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Three dimensional simulation of transport and fate of oil spill under wave induced circulation

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ABSTRACT

An oil spill model is developed and coupled to a current-wave model to simulate oil spill transport in aquatic environments where waves are present. The oil spill model incorporates physical–chemical processes of oil spill, and simulates oil slick transport by a circulation-driven Lagrangian Parcel model. Using the coupled oil spill model and the current-wave model CH3D-SWAN, a laboratory observed wave induced circulation and oil slick evolution are successfully simulated, while different current-wave coupling schemes generate different flow patterns and oil slick evolution. The modeling system is also shown to simulate Langmuir circulation and resulting oil slicks. Hypothetical scenarios of oil spill near Virginia coast during Hurricane Isabel and Irene are simulated using the oil spill model and the CH3D-Storm Surge Modeling System to assess the role of storm waves during oil spill. The spill area is significantly larger when storm waves are considered, implying waves significantly increase oil spill dispersion.

1. Introduction

Oil spill can significantly impact the coastal and estuarine environments, causing major damage to the ecosystem, beaches, coastal wetlands, fisheries and water supplies. Over the years there have been many famous accidents (e.g., Amoco Cadiz, Exxon Valdez, Ixtoc and DWH). The Deep Water Horizon (DWH) oil spill in 2010 covered hundreds of square miles of the surface water and lasted for three months. It was estimated that a total of 205.8 million gallons of oil and 1.8 million gallons of dispersant was introduced into the Gulf of Mexico (Azwell et al., 2011). The spilled oil impacted and significantly damaged the beaches, wetlands, and estuaries in Mississippi, Alabama and northwest Florida. Thousands of miles of the Gulf coast was closed to fishing. To protect the coastal communities and coastal ecosystems from future damage due to oil spills, improved scientific understanding of the transport and physical–chemical–biological processes of oil spill in the aquatic environments is needed and comprehensive oil spill models need to be developed and improved.

Studies have been dedicated to understand and quantify the physical and chemical processes (e.g., spreading, evaporation and emulsification) during oil spill (Fay, 1971; Lehr et al., 1984a, 1984b; Mackay et al., 1980; Stiver and Mackay, 1984; Delvigne, 1989), which are mainly empirical equations depending on calibration of parameters for specific oil types. The approaches for the behavior and fate of oil spilled in the ocean environment are systematically reviewed in Reed et al. (1999). Significant advancements have been made to improve previous empirical understanding and parameterization of those processes, such as the buoyancy velocity of oil droplets by Zheng and Yapa (2000), break-up and coalescence of oil droplets by Bandara and Yapa (2011) and emulsification by Xie et al. (2007). Yapa et al. (2010) developed by far the most comprehensive model to simulate the fate and transport of gas and hydrate from deep water oil spill.

Transport and fate of oil spill in coastal ocean have been studied using numerical approaches. Beegle-Krause (2005) developed a semi-public domain model GNOME (General NOAA Oil Modeling Environment) for the purpose of emergency response to oil spill, but the model does not have many of the physical–chemical processes related to oil. Shen et al. (1987) developed an oil spill model that incorporated several physical–chemical processes related to oil and linked it with a hydrodynamic model RLID (Schwab et al., 1981) to simulate the oil slick transport in lakes. Similar studies were conducted by Chao et al. (2003), Wang et al. (2005, 2008), and Guo and Wang (2009). However, those models are mostly designed for oil spill from the water surface, since the buoyancy effects on oil spill transport over the water column are not considered. Using the integrated model by Zheng and Yapa (2000) for buoyancy velocity of oil droplet, the oil spill model in this study provides a more accurate estimation on oil spill transport in the vertical direction, and can be used for oil spill from deep water. The primary purpose of this paper, however, is to demonstrate the importance of wave induced circulation on oil spill by using a circulation model CH3D (Curvilinear-grid Hydrodynamics in 3D) which incorporates several advanced schemes of radiation

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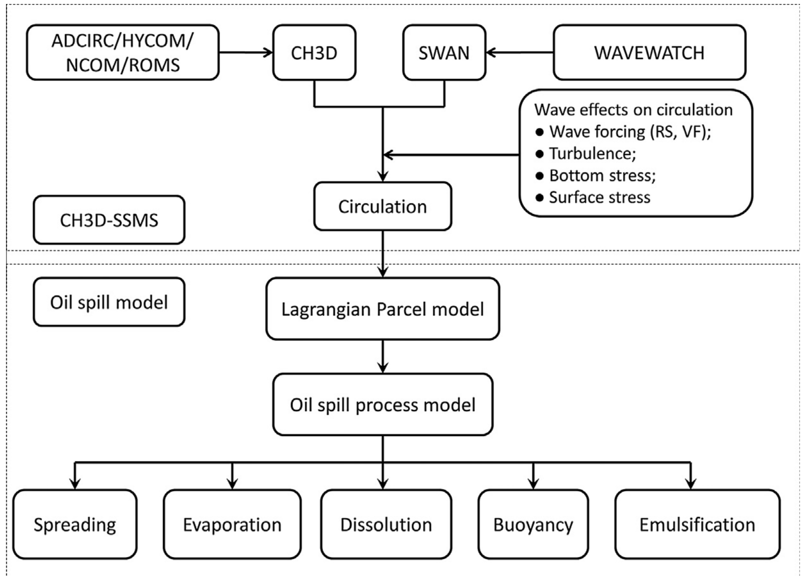

