Modeling of Two Northwest Atlantic Storms with Third-Generation Wave Models

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ABSTRACT

In this study, three state-of-the-art operational forecast wave models are implemented on nested grids in order to achieve fine-resolution wave simulations (0.1°) in the Gulf of Maine and related northwest Atlantic waters. These models are the Simulating Waves Nearshore (SWAN) model, the Wave Action Model (WAM), and WAVEWATCH-III (hereafter WW3). Model performance is evaluated through comparisons with field measurements. Four composite model systems are compared: WAM and WW3 implemented on three nested domains, SWAN nested within WAM, and SWAN nested within WW3. Storm case studies include two intense midlatitude winter storms from January 2000 and January 2002. Although the models are comparable in terms of their overall performance and skill, it is found that WW3 provides a better statistical fit to the observed wave data compared with the other models, and that SWAN gives slightly better results if nested within WW3, rather than within WAM.

1. Introduction

The simulation and forecasting of intense cyclones and their associated extreme waves have become important issues in recent years because of the increased potential for severe damage to human activities and societal infrastructure. Intense storms can exhibit rapidly varying winds that can produce large, complex ocean waves that can propagate thousands of kilometers away from the storm center, resulting in dramatic variations of the wave field in space and time (Barber and Ursell 1948). In recent years, numerical modeling has made impressive steps in forecasting waves on global and regional scales, and considerable efforts were made to measure the directional spectra of storm-generated waves and to investigate their spectral characteristics. Moon et al. (2004) present comparisons of careful simulations of ocean wave spectra using WAVEWATCH-III (Tolman 2002), in comparison with buoy data and National Aeronautics and Space Administration Scanning Radar Altimeter observations. They used a model spatial resolution of 1/12° × 1/12° in order to capture the rapidly varying wave field generated by Hurricane Bonnie, which is much finer than is typically implemented in operational forecasting. For example, the fine-resolution wave model grid for the Gulf of Maine Ocean Observing System (GoMOOS; information online at www.gomoos.org) is 0.2° × 0.2°.

In this study, three modern widely used third-generation spectral wave models are evaluated: (a) the Simulating Waves Nearshore (SWAN) model, version 40.20 (Booij et al. 1999); (b) the Wave Action Model (WAM; WAMDI Group 1988), version WAM-Pre-Operational Modelling in the Seas of Europe (PROMISE; hereafter denoted WAM) from Monbaliu et al. (2000), which is a modified version of WAM cycle 4; and (c) WAVEWATCH-III (hereafter WW3), version 2.22 (Tolman 2002; Tolman et al. 2002). SWAN was originally developed for high-resolution coastal and nearshore applications. WW3 is suitable for global and regional basin-scale and shelf-scale applications, as is WAM. The WAM version implemented in this study...
has several features that make it efficient in shallow-water and high-resolution applications. Moreover, WAM and WW3 have numerical and physical parameterizations that make them able to run on scales smaller than those of ocean basins and shelf scales, including high-resolution shallow-water regions. Although SWAN is able to run on any oceanic scale, it is not as efficient as WAM or WW3 on such scales. Model validation is based on data from buoys (Bidlot et al. 2002) and an acoustic Doppler current profiler (ADCP).

A hierarchical system of nested grids is used to address several concerns. Nested grids enable us to simulate remotely generated swell waves in the North Atlantic propagating into the Gulf of Maine, and to avoid excessively expensive high-resolution grids for the entire computational domain. Nested grids provide high resolution in coastal areas, and over extensive shallow areas such as Georges Bank, where they can be used to investigate processes that are poorly understood, for example, depth-induced breaking, and nonlinear wave–bottom interactions. Moreover, although high-resolution nested grids are not generally essential for simulations of the entire continental shelf, they minimize the biases due to the interpolation of model results to observation locations. The nested grid system approximates the nested forecast system used in operational wave forecasts that are routinely produced for GoMOOS. Thus, comparisons presented in this study provide an assessment of the GoMOOS wave forecasts during storms.

