Estimating Nearshore Waves at a Morphologically Complex Inlet during Extreme Storm Conditions: Comparative Performance of Two Phase-Averaged Models

Hans R. Moritz, P.E., Heidi P. Moritz, P.E., and David R. Michalsen

U. S. Army Corps of Engineers, Portland District
P.O. Box 2946, Portland, OR 97208-2946. Tel: 503-808-4864; FAX: 503-808-4875
hans.r.moritz@usace.army.mil.

1. INTRODUCTION

As large ocean waves propagate shoreward toward the coast, they encounter the bathymetry of the continental shelf. Smaller waves pass unaffected over shelf features such as canyons, rock ridges, and reefs. However, large waves (in terms of wave length and amplitude) may “feel” the presence of canyons and other bathymetric variations along the continental shelf, and can be affected many miles offshore by such features in water depths of 200 meters or more. As ocean waves continue propagating toward the coastal zone, the waves are further transformed due to decreasing water depth and interaction with the underwater morphology of the coastal ocean. Many aspects of maritime commerce and activities associated with the development/maintenance of coastal margin infrastructure demand accurate estimation of storm wave parameters and related environmental loading. Proper description of the nearshore wave environment is contingent upon the accurate representation of wave transformation phenomena, as it occurs from the edge of the continental shelf to the shoreface. Spectral wave models, based on the wave-action conservation equation, have become a standard tool for estimating the nearshore wave environment along the open coast and at inlets.

This paper compares the results of 2 phase-averaging numerical wave models (STWAVE and WABED) when applied to estimate the nearshore wave environment at the Mouth of the Columbia River (MCR) during extreme storm conditions. STWAVE and WABED results are also compared to prototype measurements obtained at several MCR locations. The MCR is located on the Pacific Northwest Coast of the USA, at Long-Lat 124 W-45 N, between the states of Oregon and Washington (figure 1). Offshore of MCR, the storm-wave environment can be severe. Although “storm surge” is less than 2 meters due to the steep continental shelf and speed of storm passage, waves offshore MCR regularly exceed 10 m (Hmo). The seabed of MCR (and adjacent areas offshore) is composed of sand, yet the morphology at the inlet is highly complex due to asymmetry of its ebb and flood tidal shoals, remnant dredged material disposal site mounds, and rubble mound jetties. To complicate matters, Astoria Canyon can modify large deepwater waves propagating shoreward. In summary, the scale of processes at MCR combined with available in-situ data makes the location an excellent venue for testing model skill. A parallel objective of this paper is to apply STWAVE and WABED to investigate two distinct “zones” where large storm waves can be affected by the bathymetry of the coastal ocean of the U.S. Pacific Northwest coast:

A) Large-scale bathymetric features located along the mid-continental shelf, and
B) The nearshore morphology of a major estuary inlet.

Within the scope of this paper, these two models are treated as black boxes. A detailed description of the numerics behind each model will not be discussed here; the interested reader is referred to Mase et al (2005) and Smith et al (2003). STWAVE is the present “benchmark” model used by Corps of Engineers, Portland District for analysis of nearshore wave transformation. STWAVE applications within Portland District include: Estimating parameters (wave height, period, and direction) for design and repair of jetties and shore protection, assessing inlet navigability, calculating wave-induced sediment transport and scour (seabed radiation stress), and assessing wave behavior over seabed areas modified by the accumulation of placed dredged material. Usually, prototype data is not available for firm verification of a model at a specific project site, which means that no one model can be relied upon to answer all questions. When analyzing waves for detailed study it is desirable to apply different models to gain complimentary insight to various processes affecting nearshore wave transformation, thereby increasing the reliability of wave-related estimates. In a similar spirit, the results presented within this paper will be based on a comparative and complimentary basis: Inconsistent results will not be disparaged, rather the results will be used to improve our understanding of the problem.

This paper is organized into three parts. Part I describes the general environment at the MCR, observed prototype wave data, and the procedure to set-up the WABED and STWAVE models used herein. Part II describes model application to investigate the effect deepwater wave refraction as motivated by Astoria Canyon. Part III describes model application to investigate the effects of diffraction, refraction, and shoaling of large storm waves at the nearshore waters of MCR.

2. PART I: MCR PHYSICAL ENVIRONMENT and WAVE MODEL SET-UP

In the northeast Pacific Ocean during winter, weather fronts associated with eastward moving maritime cyclonic storms can extend over the ocean for 1000's of km and cover a latitude difference of 25 degrees. When these fast moving maritime low-pressure systems make land fall on the U.S. Pacific Northwest, the coast can be subjected to hurricane-like conditions. Offshore MCR, wind fields associated with intense winter low-pressure weather systems can create sustained wind speeds greater than 20 m/s for fetches greater than 200 km. The resulting wind stress can produce ocean waves (Hmo) greater than 10 m high having wave period (Tp) greater than 16 seconds. The approach and passage of intense maritime storm systems can create a 1-2 meter "surge" of the water surface. The wintertime sea state affecting the jettied estuary entrance of MCR is characterized by large swell approaching from the northwest to southwest combined with locally generated wind waves from the south to southwest. Astronomical tides at MCR are mixed semi-diurnal with a diurnal range of 2.6 m. In terms of bathymetry change, the transition from coastal regime to oceanic is abrupt. Excluding Astoria Canyon, which is located 17 km offshore, the continental shelf break (240 m isobath) is 30 km offshore from the MCR. The nearshore of MCR is dominated by rubblemound jetties and large-scale morphology (figure 3c). The MCR north and south jetties extend 3.3 km and 6.5 km, respectively, into the ocean and have a significant role in modifying waves as they enter the inlet (thru diffraction effects). Note that a significant length of each jetty is submerged along the seaward ends (1.2 km for the south jetty and 0.5 km for the north jetty). Finally, the MCR navigation channel is maintained at approximately 18 meters depth providing a wave guide which further complicates wave transformation thru the inlet.

2.1 Model Description

WABED and STWAVE are steady-state spectral wave models developed for simulating nearshore wave transformation. Both models use the wave action conservation equation, solved in the frequency domain using phase averaging to simulate wave propagation. This means that the WABED and STWAVE neglect changes in wave phase and superposition of waves having different phases; results for wave height (hmo at a specific x,y location) are phase averaged. Phase-averaging limits these models from directly solving for wave diffraction and reflection caused by bathymetric features and surface piercing structures. However, approximation methods have been incorporated into STWAVE and WABED to indirectly account for wave diffraction and reflection. Refer to Smith et al (2003) and Mase (2005) for additional details.

STWAVE and WABED are similar in that both are half-plane models that propagate waves only from the seabed boundary toward shore. However, the two models are different in how they solve the wave action conservation equation (STWAVE uses an explicit forward marching finite difference method and WABED uses an implicit forward marching finite difference method). The models employ different methods to estimate wind effects on spectrum (wave energy) growth, wave breaking/dissipation, wave-wave interaction, diffraction, and reflection. WABED approximates forward wave reflection, STWAVE does not. Although WABED and STWAVE utilize different numeric schemes to estimate wave propagation, both models use same input/output formats. This means that STWAVE and WABED can read the same gridded domain file, with attendant model control and boundary condition specifications and produce outputs that can be directly compared.

2.2 General Modeling Approach and Set-up

The imperative was to accurately model storm wave propagation from the continental shelf to within the MCR inlet, accounting for: A) high wind stress which can modify the energy of a wave field, deep water refraction due to Astoria Canyon, nearshore shoaling and refraction due to abruptly changing bathymetry/morphology, diffraction associated with extensive jetties, and a deeply maintained inlet channel. Application of STWAVE and WABED at MCR will highlight the differences in how each model estimates wave propagation, giving insight to strength and weakness of each model.

The overall area of interest, shown in figure 1, was too large (76 km x 50 km) to effectively apply WABED or STWAVE due to run time requirements for a desk-top PC. So, two separate model domains were developed to analyze wave propagation from the continental shelf-break to the inlet of the MCR. An “offshore” domain spanning an area of 47 km x 40 km with depth range of 30 to 900 m (using 60-meter cells), was used to comparatively investigate how each model would perform with simulating storm wave interaction with Astoria Canyon. An “inshore” domain spanning an area of 33 km x 41 km (using 20-meter cells) from 0 m to the head of Astoria Canyon (335 m depth), was developed to fully resolve the complex nearshore morphology and the jetties of MCR and test each model’s skill in simulating wave propagation over these features. The bathymetry for each model domain was generated by an automated gridding procedure (SMS) using detailed bathymetry data compiled by the US Army Corps of Engineers, NOAA, and the USGS-Menlo Park.

