, with high probabilities of seas exceeding 8 ft over a large area, even 84 h into the forecast period. The area of Hs expected to exceed 8 ft in the NCEP-WES probabilities looked very much like

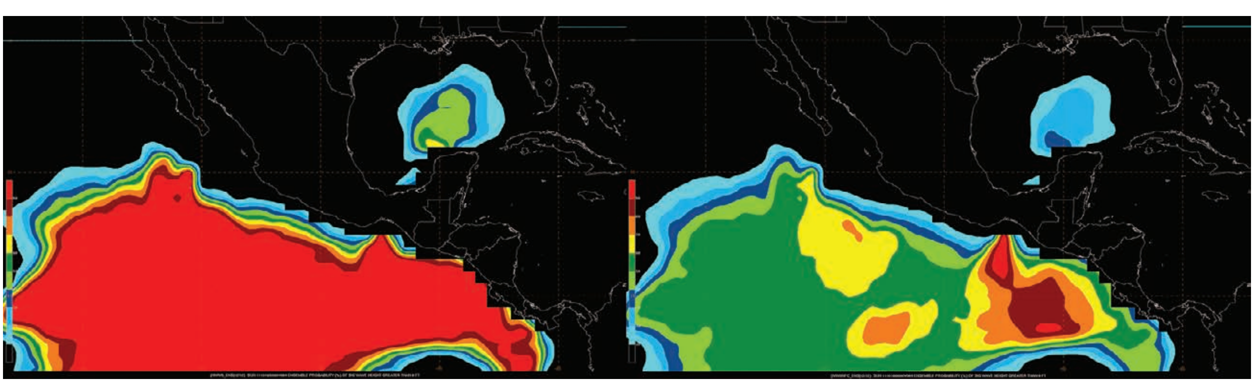

Fig. 7. Probability of seas exceeding 8 ft in the 1200 UTC 12 Oct 2011 runs of the (left) NCEP-WES and (right) NFCENS Hs 84-h forecast product, valid 0000 UTC 16 Oct 2011.

the forecast for 8-ft Hs from NCEP's deterministic wave model. The NFCENS Hs data had more variability, providing a more reliable basis for the analyses made at the NHC.

At 0000 UTC 13 October 2011, cross-equatorial 16–18-s period swell dominated much of the area south of Irwin. Predictions of Hs from the 10 October 1200 UTC runs of NCEP deterministic wave model and from the NFCENS product means varied considerably south of Irwin at the 60-h forecast, whereas both Hs means were too high south of 10°N when compared to altimeter data. However, the NFCENS mean was closer to the observations. In addition to the winds associated with Irwin, 20–25-kt west-southwest winds prevailed over much of the region near the Mexican coast. Again, the NFCENS mean Hs predictions for that region provided the best agreement with a *Jason-2* pass on the western side of Irwin. The region south of Mexico also saw southwest swell, with periods of 12–14 s, merging with 8–10-s period southeast swell originating from the South Pacific. Again, the combined ensemble was in closer agreement with altimeter data passes indicating sea states over 11 ft, primarily associated with swell.

The NFCENS probabilistic forecasts proved extremely useful for the determination of 12-ft sea radii for tropical cyclones when compared against the suite of global wave models and observations. This was apparent for Irwin and Jova. Figure 8 shows the probability of seas exceeding 12 ft in the vicinity of then–Hurricane Irwin (hurricane symbol) and then–Tropical Storm Jova (tropical storm symbol), in the 0000 UTC 8 October 2011 runs of the NCEP-WES (left) and the NFCENS (right) at the 0-h forecast. The trajectory of both systems is reflected in the shape of their respective 12-ft sea fields, with larger radii on the east sides of both systems. Figure 8 shows side-by-side comparison of the NCEP-WES (left) and the NFCENS (right) probabilistic forecasts for Hs larger than 12 ft, at 0000 UTC 8 October. The white cross-hatched areas over each brightly colored wave field depict the NHC analyzed 12-ft Hs contour, while the red points show the NHC best-track positions of the tropical cyclones. The surrounding area had been sampled several times in the previous 48 h by both scatterometer and altimeter passes. Successive altimeter passes across the northwest quadrant of Jova provided NHC forecasters conclusive evidence to expand the 12-ft sea radii well beyond the initial guidance.

