NCEP NOTES

Evaluation of Wave Forecasts Consistent with Tropical Cyclone Warning Center Wind Forecasts

CHARLES R. SAMPSON,* PAUL A. WITTMANN,+ EFREN A. SERRA,# HENDRIK L. TOLMAN,@ JESSICA SCHAUER,& AND TIMOTHY MARCHOK**

** Naval Research Laboratory, Monterey, California*
+ Fleet Numerical Meteorology and Oceanography Center, Monterey, California
 # DeVine Consulting, Monterey, California
@ NOAA/NCEP/Environmental Modeling Center, Camp Springs, Maryland
& National Hurricane Center, Miami, Florida
*** NOAA/GFDL, Princeton, New Jersey*

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ABSTRACT

An algorithm to generate wave fields consistent with forecasts from the official U.S. tropical cyclone forecast centers has been made available in near–real time to forecasters since summer 2007. The algorithm removes the tropical cyclone from numerical weather prediction model surface wind field forecasts, replaces the removed winds with interpolated values from surrounding grid points, and then adds a surface wind field generated from the official forecast into the background. The modified wind fields are then used as input into the WAVEWATCH III model to provide seas consistent with the official tropical cyclone forecasts. Although this product is appealing to forecasters because of its consistency and its superior tropical cyclone track forecast, there has been only anecdotal evaluation of resulting wave fields to date. This study evaluates this new algorithm for two years' worth of Atlantic tropical cyclones and compares results with those of WAVEWATCH III run with U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) surface winds alone. Results show that the new algorithm has generally improved forecasts of maximum significant wave heights and 12-ft seas' radii in proximity to tropical cyclones when compared with forecasts produced using only the NOGAPS surface winds.

1. Introduction

Intense tropical cyclones (TCs, also known as hurricanes and typhoons) have tremendous impact on U.S. naval vessels due to the high seas associated with the strong winds. The worst naval disaster in U.S. history was the result of Typhoon Cobra on 18 December 1944 (Drury and Clavin 2007), in which three ships broke up and sank with their crews. Although these accidents should decrease due to improved TC forecasting (Rappaport et al. 2009), there will continue to be periodic incidents with naval assets that remind us of how important it is to continue to improve TC wind and wave forecasts. The cost of a fleet sortie (where ships at a base are sailed out to sea and away from TCs) is high and needs to be avoided, if possible. On the other hand, remaining in port during a TC passage could result in major damage to ships and their docks from collisions and unintentional beaching. Fleet sortie costs are in the tens of millions of U.S. dollars, but replacement of a large U.S. naval vessel could run into the billions of dollars (U.S. Navy 2008). Sortie decisions are frequently made at least 72 h ahead of a TC passage in order to provide enough lead time for ships to get under way and out of the path of the approaching TC, so long-range (3–5 day) forecasts are of great interest to U.S. Navy operational forecasters. Similar arguments can be made concerning the costs of disaster preparedness for non–U.S. Navy vessels, coastal communities, and offshore oil platforms.

Traditionally, third-generation spectral ocean wave models such as WAVEWATCH III (Tolman 1991; Tolman et al. 2002) are run with NWP model surface winds to produce significant wave height forecasts. The Fleet Numerical Meteorology and Oceanography Center

Corresponding author address: Charles R. Sampson, NRL, 7 Grace Hopper Ave., Stop 2, Monterey, CA 93943-5502.
E-mail: sampson@nrlmry.navy.mil