Fig. 1. The simulation process of the circulation model and oil spill model. RS represents the radiation stress formulation; VF represents the vortex force formulation.

stress and vortex force formulations and appropriate physical and chemical processes governing the oil spill. As such, many processes such as weathering, particle size distribution, multiple phases including gas and hydrates are not considered here.

This study aims to integrate an oil spill model with a coupled current-wave model to investigate the influence of wave induced circulation on oil spill transport in coastal ocean. An oil spill model, which includes a Lagrangian Parcel (particle tracking) model and an oil spill process model, is developed and coupled with a three-dimensional current-wave modeling system CH3D-SWAN (Sheng et al., 2010a, 2010b; Sheng and Liu, 2011). An oil spill event driven by wave induced circulation in a laboratory experiment is simulated and compared with observations. Oil spill during Langmuir circulation is demonstrated. Hypothetical scenarios of oil spill near Virginia coast during Hurricanes Isabel and Irene are simulated, and the effects of storm waves on oil spill transport are assessed.

Section 2 of the paper describes the hydrodynamic model CH3D, the Lagrangian Parcel (particle tracking) model and oil spill process model. Section 3 presents test simulation results using the oil spill model. Conclusions are given in Section 4.

2. Methodology

2.1. Coupled current-wave model – CH3D-SWAN

The oil slick transport is driven by circulation produced by a hydrodynamic model CH3D, which is a three dimensional circulation model originally developed by Sheng (1986) and has been successfully applied to simulate the circulation driven by tide, wind, density gradients and waves in various water bodies (e.g., Sheng et al., 2008, 2010a,b; Sheng and Kim, 2009; Sheng and Liu, 2011). CH3D uses a boundary fitted non-orthogonal curvilinear grid in the horizontal directions to resolve complex shoreline and geometry, and a terrain-following σ-grid in vertical direction. The model uses a Smagorinsky type horizontal turbulent eddy coefficient (Smagorinsky, 1964) and a robust turbulent closure model (Sheng and Villaret, 1989) for vertical mixing.

Sheng et al. (2010a, 2010b) and Sheng and Liu (2011) dynamically coupled the hydrodynamic model CH3D with a wave model

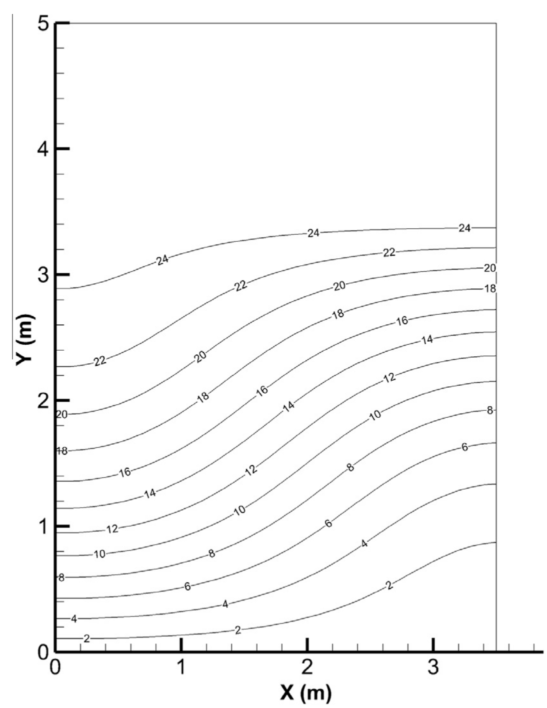

Fig. 2. Bathymetry of the domain used for simulation. Numbers on the contour line indicate water depth (unit: cm).

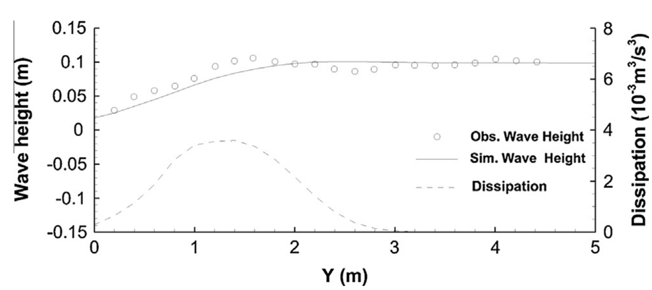

Fig. 3. Comparison of observed and simulated wave height, and dissipation calculated by SWAN at $x = 2.275$ m.