INTERCOMPARISON OF MODERN OPERATIONAL WAVE MODELS

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1. INTRODUCTION

In this study three numerical wave models, SWAN, model Version 40.20 (Booij et al., 1999), WAM (version WAMC4–PROMISE by Monbaliu et al., 2000 based on WAM4 version of the WAMDI Group, 1988), and WaveWatch–III (Version 2.22 by Tolman, 2002, hereafter WW3) are evaluated through comparisons with measurements. These models can all run for deep or intermediate water, on Cartesian or spherical grids. They include time–dependent depth and refraction by current and depth variations, except that WAM assumes steady depths and current fields. They can be set up for any local or global grid and nested for fine–scale applications. Measurements include a directional wave rider (DWR) and an acoustic doppler current profiler (ADCP), co–located in shallow water. The models are implemented in nested domains: coarse (1^o) resolution for the North Atlantic, intermediate (0.2^o) resolution for the Northwest Atlantic and fine (0.1^o) resolution for the Gulf of Maine. Four composite systems were set up: WAM and WW3 implemented on the three grids, SWAN nested within WAM and SWAN nested within WW3. The models are driven with wind fields from two severe winter storms: the so-called 'Superbomb' of January 2000 and the 'Bomb' of January 2002. Observations of peak waves from these storms are used to inter-compare the capabilities the (above mentioned) wave models to simulate extreme waves. We also consider the quality of the ADCP and DWR data.

Section 2 describes the setups of the models, and Section 3 gives the storm cases. Section 4 discusses results, and Section 5 gives conclusions. We show that WAM is the most efficient model on the fine grid followed by SWAN. However, all three models underestimate the significant wave height at the peak of both storms, and the simulated wave growth does not match the observed wave growth, to some extent. WW3 outperforms the other models for both storms, in terms of comparisons with field data. SWAN gives slightly better results, nesting within WW3, rather than within WAM.

2. MODEL SETUPS

The models were implemented in the North Atlantic on a three-nested grid system (Fig. 1), with spatial resolution of 1^o in the coarse grid, 0.2^o in the intermediate grid, and 0.1^o in the fine resolution grid. The so–called "fine–extended" grid is an extension of the fine resolution grid by 4^o to the east, in order to include *in situ* measurements available for the Superbomb of January 2000. Etopo2 bathymetry (US National Geophysical Data Center http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html) at 2 minutes resolution was used, as shown in Fig. 2. WAM and WW3 models provide simulations on the coarse, intermediate and fine–resolution grids, and SWAN, on the fine grid with boundary wave conditions from WAM or WW3. Details of the spectral domain are given in Table 1, where f_{low}, (f_{high}), nf and Δf are the lowest (highest) frequency, the number of points and the resolution in frequency f and direction $\Delta\theta$, respectively.

Statistical parameters used are:

i) Bias, the difference between the mean of observed data (x_i) and the mean of model data (y_i) is

$$\text{bias} = X - Y \qquad (1)$$

where $X = (\Sigma_i x_i/N)$, is the mean of variable x_i, and N is the number of data points.

ii) RMSE, the root mean square error is

$$RMSE = [1/N\, \Sigma_i (y_i - x_i)^2]^{1/2} \qquad (2)$$

iii) SI, the scatter index,

$$SI = RMSE / (XY)^{1/2} \qquad (3)$$

iv) IOA, the index of agreement or relative error,

$$IOA = 1 - (N \times RMSE^2) / PE \qquad (4)$$

where $PE = \Sigma_i [| y_i - Y| + | x_i - X|]^2$ is the so-called potential variance. The IOA reflects the degree to which observations and model results agree.

3. STORM CASES

The Bomb of January 2002 was generated off the coast of North Carolina on 1200 UTC 13 January and deepened rapidly over the next 12 hours as it moved north-eastward. Winds reached a maximum of 33 ms^{-1} off southwest Nova Scotia on 0000 UTC 14 January, and the storm attenuated as it crossed Nova Scotia and Newfoundland, dissipating by 15 January. Coarse grid 1^o six–hourly NOGAPS (US Navy Operational Global Atmospheric Prediction System) winds were used for the coarse–resolution domain, with 0.2^o COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System) winds for the intermediate– and fine–resolution grid domains. We denote the composite NOGAPS–COAMPS wind fields as "COAMPS" winds, here. Non-directional wave data from the National Oceanic and Atmospheric Administration/ National Data Buoy Center (NOAA /NDBC–USA) and Environment Canada (EC) buoys in the Gulf of Maine region provided *in situ* model validation. Directional wave measurements from a directional wave rider (DWR) and an acoustic doppler current profiler (ADCP) in 19 m shallow water near Seal Island, N.S. (66.01^{o}W, 43.31^{o}N) were also collected. The ADCP averages over bursts of sampling at 2Hz for 20 minutes once every two hours. The two instruments were found to give very nearly the same results, except near the storm peak, where the DWR wave estimates are slightly higher.