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(FNMOC) runs WAVEWATCH III using winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond 1991) as described in Rogers et al. (2005), which will be referred to as NOGAPS/WW3 in the future. One issue with using NOGAPS/WW3 in TC forecasting is that the differences in TC structure and motion between NOGAPS and the official forecast from the Joint Typhoon Warning Center (JTWC) or National Hurricane Center (NHC) could lead to inconsistencies between the distribution of the significant wave heights from the model and the likely distribution of significant wave heights associated with the official forecast. The U.S. Navy generally routes ships around areas with significant wave heights higher than 12 ft.[1] For the 120-h forecast case shown in Fig. 1, the 12-ft seas contour for NOGAPS/WW3 are clearly northeast of the official JTWC forecast, which could generate confusion about the timing and location of the TC passage near the U.S. Navy base in Yokosuka, Japan. In addition, the coarse-resolution global NWP models can have difficulty maintaining small intense circulations such as those in TCs. It has been shown that using a higher-resolution model such as the Geophysical Fluid Dynamics Laboratory hurricane model (GFDL; Kurihara et al. 1998) with a background field from a global model [e.g., the Global Forecast System, GFS; Moorthi et al. (2001)] can provide improved prediction of the extreme sea states generated by TCs [the North Atlantic Hurricane WW3 or NAH; Tolman et al. (2005); Chao et al. (2005)], so a procedure to blend official forecast winds (winds at the radius of maximum winds, 64-, 50-, and 34-kt wind radii, and at the radius of the outermost closed isobar) into a NWP model background wind field should provide improved sea state guidance for intense TCs. Some approaches to this problem include using a parametric model to simulate extreme waves from TCs (MacAfee and Bowyer 2005; Bowyer and MacAfee 2005) and inserting a high-resolution analysis of TC winds (H*WIND; Powell et al. 1998) into a GFS background to produce realistic extreme wave heights (Wang and Oey 2008). Sampson et al. (2010) developed a method to insert official TC forecasts into a NWP model background after removing the NWP model vortex [hereafter called JTWC/WW3 for the Joint Typhoon Warning Center (JTWC) version running in the western North Pacific and Indian Oceans, and OFCL/WW3 for the National Hurricane Center (NHC) version running in the Atlantic and eastern North Pacific Oceans]. The WAVEWATCH III is tolerant of abrupt changes in surface wind input so no special care is taken to smooth the official forecast winds before they are used as input into WAVEWATCH III. The JTWC/WW3 and OFCL/WW3 products have been used as guidance at the JTWC and NHC for the last few years, especially for cases where the NWP model track and/or intensity forecasts deviated significantly from the official forecasts (Fig. 1). One deficiency in Sampson et al. (2010) is that there is little verification of OFCL/WW3 and JTWC/WW3, so the biases and errors of the algorithms are unknown.

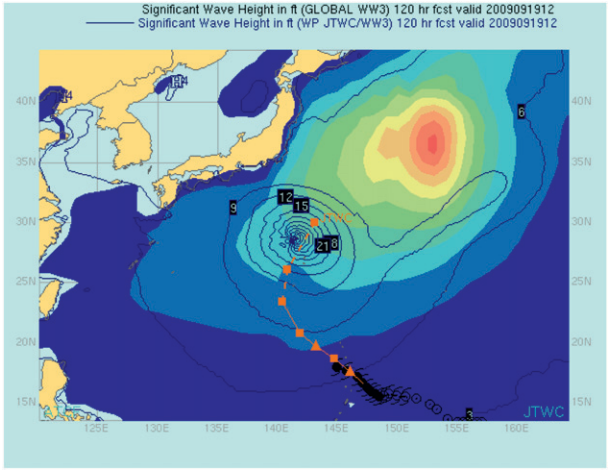

FIG. 1. Forecast example of differences in geographical location of significant wave heights associated with TCs. The open blue contours represent a 120-h forecast of significant wave height from a version of WAVEWATCH III run with winds generated from the JTWC forecast inserted into an NWP model background field (JTWC/WW3). The shaded contour field is the 120-h forecast of significant wave height from NOGAPS/WW3. First green shade indicates area of significant wave heights > 12 ft. Black and orange tracks are the past positions and JTWC forecasts, respectively. This particular case is a 120-h forecast of Typhoon Choi-Wan (2009) at 1200 UTC 14 Sep 2009.

The purpose of this paper is to evaluate OFCL/WW3 (and, by extension, JTWC/WW3) and compare its performance with that of the available guidance at FNMOC (NOGAPS/WW3). It is expected that highlighting the error characteristics of these wave forecasts will assist operational forecasters on a daily basis. Section 2 briefly describes the algorithm and verification process, section 3 describes the results from the Atlantic 2010 and 2011 seasons, and section 4 discusses conclusions, possible uses of the conclusions in daily forecasting, and future work.

