A FINE-RESOLUTION OPERATIONAL WAVE MODEL FOR THE NW ATLANTIC

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1. INTRODUCTION

A fine-resolution operational wave model system for the NW Atlantic has to attempt to address questions related to shallow water, time-dependent water depth, wave-current interactions, and also account for large waves from episodic storms. It also should be suitably flexible in model architecture to allow incorporation of improvements to modules of the computer codes. We are in the process of implementing and testing major versions of updated WAM-type models (Hasselmann et al., 1988; Komen et al., 1994) at BIO (Bedford Institute of Oceanography). This study considers models implemented on coarse- and intermediate-resolution domains for the NW Atlantic, as well as a fine-resolution domain, for example 0.1^{o}, for the coastal waters of Atlantic Canada. The focus of the study is simulation of a meteorological "bomb" from the GoMOOS (Gulf of Maine Ocean Observing System) field program conducted during the winter of 2001-02. The Gulf of Maine has great strategic importance because it is home to important coastal fisheries and related ecosystems, coastal transport routes, tourism and recreation, and potential hydrocarbon developments.

2. NUMERICAL SET-UP

2.1 *Wave Model System*

At the Workshop we will report on model comparisons that were completed. In one model system, we implemented the NCEP (National Center for Environmental Prediction; Washington, USA) operational wave model, WaveWatch3 (WW3) on the coarse- and intermediate-resolution domains. We implemented the SWAN wave model for the fine-resolution domain. In a second model system, we implemented SWAN in all three, fine-, intermediate- and coarse-resolution nested grids. WW3 is available at the web site, http://polar.wwb.noaa.gov/waves. Relevant WW3 features include innovations such as:

a). Refraction and straining of wave field due to temporal and spatial variations of the mean water depth and mean current (tides, surges…).
b). New formulations for wind input, wave-wave interactions, white-capping dissipation.
c). Longitude-latitude grid, and flexible increments in each direction.
d). Source terms are integrated in time using dynamically adjusted time-stepping, adapting to conditions of rapid spectral changes.
e). Outputs such as significant wave height, Hs, mean wave direction, $<\theta>$, peak wave period, Tp, etc., at selected locations, along arbitrary satellite tracks.

SWAN (Simulating Waves Nearshore) has been tested and validated (Booij et al., 1999; Ris et al., 1999). It is available at http://swan.ct.tudelft.nl. Relevant features include:

(a) Third-order wave propagation in time and space, shoaling, refraction due to currents and depth, frequency shifting due to currents and non-stationary depth.
(b) White-capping, bottom friction and depth-induced breaking, as in WW3
(c) Three- and four-wave interactions and wave-induced set-up
(d) Outputs include 1- and 2-dimensional spectra, significant wave height and mean period, etc., wave-induced force (from radiation-stress) and wind-induced set-up
(e) 3-wave interactions (triads) in very shallow water and variable bottom friction.
(f) Surf zone wave- and bottom-steepness dependent breaking coefficient.

Studies involving wave-bottom interactions are in progress, following Li et al. (1999) field measurements for Sable Island Bank.

2.2 *Set-up Grids*

As shown in Figure 1, the 1.0^{o} coarse-resolution domain is 10^{o} -65^{o} N, and 10^{o}-93^{o}W. This is nested to a 0.2^{o} intermediate-resolution domain, 20^{o} -55^{o} N and 55^{o}-93^{o} W. Finally, the latter is nested to a 0.1^{o} fine-resolution grid (40^{o} -46^{o} N and 63^{o}-72^{o} W), which includes the Gulf of Maine and part of Scotian Shelf, on a domain bounded by mid-Scotian Shelf and the continental shelf.

