Impact of Current-Wave Interaction on Storm Surge Simulation: A Case Study for Hurricane Bob

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Abstract

Coupled wave-current FVCOM model

This study uses the coupled wave-current version of FVCOM [Chen et al., 2006; Chen et al., 2012] within the NECFOS framework. NECFOS includes three model components: 1) a mesoscale weather model (MMS/WRPS) [Chen et al., 2003], 2) FVCOM [Chen et al., 2003], and 3) SWAVE [Qi et al., 2009]. The coupled FVCOM and SWAVE models were configured for the computational domain, with a horizontal resolution varying from ~50 m in the coastal region to 15 km in the open ocean. A NECFOS-maintained coordinate with a total of 45 layers was used in the vertical. The coupled model was run for the period August 16-29, 1991, during which time Hurricane Bob swept through this region on August 19-20. The open boundary conditions for FVCOM were specified using the Global FVCOM hindcast assimilated fields through one-way nesting. SWAVE’s open boundary conditions were specified by nesting with WaveWatch III (WWIII), which was configured for the northwest North Atlantic basin and run for the same period as SWAVE.

Surface wave simulation

Spatial distributions of model-predicted significant wave heights along the Hurricane Bob track at 06:00, 12:00 and 18:00 GMT, August 19, 1991.

Contributions of wave-current interaction to water elevation

Over the shelf, fluxes estimated in these two cases show some differences, particularly a phase shift around the maximum flux, but their maximum values are close. However, there is a second mode surge into Section A in the case with wave-current interaction after Hurricane Bob passes.

Water Level Simulation

Model-predicted water elevations were compared with observed elevations at 15 coastal tide gages available in the model.

Compressions between model-computed and observed significant wave heights and peak periods during August 19-21, 1991 at buoy 44008 and buoy 44025. Dots: observed; red line: calculated without inclusion of wave-current interaction; blue line: calculated with inclusion of wave-current interaction.

Contributions of wave-current interaction to currents

Wave-current interaction significantly changes the speed and direction of water currents over the shelf; as well as inside Buzzards Bay. Before and after Hurricane Bob’s approach, there were vast eastward water fluxes with the inclusion of wave-current interaction on the shelf.

Roles of water stratification

Time series of net water flux through Section A (upper) and Section B (lower) during August 19-21, 1991 for the model runs with homogeneous (blue line) and stratified (red line) conditions. While the maximum peak flux are quite similar in both cases, the homogeneous and stratified fluxes varied significantly before and after the hurricane center has passed, especially over the shelf.

Vertical profiles of water temperature (left) and velocity (right) before and after Hurricane Bob passed at Site a (upper panels) and Site b (lower panels). Blue, cyan and green lines were taken at a 1-hour interval in the 3 hours before Hurricane Bob arrived at the sites. Magenta, orange and yellow lines were taken at a 1-hour in the 3 hours after Hurricane Bob passed the sites. For Site a, the zero time is 18:00 GMT, August 19; for Site b, it is 15:00 GMT, August 19. Vertical mixing produced by Hurricane Bob significantly change the vertical stratification, which directly affect the surface mixing of the shelf.

Distributions of model-computed near-surface currents and their differences (bottom panels) at 16:00 and 18:00 August 19 under homogeneous (upper panels) and stratified (middle panels) conditions. Black line and red dot at the end shows the hurricane track and location of the hurricane center in each panel.

Although the vertically-averaged water velocities did not differ much in those two cases, much larger differences occurred between the near-surface and near-bottom currents. In the stratified case, the model predicted stronger surface currents in the stratified continental shelf region as a result of surface mixing layer dynamics, with differences as large as ~100 cm/s. Comparison of bottom currents especially around islands differed significantly from the homogeneous case. If we want to simulate the effect of sediment transport, we should consider the ocean stratification.

Introduction

Hurricane Bob originally appeared as a low-pressure area in the Atlantic Ocean near the Bahamas on August 16, 1991. The depression steadily intensified, became a tropical storm, and continued to strengthen as it moved northward and became "Hurricane Bob," at 77.1W, 29.0N at 18:00 GMT August 17. It initially moved northward, and brushed the North Carolina shelf, during which it reached Category 3 with maximum sustained winds of 51-4 m/s. On August 19, Hurricane Bob had dropped to Category 2 as it made landfall near Newport, Rhode Island. Shortly thereafter, it rapidly deteriorated to a tropical storm and moved across the Gulf of Maine towards Maine and Canada, finally dissipating west of Portugal on August 29. The strong (~N>90 m/s), high storm surge and heavy rains produced by Hurricane Bob caused extensive damage over New England with a total loss of $1.5 billion in economy, cleanup costs, uninsured losses and flood claims. This huge loss was due to the passage of the storm over a densely populated region.

Forcing

Hurricane Bob moved up the US east coast and crossed over southern New England and the Gulf of Maine peak marine winds up to 100 mph on 19-20 August 1991, causing significant damage along the coast and shelf. A three-dimensional fully-wave-current coupled Finite-Volume Community Ocean Model (FVCOM) system was developed and applied to simulate and examine the coastal ocean responses to Hurricane Bob. Results from process-oriented experiments show that wave-current interaction caused a significant change of the current direction and mixing, and that relatively little contribution to the maximum sea level elevation along the coast. Diagnostic analyses suggest that the contribution of hurricane-driven wave-current interaction to the net water flux varies in space and time. The wave-current interaction could generate strong vertical current shear in the straitified area, leading to strong offshore transport near the bottom and enhanced water mixing over the continental shelf. Stratification also results in a significant difference of water currents around islands where the water is not vertically well mixed.

Model-predicted water elevations were compared with observed elevations at 15 coastal tide gages available in the model.

Comparisons between model-computed and observed significant wave heights and peak periods during August 19-21, 1991 at buoy 44008 and buoy 44025. Dots: observed; red line: calculated without inclusion of wave-current interaction; blue line: calculated with inclusion of wave-current interaction.

The coupled model was run for real-time simulation with inclusion of tidal forcing, surface wind stress, heat, and evaporation, and river discharge. The wind and air pressure fields used to drive the simulation were the combined fields from MMS [Chen et al., 2004] and a hurricane model based on the symmetric modified Rankin wind speed vortex model [Phadke et al., 2003] with adjustment to 10 m height above sea level [Perswell and Black, 1999] and the addition of hurricane along-path velocity following Jelinski and Smith [1996]. The MMS and hurricane model wind and air pressure fields were merged over the transition zone 1.5-3.0 km south of the hurricane center.

The contribution of wave-current interaction to the sea level change along the coast varied from north to south.

The larger differences in the observed-modelled results between with and without inclusion of current-wave interaction are mainly at Newport, Point Judith, New London, and Montauk, the region where Hurricane Bob had the strongest effects. From statistical analysis, no significant difference was found in the modeled water elevations at these 15 coastal sites between the cases.

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References


During the hurricane period, the model compared well with observed values at 15 coastal tide gages available in the model.