2. Methods

a. *NHC forecast vortex insertion into GFS background winds*

The procedure of extracting the GFS surface wind vortex and inserting the NHC forecast winds into the

[1] Throughout this manuscript we use imperial units vice SI units because the application is designed for use in U.S. maritime operations, which is still in the habit of using imperial units.

GFS background surface wind field is described in detail in Sampson et al. (2010). The basic process is to carve out the GFS vortex using forecast information produced by the National Centers for Environmental Prediction (NCEP) vortex tracker (Marchok 2002) and replace that removed area with bilinearly interpolated data from the sides of the removed area. A series of hourly vortex forecasts from the NHC forecast periods (0, 12, 24, 36, 48, 72, 96, and 120 h) is then generated, and those forecast vortices are then converted to high-resolution hourly storm-scale gridded fields using the tessalation routine from O'Reilly and Guza (1993). Finally, the storm-scale gridded fields are inserted into the GFS background. One difference in the vortex creation method from that described in Sampson et al. (2010) is that the NHC wind speeds are no longer converted from a 1-min average to a 10-min average. The conversion (a reduction of winds to 88% of the original 1-min wind) was initially applied because it was thought that NWP model input winds to WAVEWATCH III represented 10-min mean winds; however, this was subsequently removed because a 1-min average is more consistent with the GFDL surface winds that are used as input for NAH in the vicinity of TCs. Also, a recent report by Harper et al. (2010) indicates that 1- and 10-min mean winds should be equivalent.

b. *WAVEWATCH III specifics*

OFCL/WW3, WAVEWATCH III (version 2.22), is run on a domain for the western Atlantic that extends from 0° to 50°N and 100° to 30°W. The model is ''warm started'' from GFS/WW3 at the formation of the TC, after which it is run on a 12-h update cycle at 0000 and 1200 UTC for the life of the storm. The model is forced by hourly wind fields generated from the NHC official track, intensity, and wind radii as described in the previous section. Lateral boundary conditions are ignored, as the wave field is dominated by the TC-generated waves. The drag coefficient is limited to 0.0025, based on the findings of Donelan et al. (2004). The 0.2° resolution is slightly higher than that of the NAH grid (0.25° resolution) used in the Atlantic. The success of this implementation, which includes vortex insertion from the GFDL hurricane model (Tolman et al. 2005; Chao et al. 2005; Chao and Tolman 2010), was a key reason for using this resolution.

NOGAPS/WW3 uses the upgraded version (3.14; Tolman 2009) of WAVEWATCH III, which includes more sophisticated tools to model swell decay from unresolved islands (Chawla and Tolman 2008). NOGAPS/WW3 is run for an entire globe at 0.5° resolution and uses satellite altimetry data assimilation (http://polar.ncep.noaa.gov/waves/wavewatch). Although the big differences between NOGAPS/WW3 and OFCL/WW3 are in the wind inputs that drive the model, implementation differences (e.g., resolution, altimetry assimilation, model swell decay) could also impact the results.

c. *Real-time runs*

Like NOGAPS/WW3, the 0000 and 1200 UTC runs of OFCL/WW3 are made available at approximately 0600 and 1800 UTC, respectively. Those runs use background fields from a 12-h earlier run of the GFS since the most recent run is not yet available at the Naval Research Laboratory (NRL). We run OFCL/WW3 a second time to ensure that we have the most current background fields in the results. This second run emulates what should happen in operations (e.g., at FNMOC), and those are the runs we evaluate in this paper.

