Int J Appl Earth Obs Geoinformation 67 (2018) 161–172

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

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

# Evaluation and adjustment of altimeter measurement and numerical hindcast in wave height trend estimation in China's coastal seas

Shuiqing Li[a], Shoude Guan[a,*], Yijun Hou[a], Yahao Liu[a], Fan Bi[b]

[a] Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China
[b] North China Sea Marine Forecasting Center of State Oceanic Administration, Qingdao, China

ARTICLE INFO

*Keywords:*
Wave height trend
China's coastal seas
Altimeter measurement
Numerical hindcast

ABSTRACT

A long-term trend of significant wave height (SWH) in China's coastal seas was examined based on three datasets derived from satellite measurements and numerical hindcasts. One set of altimeter data were obtained from the GlobWave, while the other two datasets of numerical hindcasts were obtained from the third-generation wind wave model, WAVEWATCH III, forced by wind fields from the Cross-Calibrated Multi-Platform (CCMP) and NCEP's Climate Forecast System Reanalysis (CFSR). The mean and extreme wave trends were estimated for the period 1992–2010 with respect to the annual mean and the 99th-percentile values of SWH, respectively. The altimeter wave trend estimates feature considerable uncertainties owing to the sparse sampling rate. Furthermore, the extreme wave trend tends to be overestimated because of the increasing sampling rate over time. Numerical wave trends strongly depend on the quality of the wind fields, as the CCMP waves significantly overestimate the wave trend, whereas the CFSR waves tend to underestimate the trend. Corresponding adjustments were applied which effectively improved the trend estimates from the altimeter and numerical data. The adjusted results show generally increasing mean wave trends, while the extreme wave trends are more spatially-varied, from decreasing trends prevailing in the South China Sea to significant increasing trends mainly in the East China Sea.

## 1. Introduction

China's coastal seas, adjacent to the western North Pacific Ocean, consist of the Bohai, Yellow, East China, and South China seas (cf. Fig. 1). The surface gravity waves are active, and have strong temporal and spatial variabilities which are dependent on the meteorological systems and complex seabed topography of the coastal seas. The wave patterns are strongly modulated by the Asian monsoon system (e.g. Wang et al., 2016), and extreme high wind waves can be generated by two different meteorological systems: cold fronts, known as Nortes, which mainly affect the Bohai and Yellow seas, and low-pressure systems, or tropical cyclones, which have a major impact on the East China and South China seas. The surface waves have strong forcing impacts on the coastal infrastructure and morphology, and the extreme high waves are a coastal hazard that needs to be fully considered in risk analysis. Moreover, waves contain energy which can be used as an important ocean resource.

The wave height trend is defined as the temporal linear changing rate of significant wave height (SWH) over a duration long enough to exclude the influence of climate cycles, such as, the Pacific Decadal Oscillation. Estimates of the wave height trend can improve the understanding and prediction of coastal hazard mitigation, coastal morphology changes, and ocean resources. Generally, the wave height climate trend was estimated from several data sources, including in-situ measurements (Gemmrich et al., 2011), voluntary ship observations (Gulev and Grigorieva, 2004; Tokinaga and Xie, 2010), satellite altimetry (Zieger et al., 2009; Young et al., 2017), numerical models (Chawla et al., 2013; Fan et al., 2014), and statistical models (Wang et al., 2012).

Among the above data sources, satellite altimeter measurements and numerical hindcasts are commonly employed, because of their long-term duration and wide spatial coverage. For example, Young

*Abbreviations:* SWH, significant wave height; ERS, European Remote Sensing; NCEP, National Centers for Environmental Predictions; CCMP, Cross-Calibrated Multi-Platform; CFSR, NCEP's Climate Forecast System Reanalysis; ECMWF, European Centre for Medium-Range Weather Forecasts; ERA-I, ECMWF Reanalysis Interim; MB, Mean Bias; SI, Scattering Index; CC, correlation coefficient; ALTW, altimeter wave data; ALTW-A, ajusted altimeter wave data; CCMPW, CCMP wave data; CFSRW, CFSR wave data; CCMPW-A, ajusted CCMP wave data; CFSRW-A, ajusted CFSR vave data; CCMPW-C, collocated CCMP wave data; CFSRW-C, collocated CFSR vave data; BYW, buoy wave data; BYW-C, collocated buoy wave data