For the “offshore” domain, the models were applied using only propagation, to focus the comparative assessment of model performance strictly on wave interaction with Astoria Canyon. Model application on the “offshore” domain did not include effects of wind (energy) input on the wave field. Model application on the “inshore” domain included propagation and wind (energy input) and referenced each simulation to the proper water level corresponding to the time of each wave field boundary condition. The directional spectrum and wind data used to force each model run (applied as a spatially constant BC along the models’ western boundary) was obtained from NDBC buoy 46029 (figure 1 and 3).

Results for the “offshore” domain were obtained for two (2) different wave events: 17NOV03 and 6FEB06. Result for the “inshore” domain were obtained for four (4) different wave events: 17NOV03, 4FEB06, 3MAR99, and 24NOV98. Prototype nearshore wave measurements corresponding to the wave events modeled within this paper, are summarized in Table 1. Wave statistics estimated by WABED and STWAVE were compared to the Table 1 prototype nearshore measurements. The selected wave conditions include the largest wave measured offshore the MCR (4FEB06). Collectively, the 4 wave conditions span a wide range of wave approach direction (Dp=SW to NW), wave period (Tp=14 to 17 sec), and wave height (Hmo = 9 to 13.8 m).

Table 1. Summary of observed wave events used to run and compare STWAVE and WABED.

	WSE†	Observed Wave Statistics									
Date of		*Offshore-NDBC 4602 9**					*Nearshore*				
Wave Event		Wind-Spd.	Wind-Dir.	Hmo	Tp	Dp	Site	Depth	Hmo	Tp	Dp
24 NOV 1998	0.8m	15m/s	228°	8.9m	14.3s	262°	**B2**	39m	7.2m	14.2s	266°
							M	34m	7.0m	14.2s	263°
3 MAR 1999	0.5m	20m/s	182°	12.8m	16.7s	222°	**M**	34m	11.2m	17.1s	220°
17 NOV 2003	0.5m	14m/s	279°	9.3m	16.7s	312°	**SJ**	14m	6.2m	16.7s	252°
4 FEB 2006	1.85m	20m/s	205°	13.8m	16.7s	230°	---------------------------------				

* = NDBC directional spectrum used as an ocean wave boundary condition to drive WABED and STWAVE models
† = Water Surface Elevation, NGVD (tide +surge). All elevations in this paper are referenced to NGVD.
0 NGVD = +1.1 m MLLW

3. PART II: MODEL APPLICATION FOR ASTORIA CANYON

Results obtained by applying WABED and STWAVE using the "offshore" domain are shown graphically in figure 2 (a and b). The models were used to simulate storm wave conditions for 17NOV03 (a NW storm event) and 4FEB06 (a SW storm event). Only results for the 17NOV03 storm are shown here in terms of predicted wave height (Hmo). Wind effects were not included in the model runs. Two different contour plots depicting simulated Hmo are shown in figure 2: The left panels compare STWAVE and WABED results based on the same contour range for each model, to enable comparison of the spatially variable estimates of Hmo on an absolute basis (to highlight where each model has differing magnitude for predicted Hmo). The right-hand side panels of figure 2 show the results of each model based on a min-max contour range applicable for each model, to enable a relative comparison (to highlight where each model is intrinsically different from the other).

Both models indicate that the presence of Astoria Canyon has a significant effect on large storm waves as they pass over the canyon. The rim of Astoria Canyon is shallow enough (150 m depth) to affect waves having a period of 15 seconds or greater. Astoria Canyon can shift the direction of the affected wave field by 7-10° and modify the wave height by 1-2 meters, through refraction effects. It is not known whether the canyon walls are steep enough to cause diffraction on the wave field passing overhead; more work is needed to evaluate this potential diffraction effect. The results shown in figure 2 indicate that STWAVE estimates a wave field which has a larger wave height (hmo) than does the WABED, when wind forcing is turned "off" in both models. STWAVE predicts a higher localized Hmo near the head of Astoria Canyon than WABED (near the center of each panel in figure 2). Closer to shore (center right side of each panel), there are significant localized differences between the two models associated with the relic dredged material mound located on the seaward flank of Peacock Spit. STWAVE results indicated that the mound can locally amplify the wavefield to a higher degree than predicted by WABED (8.8 m Hmo vs. 7.6 m Hmo). STWAVE results show a peculiar amplification effect 2 km due north of the relic dredged material mound previously referenced. This appears to be related to the combined refraction from Astoria Canyon, the dredged material mound, and Peacock Spit. WABED shows only a slight increase in Hmo at this location as compared to STWAVE (8.8 m vs. 7.0 m).

Overall, STWAVE appears to predict more vigorous refraction/shoaling than does WABED based on the results obtained from the "offshore" domain simulations. These differences may be due to the different methods that each model uses to solve the energy action conservation equation. Results obtained for the

4FEB06 wave event are similar (in terms of the qualitative differences between STWAVE and WABED) to the 17NOV03 storm wave condition.

The effect of Astoria Canyon on large wave field passing overhead extends shoreward beyond the landward boundary of the "offshore" domain. This implies that these wave refraction effects may play a significant role in the evolution of the affected wave field as it makes its way shoreward. The Astoria Canyon effect could have implications for longterm morphology development and shoreline response at MCR.

4. PART III: MODEL APPLICATION FOR NEARSHORE WATERS AT MCR

WABED and STWAVE were used to estimate wave propagation over the "inshore" domain using four (4) different wave events. Table 1 summarizes each wave event, with the corresponding water level, and wind forcing values. As noted in Table 1, STWAVE and WABED were forced using 2-D spectrum obtained from NDBC buoy 46029. The "inshore" domain was descritized using 20 m cells to reproduce the highly variable morphology of MCR, the jetties, and offshore area to the head of Astoria Canyon. Figure 1 and 3 show the extent and bathymetry for the "inshore" domain.

Figures 4-9 show the graphical results obtained from applying STWAVE and WABED on the "inshore" domain for the four wave events listed in Table 1. All results are shown here in terms of predicted spatial distribution of Hmo**,** using color contours based on a scale relative to each model run. The locations of nearshore wave observations are shown on each figure by red dots (site B2, Site M, and Site SJ).

4.1 Storm Wave Condition for 3 March 1999

Figure 4 shows WABED and STWAVE results obtained for the 3MAR99 storm (Hmo at the seaward boundary, via NDBC 46029, was 12.8 m, Tp=16.7 sec, and Dp=222°). Astoria Canyon appears along the western boundary of the figure panels. Figure 4 show that Astoria Canyon has an appreciable affect on the SW wave field, and that this deepwater refraction effect extends all the way to shore (affecting the northern lobe of Peacock Spit and areas to the north of MCR). Both models show this effect; as it was also produced within the "offshore" domain. Results from STWAVE exhibit more refraction extent due to Astoria Canyon as compared to WABED. The refraction effect from Astoria Canyon produces localized differences in Hmo of about 2 m for STWAVE and 1.5 m for WABED; there are shadow zones and amplification zones that extend all the way to shore. The same effect acts to locally shift wave direction (Dp) by 10° (max) for STWAVE, and 7° for WABED. The relic dredge material mound located near wave gauge B2 causes wave to refract onto Peacock Spit, which produces an added refraction effect along the north side of Peacock Spit. Both models show this effect, but STWAVE appears to show more refraction action, than does WABED. Both models also show the refraction effect associated with the relic dredge material mound located immediately south of the MCR navigation channel, where waves are shown to be amplified onto the western extent of the south jetty for the 3MAR99 wave condition. Both models showed similar wave effects in the lee of the south jetty, where the wave field is being modified by diffraction. Overall, WABED predicts a higher Hmo throughout the domain than does STWAVE. The difference is about 1 meter in most offshore locations; and appears to emanate from the offshore boundary.

