Continental Shelf Research 93 (2015) 81–97

Contents lists available at ScienceDirect

Continental Shelf Research

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

Examination of extreme sea levels due to storm surges and tides over the northwest Pacific Ocean

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ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form
25 November 2014
Accepted 5 December 2014
Available online 10 December 2014

Keywords:
Extreme sea level
Ocean circulation model
Extremal analysis technique
The northwest Pacific

ABSTRACT

Extreme sea levels for the 50-year return period associated with storm surges and tides over the northwest Pacific (NWP) are investigated based on results produced by a two-dimensional (2D) ocean circulation model. The model forcing includes surface wind stress and atmospheric pressure at the sea level taken from the Climate Forecast System Reanalysis (CFSR) fields at 6-hourly intervals. A parametric vortex is inserted into the CFSR fields to better represent atmospheric forcing for a typhoon or a tropical storm. The performance of the 2D circulation model in simulating tides and storm surges is assessed by comparing model-calculated sea levels with the available tide gauge observations over the NWP. Results show that the 2D circulation model reasonably reproduces tides and storm surges over the study region. The model-calculated tidal and surge-induced sea levels are used to estimate the 50-year extreme sea levels associated with tides and storm surges over the NWP by using an extremal analysis technique. It is shown that the extreme total sea levels are mainly determined by the tides and tropical cyclones. The contributions of tides and tropical cyclones to extreme total sea levels varied spatially in the NWP.

1. Introduction

Coastal regions over the northwest Pacific (NWP) Ocean are frequently threatened by extreme sea levels due primarily to storm surges combined with tides (Liu and Wang, 1989; Le, 2000; Feng and Tsimplis, 2014). Rapid urbanization and economic growth make these regions very vulnerable to extreme sea levels. For example, the coastal zone of China has become the region of highly developed economy and highly dense population, with 42% of the country's total population and 51% of the gross domestic product (Yin et al., 2011). As many of the Chinese coastal communities are in low-lying regions, big storm surges due to typhoons, tropical storms and winter storms frequently cause severe losses in human lives and properties. In 2013, for example, Typhoon Tiantu struck Guangdong and Fujian provinces of China which generated 2 m storm surges along the east Guangdong province and resulted in US$ 1.82 billion of economic loss (SOA, 2014). Also in 2013, Typhoon Haiyan killed at least 6268 people when it made its landfall in the southeast coast of the Philippines (Schiermeier, 2013; Barmania, 2013). Due mainly to the increasing flood risk associated with growing populations and properties, the changing climate and subsidence, the coastal regions of the NWP are classified as one of the most vulnerable areas in the world (Hallegatte et al., 2013). Therefore, better understanding of temporal and spatial distributions and causes of extreme sea levels in this region is essential for coastal planning and protection.

Extreme sea levels, by ignoring the effect due to ocean waves, can be considered as a combination of the mean sea level (MSL), storm surge and tides (Weisse et al., 2012) . The seasonal and inter-annual variations in the MSL not only increase the probability of coastal flooding associated with storm surge and tides in specific seasons (Torres and Tsimplis, 2012), but also modify the tidal amplitudes and phases (Pickering et al., 2012). A number of studies have examined the seasonal and inter-annual variations of the MSL in the NWP from tide gauge observations, satellite altimetry data and circulation model results. Tsimplis and Woodworth (1994) studied the spatial distribution of the seasonal cycle of the MSL at the global coasts from the coastal tidal gauge data set. Their results demonstrated that the seasonal cycle of MSL over the coastal regions of the NWP has values ranging from 5 to 30 cm, with high values along the coast of China. Based on the circulation model results, Vinogradov et al. (2008) found that the seasonal cycle of the MSL can reach 10–15 cm in the Kuroshio region, and relatively weaker seasonal cycle of 6–10 cm in the East China Sea (ECS) and the Yellow Sea (YS). Marcos et al. (2012) investigated the

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http://dx.doi.org/10.1016/j.csr.2014.12.001
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seasonal and inter-annual cycle of sea levels over the NWP based on the tide gauge observations and altimetry data and demonstrated that the inter-annual trends have clear variations in the Sea of Okhotsk, Sea of Japan, ECS and YS with values between -1.5 and 5.5 mm/yr for the period 1960–2000. This annual increases in sea levels were mainly attributed to the steric sea level changes.

Storm surges and tides are the other two important contributors to the extreme sea levels. Storm surges are the sea level response to wind stress and perturbation of atmospheric pressures at the sea level associated with tropical cyclones or winter storms in coastal areas. Storm surges can be significantly modulated by tides due to the tide-surge nonlinear interaction over some coastal areas (Horsburgh and Wilson, 2007). Park and Suh (2012) examined the tide-surge nonlinear interaction along the west coast of the Korean Peninsula using a circulation model, and their results indicated that tide–surge interactions are significant in this region. Feng and Tsimplis (2014) investigated the tide–surge interaction from tide gauge observations along the coast of China using statistical techniques and they found that most of the tide gauges experience significant tide–surge interactions. It should be noted that the nodal and perigean modulations on high tidal levels are important because these modulations contribute to the vulnerability of the coastal areas when coupled with inter-annual sea level variation or extreme storm surges. Haigh et al. (2011) investigated the global influences of the lunar nodal and perigean modulations on high tidal levels. It is shown that high tidal levels over the Bohai Sea (BS), YS and ECS are modulated by the nodal cycle with 5–10% (0.1–0.6 m) of the tidal range, while those over the Sea of Japan, Sea of Okhotsk, SCS are modulated by the perigean cycle with 10–30% (0.2–0.8 m) of the tidal range (Haigh et al., 2011).

