Ocean Engineering 108 (2015) 416–425

Contents lists available at ScienceDirect

Ocean Engineering

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

Trends of wave height and period in the Central Arabian Sea from 1996 to 2012: A study based on satellite altimeter data

N.K. Hithin, V. Sanil Kumar *, P.R. Shanas [1]

Ocean Engineering Division, CSIR-National Institute of Oceanography (Council of Scientific & Industrial Research), Dona Paula, Goa 403004, India

ARTICLE INFO

Article history:
Received 23 March 2014
Accepted 17 August 2015
Available online 8 September 2015

Keywords:
Satellite altimeter
Significant wave height
Tropical cyclone
Wind speed
Climate change

ABSTRACT

The variability of annual maximum and annual mean significant wave height (SWH) and wave period in the Central Arabian Sea is studied using satellite altimeter data from 1996 to 2012 at a deep water (water depth ~ 3500 m) buoy location (15.5°N, 69.28°E). Altimeter wave heights are validated with in-situ measurements and are intercompared. Extreme tropical storm/cyclone events that affect the wave conditions are studied using Joint Typhoon Warning Centre best-track data. The study shows a positive trend of 0.63 cm yr^{-1} in the annual mean SWH. In contrast, a negative trend of 2.66 cm yr^{-1} is found for the annual maximum SWH due to the decreasing trend of extreme tropical cyclone events. The annual mean and maximum wave period shows a decrease of 0.005 s yr^{-1} and 0.011 s yr^{-1}, respectively.

1. Introduction

Winds blowing over the sea surface generate wind waves (also known as ocean surface waves), and the data on these waves are required for planning and designing facilities in the ocean. The major sources of wave data are i) in-situ measurements, ii) model hindcasts and reanalysis, iii) voluntary observing ships (VOS) data and iv) satellite altimetry or remote sensing data. A number of satellite instruments such as the Scatterometer, the Special Sensor Microwave Imager (SSMI), the Synthetic Aperture Radar (SAR) and the Radar Altimeter are available for the determination of wave height and wind speed and direction (Young, 1999; Young et al., 2012). An important parameter that characterizes a wave is the significant wave height (SWH).

The Arabian Sea (AS) is an area of significant interest as it is marked by high wind speed and wave conditions due to the monsoon in a region that is otherwise calm (Young, 1999; Kumar and Anand, 2004; Kumar et al., 2010). In addition, the wind direction in the AS reverses between the two monsoons with winds blowing from the south–west (SW) during the summer monsoon period (June to September) and from the north–east (NE) during the winter monsoon period (October to January). The wave climate of the AS depends on the wind conditions prevailing over both monsoons and on swells coming from the Southern Ocean (Semedo et al., 2011; Glejin et al., 2013). Winds during the SW or summer monsoon result in high wave activity (SWH > 2 m), but relatively calm conditions (SWH < 1.5 m) prevail during the rest of the year.

Chen et al. (2002) observed an enhancement of wind-sea generation in the AS during the summer monsoon. Semedo et al. (2011) reported that the north Indian Ocean, with the exception of the summer monsoon period, is the most swell-dominated area of the world's oceans. Stronger storm events such as tropical cyclones produce higher waves in the AS (Kumar et al., 2010). Gray (1985) found that the north Indian Ocean accounts for 7% of global tropical cyclones. Occurrences of tropical cyclones are less in the AS compared to the Bay of Bengal, and the ratio of their frequencies is about 1:4 (Dube et al., 1997).

