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Variations of storm surge caused by shallow water depths and extreme tidal ranges

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ABSTRACT

A few studies have analyzed the characteristics of storm surge because of the difficulties involved in laboratory experiments and field observations, and little is known about the variations of storm surge on different tidal ranges. This study analyzes the influence of water depth and astronomical tide upon storm surge by using storms virtually generated by PBL-ADCIRC, a verified numerical analysis program. To examine the potential errors of the conventional method which estimates the maximum water level by linear superposition of tides and storm surge, we conducted our simulations in the seas around the Korean Peninsula which have quite different water depths and tides. Storm surge was found to be in an inverse proportion to water depth and tide. The simulation results confirmed that the coupling of storm surge and tides is essential in the coast of small water depth and large tides.

1. Introduction

Storm surge is getting severe as the intensity of storm has increased recently because of climate changes, and the damages caused by the storm surge have been increasing every year. Storm surge researches have focused on development of numerical models for forecast or hindcast by comparing storm surge with observed data. However, the characteristics of storm surge have been studied in restricted conditions because of the danger and difficulties involved in laboratory experiments and field measurements. Differences between observation data and numerical results in the area of large tidal range have been little studied.

The studies of interaction by storm surge and tide have been conducted in some ways. The variation of surge and phase of tide by interaction in the Thames estuary was studied by Rossiter (1961), Prandle and Wolf (1978) and Wolf (1981). Prandle and Wolf (1978) analyzed the observation results in the Thames estuary with a numerical model and concluded that surge peak occurred at high tide. Wolf (1981) and Horsburgh and Wilson (2007) reported that peak residual occurred several hours before the high water by the interaction between surge and tide from tidal observations. They concluded that the increased water depth by storm surge induced the speeding up of tidal wave propagation. Bernier and Thompson (2007) analyzed the oscillation of storm surge using numerical simulation and observation in the coast of northeastern United States. They described that the oscillation was caused mainly by the tide-surge interaction and nonlinear bottom stress was important factor. Zhang et al. (2010) studied the oscillation of storm surge by the tide-surge interaction in shallow water of the Taiwan Strait, and concluded that nonlinear bottom stress was a major term, whereas the nonlinear advective term and the shallow water effect were not. Rego and Li (2010) simulated storm surge over a wide continental shelf and showed the reduction of storm surge elevation at high tide along the Gulf of Mexico at the landfall of Hurricane Rata using FVCOM model. In their study, nonlinear interaction was more apparent in the variation of water depth, because the tidal range of the Texas coast was micro tide.

Many numerical models have been developed for the simulation of storm surge. Jelesnianski et al. (1992) have proposed and National Weather Service (NWS) have developed the Sea, Lake and Overland Surges from Hurricanes (SLOSH). It is the primary model that has been used by the Federal Emergency Management Agency (FEMA), the National Oceanographic and Atmospheric Administration (NOAA) and US Army Corps of Engineers (USACE). The coupled ADvanced CIRCulation (ADCIRC) and Planetary Boundary Layer (PBL) model have been developed to simulate storm surge, and it was compatible with Empirical Simulation Technique (EST) as well as Joint Probability Method (JPM). Finite-Volume Coastal Ocean Model (FVCOM) based on finite volume method was recently developed by Chen et al. (2003, 2006). Because SLOSH is computationally very efficient and needs less computation time than ADCIRC, it is suitable for real time

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forecasting by simulation. ADCIRC can produce accurate results using high resolution grids but it requires much computational time. ADCIRC shows good results in the simulation for very large area such as the coast of the US and the Gulf of Mexico.

In this study, we use the coupled numerical model which is composed of ADCIRC (Luettich et al., 1992; Westerink et al., 1992; Luettich and Westerink, 2004) and PBL hurricane model (Thompson and Cardone, 1996), and it shows the variation of storm surge in extreme conditions such as very shallow water depth with distinct tidal range. The model has shown a good agreement with the observations in storm surge researches (Heerden et al., 2007; Dean et al., 2004; Scheffner and Carson, 2001). Dean et al. (2004) reviewed the simulation of storm surge by ADCIRC and discussed the differences caused by uncertainties between model and field measurement. Mattocks et al. (2006) implemented ADCIRC model with hurricane wind models based on an asymmetric hurricane vortex formulation. Mattocks and Forbes (2008) mentioned some important metocean data such as real-time weather data stream, actual sea surface elevation and depth averaged current velocity to develop a new real-time prediction system.

Although the parameters of the wind are the most important in estimating the storm surge, the conditions of the surrounding environment also play an important role, and the environmental conditions include wave characteristics, distance from the storm center, track of storm, angle of wave approach, forward speed, duration of storm, astronomical tide, water depth, sea level rise, and geographic features. This study analyzes the effects of tide and water depth on storm surge around the Korean Peninsula. Because the coastal areas of the Korean Peninsula have drastically different water depths and tides in different locations, its unique ocean conditions are suitable for the study. The eastern sea has deep water and micro tide, but the western sea is on the continental shelf with a very shallow water depth and a great difference between the ebb and flow of the tide.