Section 2 presents an overview of the wave models and model setups. Section 3 describes the storm cases, and section 4 gives discussions of the results. Conclusions are presented in section 5.

2. Wave models

The wave models used in this study are discrete spectra and phase-averaged models (Battjes 1994). The directional spectrum is resolved at each model grid point in terms of frequency–direction (or wavenumber–direction in WW3) bands and the evolution of the wave field is found by numerically solving the spectral wave action (spectral energy in WAM) balance equation:

$$\frac{\partial N}{\partial t} + \nabla \cdot (c_{x,y} N) + \nabla \cdot (c_{x,y} \rho N)$$
$$= \frac{1}{\sigma} (S_{in} + S_{ds} + S_{nt} + S_{bf} + S_{brk})$$  \hspace{1cm} (1)

where \(N\) is the wave action spectrum, \(t\) is time, \(\sigma\) is the intrinsic angular frequency, \(\theta\) is the wave direction, \(c_{x,y}\) and \(c_{x,y}\) are the propagation velocities in physical and spectral domains, respectively. The left side of Eq. (1) represents the local rate of change of the wave action density, the propagation in physical space, the action density shifting in frequency, and the direction due to the spatial and temporal variations in depth and current. The right side represents the effects due to the wind input \(S_{in}\), the white-capping dissipation \(S_{nt}\), the nonlinear quadruplet wave–wave interactions \(S_{nl}\), the bottom friction \(S_{bf}\), and the depth-induced wave breaking \(S_{brk}\).

WAM is a third-generation wave model that solves the left side of the spectral energy balance equation (advection of wave energy), using an explicit scheme, without taking into account the source terms. The source terms on the right side are computed, using a semi-implicit second-order method, and then added to the wave spectra. As noted in the introduction, we use the PROMISE version of WAM (Monbaliu et al. 2000). The wind input \(S_{in}\) and dissipation \(S_{ds}\) are based on the quasi-linear wind–wave generation theory (Janssen 1989, 1991) following WAM cycle 4 physics. Nonlinear four-wave interactions, \(S_{nl}\), are represented by the discrete interaction approximation (DIA) of Hasselmann et al. (1985), and the bottom friction, \(S_{bf}\), follows Hasselmann (1974), with the depth-induced wave breaking, \(S_{brk}\), following Monbaliu et al. (2000), Padilla-Hernández (2002), and Padilla-Hernández and Monbaliu (2003). Depth-induced wave breaking is not invoked in WAM in this study, because WW3 does not have depth-induced breaking, and as the PROMISE version of WAM has only a preliminary untested formulation, it is not possible to make model comparisons.

WW3 uses an explicit scheme to solve the action balance in Eq. (1) for \(N\). Two combinations of the source terms \(S_{in}\) and \(S_{ds}\) are available in WW3. The default setup of WW3 corresponds to the wave–boundary layer formulation for \(S_{in}\) and \(S_{ds}\), following Tolman and Chalikov (1996). Tolman (2002) notes that application of this formulation has entailed a correction in fetch-limited wave heights that results from atmospheric stratification, which necessitates a retuning of the model by defining an “effective” wind, as well as an additional correction for the impact of stability on wave growth. An alternate combination corresponds to WAM cycle 3 physics (hereafter denoted WAMC3 physics), in which \(S_{in}\) and \(S_{ds}\) are based on WAMDI Group (1988), Snyder et al. (1981), and Komen et al. (1984, 1994). Quadruplet nonlinear interactions, \(S_{nl}\), are simulated by DIA, and the bottom dissipation, \(S_{bf}\), by the Joint North Sea Wave Project parameterization of Hasselmann et al. (1973).