Long-term wave records based on in-situ measurements are still sparse in the AS and only short-term records are available (Premkumar et al., 2000; Kumar, 2006; Sajiv et al., 2012; Glejin et al., 2013). However, several studies have reported increases of SWH in the north Pacific and north Atlantic oceans. Carter and Draper (1988) and Bacon and Carter (1993) found that, from the 1950s to the 1990s, the mean SWH increased in the north Atlantic by 3.4 and 2.2 cm yr^{-1}, respectively. In a 5° × 10° latitude/longitude box each in the north–west and north–east Atlantic, Bouws et al. (1996) reported increases in the mean SWH of 2.3 cm yr^{-1} and 2.7 cm yr^{-1}. Gulev and Hasse (1999) found that the SWH increased by 0.1–0.3 cm yr^{-1} in the north Atlantic during the period 1964–1993, except for the western and central subtropics. Allan and Komar (2000) and Gower (2002) reported an increase of 2.1 and 1.9 cm yr^{-1} at buoys 46005 and 46002 on the north-western coast of the United States of America during the period 1972–1999. An extended study by Ruggiero et al. (2010) found that the annual average SWH increased at a rate of 1.5 cm yr^{-1} from

* Corresponding author. Tel.: +91 832 2450 327; fax: +91 832 2450 602.
E-mail address: sanil@nio.org (V.S. Kumar).
URL: http://www.nio.org (V.S. Kumar).
[1] Present address: Ph.D student, Marine physics department, King Abdulaziz University Saudi Arabia, Jeddah.

http://dx.doi.org/10.1016/j.oceaneng.2015.08.024
0029-8018/

the mid-1970s to 2010, while averages of the five highest SWH have increased at the greater rate of 7.1 cm yr^{-1}. Gulev and Grigorieva (2006) analysed the variability of SWH in the north Atlantic and north Pacific using 45 years of VOS data and found that the winter SWH shows an increase of 0.1 to 0.4 cm yr^{-1}.

Similar studies in the central AS are limited. In a global study, Caires and Swail (2004) found a negative trend of 1.9 cm yr^{-1} in SWH in the AS from July to September. Based on altimeter data covering 23 years, Young et al. (2012) reported that the equatorial and tropical regions of all oceanic basins show a neutral trend for mean and 99th percentile of wave height. For the seas around India, the long-term trend in wave height is estimated based on the global atmospheric re-analysis product (ERA-I) of the European Centre for Medium-Range Weather Forecasts (ECMWF) from 1979 to 2012 (Shanas and Kumar, 2014, 2015; Kumar and Anoop, 2015; Anoop et al., in press). The limited regional studies in the AS are mainly due to the unavailability of long time series of in-situ wave data.

Studies by Chelton et al. (1981); Dobson et al. (1987) and Monaldo (1988) have shown that active remote sensing satellites are capable of providing SWH and wind speed with an accuracy comparable to in-situ observations. In oceanographic studies, satellite-based data are highly advisable due to their global coverage compared to the sparse in-situ data available from point locations (Staabs and Bauer, 1997; Challenor et al., 2006). Wave climate across the ocean basins can be described using satellite altimetry (Young, 1999; Woolf et al., 2002). With the accumulation of lengthy and carefully calibrated datasets from a number of satellite altimeters, it is possible to evaluate the seasonality and inter-annual variability of wave climate globally (Woolf et al., 2003). Even though altimeters are unable to provide a direct estimate of wave period, a number of studies are carried out based on the wave period derived from altimeter measurements of backscatter coefficient, wind speed and SWH (Challenor and Srokosz, 1991; Sarkar et al., 1998; Hwang et al., 1998; Gommenginger et al., 2003; Kshatriya et al., 2005; Caires et al., 2005; Govindan et al., 2011). Young et al., (2011) used a 23-year database of satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height. They found a general global trend of increasing values of wind speed and wave height and that the rate of increase is greater for extreme events as compared to the mean condition.

To the authors' knowledge, no regionalized studies have been carried out on the long-term variations of SWH and wave period in the Central AS based on satellite altimetry data. This work aims to fill this gap using altimetry SWH and computed wave period data. For this purpose, a deep water location (15.5°N, 69.28°E) in the Central AS was selected since buoy data available at this location for a limited period will enable validation of the altimetry data (Fig. 1).

