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Storm surges along the Tottori coasts following a typhoon

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ABSTRACT

In the present study, the after-runner surge that maximum surge height appears 15–18 h later along the Tottori coasts facing the Sea of Japan/East Sea (SJES) after typhoons undergo a change in shape and intensity as extratropical cyclones is investigated using asymmetric and symmetric wind and pressure fields of Typhoon Songda (2004). For the asymmetric wind and pressure field, the Weather Research and Forecasting (WRF) model is used, while for the symmetric wind and pressure field, a parametric wind and pressure model is used. The results indicate that both models simulate fairly well the 10 m level wind and the sea level pressure along the Pacific Ocean, while the WRF model shows better agreement with the observations over the SJES. Subsequently, from storm surge simulations for Typhoon Songda, it is found that using the deformed and asymmetric meteorological field of typhoon structures agrees well with observations. The study shows that the after-runner surge's characteristic comes from the Ekman setup in the presence of the Coriolis force over the Tottori coasts. It is critical that its behavior should be taken into account for the safety design of coastal defense structures around the Tottori coastal region.

1. Introduction

A storm surge produces a rise in sea level. In Japan, it is induced by tropical cyclones (hereafter, the word 'typhoon' is used). It is important to understand storm surge behavior in order to reduce and prevent coastal disasters by employing countermeasures against inundation of coastal areas. In general, sea level rise along the coasts of Japan appears several hours before a typhoon arrives, and the maximum surge coincides with the time of typhoon landfall. However, the time history of the surge elevation is different depending on the various regions in Japan; while the maximum surge appears at the time of landfall on coasts along the Pacific Ocean, it appears 15–18 h later along the Tottori coasts facing the Sea of Japan/East Sea (SJES) after veering northwards. Here we define the storm surge, occurring after a typhoon has passed, as the after-runner surge. For example, Typhoon Songda's maximum surge along the Tottori coasts was recorded 15 h after the typhoon passed in September 2004.

Kennedy et al. (2011) introduced that a large water level increase (called the forerunner surge) appeared along a substantial section of the western Louisiana and northern Texas coasts 12–24 h in advance of the landfall of Hurricane Ike (2008). They diagnosed the forerunner surge as being generated by Ekman setup on the wide and shallow shelf. In contrast to the forerunner surge, in this study, we will show a sea surface level rise that appeared along the Tottori coast approximately 15 h in retreat of the landfall of Typhoon Songda (2004). We will discuss that the after-runner surge comes from the Ekman setup and the predominant factor is the Coriolis force over the Tottori coast. Understanding of the after-runner surge is important for the safety design of coastal defense structures and the risk management, however no relevant study about after-runner surge in the SJES region has been previously reported.

The SJES is a sea bounded by the Korean Peninsula and the Japanese islands of Hokkaido, Honshu and Kyushu. It is linked to other seas through the Tartary Strait, La Perouse Strait and the Tsushima/Korea Strait. The surrounding mountainous terrains deform the core structure and intensity of typhoons (e.g., Bender et al., 1987). According to Kitabatake (2008), typhoons often undergo extratropical transition when they move into the mid-latitudes because of energy budgets (Palmén, 1958; DiMego and Bosart, 1982) and structural changes induced by a baroclinic environment (e.g., Klein et al., 2000). In particular, Kitabatake (2008) showed that the typhoon intensity is directly downgraded to an extratropical cyclone (maximum wind speed <8.7 m/s) or sometimes reduces to a tropical cyclone ($8.7<$ maximum wind speed <17.5 m/s) above 40°N in the SJES and North Pacific Ocean.

Since parametric wind and pressure models for typhoon are introduced by Fujita (1952) in Japan, many advances have occurred (e.g., Fujii and Mitsuta (1986); Veltcheva and Kawai, 2002). Recently, improved and new formulations were provided for predicting extreme waves generated by hurricanes along Gulf of Mexico (e.g., Jeong et al., 2012; Panchang et al., 2013). However,

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parametric models are difficult to reproduce downgraded extra-tropical cyclones above 40°N in the SJES despite of their improvement and advance. Recently, meteorological circulation models for typhoon wind and pressure fields have been used to reproduce the deformation of typhoon structure and to predict extreme waves and surges (e.g., Lee et al., 2010; Mase et al., 2008).

We investigate the effects of the deformation of the typhoon structure on after-runner surges in the present study in order to understand the after-runner surge. The event studied is Typhoon Songda in 2004. The Weather Research and Forecasting (WRF) model developed by the National Center for Atmospheric Research (NCAR) and Schloemer's (1954) parametric pressure formula, combined with a wind model of Fujii and Mitsuta (1986), are used in order to reproduce the pressure and wind fields. The WRF model is chosen to reflect the physical change in the typhoon structure and intensity. On the other hand, the parametric model is selected with no shape factors employed to determine the deformation of the typhoon structure. Subsequently, the after-runner surge due to Typhoon Songda is simulated by inputting the meteorological data sets into a coupled model of Surge, Wave and Tide (SuWAT) developed by Kim et al. (2008, 2010) to address the origin of after-runner surges.

The models, together with the experimental conditions used in the study, are explained briefly in Section 2. The experimental results and a discussion are provided in Section 3, with the main findings summarized and conclusions drawn in Section 4.