A comparison of the two ensemble outputs with other limited observations, as well as with global deterministic wave model output, provided NHC forecasters high confidence in estimating the 12-ft Hs radii for both tropical cyclones. While the NCEP-WES Hs probabilities for 0000 UTC 8 October (Fig. 8, left) yield modest gradients that are relatively uniform around both systems, stronger gradients that agree more closely with the NHC analyses are depicted by the NFCENS data (Fig. 8, right).

Ocean swell. Figure 9 shows time series of Hs during swell events observed at the location of two National Data Buoy Center (NDBC) buoys. Observations are shown alongside the expanded spread of forecast solutions from the 41 NFCENS members. NDBC buoy 41049 is located in the open waters of the central Atlantic. At the beginning of the time series at 0000 UTC 10 October 2011, buoy 41049 was reporting east-northeast wind speeds of 17 kt. The buoy was located southeast of a ridge that extended from a

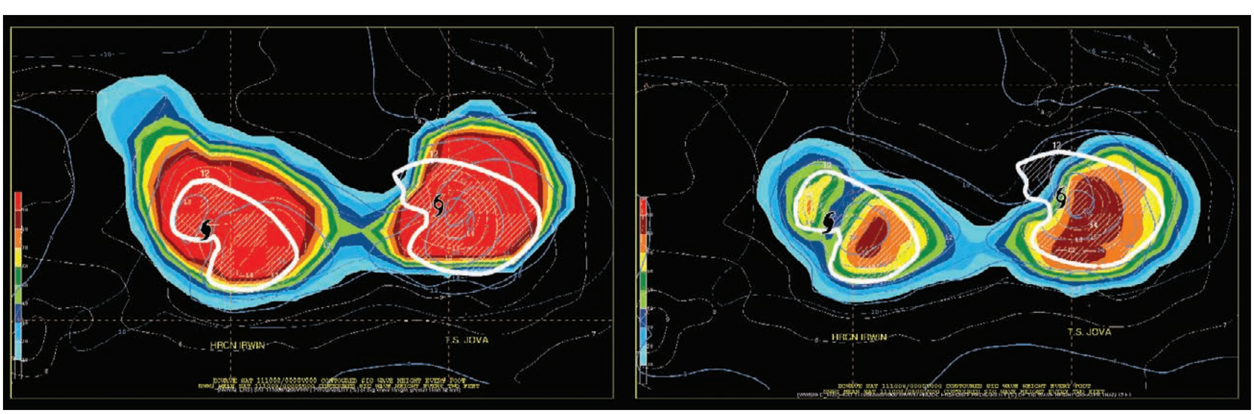

Fig. 8. Probability of seas exceeding 12 ft in the vicinity of Hurricane Irwin (hurricane symbol) and Tropical Storm Jova (tropical storm symbol), in the 0000 UTC 8 Oct 2011 runs of the (left) NCEP-WES and (right) NFCENS 0-h forecast. Bold white lines and crosshatched areas surrounding each storm identify the real time analysis by NHC for 12-ft sea radii.

1028-mb surface high over Virginia to the east of a 1002-mb surface low located over Florida.

As the low pressure system moved northwest over the next two days, the high shifted northeast of the buoy. This caused winds to veer southeastward and weaken. Buoy 41049 reported 7-ft seas at 0000 UTC 10 October, approximately 2 ft lower than the analyzed Hs of the NCEP-WES members and mean but in closer agreement with the FNMOC-WES members. The sea state was dominated at that time by north-northeast swell with 9–11-s peak periods associated with another weather system well northeast of the buoy. This swell component gradually diminished over the next two days, with the primary swell direction shifting to the east and becoming dominated by the local east-southeast wind regime by 1200 UTC 12 October.