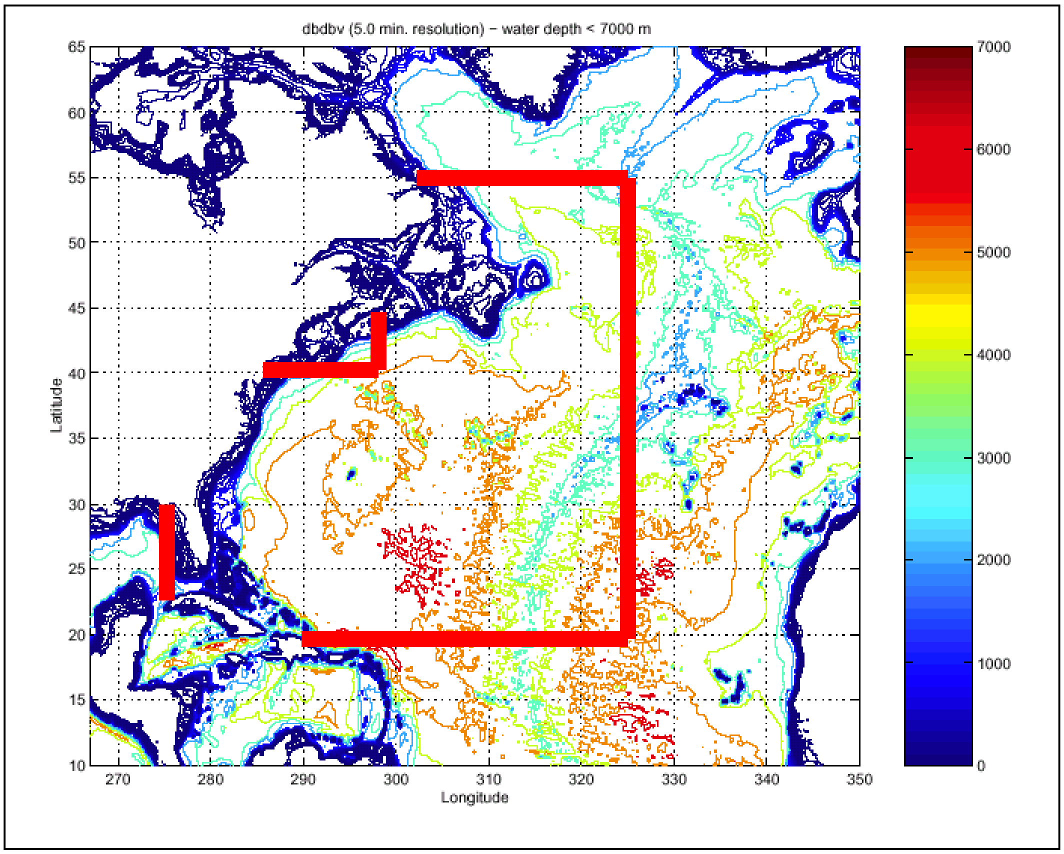

Figure 1. Nested coarse-, intermediate- and fine-resolution grids for GoMOOS.

3. THE JANUARY 2002 "BOMB"

During the 2001-02 GoMOOS field program a major winter storm occurred on 13-16 January. We report on the validation of this system using composite wave model systems: WW3-WW3-SWAN and SWAN-SWAN-SWAN, implemented for the coarse-, intermediate- and fine-resolution nested grids of Figure 1.

3.1 *Validation Data*

Model outputs are validated against a directional wave-rider buoy (DWR) and a high-frequency acoustic doppler current profiler (ADCP) deployed in 19m depth water off southwest Nova Scotia during the 2001-02 winter. Moored data used for verification consist of significant wave height time series, and 2-d wave spectra from the DWR and ADCP. The mooring location, as shown in Figure 2, is in 19m depth water. The status of additional validation, involving comparisons with wave measurements from satellite altimeter data, and SAR images of two-dimensional wave spectra from RADARSAT synthetic aperture radar will be presented at the Workshop. Tests will attempt to quantify the biases and limitations of the two model systems, using high quality fine-resolution wind fields. These are provided at 0.2 degrees resolution for the domain of the intermediate-resolution grid by the US Navy COAMPS model. These will be interpolated to fine-resolution domain for wave model simulations. For grid points of the coarse-resolution grid, outside the intermediate-resolution domain, winds are provided by the associated US Navy NOGAPS model.