Many previous studies of extreme sea levels over the NWP focused on short-term simulation of extreme sea levels associated with tides and storm surges using circulation models (Konishi and Tsuji, 1995; Guo et al., 2009; Zhang et al., 2007), or estimation of extreme sea levels based on tide gauge observations using extremal analysis techniques (Xu and Huang, 2011; Li and Li, 2013; Zuo et al., 2013). Few studies involved detailed analyses of spatial and temporal variations of extreme sea levels, or mapping the extreme sea level based on long-term numerical results with and without the climate change scenario in the NWP. Menéndez and Woodworth (2010) investigated global patterns of extreme sea level changes based on a quasi-global sea level data set using an extremal analysis technique and they found a clear trend of increase in extreme sea levels due to changes in the MSL in the NWP. They also found that the contribution of tides to extreme sea levels in the SCS is significant. Feng and Tsimplis (2014) studied the temporal and spatial distribution of extreme sea levels along the Chinese coasts based on tidal gauge observations. They found that spatial distribution of sea level maxima is primarily determined by tides and tropical cyclones and the maximum tidal residuals are significantly affected by tropical cyclones. In addition, the long-term variations of extreme sea levels along the Chinese coasts depend on MSL changes as well as changes in the tidal amplitudes caused by nodal modulation, MSL rise and coastal reclamation. Yasuda et al. (2014) evaluated the present and future storm surge risk in East Asia and Japan coast using a multi-nested ocean model driven by atmospheric forcing. The atmospheric forcing includes 6-hourly wind stress and atmospheric pressure at the sea level with horizontal resolutions of 20 km produced by an atmospheric general circulation model. The 100-year return levels of extreme storm surges were estimated based on the model results using extremal analysis techniques.

Though there were many previous studies on the extreme sea levels over the NWP, most of them were made based on tide gauge observations or storm surge model results. To our knowledge, no published studies concerned with statistical estimation of extreme total sea levels associated with tides and surges over the NWP based on ocean model results.

This paper investigates the spatial pattern of extreme sea levels due to the combination of storm surges and tides over the NWP from 32-year (1979–2010) sea level simulations produced by a 2D circulation model. The Gumbel distribution approach and Monte Carlo method are used in the estimation of extreme sea levels due to storm surges and tides. The paper is organized as follows. The sea level observations, the 2D ocean circulation model and the model external forcing are discussed in Section 2. Assessment of the 2D model performance is presented in Section 3. Estimations and spatial distribution of the extreme sea levels with a 50-year return period are discussed in Section 4. Finally, the summary and conclusion are presented in Section 5.

2. Numerical circulation model and observed sea levels

2.1. Model setup and forcing

The 2D ocean circulation model used in this study is the external (or depth-averaged) component of the Princeton Ocean Model (POM) (Mellor, 2004). The model domain in this study covers the region between 0.825°N and 63°N and between 99°E and 170°E over the NWP, with a horizontal resolution of (1/16)° (Fig. 1). The bathymetric data, which were interpolated onto the model grid, were obtained from the General Bathymetric Chart of the Oceans (GEBCO) 1 arc-minute global bathymetric dataset http://www.gebco.net/data_and_products/gridded_bathymetry_data/. The 2D circulation model has two lateral open boundaries in the east and south.

The 2D circulation model is driven by tidal forcing and atmospheric forcing. The tidal forcing includes two parts: (1) tidal elevations and depth-averaged tidal currents specified at the lateral open boundaries of the model using 13 tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, Mf, Mm, M_4, MS_2 and MN_4) produced by the global tidal circulation model (TPXO 7.2, Egbert and Erofeeva, 2002), and (2) tide generating potential specified at each model grid point (Foreman et al., 1993). It should be noted that all the above 13 tidal constituents are corrected by the 18.6-year nodal cycle due to the significant contribution of nodal modulation to tidal amplitudes (Haigh et al., 2011). The radiation open boundary condition suggested by Davies and Flather (1978) is used to allow small-scale disturbances generated inside the model domain to propagate as freely as possible through the model open boundaries.

A conventional quadratic formula is used to compute the bottom stress from the depth-mean current in the model. We follow previous studies by Fang et al. (1999) and Lu and Zhang (2006) and use a spatially varying bottom friction coefficient (C_D) over the BS, YS, ECS and SCS, which is a piece-wise linear function of local water depths over these regions (Wang et al., 2014).

The atmospheric forcing used to drive the 2D circulation model consists of the 6-hourly atmospheric pressure at the sea level (SLP) and wind stress converted from the 10-m wind velocity taken from the Climate Forecast System Reanalysis (CFSR). The bulk formula of Large and Pond (1981) is used to convert the wind velocity to the wind stress. The CFSR fields have horizontal resolutions of 0.3° and 0.5° for the winds and SLP, respectively. It should be noted that horizontal resolutions of the CFSR fields are finer than the reanalysis data produced previously by the National Centers for Environmental Prediction (NCEP) (Saha, 2010), but they are still not fine enough to represent the atmospheric forcing for a typhoon or a tropical storm. As a result, we insert an idealized vortex suggested by Holland (1980) into the large-scale CFSR