The SWAN model solves the action balance [Eq. (1)], with representative source terms for wind input,
nonlinear interactions (quadruplets $S_{n4}$ and triads $S_{n3}$): whitecapping, $S_{ds}$; bottom friction, $S_{bf}$; and depth-induced wave breaking, $S_{brk}$. Documentation is given by Ris (1997), Booij et al. (1999), and Holthuijsen et al. (2003). Two different formulations can be used for $S_{in}$: the WAMC3 physics formulation (WAMDI Group 1988; Komen et al. 1984, 1994) used in this study, and the WAMC4 physics suggested by Janssen (1989, 1991). DIA is used for $S_{nl4}$ and the lumped triad approximation from Eldeberky (1996) is used for nonlinear triad interactions, $S_{nl3}$. SWAN has several bottom dissipation $S_{bf}$ expressions, from Hasselmann et al. (1973), Madsen et al. (1988), and Collins (1972), and depth-induced wave breaking $S_{brk}$ follows Eldeberky and Battjes (1996) and Ris (1997). In this study, we use the standard WAMC3 physics for $S_{in}$ and $S_{bf}$, with DIA used to represent quadruplet interactions $S_{nl4}$, and we apply the triad interactions $S_{nl3}$ and depth-induced wave breaking $S_{brk}$ for specific tests.

The wave models are implemented on a system of three nested grids (Figs. 1a and 1b). The spatial resolution increases from 1.0° in the coarse grid to 0.2° in the intermediate grid to 0.1° in the fine-resolution grid. The grid dimensions and resolutions are given in Table 1. The “fine-extended” grid extends the fine-resolution grid by 4° to the east to simulate the January 2000 storm. The 2-minute gridded elevations/bathymetry for the world (ETOPO2) data, available from the National Geophysical Data Center, are used at 2° resolution, as shown in Figs. 1a and 1b. WAM and WW3 are used for the coarse-, intermediate-, and fine-resolution simulations. Following the Courant–Friedrichs–Lewy (CFL) stability criterion, the propagation time steps for WAM and WW3 are 40 and 10 min for the coarse and intermediate grids, respectively. For the fine-resolution grid, the CFL criterion requires 4-min propagation steps, which is implemented for WW3. However, because WAM becomes unstable and gives unrealistic results when confronted with abrupt changes in bathymetry in the fine-resolution grid, the WAM time step is reduced to 2 min. While SWAN and WW3 interpolate the wind fields to the propagation time step of the respective wave model, WAM does not have this ability; thus, we use hourly wind maps in WAM runs. SWAN is only used on the fine-grid domain, taking the wave boundary conditions from WAM or WW3, implemented on the intermediate grid, as the case may be. SWAN’s time step is 12 min, which gives stable and reliable numerical simulations. For fast-moving storms, WW3 has a built-in scheme to reduce the source term integration time step when the situation is changing rapidly. Moreover, in WW3 (and WAM) the source term integration time step can be set by the user. Thus, we reduce the source term time step to 20 min in the coarse-resolution grid to adequately simulate the storms considered here. On the intermediate and fine grids, source term time steps equal to the propagations time steps are used for WAM and WW3 (see Table 1). It is not possible to use different time steps for propagation and integration of source terms in SWAN. Details regarding the spectral range and resolution of the three models are given in Table 2, in terms of the lowest and highest frequencies ($f_{low}$ and $f_{high}$), number of points $n$, frequency resolution $\Delta f$, and angular resolutions $\Delta \theta$.

Model results are statistically compared with observed field data using bias, root-mean-square error (RMSE), standard deviation of error (STD), scatter index (si), and index of agreement (ia). Bias is the difference between the mean of the observations $x_i$ and the mean of model results $\bar{y}$, or $\bar{Y} - \bar{X}$, where $X = \Sigma x_i/N$ and $N$ is the number of data points. RMSE is
TABLE 1. Geographical location of the grids used in this study: \( \Delta_\lambda, \theta \) are the resolutions in longitude \( \lambda \) and latitude \( \phi \), and \( N \lambda \) and \( N \phi \) are the numbers of points in \( \lambda \) and \( \phi \). Finally, \( \Delta t \) is the propagation time step and \( \Delta t_{ST} \) is the required time step for source term integration for the three models, as required to satisfy the CFL criterion.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Latitude</th>
<th>Longitude</th>
<th>( \Delta_\lambda )</th>
<th>( N \lambda )</th>
<th>( N \phi )</th>
<th>( \Delta t ) (min)</th>
<th>( \Delta t_{ST} ) (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>10°–65°</td>
<td>10°–93°</td>
<td>1°</td>
<td>84</td>
<td>56</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Intermediate</td>
<td>20°–55°</td>
<td>55°–93°</td>
<td>0.2°</td>
<td>191</td>
<td>176</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Fine</td>
<td>40°–46°</td>
<td>63°–72°</td>
<td>0.1°</td>
<td>91</td>
<td>61</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Fine extended</td>
<td>40°–46°</td>
<td>59°–72°</td>
<td>0.1°</td>
<td>131</td>
<td>61</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