2. Data and methodology

2.1. Altimeter derived SWH and wind speed

Altimeter data from 1996 to 2012 was obtained from the TUDelft RADS database (Naeije et al., 2000) and used in the present study. Ku-band SWH data from the satellites *GFO, ERS*-1, *ERS*-2, *TOPEX, Jason*-1, *Jason*-2 and *Envisat*, and the data available from the *Poseidon* and *Cryosat*-2 missions were also used in the study. The resolution of the altimeter data used in the study depends on the sea condition and it ranged from 2 km (for clam sea) to 10 km (for rough sea). Altimeters provide wind speed at 10-m above the sea surface. In the study, all flagged data and data with a SWH greater than 25 m and a SWH equal to 0 are rejected. The period of data used and the satellite repeat cycle are tabulated in Table 1. *ERS*-2 and *Envisat* have a 35-day repeat cycle; *Jason*-1 and *Jason*-2 have a 10-day repeat cycle and *Cryosat*-2 has 30-day repeat sub-cycle. The most severe limitations of satellite altimetry are i) that a satellite takes at least 10 days to return to the same point, and ii) a satellite measures only the sea surface directly beneath the satellite (Hemer et al., 2010).

2.2. Buoy data

Significant wave height, wave period and wind speed data measured by a buoy at location 15.5°N, 69.28°E (water depth ≈ 3500 m) in the AS during 2004 and 2005 under the National Data Buoy Programme (Premkumar et al., 2000) are used in the study. The buoy measures wind speed at 3 m above the sea surface and SWH at a 3-h interval. Wind observation is a 10-min average with wind speed and direction sampled at 1 Hz by a cup anemometer with vane. The accuracy of wind speed measurements is 1.5% of full scale (0–60 m s^{-1}). The buoy is equipped with a motion reference unit for wave measurements. The sampling duration and frequency for wave measurement is 17 min and 1 Hz. The resolution of the wave height measurement is 1 cm and the accuracy is 5 cm. Details of the buoy configuration and sensors, including their accuracy and range, are reported by Rao and Premkumar (1998).

2.3. Tropical cyclone data

We considered AS tropical cyclones during the study period (1996–2011) based on the position and wind speed reported in the Joint Typhoon Warning Centre (JTWC) best-track dataset available at 6-h intervals (Chu et al., 2002).

2.4. Methodology

Altimeters are always calibrated and validated during the dedicated commissioning phase of a satellite and then a few months after its launch. Before using such data, the measurements have to be validated, and the quality of the data for the region has to be checked (Queffeulou, 1996; Gower, 1996; Cotton et al., 1997; Queffeulou and Bentamy, 1997). Zieger et al. (2009) carried out the calibration of multiplatform altimeter measurements of wind speed and wave height for the period 1985 to 2008. They found that the accuracies of the various altimeters were similar, with the root mean square (RMS) error being less than 0.25 m for SWH and 1.7 m s^{-1} for wind speed. We carried out the validation of altimeter wave height through measured buoy data and satellite–satellite inter-comparison.

For the comparison between satellite altimeters and a buoy, the selection of space and time collocation windows is very important (Chen, 2000). According to Caballero et al. (2011), the size of the window ranges from 0 to 150 km in the space domain while it varies from 0 to 1.5 h in the time domain. The collocation criteria of 50 km and 30 min are widely applied (Dobson et al., 1987; Monaldo, 1988; Gower, 1996; Queffeulou, 2004). Since the collocation points obtained are smaller for a 50-km window, to get a sufficient number of collocation points, we used the collocation criteria of observations occurring within 100 km and 30 min of one another. The Gaussian weight function is applied for averaging the along-track altimeter data to the exact buoy location. The collocation points for a particular buoy data point is averaged using Eq. (1), which is the method adopted by Kessler and McCreary (1992).

$$SWH(x_0, y_0, t_0) = \frac{\sum_{n=1}^{N_p} (SWH'_n W_n)}{\sum_{n=1}^{N_p} (W_n)} \tag{1}$$