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A case study of winter storm-induced continental shelf waves in the northern South China Sea in winter 2009

Junyi Li [a,b], Quanan Zheng [b], Jianyu Hu [a,*], Lingling Xie [b,c], Jia Zhu [a], Zhenhua Fan [d]

[a] State Key Laboratory of Marine Environmental Science, College of Ocean & Earth Sciences, Xiamen University, Xiamen 361102, China
[b] Department of Atmospheric and Oceanic Science, University of Maryland, College Park 20742, USA
[c] Guangdong Province Key Laboratory for Coastal Ocean Variation and Disaster Prediction Technologies, Guangdong Ocean University, Zhanjiang 524088, China
[d] The National Marine Information Center, State Oceanic Administration, Tianjin 300171, China

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ABSTRACT

This study deals with winter storm-induced continental shelf waves (CSWs) in the northern South China Sea in winter 2009 using tidal gauge data and along-track satellite altimeter data. The results show that the periods of CSWs propagating along the coast from Kanmen to Shuidong are in bands of 62 and 133 h. The phase speeds are in a range from 8 to 13 m s^{-1} between Kanmen and Shantou, from 9 to 11 m s^{-1} between Shantou and Huizhou and from 10 to 15 m s^{-1} between Huizhou and Shuidong, respectively. Satellite altimeter captured along-track sea level anomaly during the CSW events. Further analysis using the theoretical cross-shore CSW modes to fit the along-track sea level anomaly data indicates that the first three wave modes play important roles during the CSW events and the first mode is a dominant component.

1. Introduction

Continental shelf waves (CSWs) occur on continental shelves and travel along the coast on the right (left) in the Northern (Southern) Hemisphere (Mysak, 1980; Brink, 1991; Ding et al., 2012; Connolly et al., 2013; Jensen et al., 2013). CSWs may be induced by the winter storms and typhoons (Yin et al., 2014; Zheng et al., 2015; Li et al., 2015). Oscillations in the ocean are usually motivated by these atmospheric activities (Kundu, 1976; Kundu et al., 1983; Kundu and Thomson, 1985). CSWs are a kind of topographic planetary waves with a period from 1 d to several weeks (Eliot and Pattiaratchi, 2010; Thiebaut and Vennell, 2010; Woodham et al., 2013). The phase speeds of CSWs depend on the cross-shore bathymetric profiles, ranging from one to tens meters per second (Schulz et al., 2011). Camayo and Campos (2006) detected a phase speed of about 1.8 m s^{-1} of CSWs propagating along the South America coast. But along the Atlantic coast, Thiebaut and Vennell (2010) found that CSWs propagate at a speed as high as 16 m s^{-1}. Based on the period and phase speed, CSWs are able to cause the large-scale variability of the sea level in the offshore area.

In the past decades, the current and alongshore sea level measurements were used as the major methods for the observation of CSWs. The recent progress is to use satellite altimeter along-track data for the analysis of offshore structure of CSWs. Han et al. (2012) used satellite altimeter data for the observation of storm surges. Lillibridge et al. (2013) used the along-track data of HY 2A altimeter to monitor the storm surges on the east coast of the United States induced by the hurricane Sandy in 2012. Chen et al. (2014) used the satellite altimeter data to derive a cross-shore e-folding decay scale of storm surges.

The northern South China Sea (NSCS) is adjacent to the Taiwan Strait in the northeast and adjoins the Luzon Strait in the east as shown in Fig. 1a. Previous investigators have documented the characteristics of CSWs in this area (Chen and Su, 1987; Hsueh and Pang, 1989; Jacobs et al., 1998; Ding et al., 2012; Yin et al., 2014; Zheng et al., 2015). The coastline of the NSCS is almost perpendicular to the ground tracks of altimeter satellites, which is an advantage for the observation of CSWs using satellite altimeter data.

The NSCS is located in the East Asian monsoon region, with the strong northeasterly winds prevailing in winter (Hu et al., 2010). Meanwhile, winter storms pass over this area every 3–10 d (Chen and Su, 1987). Therefore, the water on the continental shelf of the NSCS could be mixed homogeneously by wind in winter.

In this study, we focus on the analysis of the alongshore and cross-shore characteristics of CSWs induced by winter storms in winter 2009 in the NSCS. This paper is organized as follows. Section 2 describes the data and data analysis method. Section 3

* Corresponding author.
E-mail address: hujy@xmu.edu.cn (J. Hu).

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presents the alongshore and cross-shore characteristics of CSWs derived from the tidal gauge data and satellite altimeter along-track data. The theoretical cross-shore CSW modes are used to interpret the satellite altimeter along-track sea level anomaly (SLA) data. Section 4 analyzes the winter storms, which induced CSWs and the rest of components in the along-track SLA. Section 5 gives a summary of the analysis results.

2. Data and methodology

2.1. Tidal gauge data

Tidal gauge data at Kanmen, Shantou, Huizhou and Shuidong as shown in Fig. 1a are obtained from the National Marine Information Center of China. The data cover a period from December 15, 2009 to January 15, 2010, with a temporal resolution of 1 h and the sea level accuracy better than 1 mm. Tidal gauge data are processed by de-tiding software (Pawlowicz et al., 2002). De-tided sea level anomaly (DSLA) is calculated by removing the respective mean sea levels and corrected by the surface air pressure.