3. Results

A common way of evaluating significant wave height is to compare the results of wave model forecasts with altimeter data or buoy observations. We employed buoy observations in the Atlantic and Gulf of Mexico for case studies during the development of this algorithm, but we had issues getting enough TC passes over buoys to do a more rigorous evaluation. We also attempted to evaluate the performance of NOGAPS/WW3 and OFCL/WW3 with altimeter data from the *Envisat* and *Jason-1* platforms, restricting the evaluation to an area around the center of the TC outlined by its outermost closed isobar, a parameter analyzed by the U.S. TC forecast centers. Readily apparent in this homogeneous comparison for the entire Atlantic 2010 season (not shown) is the dearth of altimeter data needed to do the evaluation as there are only about 20 passes for the entire dataset and some of those passes do not capture the area where significant wave heights are greater than 12 ft. The reason for the small dataset is that the altimeter footprint is small and rarely passes over the area defined by the outermost closed isobar. Results from this small amount of data suggest that NOGAPS/WW3 outperforms OFCL/WW3 at analysis time (not shown). A probable explanation is that NOGAPS/WW3 assimilates the altimeter data and has a more sophisticated and reliable warm start capability than does OFCL/WW3. However, results also show that the NOGAPS/WW3 forecasts underestimate extreme waves within TCs. OFCL/WW3, on the other hand, has less of a negative bias for these extreme wave events.

Another source of data used for evaluation is the 6-hourly real-time analyses of maximum significant wave height and 12-ft seas radii (i.e., the radii of 12-ft significant wave height) generated by the Tropical Analysis

and Forecast Branch (TAFB) of the NHC. Sources of data that go into these analyses are buoy reports, ship reports, altimeter passes, and WW3 output from the NAH. The process is subjective and the products are most accurate in the Gulf of Mexico, the Caribbean Sea, and the westernmost Atlantic Ocean where there are numerous buoy and ship reports to include in the analysis. The 12-ft-sea radii estimates (in the compass quadrants NE, SE, SW, NW from the center of the TC as defined by NHC) are part of the NHC advisory messages and are stored in the Automated Tropical Cyclone Forecast System (ATCF; Sampson and Schrader 2000) database. The estimates of maximum significant wave heights associated with TCs are not saved in a database per se, but are part of the TAFB high-seas forecasts issued every 6 h. In these TAFB forecasts the NAH is used as a starting point for determining 12-ft seas, which admittedly makes using the estimates of 12-ft seas from TAFB somewhat unfair for comparison to other algorithms; however, all available ship, buoy, and altimeter observations are used to adjust the NAH output at the synoptic time. These adjustments are typically most significant in the previously mentioned data-rich regions where the data are more plentiful than in the open waters of the North Atlantic. If we treat these TAFB analyses of maximum significant wave height and 12-ft seas as ground truth, we can evaluate both the forecasts of maximum seas within and the 12-ft-sea radii surrounding the TC circulation. We also have the centers of the TC wind circulations in the NHC best-track archive (www.nhc.noaa.gov), which we can use as geographic centers of the TC atmospheric circulations. The three parameters (location of the atmospheric circulation center, maximum significant wave height, and the radii of 12-ft seas) provide a reasonable suite for evaluation of extreme waves near TCs. It should be noted here that neither the TAFB analyses nor our method defines the maximum seas at the center of the atmospheric circulation, and that those seas would just be somewhere in the vicinity of the TC.

Figure 2 shows mean forecast position errors for NOGAPS and the NHC for the 2010–11 Atlantic seasons. The mean position errors are relatively close in the early part of the forecast, but then are quite different at the longer range. At 120 h the mean track forecast errors for NOGAPS approach 350 nautical miles (n mi; where 1 n mi = 1852 m) while the official NHC forecast errors are approximately 235 n mi [significantly smaller using a one-tailed Student's t test and the 95% level; Spiegel (1961)]. So not only is the NOGAPS/WW3 forecast area of high seas inconsistent with the official forecast, the center of the TC (which generally has the highest significant wave heights) is also likely to be