3.2 Case Study

Analysis of the “Bomb” from 13-16 January 2002, implies that it generated 8m significant height waves at the DWR mooring off Yarmouth, Nova Scotia. This event involved a cyclonic low passing from west to east, indicated in Figure 2. During the initial phase of the storm, winds at the buoy mooring are almost southerly with moderate speeds that did not exceed 12 m/s until after January 13 at 06 UTC. With the approach of the storm, the wind direction shifted to almost easterly, with winds increasing to about 20 m/s at the DWR mooring, by 18UTC. By 6 hours later, the central depression is at the mouth of the Bay of Fundy. The maximum winds are northwesterly in the middle of the Gulf of Maine with speeds of 33 m/s. By January 14 at 06UTC, the main storm region has moved to Scotian Shelf, around Sable Island, and winds at the mooring are northwesterly and in the 21-24m/s range. This storm is of interest because the waves have large enough wavelength that they should have felt the bottom at the mooring.

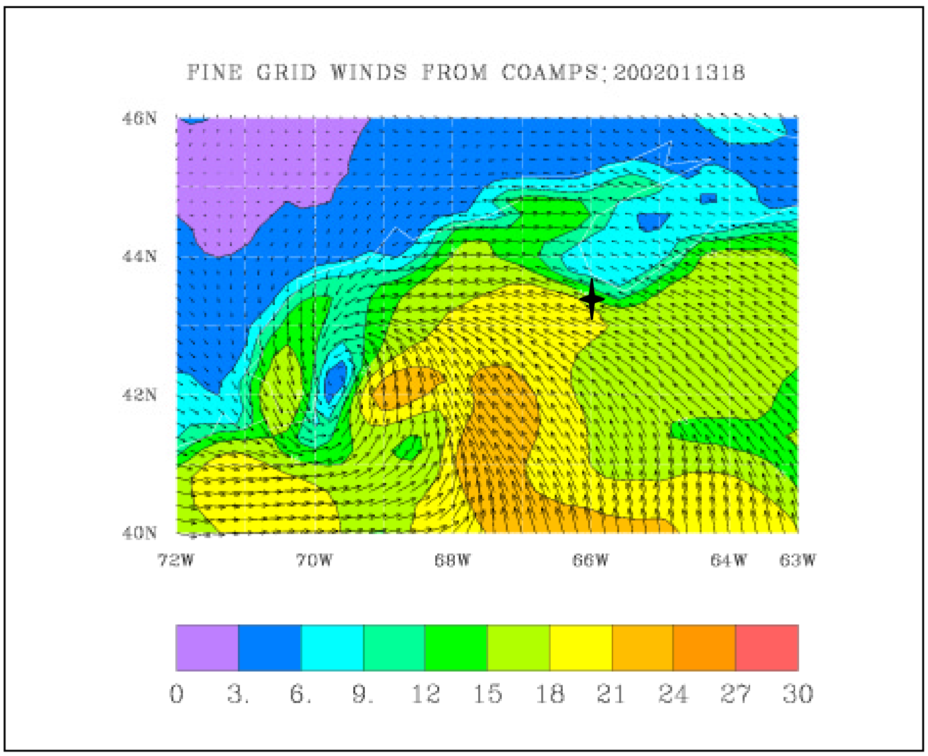

Figure 2. Wind speeds for the synoptic situation at the beginning of development of the 13-16 January 2002 storm, on the fine-resolution grid. Position of the DWR buoy and ADCP mooring is indicated by +.

