Continental Shelf Research 169 (2018) 1–16

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Forerunner storm surge under macro-tidal environmental conditions in shallow coastal zones of the Yellow Sea

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ARTICLE INFO

Keywords:
Yellow Sea
Forerunner surge
Kelvin waves
Geostrophic setup
Resonance
Nonlinear effects

ABSTRACT

Typhoons affecting the west coast of Korea (WCK) in the Yellow Sea (YS) typically enter the continental shelf across the Ryukyu Islands, where surges can develop in the shallow water and interact with the macro-tidal environment. In this study, we investigate the generative mechanism of forerunner surge (FS) occurring before the main surge of two typhoons in the WCK, Prapiroon, and Bolaven. Sensitivity analyses of FS generation to bottom friction, Coriolis effects, tides, wind, and pressure forcing were conducted. The effect of the Coriolis force, which depends on latitudinal position, is not an influential factor in the FS along the shallow inner shelf of the WCK. However, Kelvin waves move along the WCK and cause nonlinear characteristics that amplify or dampen the FS, depending on the timing of flooding or ebbing tides. We found that the FS appeared at least 12.6 h prior to the main surge, which is almost the same as the geophysical resonance period. Moreover, the FS was not only influenced by the geostrophic setup, represented by the distance from the coast, but may also be amplified by topographic effects, such as the concavity of the coastline. When a typhoon enters the Ryukyu Islands at an angle $< 20^{\circ}$ and moves at a relatively slow speed ($< 20\,\mathrm{km\,h^{-1}}$), a FS is more likely to occur.

1. Introduction

As global climate change progresses, coastal hazards have increased, and therefore the need for mitigation or preparedness for storm surges has also risen (Hoffman et al., 2010; IPCC, 2011). During the storm season, meteorological agencies mostly announce possible peak surge height (SH) values when tropical cyclones are approaching coastal regions. However, surges occasionally occur 12–24 h prior to the main surge with significant water surface anomalies. Probabilistic modeling alone cannot capture these precedent surges, also termed forerunner surges (FS). Sometimes, the SH of FSs exceeds that of normal storms, as observed for Hurricane Ike, which had a SH of 1.7–2.5 m in Galveston Bay, Texas in 2008 (Hope et al., 2013).

Hurricane Ike gained public and scientific attention because it had a similar strength, track, and forward speed as Hurricane Rita in 2005; however, it exhibited quite different surge processes. Due to its large size and strong shore-parallel shelf current, Hurricane Ike generated the largest recorded geostrophic setup or forerunner (Kerr et al., 2013a, 2013b). Kennedy et al. (2011) explained that a large and unpredicted increase in water level appeared along a prominent section of the western Louisiana and northern Texas (LATEX) coasts 12–24 h before the landfall of Hurricane Ike. In some areas, water levels reached 3 m above mean sea level. However, SHs reaching 3 m occurred prior to the main surge, and could not be predicted by prevailing probabilistic analyses.

Hurricane Ike demonstrates that predicting FSs is extremely important for storm preparedness. Real-time guidance systems, such as the Coastal Emergency Risks Assessment (CERA, http://coastalemergency.org), employ deterministic simulations, which can provide estimates of maximum SHs. The deterministic approach can provide not only

Abbreviations: ADCIRC, Advanced Circulation Model; ASGS, Advanced Surge Guidance System; ATCF, Automated Tropical Cyclone Forecasting System; CERA, Coastal Emergency Risks Assessment; DH, Daeheuksando; EWS, Early Warning System; ECS, East China Sea; FES2012, Finite Element Solution 2012; FS, Forerunner Surge; GSHHG, Global Self-consistent, Hierarchical, High-resolution Geography Database; GOM, Gulf of Mexico; IC, Incheon; IPCC, Intergovernmental Panel on Climate Change; KHOA, Korea Hydrographic and Oceanographic Administration; KMA, Korea Meteorological Agency; KO, Kunsan outer port; MP, Mokpo; LATEX, Louisiana and Northern Texas; NGDC, U.S. National Geophysical Data Center; NWP, Northwestern Pacific; PS, Primary Surge; RDAPS, Regional Data Assimilation and Prediction System; RMW, Radius of Maximum Wind speed; SH, Surge Height; SP, Seogwipo; UTC, Universal Time Coordinated; WCK, West Coast of Korea; WSE, Water Surface Elevation; YS, Yellow Sea