* Corresponding author.
*E-mail addresses:* lishuiqing@qdio.ac.cn (S. Li), guanshoude@qdio.ac.cn (S. Guan), yjhou@qdio.ac.cn (Y. Hou), yhliu@qdio.ac.cn (Y. Liu), bifansd@163.com (F. Bi).

https://doi.org/10.1016/j.jag.2018.01.007
Received 30 September 2017; Received in revised form 3 January 2018; Accepted 15 January 2018
0303-2434/ 

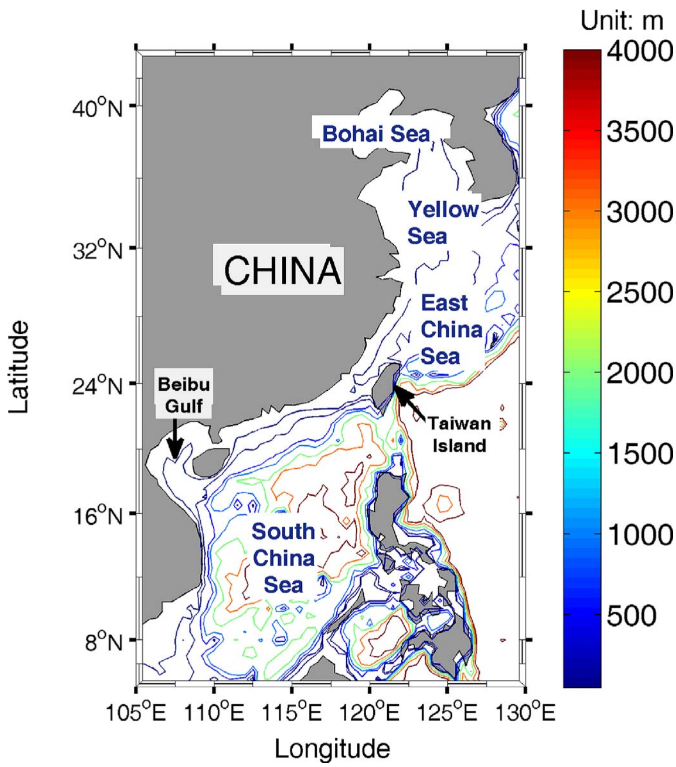


**Fig. 1.** Topography of China's coastal seas.

et al. (2011) investigated the global change of ocean surface waves for the period 1985–2008 using a 24-year dataset of multi-altimeter measurements. Their results revealed significant increasing trends of SWH, particularly, the high-percentile SWH. Altimeter wave data were also applied in basin-scale or regional studies (e.g. Woolf et al., 2002; Liu et al., 2016).

Extensive wave data can be obtained from numerical or analytical models according to pioneering work by Cox and Swail (2001), who assessed the wave climate trend at global scale based on wave hindcasts recorded during 1958–1997. It has also been widely used in regional studies. In wave trend studies of China's coastal seas, Zheng and Li (2015) reported a significant increasing trend of mean SWH (a mean rate of 1.52 cm $yr^{-1}$ during 1988–2011) using numerical wave hindcasts. More recently, Wang et al. (2016) found an increasing trend of SWH in the East China Sea (0.5 cm $yr^{-1}$ for mean SWH and 1 cm $yr^{-1}$ for extreme SWH during 1979–2014) using wave dynamical reanalysis of ocean waves from European Centre for Medium-Range Weather Forecasts (ECMWF). Wu et al. (2014) studied the historical wave height trends (1911–2010) in the South and East China seas by wave simulation based on sea level pressure using a statistical model. Their results indicated a dominantly negative trend.