4.1 Storm Wave Condition for 17 November 2003

Figure 5 shows WABED and STWAVE results based on the 17NOV03 storm wave condition (Hmo=9.3 m, Tp=16.7 sec, and Dp=312°). Figure 5 can be compared to Figure 2 (right panels); same wave condition, but different domains. Note that the "offshore" domain modeling (figure 2) did not include wind forcing. Both figure 2 and 5 show that Astoria Canyon has an effect on the NW storm waves. The results shown in figure 2 account for more of the canyon acting upon the wave field; showing a more correct and greater degree of canyon related refraction. Figure 5 shows how the refraction effect of Astoria Canyon develops for storm wave approaching from the NW; the related refraction extends to shore south of MCR affecting how waves interact with the morphology of MCR. The wave field estimated by WABED is about 0.5 meters higher than STWAVE. Note that for STWAVE, the largest Hmo generally occurs along the western boundary, where the wave BC is applied; waves begin to shoal and dissipate quickly. The wave field for WABED increases as it propagates shoreward from the western boundary, reaching a maximum about 1/4 - 1/3 into the "inshore" domain. These differences indicate that the WABED model may be over predicting Hmo based on the added source of energy from wind input.

4.2 Storm Wave Condition for 24 November 1998

Figure 6 shows WABED and STWAVE results based on the 24NOV98 storm wave condition (Hmo=8.9 m, Tp=14.3 sec, and Dp=262°). Note that the wave period for this storm is 14.3 sec; which renders the wave field as "deepwater" when compared to the bathymetry of Astoria Canyon; there was no refraction effect for this wave field due to Astoria Canyon, as simulated by either WABED or STWAVE. For this reason, Figure 6 omits the western part of the "inshore" domain. STWAVE results show more refraction effect (vs. WABED) due to wave interaction with Peacock Spit, dredged material mounds and morphology within the MCR inlet. Note how the refraction effect for STWAVE impacts the south jetty to a higher (relative) degree than WABED. WABED and STWAVE produce different estimates for the distribution of Hmo within the lee of the south jetty and within the MCR inlet. Overall, WABED produces a wave field that is about 1 meter higher than STWAVE for the 24NOV98 storm.

4.3 Storm Wave Condition for 4 February 2006

Figure 7 and 8 show the model results obtained for the storm wave conditions of 3MAR99 and 4FEB06 (3MAR99 is also shown in figure 4). The 4FEB06 storm is the storm of record for MCR; having Hmo=13.8m, Tp=16.7 sec, and Dp=230°, as observed at NDBC 46029. The figures show a close-up view of the model results near the MCR inlet. The far-field wave refraction effect from Astoria Canyon can be seen in the upper part of each figure. The results are similar for each storm (i.e. compare STWAVE MAR99 to STWAVE FEB06). STWAVE shows more sensitivity for refraction and shoaling than WABED, for storm events shown in figure 7-8. The area just south of the MCR north jetty is an active disposal site (and exhibits about 8 ft of localized mounding). Note how STWAVE shows more wave amplification within this area than does WABED (this is also true for the other wave conditions previously discussed). Diffraction around the south jetty appears to be represented similarly by WABED and STWAVE. There is a difference near the seaward end of the south jetty (for the 3MAR99 event), where WABED shows wave diffraction thru a small gap in the jetty; STWAVE does not show this important effect. WABED does not show this gap effect for the 4FEB06 storm because the water level on 4 FEB04 was high enough as to submerge the area of the south jetty near the gap.

"Alongshore" and "offshore" transect locations are shown on figure 8. WABED and STWAVE results were "cut" along each transect (along with depth) to highlight differences between each model for the storm of record for MCR (4FEB06). Results of the transect comparison are shown in figure 9. The top panel of figure 9a compares STWAVE and WABED along the "offshore transect" (view into the page is toward the south). Hmo for WABED is 2 meters higher than STWAVE for the offshore 1/3 of the transect (9-12.5 km). The offset between the two model estimates reduces to less than 0.5 meter as one moves inshore to about 7 km, then WABED Hmo increases in offset to about 1.5 m, and finally reduces to less than 0.5 m at 1.5 km. It appears that the difference between STWAVE and WABED (along the offshore transect) is greatest when the rate of change in seabed elevation is constant. When the rate of seabed elevation change is not constant (curvature is present), the difference between the two models (for Hmo) is reduced. Comparing results of STWAVE and WABED based on the “alongshore transect”, shows that WABED Hmo is typically higher (offset) than STWAVE by an average difference of 1 m. The effect of wave refraction around the relic dredged material mounds can be seen at 4.5 km and 8.5 km; WABED and STWAVE produce qualitatively different estimates for Hmo in these areas. Overall, STWAVE has more sensitivity in its handling of wave refraction/shoaling. WABED produces Hmo estimates that are usually higher than STWAVE.

4.4 Comparison of Model Estimates to Observed Prototype Data

Model results obtained for the “inshore” domain based on the storms of 24NOV98, 3MAR99, and 17NOV03 were compared to prototype data measured at Sites B2, M, and SJ (see figures 4-8 and Table 2). Model comparison to observed data was ranked as good, fair, and poor based on the criteria presented at the bottom of Table 2. Both STWAVE and WABED provided good results for station M and SJ for the storms of 3MAR99 and 17NOV03, being within 10% of the observed values for Hmo, Tp, and Dp. The 24NOV98 wave event proved to be more challenging for the models; WABED did poorly by over-estimating Hmo by 30% compared to observed value for Station M and B2. STWAVE performed fair, having overestimated M and B2 wave height by 15%. Note that the observed wave period for this storm was significantly less than the other 2 storms. The difference between model estimates and observation for the 24 NOV98 storm, may be attributed to the temporal lag in time (change in wave field) between observing the waves at NDBC 46029 and observing the waves at Sites B2 and M.

Table 2. Comparison of observed wave events to STWAVE and WABED estimates.

	Modeled Wave Statistics						**Observed Wave Statistics**				
Date of Wave Event	***WABED***			***STWAVE***			**Nearshore**				
	Hmo	Tp	Dp	Hmo	Tp	Dp	Site	Depth	Hmo	Tp	Dp.
24 NOV 1998	9.8m	14.3s	244°	8.3m	14.3s	254°	**B2**	39m	7.2m	14.2s	266°
	9.7m	14.3s	241°	8.3m	14.3s	251°	**M**	34m	7.0m	14.2s	263°
3 MAR 1999	11.2m	16.7s	218°	10.6m	16.7s	224°	**M**	34m	11.2m	17.1s	220°
17 NOV 2003	6.8m	16.7s	267°	6.8m	16.7s	268°	**SJ**	14m	6.2m	16.7s	252°

RED = poor model comparison to observation (>± 30% difference)
BLUE = fair model comparison to observation (>± 10% and <20% difference)
GREEN = good model comparison to observation (<10% difference)

5. CONCLUSIONS

Astoria Canyon has a significant effect on large storm waves passing over the canyon as they move toward shore, acting to refract the waves as they encounter the canyon’s rim. Large waves are considered to have Tp greater than 15 seconds. This effect should be anticipated since the Canyon’s rim begins at about 150 m depth (waves having Tp 15 sec or greater begin to feel the bottom at about 175m, d/L>1/2 for deepwater waves). Wave diffraction motivated by Astoria Canyon can cause the affected wave field to change direction by 7-10° and have Hmo changed by 1-2 meters. These effects can extend all the way to shore. Some of the shoreline and nearshore morphology changes occurring at MCR may have been caused due to this Astoria Canyon effect (most notably, Peacock Spit evolution). This finding highlights the need to extend the boundaries of wave models outward to include all bathymetry features that have the potential to affect the wave field of interest.

For the wave cases applied within this paper (Table 1), WABED appears to estimate a higher Hmo (by 0.5-2m) than does STWAVE when wind forcing is included within the simulations. This effect is prevalent for the areas beyond (oceanward) from the nearshore, where waves have not yet been significantly affected by refraction and shoaling. If no wind forcing is included in the simulations (as was the case for the offshore" domain), then STWAVE tends to predict higher Hmo than WABED. Based on the results obtained herein, it appears that WABED may be over predicting wave height when wind forcing is included in the model (and under predicting wave height when wind forcing is turned off). These "wind" differences appear to diminish as the wave field propagates closer to shore where the wave field is being affected by depth limited shoaling and refraction.

Shoaling and refraction appears to be more vigorously simulated within STWAVE than WABED; likely the result of how the wave action conservation equation is solved within each model. More work is needed to determine which model is more accurate in this regard.

