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Long-term trend of satellite-observed significant wave height and impact on ecosystem in the East/Japan Sea

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ABSTRACT

Significant wave height (SWH) data of nine satellite altimeters were validated with *in-situ* SWH measurements from buoy stations in the East/Japan Sea (EJS) and the Northwest Pacific Ocean. The spatial and temporal variability of extreme SWHs was investigated by defining the 90th, 95th, and 99th percentiles based on percentile analysis. The annual mean of extreme SWHs was dramatically increased by 3.45 m in the EJS, which is significantly higher than the normal mean of about 1.44 m. The spatial distributions of SWHs showed significantly higher values in the eastern region of the EJS than those in the western part. Characteristic seasonality was found from the time-series SWHs with high SWHs (> 2.5 m) in winter but low values (< 1 m) in summer. The trends of the normal and extreme (99th percentile) SWHs in the EJS had a positive value of 0.0056 m year^{-1} and 0.0125 m year^{-1}, respectively. The long-term trend demonstrated that higher SWH values were more extreme with time during the past decades. The predominant spatial distinctions between the coastal regions in the marginal seas of the Northwest Pacific Ocean and open ocean regions were presented. In spring, both normal and extreme SWHs showed substantially increasing trends in the EJS. Finally, we first presented the impact of the long-term trend of extreme SWHs on the marine ecosystem through vertical mixing enhancement in the upper ocean of the EJS.

1. Introduction

Satellite-derived significant wave height (SWH) is one of the most important oceanic variables to affect not only the physical processes but also the biological ecosystem. When wind blows over the sea surface, wind energy is transferred into the ocean at a rate of approximately 60 TW (1 TW=10^{12} W) (Wang and Huang, 2004). The wave energy transmitted from the wind field generates turbulence and drives the vertical mixing of the upper ocean through the wave-breaking process (Craig and Banner, 1994; Weber, 2008). The interactions among the waves, mean current, and turbulence fields can also intensify the vertical mixing of the upper ocean (Jiang et al., 1990; Babanin, 2006; Dai et al., 2010; Huang and Qiao, 2010). The vertical mixing from the wave interactions controls the movement of fish larvae and suspended materials such as nutrients and pollutants (Craig and Banner, 1994). In light of this, information of SWHs is significant for diverse oceanic and atmospheric applications.

Data from oceanographic buoys, satellite altimeters, and models have been used to determine trends by using a time series of SWH data. Previous studies using long-term buoy observations have reported that the SWHs in the North Atlantic and Northeast Pacific gradually increased (Carter and Draper, 1988; Bacon and Carter, 1991; Allan and Komar, 2000; Gower, 2002; Menéndez et al., 2008; Ruggiero et al., 2010). Carter and Draper (1988) and Bacon and Carter (1991) found that SWH in the Northeast Atlantic increased by 0.034 m year^{-1} and 2% per year based on ship wave recorder and ocean weather station data from the early 1960s to the late 1980s. Wave heights measured by the National Oceanic and Atmospheric Administration (NOAA) buoys in the eastern North Pacific also showed a positive trend (Allan and Komar, 2000; Gower, 2002; Menéndez et al., 2008; Ruggiero et al., 2010). In particular Menéndez et al. (2008) and Ruggiero et al. (2010) revealed that the positive trends of the extreme wave heights were more apparent than the mean wave heights, and they analyzed the relationship between the extreme waves and El Niño. Because most buoy stations are located near the coast, it is difficult to understand the variability of offshore SWHs. Moreover, they are unevenly distributed in space and have a limitation of spatial coverage. For this reasons, buoy SWH data are not appropriate for estimating the characteristics of SWHs at the basin or sub-basin scale (Queffeulou and Bentamy, 2007).

Improvements in the accuracy of wind data used for model input

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data and developments in data assimilation techniques have enabled wave models to produce long-term and gridded SWH reanalysis data (Cox and Swail, 2001; Uppala et al., 2005; Dee et al., 2011). Semedo et al. (2011) analyzed the interannual variability of SWHs using the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) wave spectrum for the period of 45 years and showed that a significant increase of SWHs in winter appeared with a positive trend of 0.016–0.020 m year^{-1} in the North Pacific and North Atlantic. Shanas and Kumar (2015) also identified positive trends of extreme SWHs with a magnitude of 0.002 m year^{-1} in the Central Bay of Bengal using the ECMWF ERA-Interim reanalysis data. However, SWH reanalysis data can be inaccurate and inhomogeneous owing to the assimilation of inaccurate altimeter SWH data (Caires and Sterl, 2003; Caires et al., 2004). Therefore, accuracy assessment and correction of model SWHs data should be conducted for long-term trend analysis (Caires and Sterl, 2005).

Since the Geosat began operation in 1985, sufficient satellite SWHs data have been accumulated over the decades to investigate the wave climate and long-term trend of SWHs. Young et al. (2011) used the SWH data of 7 satellites for 23 years to determine that global SWHs are increasing and that the magnitudes of extreme SWH trends are larger than the mean SWH trends. Izaguirre et al. (2011) and Young et al. (2012) realized the importance of understanding the variability of extreme SWHs and suggested statistical methods for determining these values. They explained the interannual variability of global extreme SWHs compared with the climate index and analyzed the trend of the extreme SWHs. In addition, several studies have investigated the long-term variability of satellite SWHs in regional oceans such as the North Atlantic, Mediterranean Sea, and Central Arabian Sea (Woolf et al., 2002; Queffeulou and Bentamy, 2007; Hithin et al., 2015).

