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Inner shelf response to storm track variations over the east LeiZhou Peninsula, China

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ABSTRACT

The LeiZhou Peninsula is situated at the southern tip of mainland China with frequent tropical cyclone activity. Its special feature of large-scaled westward concaved coastline results in complex storm-induced hydrodynamic processes in a variety of spatial scales. Statistics show that the surge distributions in the east LeiZhou Peninsula are sensitive to the landfall location and moving direction of the storm tracks. This paper provides a detailed assessment to investigate the nearshore and coastal responses to different tropical cyclone behaviours in this region. A high-resolution integrally-coupled wave and circulation model (FVCOM-SWAVE) on a large-domain unstructured mesh containing the northern South China Sea is applied in this study. The model is validated by observed water level records during three typical typhoon events of Krovanh (2003), Kai-tak (2012) and Mujigae (2015). Induced by the right-handed cyclone wind rotation at the northern hemisphere, surges at ZhanJiang and NanDu perform as set-up processes when the storm lands to the south of the ZhanJiang Bay and as mixtures of slight set-up and medium set-down when the storm lands to the north of the ZhanJiang Bay. For set-up cases, the storm tracks with moving direction of WNW ($\alpha = 10^{\circ} \sim 30^{\circ}$) are more likely to cause heavy surges. Complex coastal morphology has great impacts on the surge distributions. For outer-bay coastlines, the area at the distance of $1 \times RMW \sim 1.5 \times RMW$ right to the cyclone track is most dangerous prone to high surge. For inner-bay areas, three high-risk regions—the NanSan Channel, the HuGuang branch of the ZhanJiang Bay and west coast of the LeiZhou Bay—are more likely to generate violent surges because of their westward narrowing-down configurations. Protected by a narrow entrance oriented to ESE, surge variations in the ZhanJiang Bay are less sensitive to the variations of landfall location and moving direction than that in the LeiZhou Bay.

1. Introduction

Storm surge is the abnormal rise of sea surface height caused by atmospheric forcing, including the wind stress and atmospheric pressure associated with extratropical cyclones or tropical cyclones such as hurricanes or typhoons (Kerr et al., 2013). The generation of storm surge has increased the susceptibility of wide-spread flooding in low-lying coastal areas due to changes in storm climatology and sea level rise (Liu et al., 2018; Qi and Du, 2018). The LeiZhou Peninsula, situated at the southern tip of mainland China in the GuangDong Province, frequently suffers from tropical storm activities in the South China Sea (Guan et al., 2018). Statistics show that, from 1949 to 2005, 27 storm surge disasters have inflicted the LeiZhou Peninsula, 9 of which were extra severe events with over one thousand deaths or one hundred million economic loss (Zhang, 2008). The station NanDu has measured a surge of 5.90 m during Typhoon Joe in 1980, which is the highest historical surge record in China and ranked fifth in the world (Dong et al., 2014).

The storm surge levels are related to the storm intensity, moving directions, storm scale of tropical cyclones and the landing position, coastal feature and the astronomical tide at the landing time. Lots of studies (Chen et al., 2002; Shi et al., 2004) have pointed that, storm surges occurred in the east coast of the LeiZhou Peninsula are related to the cyclone wind field at the landing time and the special large-scaled westward curved coastline of the east peninsula. Table 1 lists typical surge height records after 2000 and shows some regularity. First, the storm surge characteristics in the east of the LeiZhou Peninsula are sensitive to the landfall positions and moving directions of the cyclone tracks. For most stations, if the cyclone lands to the south of the ZhanJiang Bay (e.g., at Xuwen or NaoZhou), the surge tends to be larger than that caused by the cyclone landing to the north of the ZhanJiang Bay (e.g., at BoHe or Jian River). Second, significant regional

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Table 1
Collections of tropical cyclones and surge records in the east LeiZhou Peninsula after 2000.

Landfall Region	Cyclone Name	Landfall Location	Landfall Intensity	Moving Direction (α in Fig. 10)	Lowest central pressure (hPa)	Maximum wind speed (m/s)	Moving speed (m/s)	Maximum Surge at stations(cm)		
								ZhanJiang	NanDu	NaoZhou
At the ZhanJiang Bay	Mujigae (2015)	ZhanJiang	STY	WNW(35°)	940	50	5.5	211	155	104
South to the ZhanJiang Bay	Kai-Tak (2012)	NaoZhou	TY	WNW (17°)	968	38	6.9	245	169	150
	Kalmaegi (2014)	XuWen	STY	WNW (18°)	910	60	8.3	435	495	388
	Krovanh (2003)	XuWen	TY	WNW(22°)	965	33	6.1	270	369	207
	Nesat (2011)	XuWen	STY	WNW (24°)	970	35	3.1	287	256	270
	Rammasun (2014)	XuWen	Super TY	WNW (34°)	960	42	6.1	256	392	260
North to the ZhanJiang Bay	Hagupit (2008)	BoHe	STY	WNW (26°)	950	45	6.9	149	124	
	Imbudo (2003)	BoHe	STY	NW(43°)	945	45	10.0	127	128	135
	Prapiroon (2006)	BoHe	TY	NW (42°)	975	33	5.5			93
	Vicente (2012)	ChiXi	STY	NW (44°)	960	45	5.5	< 70		
	Chanthu (2010)	Jian River	TY	NNW(52°)	970	35	4.2	65		75