WABED employs a more sophisticated algorithm to estimate wave diffraction than does STWAVE, yet the two models produced similar results for the wave field in the lee of the south jetty for storm waves approaching from the SW. It appears that the diffraction method used within STWAVE is robust enough for engineering estimates at MCR, where the jetties are concerned. More work is needed to evaluate diffraction within both models (comparison to prototype data).

In summary, STWAVE and WABED were applied on a highly variable bathymetry spanning depth range of 0 m to 900 m. The models were forced using observed direction spectra corresponding to 4 severe storm conditions. Wind forcing was included in some of the model runs. Current forcing was not included. Storm wave conditions had a directional variation (between events) of 90° (NW to SW). The two models produced results that in many ways were qualitatively similar. But there were significant absolute differences between the two models at locations where refraction was severe. Wind forcing appears to be treated significantly differently between the two models, producing results which may be substantially different in terms of Hmo.

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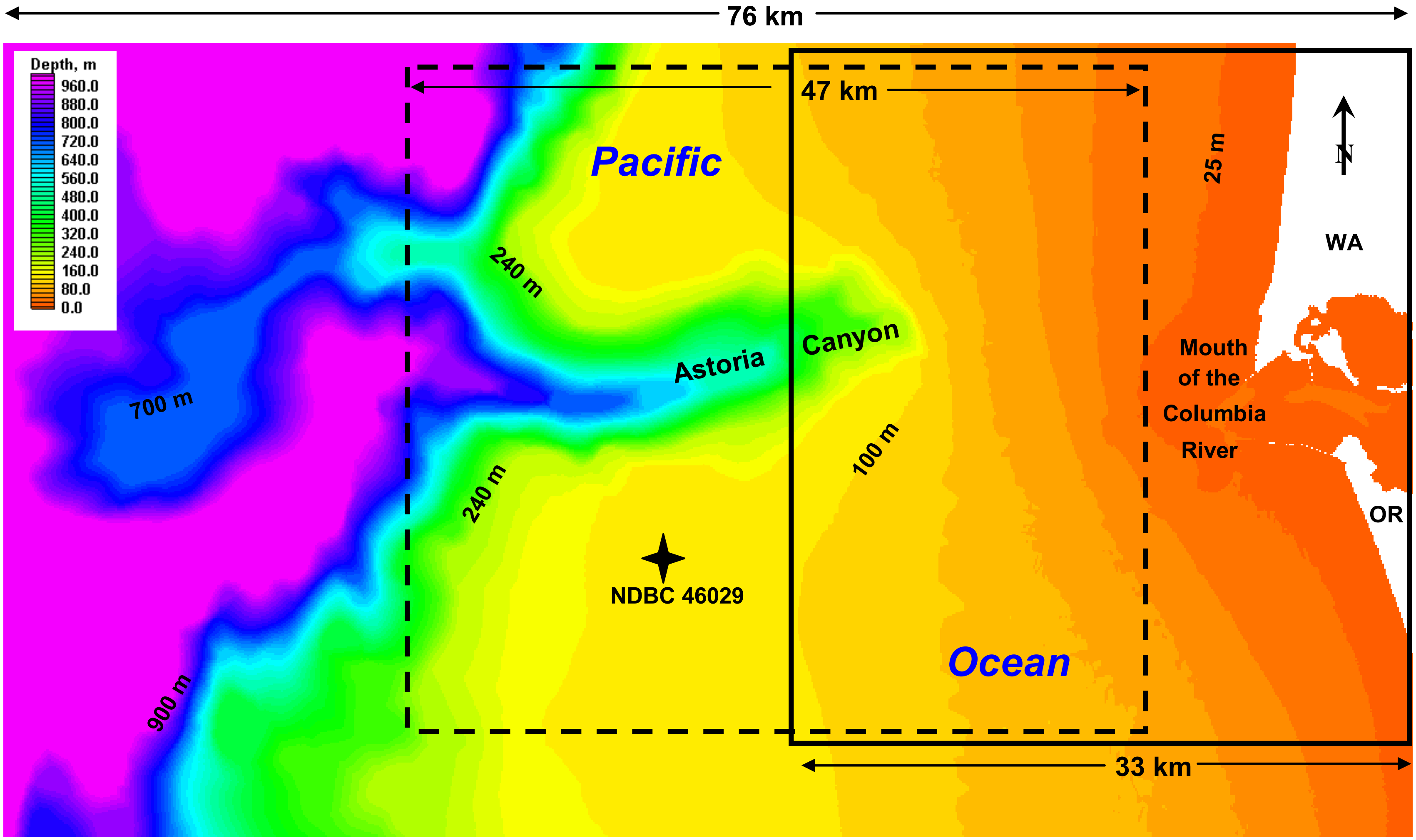
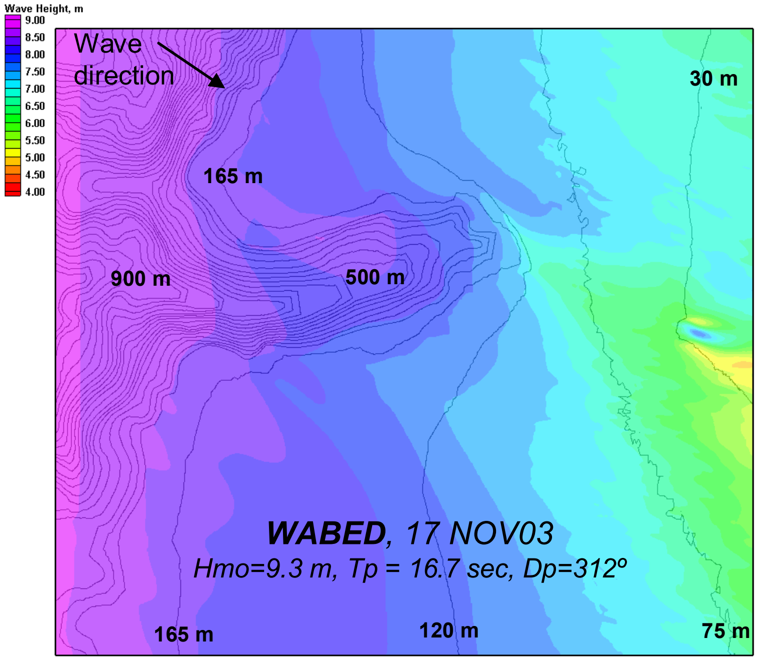


Figure 1. Bathymetry offshore of the Mouth of the Columbia River (MCR). The sandy morphology near MCR (to water depths of 50 m) is dominated by ocean wave action interacting with tidal-driven circulation of the Columbia River estuary. The head of Astoria Canyon (130 m depth) lies within 17 km of the MCR jetties. The area shown by a dashed line (47 km x 40 km) defines the "offshore" domain used to simulate ocean wave interaction with Astoria Canyon. The area inscribed within the solid line (33 km x 41 km) defines the "inshore" domain used to simulate coastal wave transformation as waves encounter the head of Astoria Canyon and the morphology of MCR. WABED and STWAVE models were applied in each non-nested domain. The "offshore" area was descritized using 60-meter square cells, and the "inshore" area was descritized using 20-meter square cells. NDBC buoy 46029 lies within 33 km of MCR.