The January 2000 Superbomb was generated over the warm waters of the Gulf Stream, by Cape Hateras. It tracked rapidly north–eastward along the coast, deepening from 997 hPa to 955 hPa in the 24-h period starting on 1200 UTC 20 January, and remaining at about that level until 0000 UTC 22 January, when it made landfall in Cape Breton, Nova Scotia. Simulated 6-hourly and 1-hourly winds from the MC2 model (Canadian Mesoscale Compressible Community Model) on a 0.2^o grid were used in this study. Wave measurements from a wave rider buoy (WR) are available at Panuke, and buoys 44142 and 44011.

4. RESULTS

4.1 January 2002 Bomb

Figure 3 shows the relative CPU time required by each model on the different grids, normalized by the time spent by the most expensive model for the January 2002 Bomb. WAM is 33% cheaper than WW3 on the coarse grid, and about 50% cheaper than WW3 on the intermediate grid. On the fine grid, SWAN is the most expensive model using a propagation time step of 4 minutes. However as SWAN uses an implicit scheme, it can run with time steps exceeding the CFL–criterion, 12–minute time steps reduce its CPU time to 1/3 of the time needed by WW3. SWAN with time steps of 12 min (16 min) is 30% (20%), more expensive than WAM. WW3 is 50% more expensive than WAM on the fine grid. Thus, SWAN with 12 minute time steps will be used in this study. Simulations were by a dual processor 1 GHz Pentium–II.

Because the DWR and the ADCP data are almost the same, it was decided to evaluate the hindcast wave parameters (i.e. Hs and Tp) from the three models using the mean data values, as well as each instrument separately. Significant wave height Hs time series from the three models are compared to measured Hs from the ADCP and DWR, separately, in Fig. 4. The peak modeled Hs values are delayed compared to the mean measured peak Hs: with the delay 4 hours for WW3 and SWAN, and 6 hours for WAM. This may be attributed to the time–resolution of the wind and to the methodology implemented in the models to use wind fields. Six-hourly winds are interpolated in time by WW3 and SWAN, for every propagation time step, while WAM assumes constant winds between each 6–hourly wind updates. Also there is a 6 hour lag in the COAMPS peak winds, as shown by comparison (not shown) with measured winds at Buoy L, implying that a time–lag in the simulated maximum Hs is due to a phase–lag in the COAMPS winds. Thus, WAM gives a drop in Hs during the increasing phase of the storm at 00 UTC on 14 January, because it keeps a constant wind for 6 hours, rather than using interpolated winds.

Additional results on the spectral distributions of the ADCP, the DWR and the three models will be presented at the Workshop. Differences include the fact that 1) there is one main ADCP peak and one small secondary peak, whereas the DWR shows two peaks having almost the same amount of energy, 2) the location of the ADCP spectral peaks do not coincide in frequency with either of the two main DWR peaks, however they coincide in time, 3) the ADCP spectra are narrower than the DWR spectra, especially at the time when the most energetic waves are present, 4) in general the ADCP spectra exhibit more variability than those from the DWR.

4.2 Superbomb (2000)

CPU requirements for more computational points for the extended fine-resolution grid needed for this storm are given in Fig. 5. This shows that relative to CPU times in Fig. 3 for the January 2002 Bomb, on the fine–extended grid, WAM is computationally 29% cheaper than WW3.

As in Fig. 3, SWAN is the most expensive model on fine–extended grid using 4 minute time steps, whereas using 16 minute (20 minute) time steps, it becomes 11% (28%) better than WAM, and 35% (49%) better than WW3.

Hs time series at Panuke are presented in Fig. 6, in comparison with observed data. Estimated Hs is shifted, by all models, by about two hours compared to the observations. WW3 performed best, using hourly winds compared to the other models. The relative peak in Hs occurred at about 14 UTC January 21, with later low Hs observed values missed by the other simulations, except WAM because of its wind-interpolation methodology. The dip in the measured Hs time series is a consequence of the reduced winds about 16:00 UTC January 21.

The Hs time series from the four composite models (not shown), and from WW3 with hourly winds (WW3–HOURLY), interpolated to buoy 44142 implies that measured winds are better approximated by the hourly MC2 data than 6-hourly COAMPS data. All modelled time series show a dip around 7 UTC January 21, due to decreased winds. Hs is under-predicted, reflecting storm track and intensity biases. Peak period Tp is generally well simulated by all models, as will to be discussed at the Workshop, as well as buoy 44011 results.