2. Model descriptions and simulation conditions

2.1. Model descriptions

2.1.1. Weather Research and Forecasting model

We used the Weather Research and Forecasting model (WRF) to reproduce the Typhoon songda's meteolorogical field in the presence of the deformation in shape and the change in intensity. The WRF model, version 3.0, developed by NCAR (Skamarock et al., 2008) is a three dimensional, fully compressible, non-hydrostatic model formulated within a terrain-following mass coordinate in the vertical direction. Based on the previous studies over the SJES (Kim et al., 2012, 2013), the model physics in the WRF are chosen: the microphysics of Thompson et al. (2004), the land surface of Chen and Dudhia (2001), the planetary boundary layer of Hong et al. (2004), the shortwave radiation of Chou and Suarez (1994), and the cumulus parameterization of Kain (2004).

The three domains from the outermost, 2nd and 3rd, which are the two-way nesting domains shown in Fig. 1(a), are used for WRF simulations. The outermost domain (D01) with a grid size of 12 km covers the overall typhoon tracks. The intermediate domains (D02 and D03) are downscaled to grid sizes of 4 km and 1.3 km, focusing on the Tottori coasts to be suitable for storm surge simulations. In all the domains, the 40 vertical layers are used; the lowest vertical height near the surface is approximately within 10 m, the top pressure is 1000 hPa. The initial and boundary conditions for the WRF model are obtained from the National Centers for Environmental Prediction (NCEP): we use the NCEP FNL (Final) Operational Global Analysis data of 1° × 1° in space and 6 h interval in time (referred to hereafter as FNL data). A bogus data assimilation scheme to generate the initial typhoon structure is not employed in this study.

2.1.2. Parametric wind and pressure model

A parametric wind and pressure model embedded in the SuWAT model is based on the formulas of Schloemer (1954) for the pressure and of Fujii and Mitsuta (1986) for the wind. The Fujii and Mitsuta (FM) model has been used widely when simulating

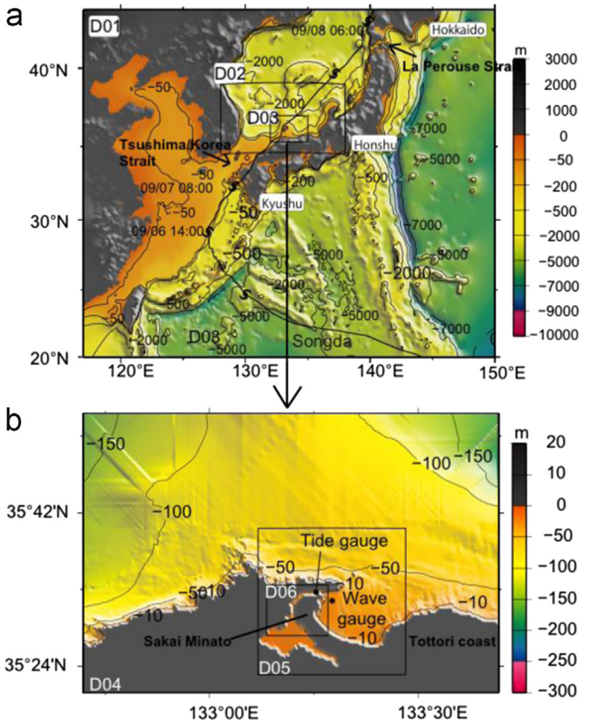

Fig. 1. Typhoon Songda's best track and the computational domains: (a) the outermost domain D01 and intermediate domains D02 and D03; (b) positions of tide and wave gauges in the intermediate domains D04 and D05, and innermost domain D06.

storm surges in coastal engineering (e.g., Kim et al., 2010). In recent years, parametric wind and pressure models have been improved to reproduce the asymmetric structure of typhoons (e.g., Veltcheva and Kawai, 2002). However, those models, studied over coasts of the Pacific Ocean, are considered only for the shape of typhoons. In addition, the change of intensity of extra-tropical cyclones has not been studied in the SJES. Therefore, the present study employed the original FM model to reproduce the Typhoon Songda's meteorological field without shape deformation.

The FM model is briefly described as follows: the ratio $G(x)$ of a surface wind to a pressure gradient wind is a function of $x = r/r_0$, where r is the radius from the typhoon center to a particular location and r_0 denotes the radius to the location of maximum wind speed:

$$G(x) = G(\infty) + [G(x_p) - G(\infty)](x/x_p)^{k-1}\exp\left\langle (1-1/k)[1-(x/x_p)^{k-1}]\right\rangle \tag{1}$$

in which $k = 2.5$, $x_p = 0.5$, $G(x_p) = 1.2$ and $G(\infty) = 0.6667$ are used originally in Fujii and Mitsuta (1986). The radius r_0 is determined by the least square method for the best fitting radius based on the observed sea level pressure at 148 stations, which are operated by Japan meteorological Agency. The pressure gradient wind is reduced by a factor $G(\infty)$ of 0.6667 to take into account the topographical friction in this study. The surface wind is obtained by multiplying the pressure gradient wind speed by the ratio $G(x)$ and setting the inflow angle between the wind vector and isobar to 30°. Finally, the wind at 10 m height is acquired as the vector sum of the surface wind and the typhoon's speed of movement. The deformation of the typhoon structure is not taken into account in this model.

2.1.3. Coupled model of surge, wave and tide

The SuWAT model, developed by Kim et al. (2008, 2010), is used to simulate the after-runner surge caused by Typhoon