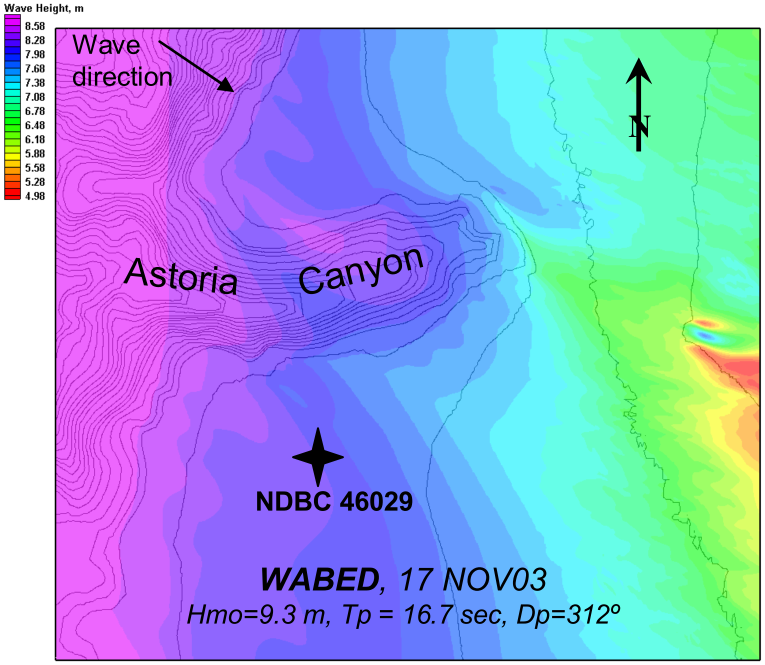
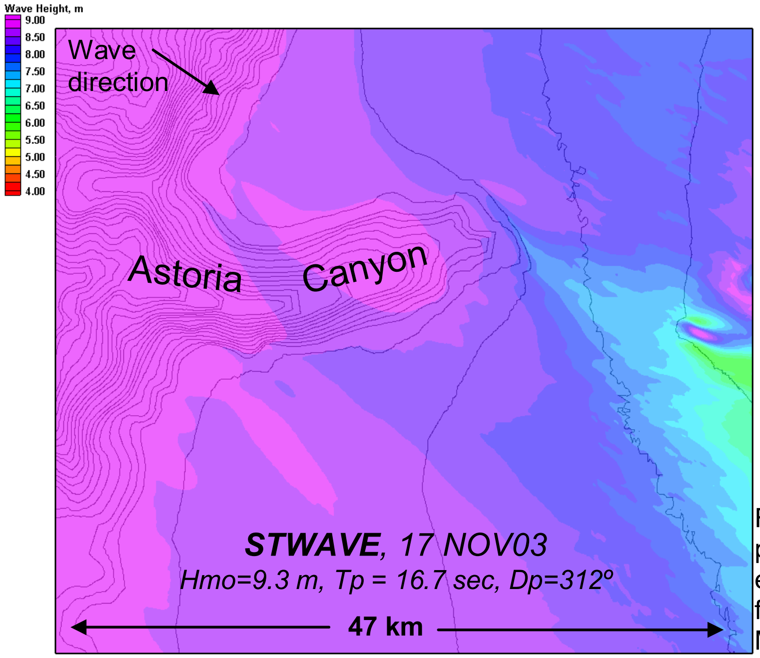


Figure 2a. Top panels show ***WABED*** estimated wave height for the area offshore MCR, for 17 NOV 2003.

Results are for wave propagation only, no wind forcing was included. Western boundary was forced using wave spectrum via NDBC 46029. Wave height is shown in color scale, water depth is shown by contour lines. Left panels show wave height based on the same contour range; to allow “magnitude” comparison between STWAVE and WABED Results . Right panels show wave height based on a relative contour range, applicable to each simulation; to allow comparison of the characteristic differences between the models. Note the effect of Astoria Canyon on the wave field.



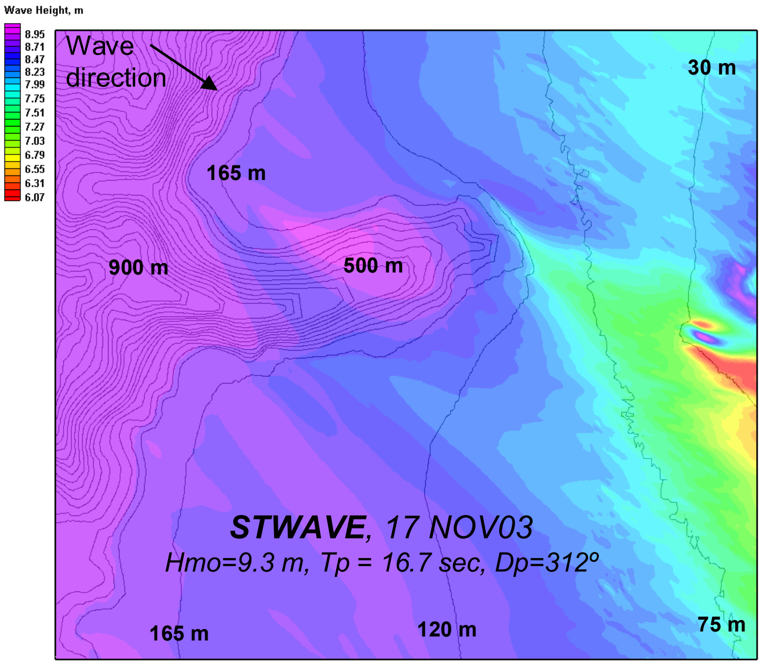


Figure 2b. Bottom panels show ***STWAVE*** estimated wave height for the area offshore MCR, for 17 NOV 2006.

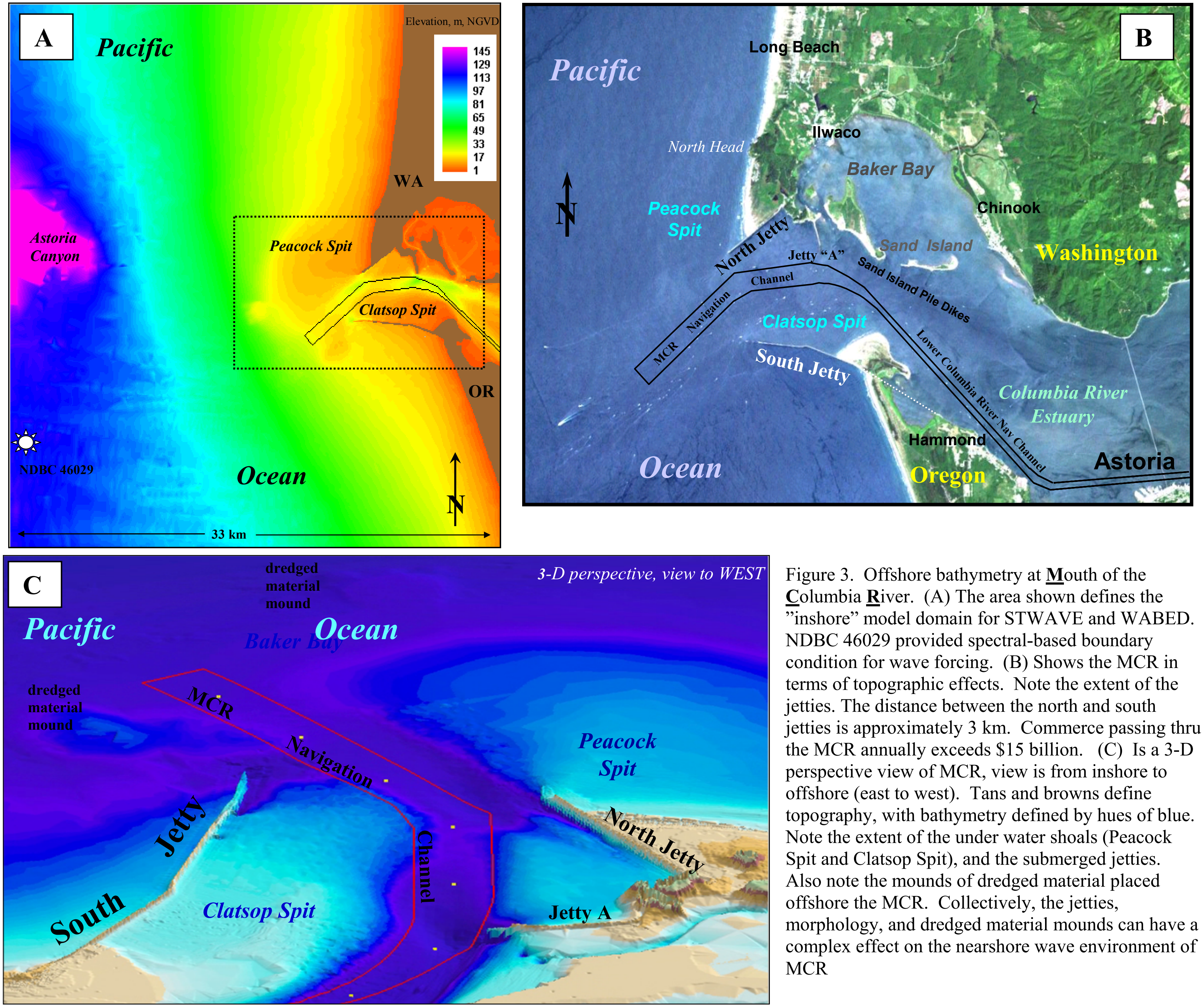


Figure 3. Offshore bathymetry at **M**outh of the **C**olumbia **R**iver. (A) The area shown defines the "inshore" model domain for STWAVE and WABED. NDBC 46029 provided spectral-based boundary condition for wave forcing. (B) Shows the MCR in terms of topographic effects. Note the extent of the jetties. The distance between the north and south jetties is approximately 3 km. Commerce passing thru the MCR annually exceeds $15 billion. (C) Is a 3-D perspective view of MCR, view is from inshore to offshore (east to west). Tans and browns define topography, with bathymetry defined by hues of blue. Note the extent of the under water shoals (Peacock Spit and Clatsop Spit), and the submerged jetties. Also note the mounds of dredged material placed offshore the MCR. Collectively, the jetties, morphology, and dredged material mounds can have a complex effect on the nearshore wave environment of MCR