Both altimeter measurements and numerical hindcasts have their strengths and weaknesses. Altimeter measurements have high accuracy, and can be homogeneous, if there is efficient calibration between the different satellite altimeters, but attention should be paid to the sparse-sampling rate. A numerical wave hindcast can result in high spatial and temporal resolution, but its performance strongly depends on the physical considerations of the model, and the quality of the wind forcing and bathymetry data. Proper evaluation of the performance of hindcasts in wave height trend estimation is needed to provide a reliable description of the wave-height trend.

In this study, the wave height trend in China's coastal seas was examined based on a detailed analysis of satellite and numerical wave data. We first performed evaluations of the two types of wave data; biases in the wave trend estimation are illustrated for both the altimeter and numerical data, and we adjusted these biases to provide a more accurate estimation of the wave height trend. The remaining paper is organized as follows: the data and methods are described in Section 2; evaluation of the altimeter and numerical wave data in the wave climate trend analysis is detailed in Section 3; adjustments of the altimeter and numerical wave data are presented in Section 4; and discussion and conclusions are provided in Sections 5 and 6, respectively.

## 2. Data and methods

### 2.1. Altimeter datasets

Spaceborne radar altimeters have been observing the sea surface gravity waves since the launch of GEOSAT in 1985. For the past two decades, high quality wave measurements of SWH were successfully collected by more than ten satellite missions. In the present analysis, altimeter data from 1992 to 2010 were used, comprising data from seven satellite missions: European Remote Sensing-1 (ERS-1), ERS-2, the Ocean Topography Experiment (TOPEX), Geosat Follow-On (GFO), Environmental Satellite (Envisat), Jason-1, and Jason-2. All the altimeter data were extracted from the European Space Agency (ESA) GlobWave Level 2 Preprocessed (L2P) dataset. For a specific satellite mission, the orbit was configured in an along-track mode with 1-Hz measurements made over footprints ranging from 1 to 10 km. For details about the data processing and quality control please refer to the GlobWave Product User Guide (http://globwave.ifremer.fr/products/globwave-satellite-data). Calibrations were applied to each of the satellite mission datasets to adjust the systematic differences between them. For the wave-trend analysis, because of the satellite spatial and time coverage, the along-track data should first be resampled to match the grid data, with the grid size ranging between 1° and 2° (Lefevre and Cotton, 2001). China's coastal seas are mainly located at mid-latitudes; thus, an intermediate value of 1.5° was chosen. The gridded ALTimeter Wave data are referred to as ALTW.

The annual mean and 99th-percentile SWH and wind speed were determined using the ALTW; the multi-year averaged values are presented in Fig. 2. The winds and waves exhibit high similarities in their spatial patterns; they are both high in the southeast of the East China Sea and northeast of the South China Sea, and gradually decrease as they approach the mainland. Some differences are noted; the winds peak in waters around Taiwan Island, whereas the waves are highest on the outer open boundaries, which is likely due to the large fetches of the off-shore winds, or the influence of non-local waves (swell) propagating from the open ocean.

### 2.2. Hindcast dataset

Numerical simulations were performed to obtain the wave hindcast dataset using the third-generation spectral wave model, WAVEWATCH III, which is a phase-averaged model that evolves the action density in the frequency and direction domains under wind forcing and geographical constraints. The model simulates waves by solving the action balance equation with the source terms accounting for the nonlinear effects, including wind–wave interactions, wave–wave interactions, and dissipation through whitecapping, bottom friction, and wave breaking. The source terms package of Tolman and Chalikov (1996) was used for the wind–wave interactions and whitecapping dissipation, and the nonlinear wave–wave interactions were modeled using the discrete interaction approximation (Hasselmann et al., 1985). The bottom friction source term was based on the JONSWAP spectrum developed by Hasselmann et al. (1973), and the depth-induced wave breaking dissipation was based on the approach of Battjes and Janssen (1978).

The geographical constraints include water depth and shoreline information, for which we applied the 1-min gridded bathymetry for the world (ETOPO1). The model was run on a spatial grid of 0.25° at a longitude range of 103–130°E and a latitude range of 8–45°N. The open boundary was forced by wave simulations in a sufficiently large