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A global high-resolution ocean wave model improved by assimilating the satellite altimeter significant wave height

Huaming Yu[a,b,c,d,*], Jiangyu Li[a,b], Kejian Wu[a,b], Zhifeng Wang[e], Haiqing Yu[a,b,c,d], Shaoqing Zhang[b], Yijun Hou[f,g], Ryan M. Kelly[h]

[a] College of Oceanic and Atmospheric Sciences, Ocean University of China, Qingdao, 266100, China
[b] Key Laboratory of Physical Oceanography, Ministry of Education, Ocean University of China, Qingdao, 266003, China
[c] Qingdao National Laboratory for Marine Science and Technology, Qingdao, 266100, China
[d] College of Fisheries, Ocean University of China, Qingdao, 266003, China
[e] College of Engineering, Ocean University of China, Qingdao, 266100, China
[f] Key Laboratory of Ocean Circulation and Waves, Institute of Oceanography, Chinese Academy of Sciences, Qingdao, 266071, China
[g] University of Chinese Academy of Sciences, Beijing 100029, China
[h] Rykell Scientific Editorial, LLC, Los Angeles, CA, USA

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ABSTRACT

This study examines the effects of data assimilation using Significant Wave Height (SWH) from three satellite altimeters, notably the Jason-2, Jason-3 and SAtellite with ARgos and ALtiKa (SARAL), orbiting in space and incorporating the data into a global high-resolution ocean wave model. The third-generation wave model, WAVEWATCH III (WW3), was adopted for numerical simulation and its spatial resolution was refined to 0.2°. Data assimilation is carried out using the Optimal Interpolation (OI) scheme to demonstrate the feasibility and the benefits of simultaneously assimilating the along-track SWH data from multi-satellite altimeters into a global ocean wave model. Higher resolution global ocean wave models can advantageously account for the swell propagation from deep ocean waters without open boundary conditions, as well as simulate smaller scale wind waves from the coastal zones conveniently, effectively and in tandem. The Root Mean Square (RMS) of non-assimilation experiment is 0.54 m, which is smaller than the previous coarse resolution global wave modelling. Minor improvement is found when only one 10-min frequency, SWH data from the Jason-2 altimeter was assimilated into the global ocean wave model. However, the RMS against buoy observations is highly reduced (i.e. approximately 0.42 m) when the SWH data from three satellite altimeters (i.e. Jason-2, Jason-3 and SARAL) are simultaneously assimilated into the global high-resolution ocean wave model and in return, led to significant model improvement. This study can also provide some implications for wave predictions in global oceans.

1. Introduction

Observations and numerical simulations are generally regarded as two major pathways for reconstruction and real-time monitoring of global ocean waves and both techniques do participate in significant roles throughout many major applications, such as calamity prevention, ocean engineering, wave energy exploitation, marine shipping, fisheries and even the enhancement of naval defenses. Since the late 1970s, the emergence of satellite techniques in monitoring the ocean and specifically, the technique of deriving ocean wave information, enables us to capture an improved insight of the basic patterns attributed to ocean waves on a global scale. In spite of this, such satellite observations still seem very sparse for the vast ocean in time and space. Therefore, it is not enough to reconstruct and fully understand the propagation of highly frequent global ocean waves by only relying on observations. The limitation can be complimented by numerical model simulations, as the ocean modelling can accurately describe the dynamics of a continuous spatiotemporal distribution of ocean waves. But, numerical model results can't satisfy the extant incongruity between observations and model simulation. Fortunately, this incongruous situation could be numerically addressed by advanced data assimilation techniques.

Data assimilation is one of the key technologies that fuse models and observations, with which the process can provide a more accurate and holistic representation of the ocean's state. It is commonly used to optimize hindcasting and model initialization in ocean forecasting. The application of data assimilation in ocean wave models didn't originate

* Corresponding author.
E-mail address: hmyu@ouc.edu.cn (H. Yu).

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Table 1
Satellite altimeters and its data period.

Satellite	Data period
SEASAT	June 1978-October 1978
ERS-1	October 1992- June 1996
ERS-2	May 1995-July 2003
T/P	September 1992-October 2005
Jason-1	January 2002-June 2006
Jason-2	July 2008-ongoing
Jason-3	February 2016-ongoing
GFO	January 2000-September 2008
Envisat	May 2002-Apr 2012
Saral	March 2013-ongoing
HY-2A	Apr-2014-ongoing
SWOT	Plan to launch in April 2021

until the 1980s. Interestingly, the first usage of data assimilation occurred in atmospheric modelling 30 years prior to its use in ocean modelling. In particular, the OI analysis method was for several decades the most popular method of automatic analysis for numerical weather prediction (Lynch 2006).

Since the 1980s, with the advent of the higher quality wind products from atmospheric models as well as the booming ocean wave observations mainly through the introduction of satellite altimeters, Synthetic Aperture Radars (SARs) and High Frequency Radars (HF), data assimilation techniques were fundamentally incorporated into ocean wave simulations. Over the years, significant scientific breakthroughs in remote sensing techniques made it feasible to acquire multi-scale daily or hourly ocean measurements. In return, these advancements made the parameterization of SWH and 2D wave spectra feasible. In comparison with SARs and HF, satellite altimeters can provide superior spatial and temporal coverage for collecting continuous ocean observations for greater than 30 years.