\[ \left( \frac{1}{N} \sum (y_i - x_i)^2 \right)^{1/2} \text{ and the index of agreement is } ia = 1 - \frac{\sum (y_i - x_i)^2}{\sum (|y_i - \bar{y}| + |x_i - \bar{x}|)^2}. \text{ The scatter index is } si = \text{RMSE}/\sqrt{\bar{X} \bar{Y}}. \text{ Where field measurements and models outputs do not coincide in time, the latter are interpolated to the time of the measurements.}  

3. Storm cases

a. The atmospheric bomb of January 2002

The largest storm that occurred during the GoMOOS field experiment in the winter of 2002 was generated off the coast of North Carolina on 1200 UTC 13 January (hereafter denoted “January bomb”) and rapidly deepened over the next 12 h as it moved to the northeast. Maximum sustained winds reached 33 m s\(^{-1}\) with a minimum sea level pressure of 962 hPa, which occurred when the storm was southwest of Nova Scotia on 0000 UTC 14 January. Thereafter, it attenuated as it crossed Nova Scotia and Newfoundland and dissipated by 15 January. We use U.S. Navy numerical weather forecast winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) from the Fleet Numerical Meteorological and Oceanographic Center. This forecast system is documented online (https://www.fnmoc.navy.mil/PUBLIC/). The NOGAPS hourly winds on a 1° × 1° latitude–longitude projection are used for the coarse-resolution domain, and corresponding 0.2° COAMPS hourly winds are used for the intermediate- and fine-resolution grids. The composite NOGAPS–COAMPS wind fields are hereafter denoted “COAMPS.” Figure 2 shows the structure and development of the January bomb as given by COAMPS. These winds are shown to compare favorably to observed winds at buoy L in Fig. 3. During the development stage of the storm, as the storm intensifies to its peak, the lag is about 3–6 h, whereas in the final decaying stages of the storm, the lag increases to about 12 h, during low wind conditions (Fig. 3).

b. The January 2000 superbomb

Areas of Sable Island Bank where hydrocarbon retrieval activities are in progress were struck by a meteorological “bomb” in January 2000, with the intensity of a 100-yr storm (hereafter denoted “superbomb”). The superbomb’s intensification occurred over the localized warm oceanic mixed layer temperatures of the Gulf Stream off of Cape Hatteras. The newly formed center began to track rapidly northeastward parallel to the coast from 1200 UTC 20 January to 1200 UTC 21 January, deepening from 997 to 955 hPa in the process. The rate of sea level pressure intensification leveled off, and its central pressure remained relatively constant at 956 hPa until 0000 UTC 22 January. The system made landfall in Cape Breton, Nova Scotia, shortly before 0000 UTC 22 January and tracked northward across the province before entering the Gulf of St. Lawrence. Hourly winds were simulated using the Canadian Mesoscale Compressible Community Model (MC2) on a 0.2° × 0.2° latitude–longitude projection in order to drive the wave models. See Perrie et al. (2005) for a description of the atmospheric MC2 model simulations of this storm. We are using MC2 winds because this storm occurred before GoMOOS became operational. The overall structure and development of the superbomb is similar to that of January bomb shown in Figs. 2a–d. Figures 4a and 4b show that at the peak of the storm, the MC2 wind field compares favorably to the Quick Scatterometer (QuikSCAT)–National Centers for Environmental Prediction (NCEP) merged wind fields (available online at http://dss.ucar.edu/datasets/ds744.4/) for 0600 UTC 21 January 2000. The overall structures of the QuikSCAT–NCEP merged wind field and the MC2 wind field are quite similar. Both estimate the same storm center at approximately (40°N, 66°W).