3.2 *Discussion*

Measurements for the January 2002 Storm consisted of wave heights and wave spectra from the DWR buoy as well as the ADCP mooring. Analysis of the buoy data was challenging because of significant spurious low- frequency instrument-related contamination. Without removal of this component of the spectrum, one could easily conclude that the maximum significant wave height (Hs) of the storm reached as much as ~12m. Removal of this spurious contribution implies a more reasonable 8m estimate for the maximum Hs for the storm, corroborated by comparison with the ADCP Hs estimates and those inferred from the 1-d spectrum from both instruments.

In Figure 3 we present a comparison of significant wave heights (Hs) from the DWR, ADCP, and the SWAN model. In this simulation, the WAM3 physics options were selected within the SWAN model. This demonstrates a good comparison between the two instruments and the model estimates. A more complete discussion will also consider 1-d and 2-d wave spectra. Further concerns are sensitivity to grid resolution and characteristics of the various physics options within SWAN. On one hand, if the results are sensitive to grid resolution, then numerics are contributing to model outputs. On the other hand, if WAM3 physics seem to offer a good comparison with these measured data, how and where is this WAM3 physics limited?

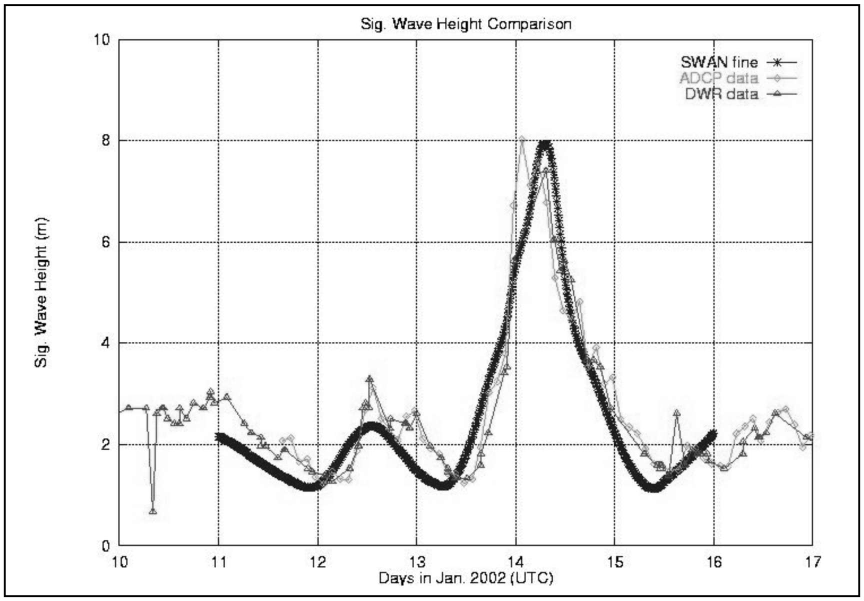

Figure 3. Significant wave height, Hs, time-series for the DWR and ADCP instruments deployed off Yarmouth during the 13-16 January 2002 storm. Comparison is made with the SWAN estimates assuming the WAM3 physics options.

If the corresponding fine-resolution grid SWAN outputs, assuming WAM4 physics are added to Figure 3, we find that maximum Hs is only about ~6m. Moreover, if we compare SWAN model estimates for intermediate 0.2 degree resolution grid simulations, running WAM3 physics and WAM4 physics, results show that the peak Hs values decline to ~6m, and ~4.5m, respectively. This suggests that not only is WAM3 physics better than WAM4 physics, in SWAN, but both cases are sensitive to grid resolution, or at least to the ability of the grids we used in this study to resolve the Gulf of Maine shallow water topography. Even 0.1^{o} resolution is not fine enough for the model to feel the 19m depth of the DWR mooring, and to allow the model to have sufficient space grid steps to respond to the shallow water, compared the adjacent deep-water grid points. One needs to consider a further ultra-fine resolution grid nesting to 0.025 degrees resolution for the shallow coastal region near the DWR buoy. For the 0.1^{o} resolution grid, the model sees the mooring as 26m depth, and there are only ~1-2 grid steps between deep water and the shallow water of the DWR mooring site. A further issue is currents, which were not modelled in this study.