Figure 9 shows that the NFCENS mean performed well during the time when the north-northeast swell was the primary contributor to the sea state at buoy 41049. Observations of Hs generally stayed within the spread of the combined ensemble members, as seas subsided through 0000 UTC 12 October, with the NCEP-WES members on the higher end of the spread and the FNMOC-WES members on the lower end. After the north-northeast swell diminished, the NCEP-WES members better predicted the sea states at buoy 41049 (Fig. 9, left).

NDBC buoy 42055 is located offshore the eastern edge of the Yucatan Channel. At 0000 UTC 10 October 2011, the buoy was exposed to west to north-northeast swell originating in the Gulf of Mexico and east to east-southeast swell generated by the flow associated with the southern side of the aforementioned high pressure system, centered over Virginia. The latter flow dominated much of the Caribbean. Observed wind speeds at buoy 42055 remained nearly constant over the next five days, whereas the wind direction shifted from east-northeast to southeast by 14 October.

FNMOC-WES Hs at buoy 42055 were generally in better agreement with observed data than the NCEP-WES Hs (right in Fig. 9). At both buoys, the early dominant component of observed sea state consisted of swell originating well north of the buoy. All NCEP-WES members had Hs larger than the observed values and also larger than most of the FNMOC members, through 1200 UTC 13 October. The NCEP-WES data remained less skillful relative to the FNMOC-WES Hs until 14 October. At that time, the northerly swell component propagating through the Yucatan Channel finally diminished and local winds turned southeasterly, the same direction as the primary swell component. Like at buoy 41049, the NCEP-WES members were again in closer agreement with observations.

Mixed wind seas and swell. NHC forecasters compared model forecasts for two areas, indicated by points A and B in Fig. 10, where wave properties were governed by differing forcing mechanisms. Point A is located in the tropical eastern South Pacific, in an area where trade winds are typically below 20 kt and prevailing seas are dominated by long period swell propagating from both hemispheres. It is not uncommon for model output to identify