As shown in Table 1, 11 satellite altimeters have been launched since 1978 and four altimeters are being used in monitoring ocean waves synchronously with intense detail. Henceforth, global high-resolution wave information can be accessed at any time. Between the rapid development of computer technology and a 40-year collection of satellite altimeter data, it would be suitable to develop a global high-resolution data assimilation wave model. Even if earth observation products cannot fully replace buoy monitoring or field investigations with oceanographic vessels they reveal multi-scale surficial spatial patterns in different time frames otherwise not observable with conventional methods (Manzo et al., 2018). The combined use of remote sensing and *in situ* data, and more recently theoretical models, are quite promising for quantifying coastal processes (Manzo et al., 2018). This model would help improve the precision of wave simulation in both deep open oceans and the coastal zone scenarios without open boundary conditions. The availability of global real-time wind and wave observations has provided a prerequisite for developing global high-resolution wave data assimilation schemes.

Applications involving wave data, available from buoys and remote sensing observing systems for ocean wave models, have been discussed extensively in many studies. Most applications focus on wave simulation within the regional or coastal zones for short time periods (Thomas, 1988; Voorrips et al., 1997; Siddons, 2007; Portilla, 2009; Siddons et al., 2009; Sannasiraj and Goldstein, 2009; Waters et al., 2013). Thomas (1988) proposed an assimilation method to update the 2D wave spectra for the North Sea, Baltic Sea and Mediterranean Sea using SWH records and a wind dataset from 3 buoy stations during a 6-month period. Wave energy spectra were redistributed between a swell and wind wave, according to the overall energy conservation from the first guest of wave modelling. Thomas (1988) improved the spectral parameters in contrast to a non-assimilation scenario. Voorrips et al. (1997) assimilated a partitioned wave spectra from 7 buoys into a third-generation wave model for the North Sea. The assimilating experiments showed some improvement for the sea state simulation, but the wave forecast is only improved marginally because the spatial domain was just limited to the North Sea and swell errors generated from the open boundary conditions in the northern Norwegian Sea.

Hasselmann et al. (1997) developed another OI assimilation model in which 2D wave spectra retrieved from SAR was assimilated into the wave model of the Atlantic Ocean. The study contributed towards the development of data assimilation using SAR numerics into ocean wave models.

Greenslade (2001) adopted the method of statistical interpolation to reconstruct analyzed SWH fields surrounding Australia by assimilating data from the satellite altimeter ERS-2. It was determined that modelling errors arise from the combined effect of overestimated wind speed and amplified wave dissipation at low wave numbers.

Siddons (2007), Siddons et al. (2009), assimilated the wave data from a HF radar into a coastal wave model for England. Three different data assimilation methods were checked and it was discovered that the 3D-VAR and OI methods improved the general modelling accuracy, but the accuracy for the Kalman Filter method was inconsistent. They suggested that it was necessary to adopt strict quality control with regards to the HF wave data before using it for data assimilation purposes.

Wave data from a lone buoy was assimilated by Portilla (2009) into a Belgium-based coastal wave model and the RMS error decreased. Sannasiraj and Goldstein (2009) assimilated wave data from three different buoys into WAM in the Arabian Sea. The RMS error of SWH decreased by 30%. Waters et al. (2013) assimilated HF radar data into a high-resolution regional WW3 wave model in the Celtic Sea and discovered that HF radar data was an ameliorated additive during the period of high sea states. Additionally, assimilating HF radar data led to improved SWH but the modelled mean wave periods didn't amend in the study.

However, there are limited papers concentrated on wave data assimilation into global wave models, with a sparse amount of studies demonstrated in the 1980s and 1990s (Esteva, 1988; Francis and Stratton, 1990; Bauer et al., 1992; Foreman et al., 1994). Esteva (1988) adjusted the wave model spectra using the SWH from SEASAT by a constant factor so that wave modelling SWH matched the observed SW Bauer et al. (1992) described a similar wave assimilation experiment that, nonetheless, assimilated more frequently and modelled the wave field over a larger open sea. The work from Bauer et al. (1992) differed from Esteva (1988) by only assimilating data at the observation points. Therefore, the modelled SWH was improved significantly, especially in swell-dominated regions compared with Esteva (1988).

Francis and Stratton (1990) assimilated the SWH from the SEASAT altimeter into a global wave model for 5 days with use of additional wind data from the altimeter. The assimilation experiments improved the SWH, which impacted the following wave forecast for at least five days.

Wave spectra were classified as wind-wave, swell and mixed types by Lionello et al. (1992) in order to scale the spectrum dependently using a sequential method to assimilate both SEASAT and GEOSAT altimeter data into a global wave model. The results demonstrated that the data assimilation technique improved the modelled results, but the study couldn't narrow the gap between modelling and buoy observation.

Foreman et al. (1994) estimated the data quality of the satellite ERS-1 altimeter firstly and then assimilated the SWH from ERS-1 into a second-generation global ocean wave model in real-time. The assimilated experiment effectively increased swell and the modelled mean bias decreased by 0.3 m for large amplitude wave heights.

The studies above either focused on the small coastal ocean domains without consideration for swell propagation from the open ocean, or conducted a global wave simulation using a coarse mesh without consideration for coastal wave accuracy. The aim of this work is to develop a high-resolution wave model assimilating an extensive SWH dataset by fully incorporating three satellite altimeters: Jason-2, Jason-3 and