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https://doi.org/10.1016/j.csr.2018.09.007
Received 13 June 2017; Received in revised form 18 July 2018; Accepted 16 September 2018
Available online 18 September 2018

maximum SHs, but also the heights of the FS or later surges according to updated meteorological databases of typhoons or hurricanes (Suh et al., 2015). Adopting a deterministic storm surge model may allow time-variant forecasts of both the main surge and FS as an advantage over the probabilistic approach. To aid in storm preparedness, early warning systems, such as the Advanced Surge Guidance System (ASGS), can be incorporated into the emergency management framework.

Storm phenomena are both time-variant and site-specific; thus, it is important to understand the ambient tidal hydrodynamics of a given region of interest. Thiebaut and Vennell (2011) analytically demonstrated that a combination of the storm translation speed (relative to depth), timescale, and direction could generate a resonant response in the ocean, and enhance storm surges as the disturbance crosses a vertical coast, step, or shelf. Wolf (1981) and Bertin et al. (2012) argued that the effects of shallow water are important in surge analysis for tidal ranges larger than 3 m and water depths below 10 m. Many secondary factors influence the magnitude of a storm surge through the Coriolis effect in the form of coastal upwelling and forerunners. While these factors may be secondary to winds in generating surges, they can be of great importance under certain storm conditions and coastal environments (Veeramony et al., 2012). Studies on the primary mechanisms underlying the generation of forerunners (Hope et al., 2013; Kennedy et al., 2011; Sebastian et al., 2014) have found that geometrical characteristics, Ekman setup, and size of the wind field can affect the FS height by ~1 m. Factors controlling the Coriolis-driven early setup include the cross-shelf wave, which has an approximate period coinciding with the resonant period of the shelf and coastally trapped Kelvin waves.

Resonant coupling between typhoons, tides, and topography accounting 12.6 h of the natural period of the Yellow Sea (YS) contributed to further enhancement of the storm surge in Typhoon Bolaven (Kim et al., 2014). The YS is a semi-enclosed marginal sea in the northwestern Pacific Ocean that is surrounded by the Korean Peninsula, the Chinese coast, and the Ryukyu Islands. Careful analysis of the conditions required to understand typhoon storm surges on the west coast of Korea (WCK). The WCK has a complex coastline marked by a very shallow depth. The macro-tidal environment ranges from a 3 m mean tidal range at Mokpo near the southwestern-most end, to a 9 m range at Incheon, located near the middle of the peninsula. Along the Korean coastlines, especially the WCK, FS occasionally appears at least 12.6 h prior to the primary surge (PS) of a typhoon.

In this study, we analyzed storm surges on the WCK addressing the importance of nonlinear effects on tide-surge interactions in shallow water areas with a macro-tidal range (Wolf, 2009). We also investigated Kelvin waves, resonance, and the effects of geostrophic setup when typhoons enter the continental shelf of the East China Sea (ECS) to the YS, passing over the Ryukyu Islands. Barotropic simulations of surges were conducted in order to identify the sensitivity of FSs to various factors, such as the Coriolis force, tides, and bottom friction, and we compared our findings to the dynamics of FSs in the Gulf of Mexico (GOM).

2. Characteristics of recorded forerunners on the west coast of Korea (WCK)

In general, three or four typhoons threaten Korea during the summer, from July to September each year. Typhoons occasionally occur during the perigean spring tide when the tidal range reaches the annual maximum. Fluctuations in the water level during this period can easily lead to the inundation of low-lying coastal areas. Analyzing historical typhoon track data, Kim and Suh (2016) found that ~41.2% of the typhoons impacting Korea affect the west coast, and could be amplified or altered by the geophysical setup, and/or strong alongshore tidal currents induced by meso- to macro-tidal environments.

