Recent record-breaking high ocean waves induced by typhoons in the seas adjacent to Korea

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ABSTRACT


Estimation of extreme wave heights (EWHs) is the most important factor in the design of coastal structures such as breakwaters. In Korean coasts, the most EWHs occur during typhoon events. Recently, a number of ocean wave buoys have been deployed in the seas adjacent to Korea. This enables the measurement of record-breaking high waves during passages of recent strong Typhoons Kompasu (1007), Muifa (1109), Bolaven (1215), and Sanba (1216). This study investigates the characteristics of extreme waves during the passages of typhoons using buoy measurements and a numerical model. The wave simulations using WAVEWATCH III show that the model has the capability to reproduce the most EWHs during the four aforementioned typhoons with high accuracy, which guarantees an explanation of the mechanisms on the causes of such high wave generations over these regions. The analysis reveals that the occurrence of EWHs is influenced by not only storm intensity (i.e., maximum wind speed), but also the size, translation speed, and track of typhoons. Particularly, the record-breaking maximum wave height of 19.7 m observed during Typhoon Bolaven was the combined result of high winds, fast translation speed, big size, and straight track of Bolaven, which can maximize the increase of the dynamic fetch and duration.

ADDITIONAL INDEX WORDS: Extreme high waves, typhoon, wave modeling.

INTRODUCTION

The observation and estimation of extreme wave heights (EWHs) is important both scientifically, for the design of breakwaters, drilling platforms, and seabed mining facilities, as well as operationally, for the predictions of potentially hazardous conditions for ship navigation and coastal regions. In many cases, EWHs occur during tropical cyclone (TC, also called typhoon or hurricane) events with intense and fast-varying winds (Moon et al., 2003; Kim et al., 2014). The existence of gigantic maximum wave heights (Hmax) during hurricanes or typhoons has been reported from all over the world’s oceans. Wang et al. (2005) reported a Hmax of 27.7 m derived from a deep-sea pressure gage in the northern Gulf of Mexico during the passage of hurricane Ivan in 2004. Holliday et al. (2006) discovered a recorded Hmax of 29.1 m from the Shipborne Wave Recorder onboard RRS Discovery in the northeast Atlantic Ocean. Most recently, Liu et al. (2008) measured a Hmax of 32.3 m from a discus buoy deployed near northeast Taiwan in the western Pacific, during the event of Typhoon Krosa on 6 October 2007, which could potentially be the largest Hmax ever recorded.

Figure 1. Pictures of breakwaters in (A) Gageodo and (B) Seogwipo, which were damaged by Typhoons Muifa (1109) and Bolaven (1215).

In the seas adjacent to the Korean peninsula (KP) including the Yellow Sea, the South Sea, and the East China Sea, such
extraordinarily huge waves have never been measured until now. This is most likely due to the relatively shallow water depths in these regions, the limited dynamic fetch for wave growth due to a bay-like shape surrounded by land, and the smaller intensity of storms compared to those in tropical regions. The lack of wave measurements in these areas also appears to contribute to the missing high wave observations.

Recently, a number of ocean wave buoys have been deployed in the seas adjacent to the KP. Fortunately some buoys that were located in the passage of recent strong Typhoons Kompasu (1007), Muifa (1109), Bolaven (1215), and Sanba (1216), measured record-breaking high waves in these regions. This study investigates the characteristics of the observed extreme waves using an ocean wave model during the passages of the four typhoons that caused great damage to the coastal area (Figure 1), with a special focus on examining the occurrence mechanism of the extreme waves.

A brief outline of the dataset and wave model used in the present study is described in the next section. The third section describes the validations of simulated waves with observational data, and also explains the characteristics of extreme waves under typhoon forcing. The summary and conclusions are given in the last section.

**METHODS**

Information on four typhoons was obtained from the best track archives of the Regional Specialized Meteorological Center (RSMC) in Tokyo. The data consist of the names of the TCs, their central positions (latitude and longitude), their minimum surface central pressures, and their maximum sustained wind speeds (MSWS: 10-min averaged maximum winds to the nearest 5 kts) measured every 6 hours.