*Meteorological data are obtained from the China Meteorological Administration, and the translation speeds are estimated from the six-hourly positions of the three tropical cyclones.

differences exist and surge patterns in the east LeiZhou Peninsula are complicated since each storm has its particularity. For example, the surge at ZhanJiang is about 70 cm larger than that at Nandu in Typhoon Mujigae and Kai-Tak; while, in Typhoon Krovanh, the surge at ZhanJiang is 90 cm smaller than which at Nandu. Generally, the surge height inside the bay (e.g., ZhanJiang and NanDu) is larger than that in the coastlines facing the open sea (e.g., NaoZhou).

Some recent storm surge processes caused by the tropical typhoons from the South China Sea, such as Typhoon Krovanh (2003) (Cao et al., 2006; Li et al., 2004), Prapiroon (2006) (Wang et al., 2008), Chanthu (2010) (Zhang et al., 2011), Rammasun (2014) and Kalmaegi (2014) (Ma and Yang, 2015), have been simulated by lots of researchers. However, each cyclone includes its own distinctive characteristics and can cause unique storm surge pattern in the east LeiZhou Peninsula. It is not common to describe the surge characteristics in the east LeiZhou Peninsula by simulations of individual storms alone. Zhang et al. (2015) have studied the effects of the moving direction and moving speed of the cyclone on the surge properties in the ZhanJiang Bay based on simulations of two cyclones of Rammasun and Kalmaegi. As far as we know, there is no report of study about how the landfall location affects the surge pattern in the east LeiZhou Peninsula.

This study aims to investigate the inner shelf response to the variations of the landfall location and the moving direction of tropical cyclones in the east LeiZhou Peninsula. The paper is organized as follows: First, the numerical model is presented and followed by a description of data source used, unstructured mesh generation and model forcing. The model is validated by observed tide records in three typical typhoons of Mujigae (2015), Kai-Tak (2012) and Krovanh (2003). Second, 28 ideal storm tracks, including four typical landfall locations and seven moving directions, are designed to make discussions about inner-bay and outer-bay surge responses in the east LeiZhou Peninsula coast. Our results also provide new insights into how the storm tracks affect the surges for different shelf configurations.

2. Methods

2.1. Model description

FVCOM is the three-dimensional (3-D) primitive equation, unstructured grid, general terrain-following coordinate, finite-volume Community Ocean Model developed originally by Chen et al. (2003). FVCOM utilizes the second-order approximate finite-volume discrete algorithm with an integral form of governing equations over momentum and tracer control volumes in the terrain-following generalized vertical coordinate system with either Cartesian coordinates or spherical coordinates, integrated with time with options of a mode-split solver in which external and internal modes are advanced at different time steps and a semi-implicit solver with a single time step inversely proportional to water current magnitude. The wave model in FVCOM is SWAVE, an unstructured-grid version of SWAN solved by a second-order approximate semi-implicit finite-volume discrete method (Qi et al., 2009). SWAVE is coupled with FVCOM through radiation stress and surface stress in the momentum equations and the wave-current interaction functions in the bottom boundary layer.

2.2. Study area and datasets

Our model domain extends from the Vietnam coast to the Pacific Ocean east of the Philippines, with 3300 km open boundary covering water depths of 1000–5500 m. All the coastlines of the TaiWan Island, HaiNan Island, GuangDong and GuangXi are included in this domain. A total of 163577 triangular cells with 84354 nodes comprise the horizontal, shown in Fig. 2 and three sigma layers comprise the vertical. The grid resolution increases from 40 km on the open boundary toward the study area. It becomes 500 m ~ 1000 m on the continental shelf between the LeiZhou Peninsula and Zhujiang Estuary, the north coast of the HaiNan Island and in the QiongZhou Strait. The finest resolution of 100 ~ 200 m is applied in the east coast of the LeiZhou Peninsula. Although this grid captures the entire bathymetry of the northern South