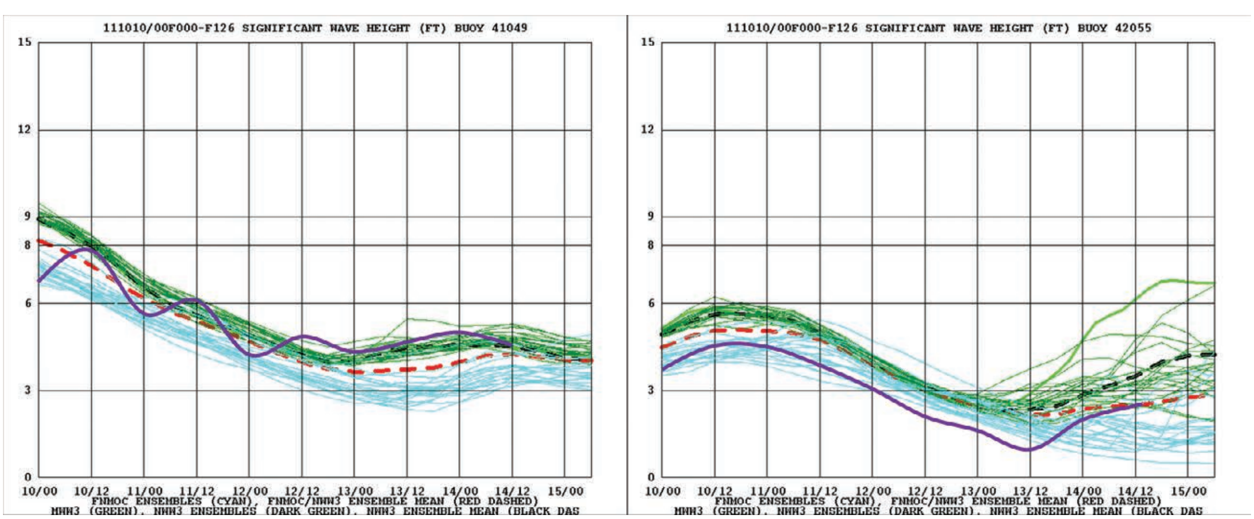

Fig. 9. Five-day time series plots of Hs at NDBC buoys (left) 41049 and (right) 42055, predicted by the NFCENS initialized at 0000 UTC 10 Oct 2011. Shown are the NCEP-WES members (green), the FNMOC-WES (blue) members, the NFCENS mean (dashed red line), and the NCEP deterministic model mean (dashed black line). Observations from the NDBC buoys are plotted in purple.

3–5 wave components moving through this area on any given day.

In contrast, point B is located in the tropical eastern North Pacific, within the downstream plume of a gap wind region, where Caribbean trade winds frequently spill across Central America and then exit and accelerate downstream of the waters of the Gulf of Papagayo. Offshore winds from the east and northeast frequently exceed 15–20 kt for days at a time, extending several hundreds of miles downwind of this gulf (Chelton et al. 2000; Risien and Chelton 2006). Point B provides a test zone to evaluate rapid wave growth, associated with the onset of gap-wind events. Sea states are, therefore, dominated by developing shorter-period wind seas, coexisting with occasional long-period swell propagating into the region.

Figure 11 shows time series of Hs during sea-state scenarios representing the typical wave climate conditions at points A and B, as described above, for all members of both NCEP- and FNMOC-WES, as well as their respective means. Again, the NCEP-WES members are typically on the high end of the model data cloud, reflecting a high bias discussed in previous sections. In contrast, the FNMOC-WES members predict Hs values on the lower end. As a consequence of the relative biases between the two WES, the combined mean provides what NHC forecasters qualify as a more reliable estimate of the true sea states. Probabilistic forecasts for Hs larger than 8 ft from the two WES are shown in Fig. 10. As was the case in numerous instances during the evaluation made at NHC, probabilistic forecasts from the combined NFCENS Hs product showed more realistic, improved variation and gradient relative to the NCEP-WES data alone.

The general lack of variability in severe sea-state forecasts from the NCEP-WES, seen in some of the case studies reported above, was likely related to the lack of diversity in the NCEP-GEFS surface wind fields. Since the period when the case studies were performed, the GEFS has been upgraded on February 2012. Upgrades included an improved physics scheme, increasing the horizontal resolution from T190 (about 70 km) to T254 (about 50–55 km) for the first 192 h (8 days) of model integration, increasing vertical resolution from 28 to 42 levels for 0–384 h-(0–16 days) forecasts, improving the ensemble initialization method by inflating the initial perturbations between the Earth surface and 500 mb, and optimizing its stochastic total tendency perturbation scheme. The result was increased diversity that reflected in higher variability of simulated ensemble wave heights. The effects of these changes on the NCEP-WES will be assessed after the latter system is upgraded to reflect the recent GEFS upgrades, in the near future.

THE NORTH AMERICAN WES. The successful operational implementation of the NFCENS has brought new opportunities for collaboration with Environment Canada. Operational wave forecasting at EC is currently limited to Canada's coastal regions. EC is in the process of adding both deterministic and ensemble global wave model products to its existing suite of operational regional products. The Canadian Global Ensemble Wave Prediction System (GEWPS) under development will extend farther north than the current NFCENS to cover most summer open water in two ocean areas (METAREAS), where Canada is responsible for providing marine safety information, following the Global Maritime Distress and Safety System (GMDSS: METAREAS XVII and XVIII). Implementation is planned for late 2013. GEWPS will be driven by the recently upgraded Global Ensemble