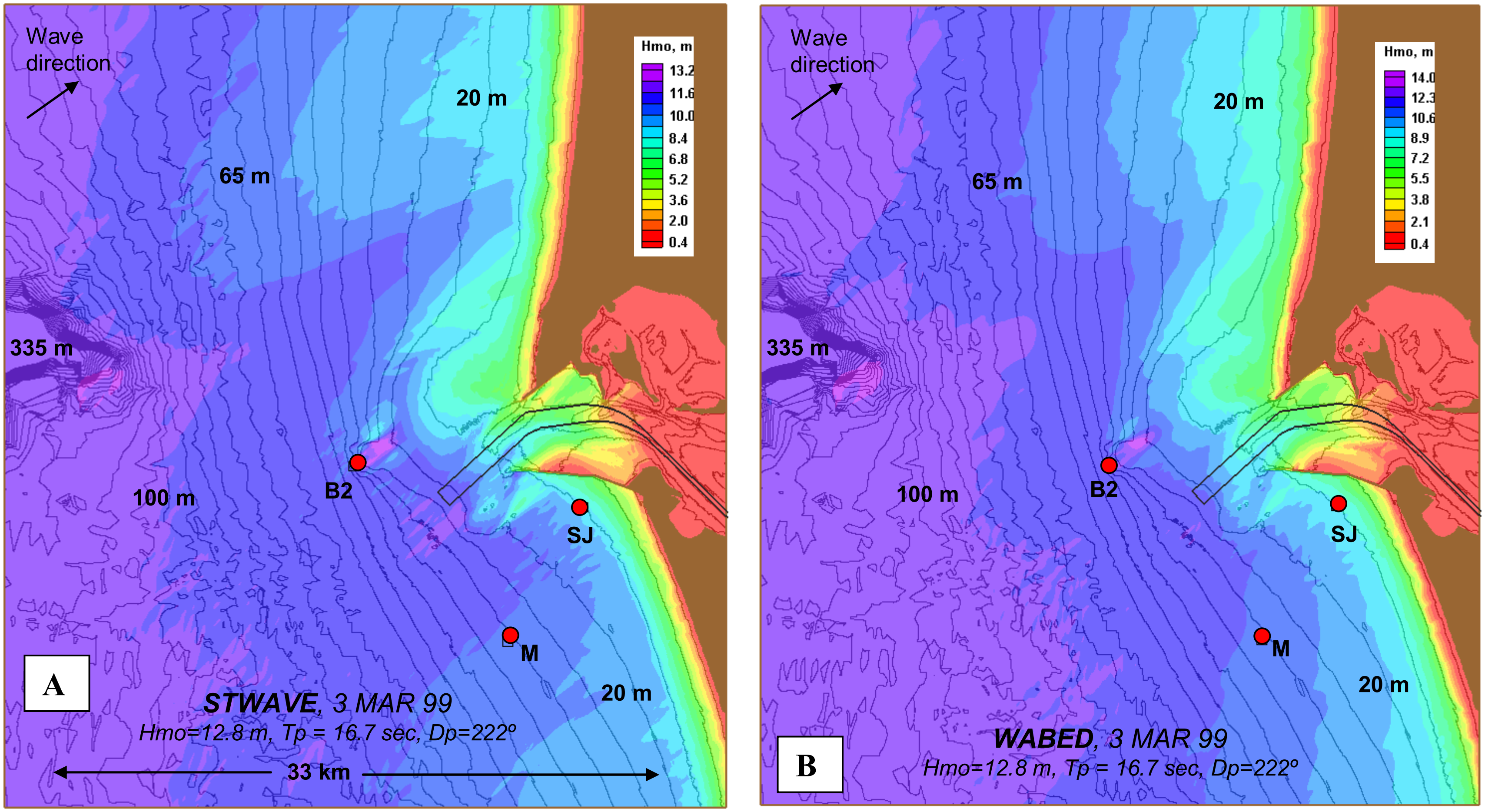
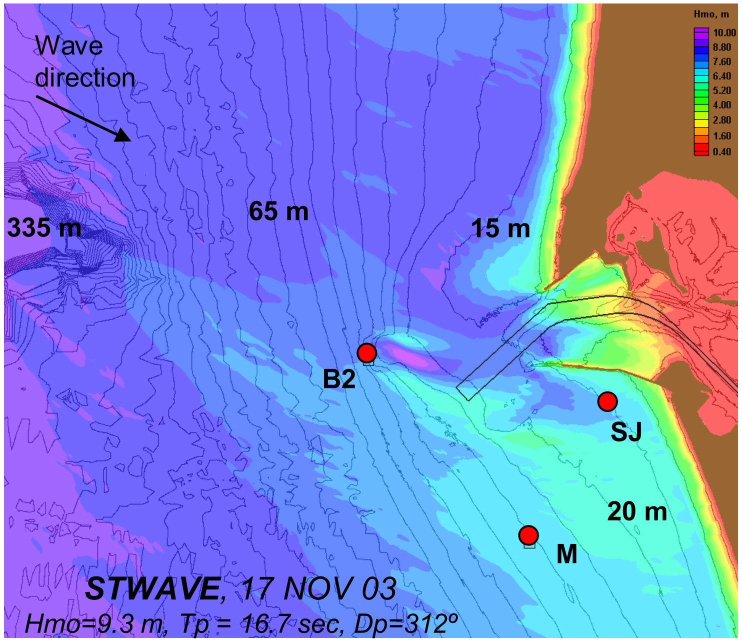


Figure 4. STWAVE (A) and WABED (B) simulations of the 3 MAR 99 storm event using the "inshore domain" (refer to figure 1). Offshore wave direction (at the model boundary via NDBC 46029) is 222º (SW). Both models show a pronounced effect of wave refraction caused by Astoria Canyon . This deepwater effect extends to the shoreface north of MCR where Peacock Spit transitions shoreward. The storm event had a Tp of 16.7 sec which could be affected by seabed at a depth of 225 m. The rim of Astoria Canyon is located at 150 m depth. The dredged material mounds (near wave gauge B2 and southwest of the south jetty head) have a pronounced refraction effect upon the nearshore wave field; and the refraction effect extends far from the source. Note the diffraction effect in the lee of the south jetty. Both models appear to reproduce similar diffraction estimates. For the 3 MAR 99 storm, WABED estimates for Hmo are about 1 meter higher than for STWAVE, the difference emanates from the offshore. The STWAVE model appears to produce more sensitivity to wave refraction and shoaling.