TABLE 2. Spectral domains for all models. Here, \( f_{low} \) and \( f_{high} \) are the default values.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{low}, f_{high} ) (s(^{-1}))</td>
<td>0.04118, 0.4056 (SWAN and WW3)</td>
</tr>
<tr>
<td>( f_{low}, f_{high} ) (s(^{-1}))</td>
<td>0.04118, 0.4060 (WAM)</td>
</tr>
<tr>
<td>nf, ( \Delta f )</td>
<td>25, 1.1 × f</td>
</tr>
<tr>
<td>n( \theta ), ( \Delta \theta )</td>
<td>24, 15°</td>
</tr>
</tbody>
</table>
While QuikSCAT–NCEP estimates suggest that the maximum wind speed is 42 m s\(^{-1}\), the MC2 model estimate is 41 m s\(^{-1}\). While the winds are not without error, their skill is competitive with COAMPS winds and winds from other weather forecast offices, for locations over the open ocean (Perrie et al. 2005; Zhang et al. 2006).

4. Wave model–measurement comparisons

a. January bomb 2002

For this storm, the simulation period is from 0000 UTC 12 January to 2100 UTC 15 January. Statistical analysis covers the peak of the storm, from 0000 UTC 13 January until 1800 UTC 15 January, and excludes the quiescent periods before and after the passing of the storm. With this short spinup, swell does not propagate far and the nesting is adequate. Longer spinup times were tested and shown to not be necessary, because of the severely forced storm conditions.

1) Wave measurements

Directional wave measurements were derived from a directional wave rider (DWR) and an ADCP placed in 19 m of shallow water off of Seal Island, Nova Scotia.
(43.31°N, 66.01°W). These instruments were collocated in order to assess the ADCP wave data, in anticipation of future deployments, for example in ice-infested Arctic waters where buoys are not feasible. Every half hour, the DWR’s onboard processor calculates a complete spectrum and cross-spectrum from eight consecutive 200-s blocks of the translational data. By comparison, the ADCP data collection scheme averages over sampling bursts occurring at 2 Hz for 20-min periods every 2 h, starting at the top of the hour.

A comparison of the time series of significant wave heights (Hs) from the two instruments (Fig. 5a) suggests that they give comparable results, except near the storm peak, where the DWR results are higher, and the acoustic signal is biased low because it is not calibrated for excessively high waves. For the peak of the storm, we suggest that the DWR data are more reliable than the ADCP data, because the former is a more direct measure of the waves than the latter. In fact, a scatter-plot in which the DWR data are subsampled at 2-h intervals to match the ADCP data sampling frequency suggests that DWR wave height values tend to exceed ADCP values, particularly for wave heights exceeding 5 m (Toulany et al. 2002). Part of the discrepancy is due to spurious low-frequency energy, which is common in low-frequency one-dimensional DWR wave spectra. Following Dobson et al. (1989) and Perrie and Toulany (1990), this error is resolved by removing all energy below 0.05 Hz (periods >20 s) prior to calculating Hs.

In spite of this, the ADCP measurements still...
predict the corresponding DWR data, for high wave states.

Comparison of the peak period (Tp) time series (Fig. 5b) suggests that the ADCP estimates are relatively well correlated with DWR estimates throughout the storm’s development. There is no discernible bias and the actual scatter is roughly $\pm 1$ s, which is equivalent to the accuracy of operational National Data Buoy Center wave buoys. Additional wave data, included in the statistical analysis (Tables 3 and 4) of the model performance is available from buoy 44005 (Cashes Ledge; 43.17°N, 69.22°W) in 195.7-m depth, which is more remotely located compared with the storm track.