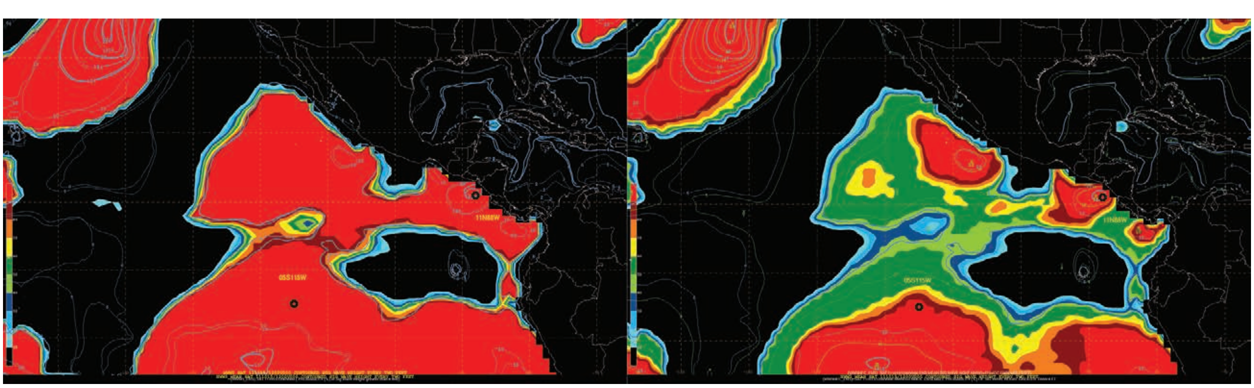

Fig. 10. Probability of seas exceeding 8 ft in the 1200 UTC 15 Oct 2011 runs of the (left) NCEP-WES and (right) NFCENS 0-h forecast. Indicated data points A (05°S, 115°W) and B (11°N, 88°W) are used to compare model output from diverse wave forcing mechanisms.

Prediction System (GEPS) winds (Houtekamer et al. 2009; Charron et al. 2010).

The planned upgrade to the current NFCENS wave multicenter ensemble includes the addition of 20 members from the Canadian GEWPS. Upon this upgrade, scheduled to become operational at all participating centers by 2014, the NFCENS will be renamed North American Wave Ensemble System. Initially, governance of NAWES will be established on the basis of the successful cooperation of NCEP, FNMOC, and EC in creating a multicenter atmospheric model ensemble system, the North American Ensemble Forecast System. Ultimately, after testing and operational implementation, this will lead to NAWES being fully integrated to NAEFS, complying fully in its governance in terms of data exchange, postprocessing, product development, and verification.

The planned development of NAWES entails an exchange of model configurations and grids that will allow the three operational centers to initially run identical wave model settings, using different forcing data provided locally, following the guidelines established within NAEFS. Relative to the current NFCENS, the new NAWES settings will include an upgrade of WAVEWATCH III model physics to the current source-term package used for deterministic wave forecasts at NCEP (Tolman et al. 2011). Full coverage of the Southern Ocean and coverage of the Arctic Ocean up to 86°N are currently being tested. The upgrade will also include an increase in spatial and spectral resolutions: the new spatial domain will be composed of a three-grid mosaic covering the globe, with 0.5 × 0.5 resolution, whereas the internal discrete spectral model grid will have 50 frequencies, ranging within 0.035–0.96 Hz, and 36 directions, with a 10° directional resolution.

CONCLUDING REMARKS AND FUTURE DEVELOPMENTS.

The combination of ensemble predictions of Hs generated at the two major operational forecasting centers in the United States, NCEP and FNMOC, has established the NFCENS, the first multicenter ensemble to provide probabilistic forecasts in the marine environment. Combined Hs probabilistic forecasts and mean ensemble values from the NFCENS provide a significant improvement relative to forecasts issued individually by the originating forecast centers.

Validation of the combined Hs product against two years of altimeter measurements has shown that the NFCENS Hs product is nearly unbiased, outperforming individual WES and also deterministic runs made at NCEP and FNMOC, at all forecast times. A welcome property of the combined Hs product is a consistent reduction of total error that is also shown to better represent forecast uncertainty. In terms of reliability, the NFCENS multicenter ensemble consistently outperforms all other deterministic and probabilistic forecasts and nowcasts, providing a more reliable estimate of Hs at all forecast ranges. Finally, several case studies made at NHC demonstrate that such quantified improvements led to a new product that has shown to be very useful to the forecasting community.