The surface winds for typhoons, used as input data to the wave model, were obtained from the National Centers for Environmental Prediction’s (NCEP) Global Forecast System (GFS). In this study, GFS winds near the storm core are modified using a weighted correction proportional to the distance (up to 223 km) from the position with the maximum difference in order to reduce the difference of the MSWS between GFS and best track (Figure 2). This modification allows us to resolve the problem of GFS winds, which usually underestimate the wind speed at a storm core due to its low spatial resolution (1 degree).

Wave data, $H_{max}$, and significant wave height ($H_s$), are obtained from three separate sources: (1) three ocean buoys (Chilbando, Geojedo, Marado) from the Korean Meteorological Agency (KMA); (2) the Ieodo Ocean Research Station (IORS); and (3) five ocean buoys from the Korea Hydrographic and Oceanographic Administration (KHOA). Among them, KOGA-S01, IORS, and KOGA-S04 are open ocean sites, and KOGA-S01 is located in the southernmost point. Locations and pictures of the buoys and IORS are presented in Figure 3.

The wave model used in the present study is WAVEWATCH III (WW3), which is developed at the National Oceanic and Atmospheric Administration (NOAA)/NCEP. The WW3 has been used in many research programs to study surface wave dynamics, and also as the operational wave model of NCEP for global and regional wave forecasts (Tolman 2002; Tolman et al. 2002). The WW3 explicitly accounts for wind input, wave–wave interaction, and dissipation due to whitecapping and wave–bottom interaction. It solves the spectral action density balance equation for directional wavenumber spectra. The source terms of the WW3 use wind–wave interaction according to Chalikov and Belevich (1993), as modified by Tolman and Chalikov (1996) and Tolman (1999), discrete interaction approximation (DIA) for nonlinear interactions (as in WAM), dissipation from Tolman and Chalikov (1996), and bottom friction as in the Joint North Sea Wave Project (JONSWAP, as in most WAM models). A detailed description of the model is given by Tolman (1999) and Moon et al. (2003).
The wave model used in this study is a two-way nest version of the WW3, in which the results calculated from higher-resolution nests are transferred to coarse domain. The model consists of three domains: the global domain (1°x1° spatial grid resolution extending from 75°S to 75°N and 180°E to 180°W), the northwestern (NWP) domain (1/12°x1/12°, extending from 17° to 50°N and 115° to 155°W), and the Korean peninsula (KP) domain (1/30°x1/30°, extending from 29° to 41°N and 120° to 135°W). This two-way interacting system with high-resolution nests is necessary to resolve the quickly varying wave fields associated with a typhoon.

Figure 4. Distributions of (A) simulated $H_s$ and (B) wind speed for Typhoon Bolaven at 12Z 27 August 2012. In (A), contours and arrows represent $H_s$ and dominant wave direction/wavelength, respectively. The arrow length is proportional to the dominant wavelength. Solid line with dot is the track of Bolaven every 6 h.

RESULTS

Figure 4a shows distributions of $H_s$ (contours), dominant wave directions (arrows), and dominant wavelengths (proportional to the arrow length) for Typhoon Bolaven at 12Z 27 August 2012, simulated by the present model. The $H_s$ reached 14.4 m in the East China Sea, at which time the maximum wind speed was 33.4 m/s. The peak $H_s$ and lengths are found in the right forward quadrant of a typhoon’s center and propagate in the same direction as the typhoon. The asymmetric distributions are distinct in both fields of winds (Figure 4A) and waves, which appear to be due to the high storm translation speed (above 9 m/s). The high and long waves mostly propagated to the southern coasts of the KP and Jeju Island (Figure 4B).

Figure 5. Comparisons of significant wave height ($H_s$) between model (blue line) and observation (green dot) during the passage of typhoon Bolaven (1215) at (A) Chilbaldo, (B) Geojedo, (C) IORS, (D) KOGA-S01, (E) KOGA-S04, and (F) Marado. Red dots represent the observed maximum wave height.