2.2. Satellite altimeter data

Satellite altimeter along-track SLA data are produced and distributed by the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO), Center National d'Etudes Spatiales (CNES) of France. Satellites Jason-1, Jason-2 and Envisat repeat their ground tracks every 9.9, 9.9 and 35 d, respectively. The corrections for tides and ionosphere, as well as multi-mission cross-calibration, have been applied to the data. The temporal resolution is 1 s, and the spatial resolution is about 7 km in the study area. 8-point moving average is applied to the data to filter out the ocean processes with the length scale less than 50 km. Monthly and daily delayed-time gridded SLA data are also used in this study. The resolution of the gridded SLA data is about 0.25° in latitude and longitude with global ocean coverage. The data merged from multiple altimetry sensors are computed with respect to a twenty-year mean (Collecte Localisation Satellites, 2011).

2.3. Surface air pressure, air temperature and wind data

Observed surface air pressure and air temperature data at Shantou and Huizhou from December 15, 2009 to January 15, 2010 are obtained from National Climatic Data Center (NCDC), China. The temporal resolutions of the pressure and temperature data are 3 and 1 h, respectively. The mean value of the surface air temperature data is removed for the winter storm analysis. We interpolate the air pressure data with a temporal resolution of 1 h, and use the interpolated data to calculate the hydrostatic response of the ocean, in which 1 h Pa increase (decrease) in the air pressure corresponds to 0.01 m decrease (increase) in the sea level. We note that the air pressure could oscillate with a period of 3 h during major storms. Therefore, the interpolated air pressure data could introduce error into the air pressure corrected DSLA data. Since the frequency of the error is much higher than that of the CSWs, the error is ignorable.

Surface wind data are obtained from the Cross-Calibrated Multi-Platform (CCMP) project created by US National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (Atlas et al., 2011). Temporal resolution of the dataset is 6 h, and spatial resolution is 0.25° × 0.25°. Wind vectors are decomposed into the cross-shore and alongshore components on the continental shelf area. Alongshore components are averaged on wind sections as shown in Fig. 1a.

2.4. Ensemble empirical mode decomposition analysis

Ensemble empirical mode decomposition (EEMD) is a noise-assisted data analysis method, which is applied to decompose nonlinear and non-stationary signals (Wu and Huang, 2009). EEMD is developed from empirical mode decomposition (EMD). Based on the characteristic time scale of the signal, EMD could decompose a signal into a collection of intrinsic mode functions (IMFs) and a residual (or trend). However, mode mixing could

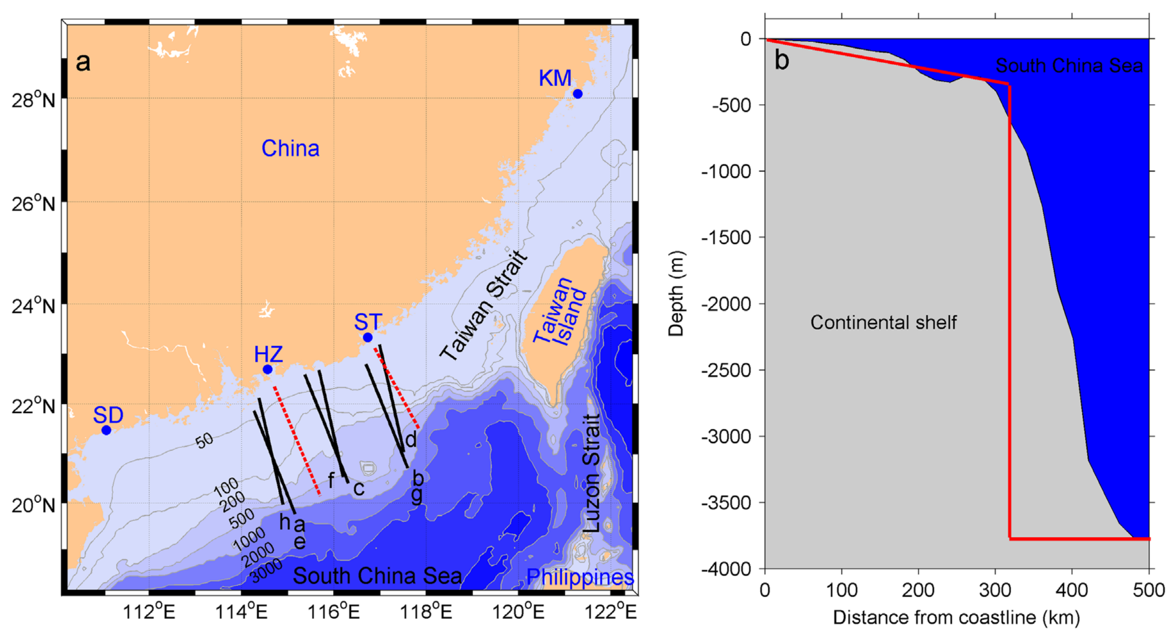

Fig. 1. (a) Study area, tidal gauge stations (blue dots) and satellite altimeter ground tracks (black lines), (b) mean cross-shore bathymetric profile between sections HZ (for Huizhou) and ST (for Shantou). Black encoded lines in (a) are satellite ground tracks and blue dots represent tidal gauge stations HZ, ST, KM (for Kanmen) and SD (for Shuidong). Red dashed lines in (a) are sections for alongshore wind calculation. Numerals on isobaths in (a) are in m. Red curve in (b) represents an idealized depth profile. Ocean bottom topography is shown in gray.