The first step into future developments of the NFCENS will be the establishment of NAWES,

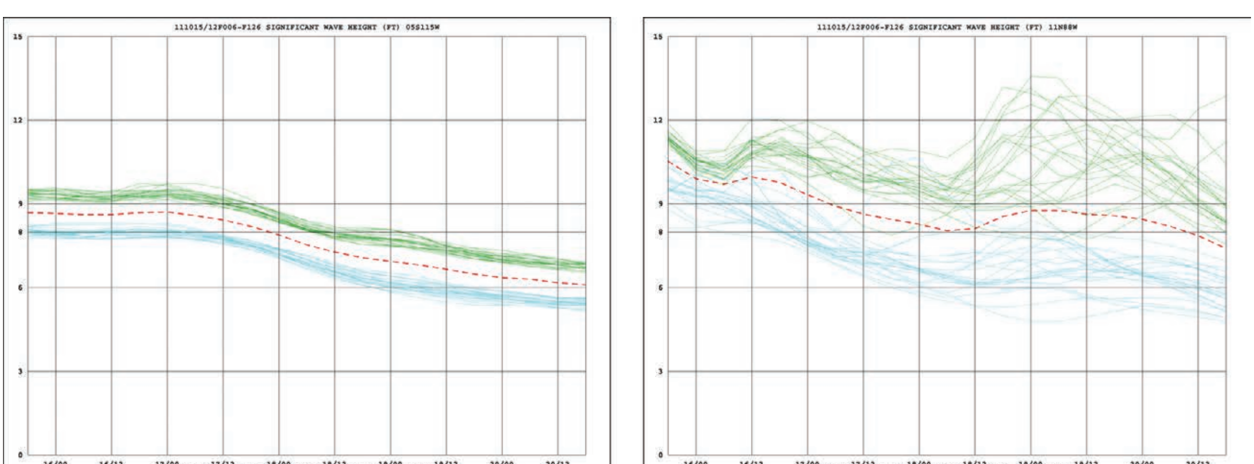

Fig. 11. Five-day time series plots of significant wave height for (left) point A at 5°S, 115°W and (right) point B at 11°N, 88°W predicted by the combined NCEP/FNMOC WAVEWATCH III ensemble initialized at 1200 UTC on 15 Oct 2011. The NCEP WAVEWATCH III ensemble members are plotted in green and the FNMOC WAVEWATCH III members are plotted in cyan. The NFCENS mean Hs is displayed as a dashed red line.

planned to become operational by 2014. Based on previous studies of ensemble size and multimodel combination (where multimodel here includes atmospheric conditions that stem from different atmospheric models), the addition of the Canadian members should improve the overall skill of NAWES (e.g., Richardson 2000; Weigel et al. 2008). In particular, increasing the ensemble size is expected to add value for less predictable events (e.g., Richardson 2001; Mullen and Buizza 2002).

At the same time, several lines of research will be undertaken individually and jointly at NCEP, FNMOC, and EC to investigate ways to increase the reliability of WES products and expand their usefulness to the marine forecasting community. Some research initiatives under consideration include introducing new ensemble members representing uncertainties in current parameterizations of wave model physics, using neural networks to increase the number of ensemble members, also allowing a possible extension of ensemble data to near-shore environments, and the establishment of a NCEP–EC joint Great Lakes WES.

Following the footsteps of the NAEFS, the establishment of a first wave multicenter ensemble system involving NCEP and FNMOC is a successful outcome of interagency collaboration. Its unfolding path of future possibilities for expanding partners, developing technology, and perfecting products targeting the marine forecasting community has the potential to further increase the accuracy of probabilistic forecasts within the oceanic environment. These outcomes are expected to be of great benefits to marine safety, the environment, the economy, and society.

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