Figure 5 shows a comparison of $H_s$ between the model (blue line) and observations (green dot) for Typhoons Bolaven at Chilbaldo, Geojedo, IORS, KOGA-S01, KOGA-S04, and Marado. The peak $H_s$ at these points reached 5.1, 6.5, 11.1, 12.4, 11.2, and 10.2 m, respectively. At that time, the $H_{max}$ (red dot) reached 9.5, 9.9, 17.3, 19.7, 17.2, and 13.7 m. The $H_{max}$ at all points except Geojedo were the largest ever recorded in the individual regions. The same comparisons were made for Typhoon Sanba at Chilbaldo, Geojedo, Haeundae, KOGA-S02, KOGA-S03, and Marado (Figure 6). The peak $H_s$ at these points reached 4.8, 9.6, 5.4, 80, 10.8, and 6.2 m, respectively. At that
time the $H_{\text{max}}$ reached 6.1, 13.4, 6.9, 11.4, 15.5, and 10.3 m. The $H_{\text{max}}$ at Geojedo was the highest ever recorded in this region. The time series of $H_{\text{max}}$ and $H_{\text{s}}$ for Typhoons Kompasu and Muifa also reveal that some values almost approached the highest records although they did not break the records set by Bolaven and Sanba (not shown).

The simulated $H_{\text{s}}$ are generally in good agreement with the observations throughout all typhoon passages (Table 1). The computed peak $H_{\text{s}}$ are also well matched with their corresponding observations, although the model had a tendency to underestimate the peak values at some points. The estimated rms errors between simulated and observed $H_{\text{s}}$ during the passage of Typhoons Kompasu, Muifa, Bolaven, and Sanba were 0.75 m, 0.58 m, 0.55 m, 0.44 m, respectively. This statistics suggest that the present model is capable of simulating $H_{\text{s}}$ with high accuracy under typhoon forcing, which guarantees that the model results can be used in examining the causes of record-breaking extreme wave generations over these regions.

<table>
<thead>
<tr>
<th></th>
<th>Kompasu</th>
<th>Muifa</th>
<th>Bolaven</th>
<th>Sanba</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias [m]</td>
<td>0.03</td>
<td>-0.35</td>
<td>-0.10</td>
<td>-0.22</td>
</tr>
<tr>
<td>Rmse [m]</td>
<td>0.75</td>
<td>0.58</td>
<td>0.55</td>
<td>0.44</td>
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It is important to investigate the spatial distribution of the severest wave conditions generated by typhoons from the perspective of structural engineers. Figure 7 compares the swath pictures of $H_{\text{s}}$, which show the maximum values at each grid point throughout the passages of each typhoon. For all typhoons, the higher waves appear to the right of the typhoon along their tracks. The areas with the higher waves extended to Jeju Island along the tracks. It is interesting that Jeju Island appears to play a role of breakwater that prevents high waves from propagating to the southern coasts of the KP.

The spatial patterns reveal that Bolaven produced the highest $H_{\text{s}}$ for broad areas. Kompasu and Muifa showed also a similar spatial pattern to Bolaven in their tracks similarly passed through the left side of Jeju Island in a straight manner, but they were different in that their magnitudes of $H_{\text{s}}$ were weaker than those of Bolaven. It should be noticed that the peak $H_{\text{s}}$ of Kompasu is lower than that of Bolaven in the East China Sea, although the wind speed of Kompasu is much higher than that of Bolaven (Figure 8A & 8B; Figure 3).

In addition to wind speed, the dynamic fetch and duration are crucial factors that determine wave growth. It is known that as the storm translation speed (STS) becomes comparable to the...
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Recently record-breaking high ocean waves were measured from ocean buoys and research stations during the passage of Typhoons Kompasu (1007), Muifa (1109), Bolaven (1215), and Sanba (1312). This study simulated the extreme waves and investigated the mechanisms of high-wave generation by using a high-resolution wave model that allows a two-way interacting nest, as well as improving surface winds used for the input data of wave model. The comparisons of the model results with observations reveal that the present model was capable of simulating $H_s$ with high accuracy under typhoon forcing. Spatial distributions of the maximum $H_s$ for 4 typhoons show that Bolaven produced the highest $H_s$ for broad areas, although the maximum wind speed of Bolaven was not the highest. In Bolaven’s case, we found that its large size, fast translation speed similar to the group speed of dominant waves, and its straight track maximized the increase of the dynamic fetch and duration, leading to the generation of high waves. The present measurements and modeling results for extreme waves induced by the four typhoons suggest that the update of design waves in these regions is required.

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