In the past, the simulations of storm surge and tide were conducted separately because of the difficulty in coupling the storm surge and tide, and the maximum water level was estimated by the sum of each separate simulation result. It was a simple method used for most cases. We found that storm surge is strongly dependent on the variation of water depth, and the conventional estimation method is liable to make errors in the coasts of small water depth and large tides. In this respect, the objective of this study is to enhance the understanding of the variations of storm surge at different water depths and tides.

This article is organized as follows: Section 1 introduces the problems with the conventional way of storm surge simulation; Section 2 describes the study area and the methodology. The numerical model used in analyzing the storm surge is described in Sections 3 and 4 analyzes storm surge by water depth. Section 5 describes variations of storm surge caused by extremely high tide in shallow water depth. Conclusions are given in Section 6.

2. Study area and method

The study area is the seas around the Korean Peninsula. The numerical grid and the information of typhoons are shown in Fig. 1. The computational domain is located between 117°E to 136°E and 30°N to 42°N, which is surrounded by the Yellow Sea, the South Sea and the East Sea located in the west, south, east side of the Korean Peninsula, respectively.

The Yellow Sea is the western sea of Korea, and its average and deepest water depths are 44 m and 103 m, respectively. The shallow Yellow Sea forms a continental shelf, and its tidal range is one of the largest in the world with the 9 m spring tidal range in Incheon, Korea. However, the East Sea, which lies in the east of Korea, has water depth and tide completely different from the Yellow Sea. The average depth, the deepest depth and the tidal range of the East Sea are 1530 m, 3762 m and 0.3 m, respectively. The South Sea of Korea has about 2200 islands and its average depth and the deepest depth are 100 m and 227 m, respectively. The information on these seas is given in Table 1. Because the Korean Peninsula has various water depths and tidal ranges,

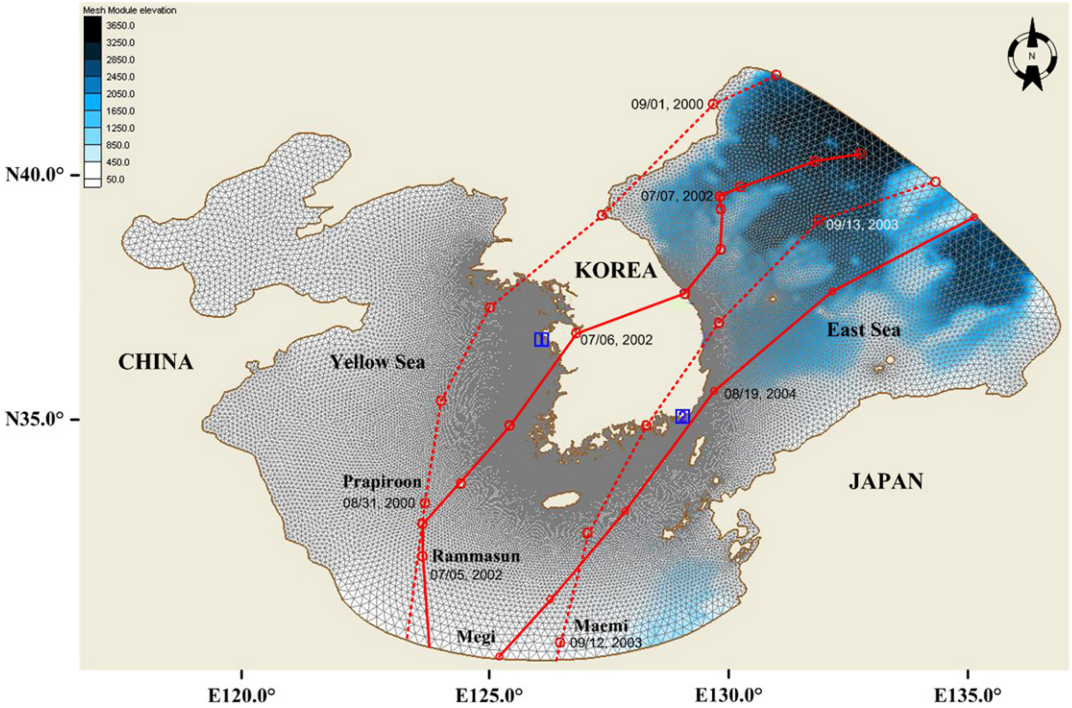

Fig. 1. The numerical grid and the tracks of typhoon Maemi (2003), Megi (2004), Prapiroon (2000) and Rammansun (2002) at every 6 h. The locations of two tidal stations (1. Anhung, 2. Busan).