In this study, two typical typhoon tracks passing the ECS and YS, Typhoons Prapiroon (TY0012) and Bolaven (TY1215) were selected to analyze FSs occurring due to geostrophic effects in the WCK. According to the best tracks, Prapiroon traveled northwest, and the wind field strengthened until it reached a 10 min sustained wind speed of 36 m s^{-1} and a radius of 290 km. Similarly, Typhoon Bolaven traveled north, and the wind field intensified until it reached a 10 min sustained wind speed of 64 m s^{-1} and a radius of 240 km. The maximum winds were 34 kt at

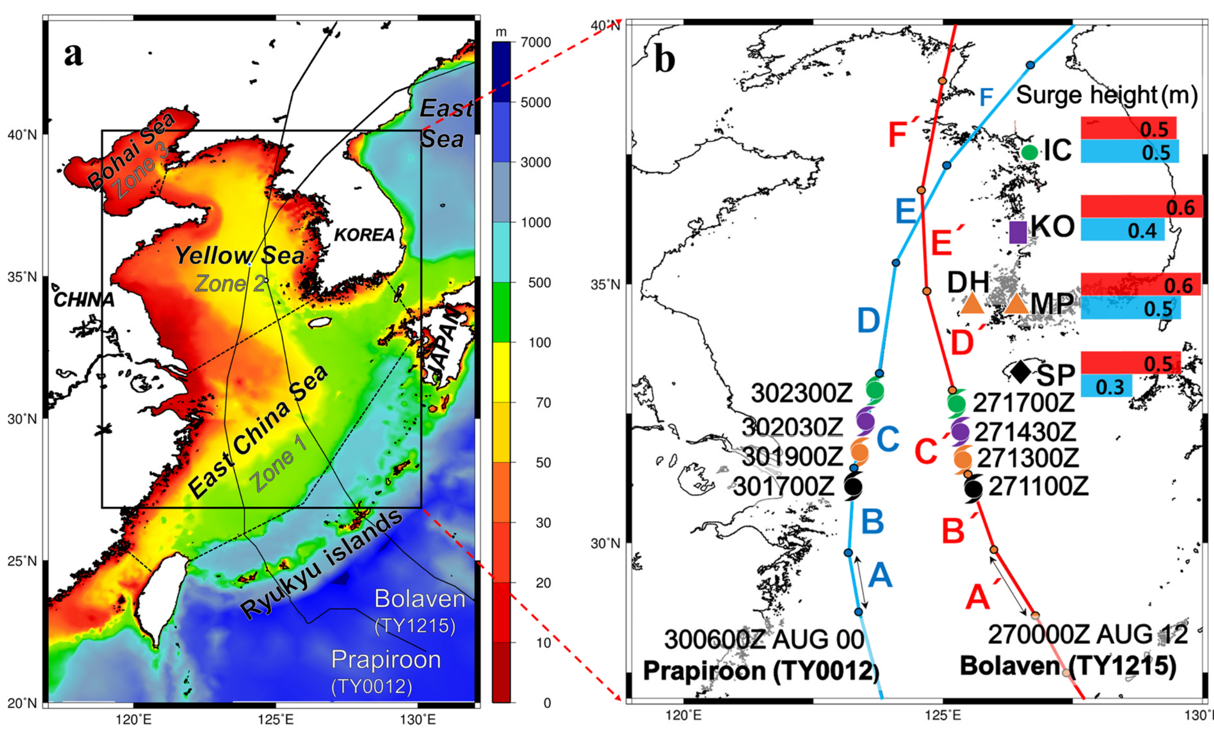

Fig. 1. (a) Typhoon tracks of Prapiroon and Bolaven passing the Ryukyu Islands. (b) The location of Prapiroon (blue line) and Bolaven (red line) when the FS reached the corresponding colored tidal station. The FS heights at the four stations are also shown.