2) SIGNIFICANT WAVE HEIGHT AND PEAK PERIOD

Figures 5a and 5b show the Hs and Tp time series estimates from the three models for the January bomb, compared with the measured Hs values at the ADCP and the collocated DWR location.

Overall, the modeled Hs peaks (Fig. 5a) from the model simulations are comparable to the observed data. Results from WAM and WW3 (using WAMC3 physics) are relatively close to the observed peak Hs values, and they achieve accurate timing of the observed peak storm waves, at about 0200 UTC 14 January. Estimated peak Hs values from WW3 using Tolman–Chalikov physics, denoted WW3(TC), are intermediate between the DWR and ADCP measurements. Modeled Hs estimates from SWAN [nested within either WAM or WW3(WAMC3)] are in good agreement with DWR buoy results, although slightly higher than ADCP Hs estimates. All three models appear to simulate Tp values that are in general agreement with measurements at the peak of the storm. The Tp results are less accurate in low wave conditions on 13 January, before the storm intensity begins to build, and also on 15 January, after the storm has passed this location and waves are decreasing in magnitude. In low Hs conditions (on 15 January), the models tend to underpredict Tp, with the exception of WW3(TC). Depth-induced breaking and triads have no apparent effect on the Hs or Tp estimates.

Table 3 gives the statistics of Hs and Tp for the three wave models compared with the DWR and ADCP results. All models give favorable simulations of Hs, with SWAN providing the best results and WW3(WAMC3) giving almost zero bias. However, in the modeling of Tp, WAM gives the best results for bias, RMSE, index of agreement, and scatter index, while WW3(TC) gives the best standard deviation results and SWAN exhibits the largest bias. Poor Tp simulations may result from high variability in the observed data, particularly in low Hs conditions in the initial (≈13 January) and final storm phases (≈15 January), compared with the smooth behavior of the modeled Tp values, shown in Fig. 5b.

3) SPECTRAL DISTRIBUTION

Figures 6a and 6b show the observed one-dimensional (1D) spectra time series from the ADCP

<table>
<thead>
<tr>
<th>Model</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (m)</td>
<td>RMSE (m)</td>
</tr>
<tr>
<td>WAM</td>
<td>−0.05</td>
<td>0.61</td>
</tr>
<tr>
<td>WW3(WAMC3)</td>
<td>0.01</td>
<td>0.57</td>
</tr>
<tr>
<td>WW3(TC)</td>
<td>−0.24</td>
<td>0.60</td>
</tr>
<tr>
<td>SWAN in WAM</td>
<td>−0.26</td>
<td>0.51</td>
</tr>
<tr>
<td>SWAN in WW3</td>
<td>−0.22</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 4. Statistical analysis comparing model results with observed data at all locations for the wave models. The number of measurements used for the analysis was 173 for each parameter.
and the DWR, normalized with their maximum energy. Although similarities are present, they exhibit notable differences, which are also evident in the modeled $H_s$ time series in Fig. 5a. While the ADCP data suggest a main peak and a small secondary peak, the DWR data suggest two peaks of almost the same energy. The ADCP spectral peaks do not have the same frequency locations as either of the two main DWR peaks, although they do approximately coincide in time. Moreover, the ADCP spectra are narrower than the DWR spectra, especially when the most energetic waves occur. Finally, the ADCP spectra generally exhibit more variability than do the DWR spectra.

Corresponding time series of 1D model spectra are shown in Figs. 6c–g. The spectral distributions are very simple. All 1D spectra time series are single peaked and exhibit similar shapes. It is interesting that the resulting spectra are somewhat similar, despite the fact that the results are strongly forced by storm winds, implying that wave processes are dominated by the source terms, and despite the fact that the source terms are not exactly the same in all simulations displayed in Figs. 6c–g.