4.3 Overall performance

In general, all models underestimate the peak Hs values of the storms, as may be shown by scatter plots. This fact has been identified in other model studies (Cardone et al., 1996). The largest Hs deviation occurred at buoy 44142. During storm intensification stages, simulated Hs growth lags at all observed locations, indicating the models' response to rapid wind changes. SWAN responds more slowly to rapid wind changes than WW3 or WAM. Although the latter two respond similarly, WAM delays the Hs response to a perturbation in winds, but recovers quickly. Thus Hs simulations from hourly winds are generally better than those from 6-hourly winds, particularly for simulating rapidly developing storms.

Mean values of the statistical parameters are presented in Table 2 to evaluate the overall models performance. For Hs, WW3 performs better than the other models (including WW3–HOURLY). It has the highest index of agreement and the smallest bias, scatter index and root mean square error. SWAN nested in WW3 performs better than SWAN nested in WAM. Regarding Tp, the correlation coefficients do not give a clear indication as to which models perform best to nest SWAN.

5. CONCLUSIONS

Three popular third–generation wave models were compared: WAM–PROMISE,WaveWatch–III and SWAN. Validation used wave measurements from wave buoys and an ADCP, and included considered the quality of the ADCP and DWR data. Models were implemented in nested domains: coarse 1^{o} for the North Atlantic, intermediate 0.2^{o}, for the Northwest Atlantic and fine 0.1^{o} for the Gulf of Maine. Composite model systems were WAM and WW3 implemented on the three grids, SWAN nested within WAM and SWAN nested within WW3.

Although ADCP and DWR data generally agree well, they differ at the storm peaks by about 1 m. Moreover, their derived 1D spectra differ in that the secondary spectral peaks don't have the same level of energy compared to their main peaks, and ADCP spectra are wider and present more complex features than the DWR spectra.

Although WAM is the most efficient on the fine grid followed by SWAN, in increasing the number of sea points, SWAN can become more efficient than WAM or WW3. Moreover SWAN run with a higher resolution in spectral space, nested in low spectral resolution models, which neither WAM nor WW3 can do, making them potentially expensive.

All models generally underestimate the peak storm Hs values. Moreover, the simulated Hs growth in intensifying storms tends to lag the observed wave growth, suggesting that updating winds as rapidly as possible is important. Although all models provide skillful hindcasts, results show that WW3 out-performs the other models, in comparison with observed wave data, and SWAN can give slightly better results nested in WW3, rather than in WAM.

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6. References

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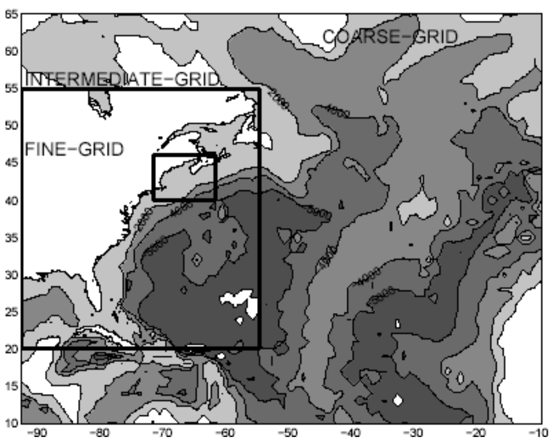

Figure 1: Nested grid system in the North Atlantic.

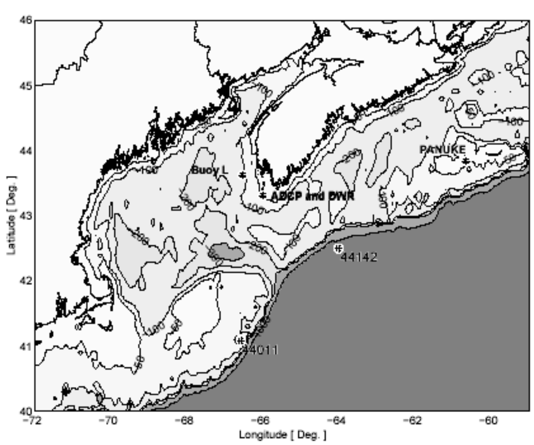

Figure 2: Gulf of Maine showing locations of buoy L, the ADCP, DWR, Panuke, buoys 44142, 44011.