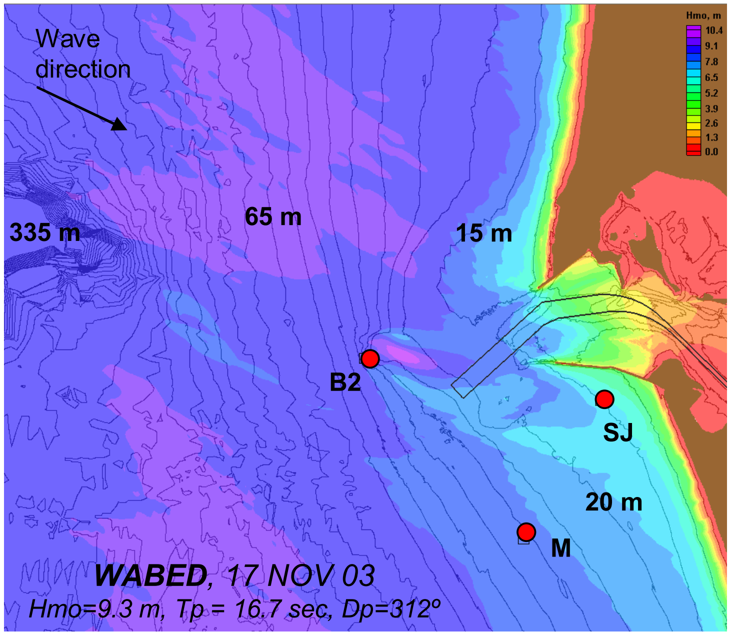
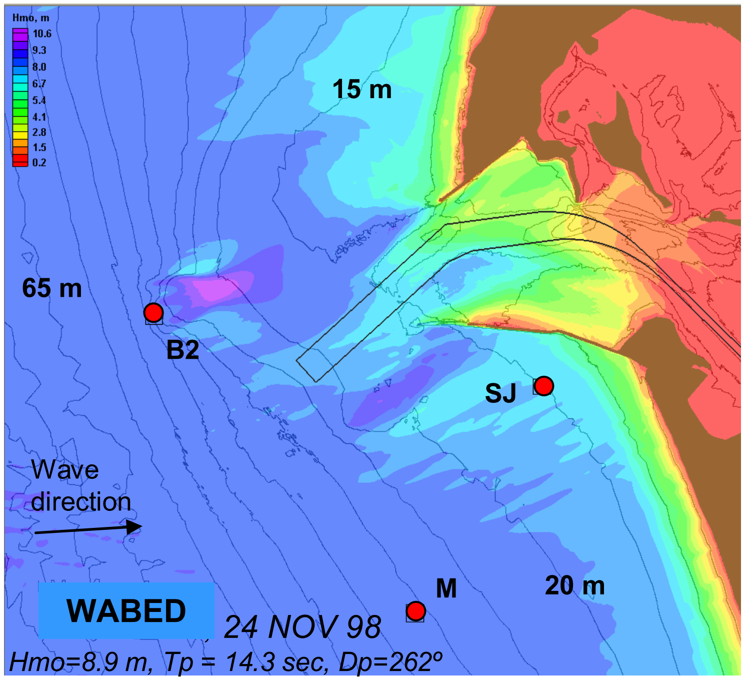


Figure 5. Top panels are STWAVE (left) and WABED (right) simulations of the 17 NOV 03 storm event. Offshore wave direction is 312º (NW). STWAVE shows a more pronounced effect of wave refraction caused by Astoria Canyon and the dredged material mounds. WABED estimates for Hmo are about 0.5 meters higher than for STWAVE, the difference emanates from the offshore. The STWAVE model appears to produce more sensitivity to wave refraction and shoaling.



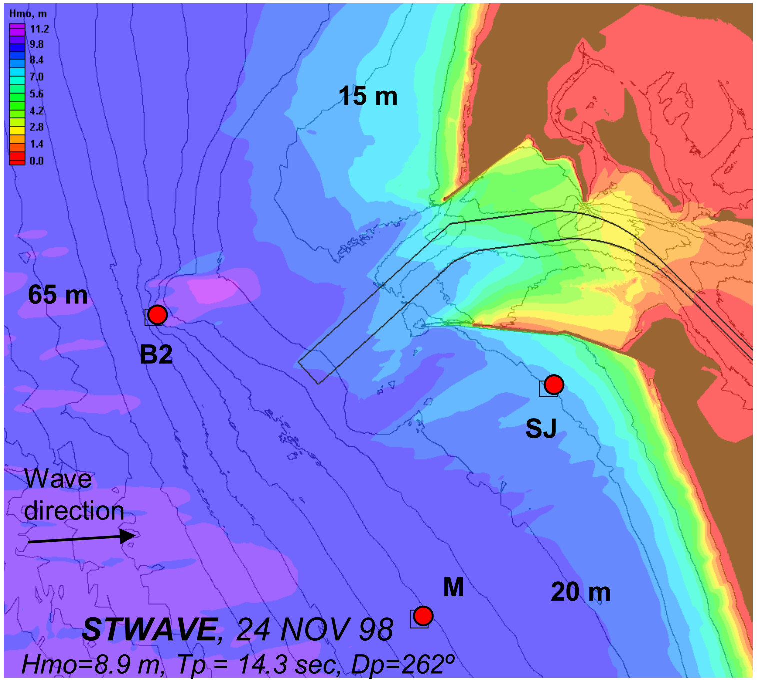
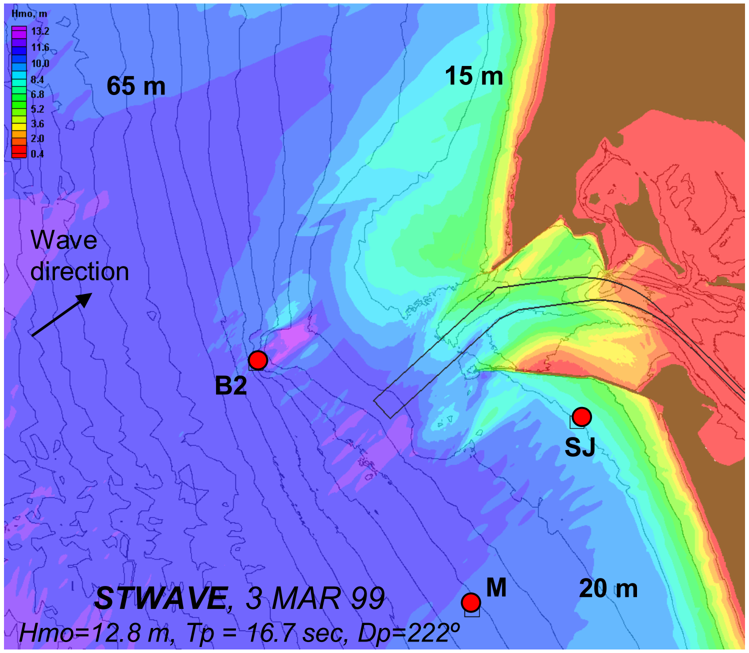


Figure 6. Bottom panels are STWAVE (right) and WABED (left) simulations of the 24 NOV 98 storm event. Offshore wave direction is 262º (W). STWAVE shows a more pronounced effect of wave refraction-shoaling caused by nearshore bathymetry and dredged material mounds. WABED estimates for Hmo are about 1 m higher than for STWAVE, the difference emanates from the offshore.



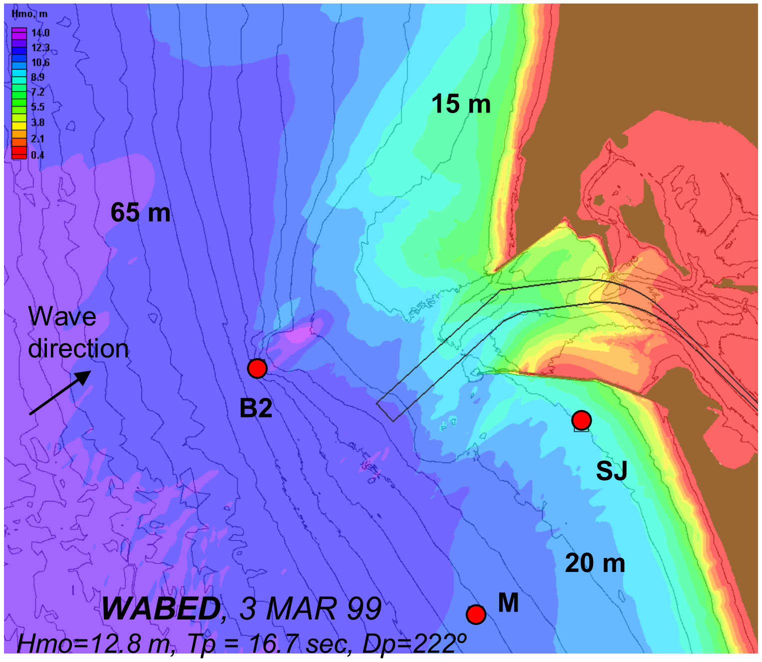
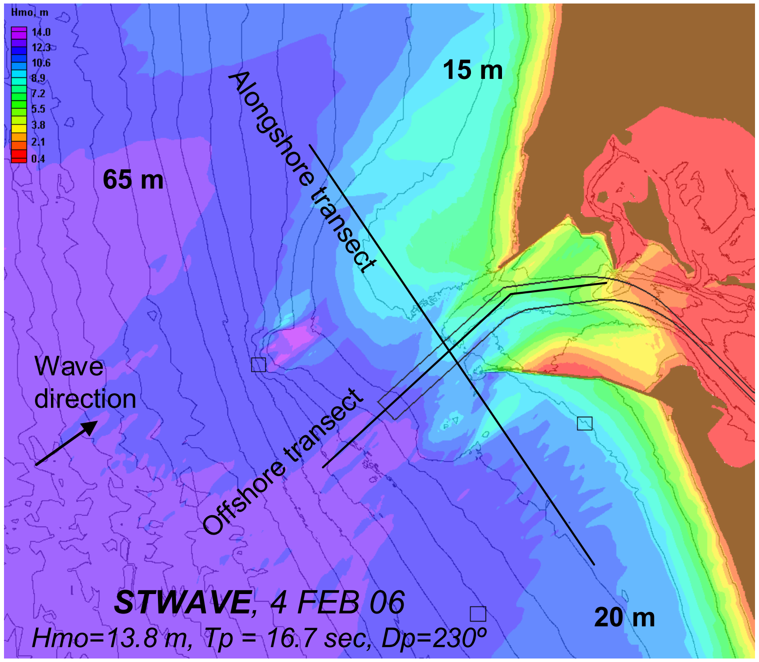