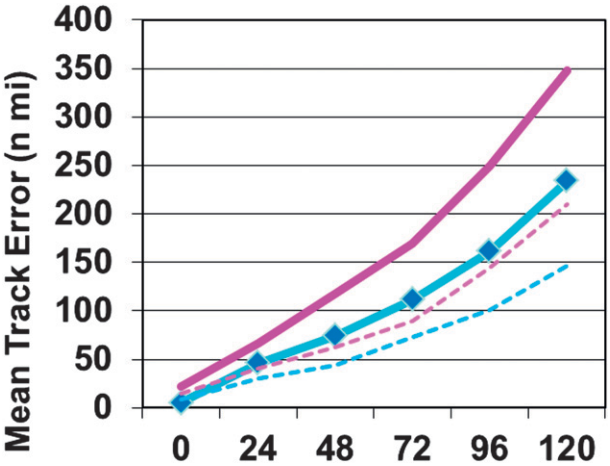

FIG. 2. Official NHC (blue) and NOGAPS (purple) mean track forecast errors for the Atlantic 2010–11 seasons at different forecast periods (x axis). Dashed lines indicate standard deviations and dark blue dots indicate statistically significant differences between the two sets of track forecast errors. Numbers of cases are 333, 261, 199, 150, 113, and 85 for 0, 24, 48, 72, 96, and 120 h, respectively.

farther away from the verifying position. The NOGAPS forecast is available approximately 3 h later than the official forecast, so the comparison shown here is applicable only to our specific use of the forecasts.

Figure 3 shows the mean forecast maximum significant wave height errors and biases for both NOGAPS/WW3 and OFCL/WW3 for the entire 2010–11 seasons in the Atlantic. The OFCL/WW3 maximum significant wave height errors are somewhat lower than those from NOGAPS/WW3 out to 96 h, where both methods reach mean forecast errors of approximately 10 ft. Figure 3 also shows that the NOGAPS/WW3 forecasts of maximum significant wave height are generally biased low, anywhere from approximately 5 ft at analysis time to nearly 10 ft at 120 h. The OFCL/WW3 forecast bias is somewhat less out to 96 h. The maximum significant wave height errors and biases as percentages of the analyzed significant wave height are also shown in Fig. 3. The NOGAPS/WW3 errors are nearly 30% of the estimated maximum significant wave height while the OFCL/WW3 errors are somewhat less. The biases expressed as percentages indicate that NOGAPS/WW3 has a nearly 30% low bias while the OFCL/WW3 low bias is between 13% and 27%. From Fig. 3 we can conclude that much of the error for maximum significant wave height is from low biases, and detailed inspection of the data confirms this (not shown). This is not a surprising result for NOGAPS/WW3 because routine inspection of the intensity (maximum 1-min mean wind speeds near the center of the storm) and the surface wind field indicates that NOGAPS generally does not retain very high winds