To begin to consider questions regarding numerics and physics, we attempted fetch-limited SWAMP tests on a 2000km $\times$ 2000km ocean. A variety of conditions were used; winds from west to east on the x-axis at 20 m/s and 30 m/s; constant depths ranging 50, 20, 10, 5, 2m; and space grid resolutions of 50km, 10km and 5km. Testing SWAN with SWAMP tests using either WAM3 or WAM4 physics, we found that when the depth is constant over the entire ocean, model results are insensitive to space grid resolution, for given wind fields and *constant* depths. Thus resolution of topography is important to differentiate between WAM3 and WAM4 physics.

Is WAM3 physics better than WAM4 physics, in the SWAN model? For 20 m/s winds, WAM3 physics always gives higher Hs wave heights than WAM4 physics. For long duration (>24hr) and large fetch, the difference is as much as ~50% for depths in excess of 50m. As depths decrease, these Hs estimates converge from WAM3 and WAM4 physics. By comparison, for 30 m/s winds, WAM3 physics give Hs estimates that are ~30% in excess of Hs estimates resulting from WAM4 physics, for a 50m depth SWAMP ocean. As depths decrease, this difference decreases as well. At 20m depth, WAM3 and WAM4 physics give about the same values for Hs. At 2m depth, WAM4 physics gives Hs values that exceed those from WAM3 physics by about 10%. Thus wind speed dependence is evident in this comparison.

SWAMP tests were also considered with currents against the wind direction, and at 90^o to the wind direction. Qualitatively results are similar to cases without currents in terms of Hs values from WAM3 physics, compared to those from WAM4 physics. Moreover, in the WAM3 case, currents against the wind direction, Hs values are enhanced by about 20%, in the 50m depth case. By comparison, currents at 90^o to the wind direction give Hs values reduced by about 6%, in the 50m depth simulation. These effects are reduced for shallower depths. This shows that currents have significant impact on waves.

4. CONCLUSIONS

As part of the GoMOOS (Gulf of Maine Ocean Observing System) model study, we have completed preliminary tests with the SWAN model on nested (1.0^o) coarse-, (0.2^o) intermediate- and (0.1^o) fine-resolution grids for the NW Atlantic. Similar tests using WW3 implemented for these grids are in progress. It is suggested that a further nesting to a finer-resolution grid 0.025^o should be implemented for selected areas where shallow water and high currents are present, for simulation of episodic storms. This is in accord with studies by Wornom et al. (2002).

During the GoMOOS field program of 2001-02, a meteorological "Bomb" developed and propagated across the Gulf of Maine and over Scotian Shelf. Winds reached as much as 33 m/s and measured waves, 8m significant wave height (Hs) at a DWR buoy moored in 19m water off Yarmouth. These wave measurements were validated by bottom-mounted ADCP observations at the same site. Simulations with SWAN demonstrated the ability of the model to give Hs values of comparable magnitude, assuming WAM3 physics. Associated winds were provided by US Navy models. The COAMPS model was used to provide winds for the NW Atlantic intermediate-resolution grid, and the NOGAPS model for coarse-resolution grid-points outside the intermediate resolution domain. Studies to validate these winds are in progress.

Further studies involve consideration of WAM4 physics within SWAN, in comparison WAM3 physics, and additional SWAN features such as triads, 1-d and 2-d directional spectra, depth-dependent breaking spectra and currents, shoaling and refraction.

ACKNOWLEDGEMENTS

This study was funded by the Panel on Energy Research and Development (PERD) of Canada under Projects #534201 on Advanced Wave Models and the USA Office of Naval Research (ONR) program on GoMOOS the Gulf of Maine Ocean Observing System.

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