Figure 7. Top panels are STWAVE (left) and WABED (right) simulations of the 3 MAR 99 storm event: A close-up view for figure 5. Offshore wave direction is 222° (SW). STWAVE shows a more pronounced effect of wave refraction and shoaling caused by nearhsore bathymetry and the dredged material mounds. The STWAVE model appears to produce more sensitivity to wave refraction and shoaling.



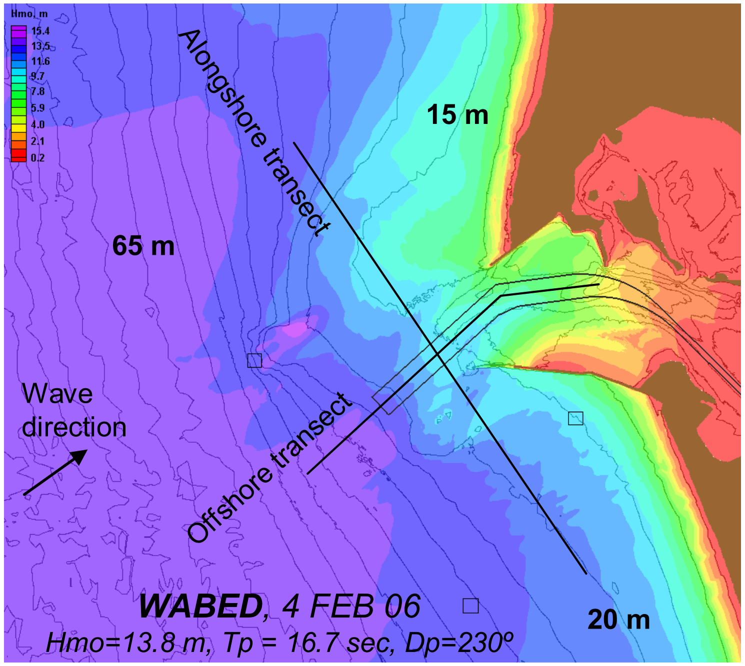


Figure 8. Bottom panels are STWAVE (left) and WABED (right) simulations of the 4 FEB 06 storm event. Offshore wave direction is 230° (SW). Results are similar to the 3 MAR 99 storm. WABED estimates for Hmo are about 1.5 m higher than for STWAVE, the difference emanates from the offshore. Additional interpretation is shown in figure 9.

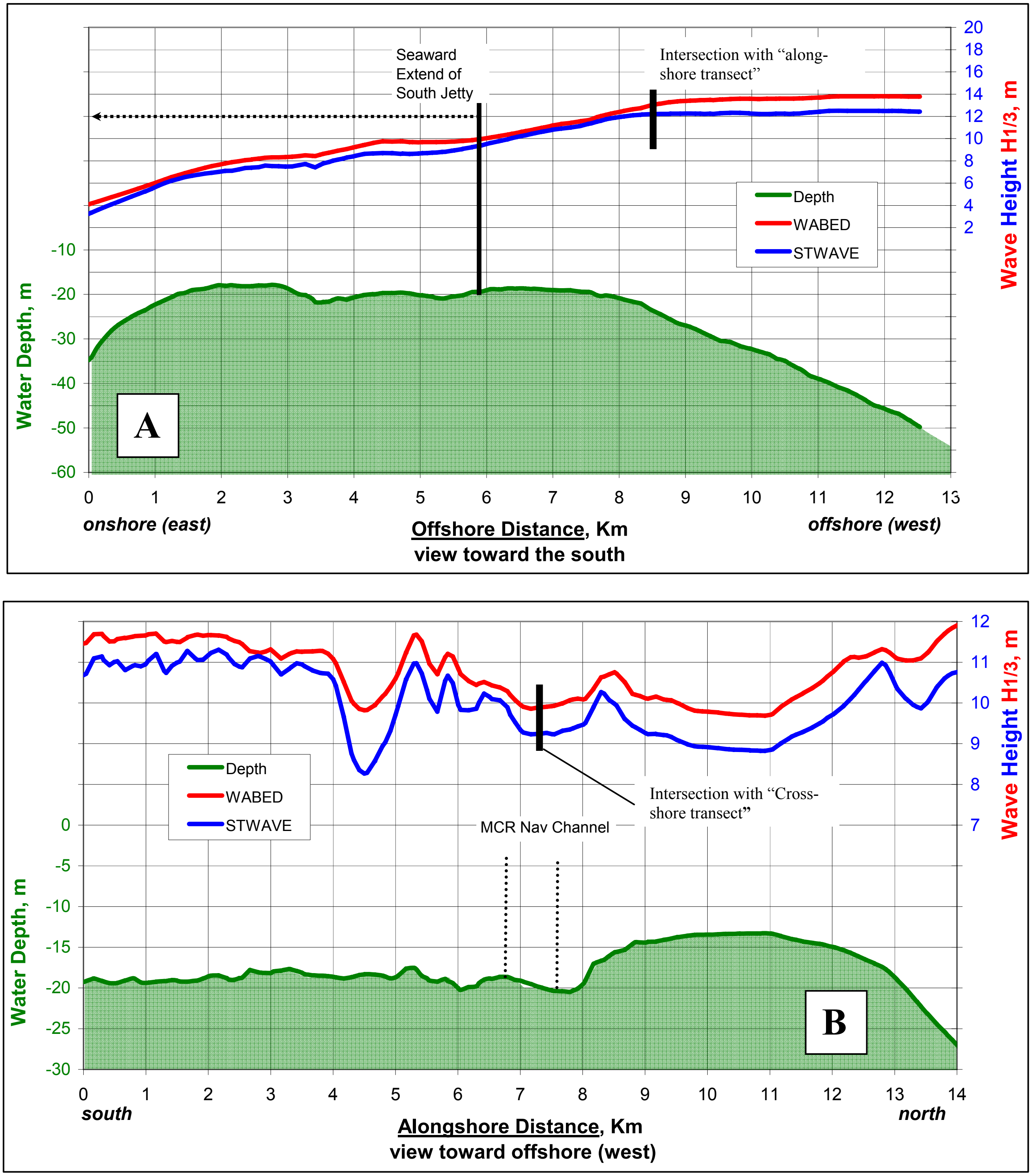


Figure 9. (A) Comparison of Hmo as estimated by STWAVE and WABED along “Offshore Transect” for 4 FEB 06 storm. Beyond 9 km, Hmo for the two models differs by about 2 meters; WABED is consistently higher than STWAVE for this case. The models converge as the seaward slope of the ebb tidal shoal affects the wave field, then diverge at 4-6 km and re-converge at 2 km. (B) Comparison of the two models on the “Alongshore transect” shows that the two models differ uniformly by about 1 m, WABED is consistently higher than STWAVE. Results indicate that energy input due to wind may be higher for WABED than STWAVE. Wave shoaling, dissipation, or breaking also appears to differ in the two models. The models appear to converge within the inlet.