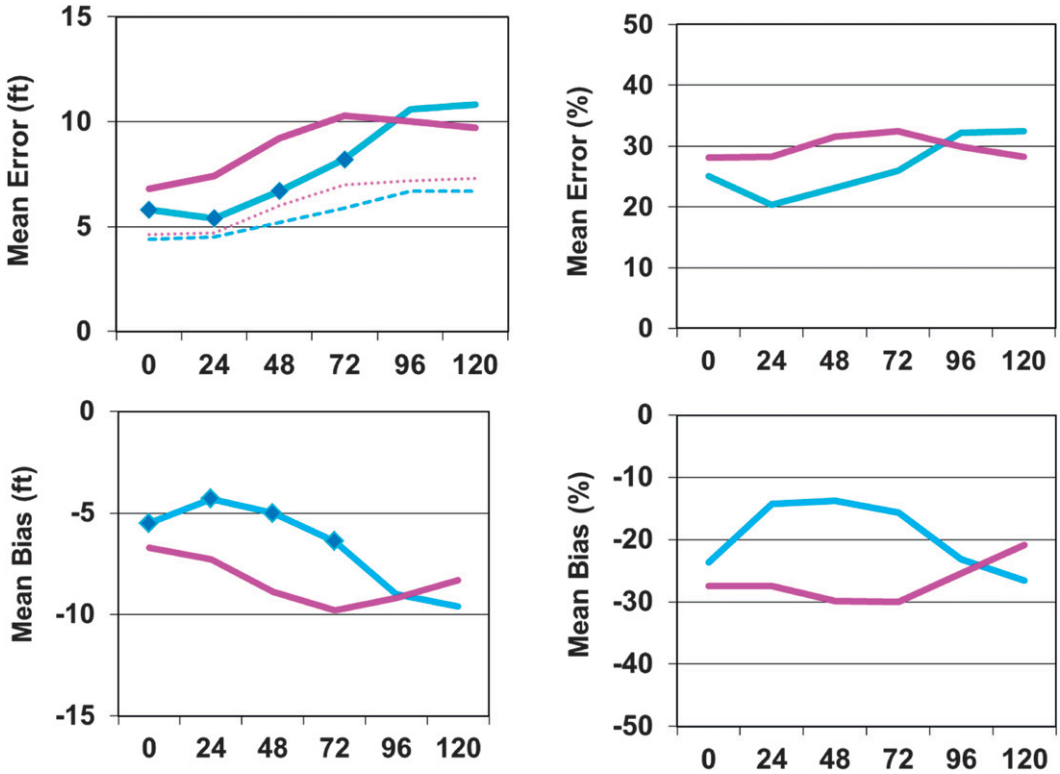

FIG. 3. (top) Mean error and (bottom) bias of maximum significant wave height for the Atlantic during 2010–11 at different forecast periods (x axes). Standard deviations are denoted by dashed lines and statistically significant differences between OFCL/WW3 (blue) and NOGAPS/WW3 (purple) are indicated with dark blue markers. Numbers of cases are 247, 180, 126, 91, 66, and 50 for 0, 24, 48, 72, 96, and 120 h, respectively. Mean error and bias as percentages of the analyzed maximum significant wave height are shown at right.

in TC circulations. It is suspected that this is an artifact of the lower resolution of NOGAPS since higher-resolution models such as the GFDL version do not have low bias issues (not shown). The low bias in OFCL/WW3 is not expected since the official NHC intensity and wind radii forecasts are generally not negatively biased (Cangialosi and Franklin 2011). WAVEWATCH III is capable of forecasting extreme waves greater than 30 ft (Tolman et al. 2005) when given the correct TC wind forcing, so the low bias is somewhat surprising since the official forecast winds have little bias.

Figure 4 shows the 12-ft-sea radii errors and biases for both the NOGAPS/WW3 and OFCL/WW3 simulations. For reference, the average wind radii for the dataset are 196, 194, 214, 240, 256, and 293 n mi at 0, 24, 48, 72, 96, and 120 h, respectively. The 12-ft-sea radii error for both algorithms rises from near 80 n mi at analysis time to nearly 140 n mi at 120 h. The NOGAPS/WW3 errors are generally lower than those of OFCL/WW3, but not significantly. The 12-ft-sea radii biases for both algorithms are generally negative, indicating that the forecast radii are generally too small. The OFCL/WW3 radii forecasts are nearly zero biased during the first forecast day, but then become generally more negative with time, reaching a value of 60 n mi at 120 h. The NOGAPS/WW3 12-ft-sea negative biases are generally more than double the OFCL/WW3 biases out to 120 h.

The radii evaluation in Fig. 4 only includes cases where at least one quadrant for each of the algorithms has a 12-ft-sea radius greater than zero. The number of cases is greater than in the evaluation of maximum significant wave height because there are four possible 12-ft-sea radii for each case. There are many cases where one or both of the algorithms did not forecast any 12-ft seas, but where the verification indicates 12-ft seas were present (misses). Figure 5 shows the probability of detection (POD) where POD = hits/(hits + misses), false alarm rate (FAR) = false alarms/(false alarms + hits), and threat score (TS) = hits/(hits + misses + false alarms) for the entire 12-ft-sea radii dataset. We consider a hit to be at least one quadrant that had 12-ft seas when the verification did, rather than defining a hit to be the more restrictive 12-ft seas in the same quadrant as the verification. False alarms are the cases that the algorithm forecasts at least one quadrant with 12-ft seas when the TAFB analysis did not show any 12-ft seas.