The East/Japan Sea (EJS) is a semi-enclosed marginal sea connected with the Northwest Pacific through the Korea Strait, Tsugaru Strait, Soya Strait, and Tatar Strait and is surrounded by a chain of high mountains. Turbulence is actively generated by various current systems such as the Tsushima Warm Current and the East Korea Warm Current, the sub-polar front located near 40°N, mesoscale eddies, and complicated topography (Huh, 1982; Park et al., 2007; Park et al., 2012). In addition, local winds have a direct influence on the sea states in the EJS (Chen et al., 2002; Park et al., 2005). Therefore, the SWH characteristics in the EJS differ from those in the open ocean. Nevertheless, few studies have investigated the long-term trends of satellite SWHs in the EJS. Moreover, the potential impacts on the marine ecosystem in the EJS and in the global oceans are rarely discussed.

Thus, the aims of this study are to validate the satellite SWH data with *in-situ* buoy measurements, to examine the spatial and temporal distribution of SWHs, to estimate the long-term trend of SWHs and its monthly characteristics, and to understand the potential impacts of long-term variability of SWHs on the marine ecosystem in the EJS.

2. Data and methods

2.1. Satellite data

To investigate the long-term variability of SWH, we collected all of the available satellite altimeter data covering more than two decades since ERS-1 began operation in 1991. In total, nine altimeter mission datasets were acquired from Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER): European Remote Sensing-1 (ERS-1), Topography Experiment/Poseidon (TOPEX/Poseidon), European Remote Sensing-2 (ERS-2), Geosat Follow-On (GFO), Joint Altimetry Satellite Oceanography Network-1 (Jason-1), Environmental Satellite (Envisat), Joint Altimetry Satellite Oceanography Network-2 (Jason-2), Cryosat-2, and Satellite for Argos and Altika (SARAL).

There is significant bias in SWH data from various altimeters, because of issues such as electronics drift and sensor degradation (Carter et al., 1992; Challenor and Cotton, 2002; Queffeulou, 2004), and because of the different characteristics of each altimeter such as band frequency and altitude (Lefevre and Cotton, 2001). Queffeulou (2003) showed significant differences between four satellites (TOPEX/Poseidon, ERS-1/2, and GFO) by comparing time series SWH averaged for a 10-day time period between 1991 and 2002. Based on this, satellite SWH data were corrected, using in-situ measurements and cross-altimeter comparison, to eliminate invalid SWH data and to obtain accurate and consistent datasets. SWH data from IFREMER used in this study were also corrected on the basis of validation and calibration procedures suggested by Queffeulou (2003) over all of the altimeters (Queffeulou, 2004; Queffeulou and Croizé-Fillon, 2015). The biases between SWH data from each altimeter from IFREMER were less than 0.1 m (Queffeulou, 2003, 2004).

Table 1
Information of satellite altimeters European Remote Sensing-1 and -2 (ERS-1/2), Topography Experiment/Poseidon (TOPEX/Poseidon), Geosat Follow-On (GFO), Envisat, Joint Altimetry Satellite Oceanography Network-1 and -2 (Jason-1/2), Cryosat-2, and Satellite for Argos and Altika (SARAL) including the operational period, band frequency, repeat period, altitude, and inclination.

Satellite	Operational period	Band (GHz)	Repeat period (days)	Altitude (km)	Inclination (deg)
ERS-1	17 Jul 1991–10 Mar 2000	Ku (13.8)	3, 35, 168	785	98.54
TOPEX/Poseidon	10 Aug 1992–9 Oct 2005	C (5.3), Ku (13.575)	9.9156	1336	66.04
ERS-2	21 Apr 1995–5 Sep 2011	Ku (13.8)	35	785	98.54
GFO	10 Feb 1998–22 Oct 2008	Ku (13.5)	17	784	108.04
Jason-1	7 Dev 2001–21 Jun 2013	C (5.3), Ku (13.575)	9.9156	1336	66.04
Envisat	1 Mar 2002–8 Apr 2012	S (3.2), Ku (13.575)	35	800	98.54
Jason-2	20 Jun 2008–Present	C (5.3), Ku (13.575)	9.9156	1336	66.04
Cryosat-2	8 Apr 2010–Present	Ku (13.575)	30	717	92
SARAL	25 Feb 2013–Present	Ka (35.75)	35	781	98.55

As denoted in the temporal coverage of each satellite during the study period of 1991–2015 in Fig. 2, satellite altimeters have observed SWH continuously from 1991 to the present. Table 1 presents brief information of the orbit characteristics of each satellite such as repeat period, altitude, and inclination. The SWH data used in this study have different repeat periods of 35 days for ERS-1/2, Envisat, and SARAL; 9.9156 days for TOPEX/Poseidon and Jason-1/2; 17 days for GFO; and 30 days for Cryosat-2. Most of the SWH data were estimated from Ku- (13.5–13.8 GHz) and Ka-band (35.75 GHz) measurements rather than C-band (5.3 GHz) and S-band (3.2 GHz) data.

2.2. Buoy data

To validate the satellite SWH in the study area, *in-situ* SWH measurements were used from six buoy stations of the Korea Meteorological Administration (KMA) and Japan Meteorological Agency (JMA). For convenience, buoy stations were marked from A to F. The locations of the KMA and JMA buoy stations are marked by red circles in Fig. 1. In most cases, for satellite SWH data verification, buoy stations located close to land (~50 km) were discarded from the analysis because the altimeter signals can be contaminated by land effects (Dobson et al., 1987; Monaldo, 1988; Zieger et al., 2009). Nevertheless, all of the available buoy stations located in the EJS were