Clearly, SWAN in WAM (Fig. 6f) is quite similar to SWAN in WW3(WAMC3) (Fig. 6g), and somewhat similar in overall shape to the DWR data (Fig. 6b). Similar results follow from SWAN in WW3(TC) and

![Figure 6](image_url)
are not shown. Although SWAN has been implemented over a rather large area, any numerical diffusion in SWAN’s energy propagation over spectral and physical space is minimized, as we have used the second-order propagation scheme with third-order diffusion, as recommended by the SWAN user manual. Thus, diffusion effects for SWAN are similar to those of WW3.

b. Superbomb 2000

The simulation period is from 0000 UTC 20 January to 1800 UTC 22 January, for this storm. Statistical analysis covers the peak storm portion of the simulation, for the period from 0000 UTC January 21 until 1800 UTC 22 January.

1) WAVE MEASUREMENTS

A complete wave rider buoy (WR) wave record for the superbomb is available from the PanCanadian oil rig stationed at Panuke, off the coast of Nova Scotia, and partial records are available from buoy 44011 (Fig. 1b), in 88-m depth, respectively. The Panuke location, in 44-m depth on Sable Island Bank, experienced the storm’s peak intensity. High waves were also reported at buoy 44011 near the storm track, and were included in the statistical analysis in Table 4.

2) SIGNIFICANT WAVE HEIGHT AND PEAK PERIOD

Time series of Hs at Panuke are presented in Fig. 7a. While all models achieve an overall agreement with the measured Hs wave data, it is evident that all models shift the simulated maximum Hs by about 2 h, compared with the observed WR data. This shift reflects a lag in the simulated wind fields compared to the actual storm development. The best performance is achieved by WW3 using WAMC3 physics, compared with the observed WR data, with WAM and WW3(TC) biased low at the Hs peak. The underprediction of WW3(TC) reflects the explosively rapid development of this storm as it approached the Panuke location, and WW3(TC)’s tendency to underestimate transient fetch-limited growth, for example, as typified in offshore moving cyclones on the eastern sides of Northern Hemisphere continents (H. Tolman 2006, personal communication). SWAN nested in WW3(WAMC3) gives results that are very similar to those of SWAN nested in WAM, and also WW3(WAMC3), although the results are slightly lagged.

Comparisons of observed Tp time series data to model estimates are given in Fig. 7b. While observed Tp values exhibit a main peak followed by a secondary peak about 6 h later, modeled Tp time series give a single peak between these two observed Tp peaks. With the exception of WW3(TC), all models tend to seriously overpredict Tp values between these two observed Tp peaks. Otherwise, the models achieve overall agreement with the observed Tp data, particularly in
the lead-up period before the storm, and the follow-on period after the storm.

3) SPECTRAL DISTRIBUTION

Time series of spectral distributions comparing measured and modeled results are shown in Figs. 8a–f. Measured 1D spectra are fairly simple, with one main peak around 2200 UTC 21 January. WAM, WW3(WAMC3), and WW3(TC) suggest that the peak occurs about 2 h later, whereas SWAN in WW3(WAMC3) suggests an occurrence about 3 h later, and SWAN in WAM has a lag of about 4 h. The dip in the observed spectral energy, and the secondary peak around 0400 UTC 22 January, shown in Fig. 7a, are also suggested in the modeled data, by the extended high $H_s$ wave height plateau values during 0600–1200 UTC 22 January in Figs. 8b–f. SWAN gives slightly wider spectra, compared with the other models.

3. Overall performance

Scatterplots of modeled and observed data are presented in Figs. 9a–e. In general, the models underestimate $H_s$ for very high waves, at the storm peaks. This was also suggested by Cardone et al. (1996) in studies of northwest Atlantic storms. Our simulations show that during the storms’ intensification stages, the observed time rate of growth in modeled $H_s$ tends to be smaller than the observed $H_s$ rate of growth, suggesting a bias in the models’ response to increases in wind speed and storm intensification. In particular, for rapid wind speed increases, WAM and WW3(TC) respond more slowly than WW3(WAMC3), and SWAN nested within WAM slightly accentuates this slow response, compared with SWAN nested within WW3(WAMC3). During the storms’ decay stages, results from the models all agree with the observed rate of $H_s$ decrease. Correlation coefficients are essentially similar for all model systems.