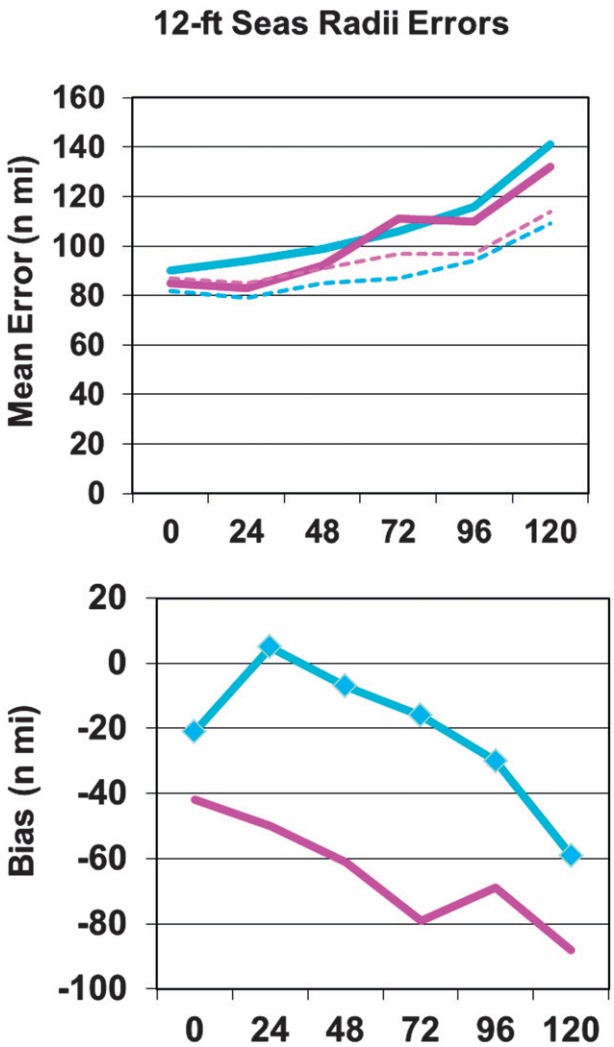

FIG. 4. (top) Mean forecast error and (bottom) bias of 12-ft-sea radii forecasts in the Atlantic during 2010–11 at different forecast periods (x axis). Standard deviations are included as dashed lines, and statistically significant differences between OFCL/WW3 (blue) and NOGAPS/WW3 (purple) are indicated with dark blue markers. Numbers of cases are 740, 696, 556, 416, 332, and 244 for 0, 24, 48, 72, 96, and 120 h, respectively.