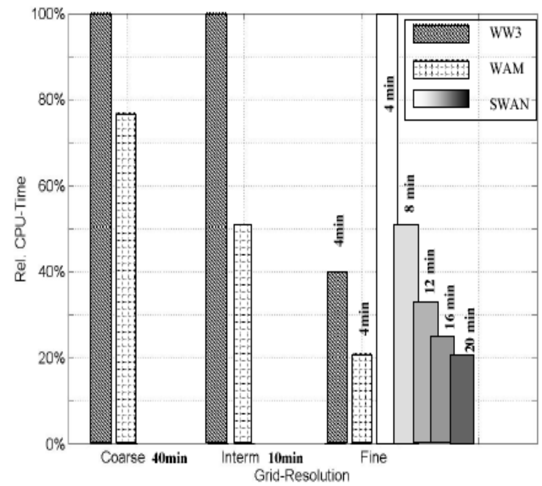

Figure 3: Relative CPU times for the models for January 2002 Bomb, with time steps indicated.

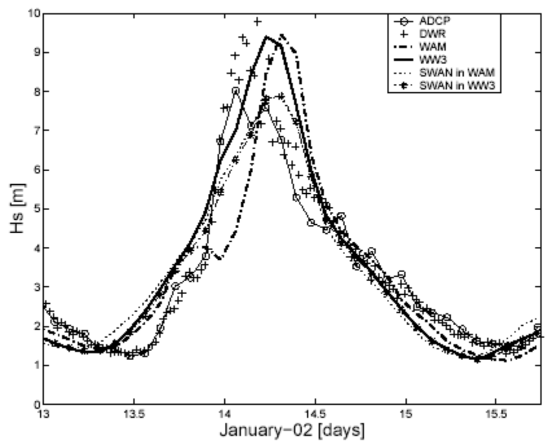

Figure 4: Hindcast and measured Hs at the ADCP – DWR location for January 2002 Bomb.

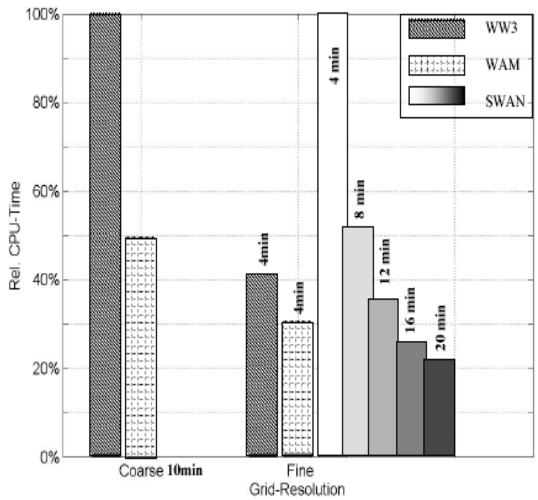

Figure 5: As in Fig. 3, relative CPU times for the models for Superbomb, with time steps indicated.

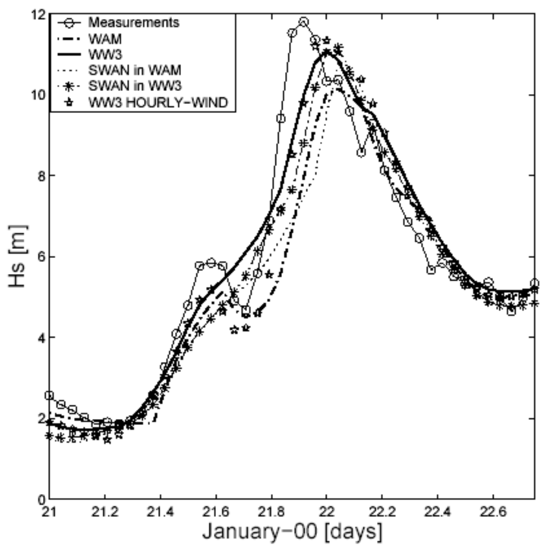

Figure 6: Hindcast and measured Hs at PANUKE location for Superbomb.

Table 1: Spectral domains for the models.

Parameters	Value
f_{low}, f_{high} [s-1]	0.0412, 0.4060
nf, f_{i+1}/f_i	25, 1.1
$n\theta$, $\Delta\theta$	24, 15^o

Table 2: Overall mean values of statistical parameters for the 4 locations: ADCP-DWR, Panuke, 44142, 44011 for the 3 models. WW3-HOURLY does not include the ADCP-DWR location.

	Hs [m]			
Model	bias [m]	si [-]	rmse [m]	ioa [-]
WAM	0.92	0.28	1.37	0.88
WW3	**0.67**	**0.20**	**1.06**	**0.92**
SWAN in WAM	1.09	0.27	1.40	0.89
SWAN in WW3	0.96	0.24	1.29	0.89
WW3–HOURLY	0.87	**0.20**	1.22	0.90