Figures 10a–e show that the models generally perform reasonably well for $T_p$ up to about 10 s. The largest deviation occurs in the longer $T_p$ interval from 10 to 13 s, where all models, with the exception of WW3(TC), underestimate $T_p$ during the decay period of the January bomb, as noted earlier, in the discussion of Fig. 5b. A second deviation occurs in the $T_p$ interval about 14–15 s, where again, all models tend to overestimate $T_p$, with the exception of WW3(TC), during the peak intensity of the superbomb, as noted in the discussion of Fig. 7b. Figures 10a–e show that model estimates for $T_p$ tend to be biased low compared with the observed data. Correlation coefficients are essentially the same for all model systems, with the exception of WW3(TC), which obtains the best value.

Table 4 presents a statistical analysis of the results for both storms. For $H_s$, WW3(WAMC3) performs better than the other model systems, including SWAN nested within WW3(WAMC3) or SWAN nested within WAM. Table 4 suggests that WW3(WAMC3) has the highest index of agreement, the highest scatter index, and the smallest root-mean-square error. For $T_p$, WW3(TC) performs better than the other model systems, in terms of RMSE, index of agreement, scatter index, and standard deviation. In terms of bias in $T_p$ estimates, WAM achieves the best results. In terms of $T_p$ and $H_s$, Table 4 suggests that SWAN nested within WW3(WAMC3) performs slightly better than SWAN nested within WAM.

5. Conclusions

Three state-of-the-art operational wave forecast models are compared for simulations of two severe win-
Fig. 9. Model–measurement scatterplots of Hs for (a) WAM, (b) WW3, (c) SWAN in WAM, and (d) SWAN in WW3 (with WAMC3 physics). LSF represents the least square fit line. ADCP and DWR measurements are indicated.
FIG. 10. Same as in Fig. 9 but for $T_p$. 

(a) WAM: $r^2 = 0.64$

(b) WW3(WAM3): $r^2 = 0.69$

(c) WW3(TC): $r^2 = 0.80$

(d) SWAN IN WAM: $r^2 = 0.64$

(e) SWAN IN WW3: $r^2 = 0.65$
ter storms in the northwest Atlantic. The models (WAM, WW3, and SWAN) are implemented in nested domains: 1.0° coarse resolution for the North Atlantic, 0.2° intermediate resolution for the northwest Atlantic, and 0.1° fine resolution for the Gulf of Maine. Four composite model systems were set up; WAM and WW3 implemented on the three grids, SWAN nested within WAM, and SWAN nested within WW3. Simulations using WW3 considered 1) Tolman–Chalikov physics for wind input $S_{in}$ and dissipation $S_{ds}$, as well as, 2) WAMC3 physics. SWAN runs tested wave-induced breaking and triad interactions. This study has relevance because it presents comparisons of the models used in GoMOOS. COAMPS winds are used for one storm, and mesoscale weather forecast results from MC2 for the other storm.

Overall, all models achieve relatively high skill in their ability to simulate Hs time series during the storms’ growth and development, as shown in Fig. 9. Differences in the statistical analysis of wave parameters among the models are small, and all models tend to be biased low for high observed Hs values. However, the simulated rate of Hs growth tends to lag the observed Hs growth. The statistical results reported in Table 4 suggest that WW3(WAMC3) outperforms the other models, in comparison with the observed Hs wave data. Results suggest that SWAN can give slightly better results if nested within WW3(WAMC3), rather than within WAM. When implemented for the Gulf of Maine, SWAN results are competitive with those of WW3 or WAM.

In terms of Tp, all models tend to have an overall low bias. WW3(TC) surpassed the other models in estimating the Tp values during the decay stage of the January bomb (Fig. 5b), and the longer-period peak Tp values during the superbomb (Fig. 7b). Statistical results (Table 4) suggest that WW3(TC) provides the best simulations of Tp, and that SWAN can give slightly better results if nested within WW3(WAMC3), rather than within WAM.

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