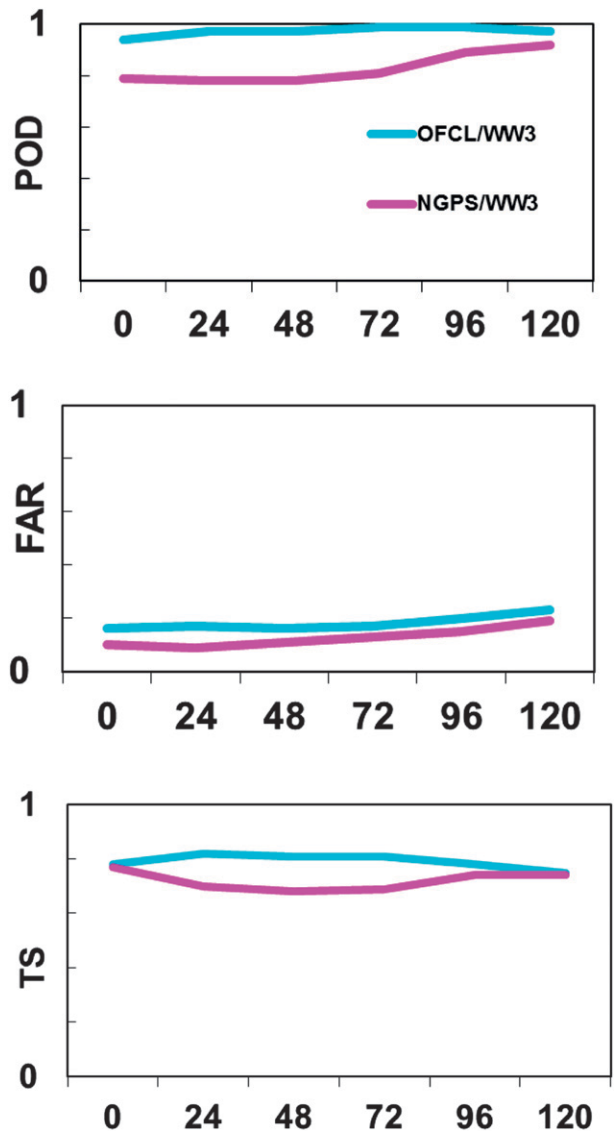

FIG. 5. (top) POD, (middle) FAR, and (bottom) TS for 12-ft-sea radii from OFCL/WW3 (blue) and NOGAPS/WW3 (purple) during different forecast periods (x axis).

The POD for OFCL/WW3 is nearly 100% through the forecast while the NOGAPS/WW3 POD is somewhat lower (0.8) out to 96 h, and then approaches 1 at 96 and 120 h. The FAR for each algorithm is in the 0.1–0.25 range and the FAR for NOGAPS/WW3 is generally lower than that of OFCL/WW3. The threat scores for both algorithms are in the 0.78–0.82 range with OFCL/WW3 having slightly higher threat scores.

4. Summary and conclusions

This paper evaluates an algorithm developed to generate significant wave heights consistent with official forecast from the U.S. TC forecast centers. The algorithm (JTWC/WW3 and OFCL/WW3) has been running in real time for maritime forecasting use for approximately 4 yr. Although the product is inherently desirable because it produces output that is geographically consistent with the official forecast, evaluating the error and bias characteristics is critical to the technique's application in operations and its utility in other operationally oriented applications. We evaluated OFCL/WW3 and NOGAPS/WW3 in the Atlantic during 2010–11 and found the following general tendencies:

1) The OFCL/WW3 position errors (errors for the location of the center of TC circulation) are smaller

than those of NOGAPS/WW3. This suggests that the OFCL/WW3 guidance adds more value compared to an NWP model-driven version of WAVEWATCH III when the NWP model track deviates significantly from the official forecast.

2) The OFCL/WW3 maximum significant wave heights are negatively biased. They are somewhat better than those of NOGAPS/WW3, but may be no better than those from an algorithm in which WAVEWATCH is driven by a somewhat higher-resolution model (e.g., the NAH run at NCEP).
3) The average OFCL/WW3 12-ft-sea errors are about 80 n mi at analysis time, increasing to about 140 n mi at 120 h. The OFCL/WW3 algorithm misses very few 12-ft-sea events; however, about 10%–20% of the forecast 12-ft-sea radii are false alarms. NOGAPS/WW3 does miss some 12-ft-sea events, but has a slightly lower false alarm rate.

OFCL/WW3 has been under evaluation at the NHC, while JTWC/WW3 has been used for approximately 4 yr by military forecasters in the western North Pacific for storm evasion and base preparedness. We intend to increase our database for future evaluation and possible adjustments to improve model performance and possibly correct the negative biases. We could also greatly increase the quality of our ground truth data if significant wave heights from the Wide Swath Radar Altimeter (Moon et al. 2003; PopStefanija and Walsh 2012) were routinely available for use in the TAFB analyses. But none of the enhancements described above can compensate for poor TC forecasts. The best way to compensate for the errors inherent in TC forecasts is to run an ensemble and produce consistent wind and wave probabilities. We recently implemented an ensemble version of OFCL/WW3 and JTWC/WW3 (128 members run at a coarse 0.4° horizontal resolution) based on forecast realizations from the official wind speed probability model (DeMaria et al. 2009); this ensemble can then be used to produce wave probabilities. These consistent wind–wave probabilities can then be used for military and civilian ship routing, base preparedness, and evacuations (Hansen et al. 2011).

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