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WINTERTIME EXTREME STORM WAVES IN THE EAST SEA (JAPAN SEA): ESTIMATION OF EXTREME STORM WAVES IN THE TOYAMA BAY, JAPAN

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ABSTRACT: In the winter East Sea (ES), abnormal high waves due to the cold and dry East Asian winter monsoon and winter storms (extratropical cyclones) are often reported causing large coastal damages along the coasts of ES. In February 2008, abnormal storm waves due to a developed atmospheric low pressure system propagating from the west off Hokkaido, Japan, to the south and southwest throughout the ES caused extensive damages along the central coast of Japan and along the east coast of Korea. In this study, we investigate a potential extreme storm wave, Yorimawari Waves in Japanese, in the Toyama Bay where the coastal structures were heavily damaged by the storm waves in February 2008. Three factors for wind wave growing, such as wind intensity, duration and fetch, are investigated for their extreme conditions based on historical data and empirical formula. Then, numerical experiments are conducted to estimate extreme wave characteristics in the Toyoma Bay using a meso-scale non-hydrostatic meteorological model, WRF, and a spectral wave model, WAVEWATCH III. The results from numerical experiments depict the potential significant wave height of 6.78 m and corresponding wave period of 18.28 sec at the Fushiki-Toyama Port in the Toyama Bay.

Keywords: storm waves, Toyama Bay, Yorimawari Waves, the East Sea, WAVEWATCH III, WRF, extratropical cyclone, meteorological bomb.

INTRODUCTION

In the winter East Sea (ES), abnormal storm waves due to the East Asian winter monsoon and winter storms (extratropical cyclones) are frequently reported causing large coastal damages along the coasts of Korea and Japan.

In February 2008, abnormal storm waves due to a developed low propagating from the west off Hokkaido to the south and southwest in the ES caused extensive damages along the coasts of Korea and Japan. The observed maximum wave heights and periods are appeared in Table 1. The abnormal storm waves propagated into the Toyama Bay, Japan, caused one of the most severe coastal damages ever induced by such conditions. Such abnormal waves are called “Yorimawari Waves” by the local people and investigated by Lee et al. (2010) on their generation mechanisms by thorough literature reviews and numerical experiments.

Recently in 3 ~ 5 April 2012, an extratropical cyclone being developed to 964 hPa in its intensity at 20:00 UTC 3 April during its passage over the ES brought record-breaking significant wave heights along the west coast of Tohoku, Japan. The observed significant wave heights by GPS wave buoys at Akita and Yamagata were 11.21 m and 12.39 m and the significant wave periods were 13.6 sec and 14.3 sec, respectively, which both were the maximum wave heights and periods ever recorded in ES due to a winter storm. Huge coastal damages were reported along the west coast of Tohoku, Japan, by the abnormal storm waves. Lee (2013a) reported the physical process of rapid intensifying of the low pressure that the moving low intensified by the enhanced local convection due to the large latent heat and vapor supply from extended Tsushima Warm Currents in the ES.

In addition, Lee et al. (2010) and Lee and Yamashita (2011) investigated past events of the winter storms and abnormal waves in the ES and demonstrated three representative meteorological patterns of developing low pressures in terms of their moving path (Fig. 1).

In the first and second patterns, there is another low pressure developed in the Pacific and moves northward east off Hokkaido. It slows down the low pressure in the ES blowing strong counter-clock wise winds with enough duration. According to Lee et al. (2010), most past events fall into the first and second patterns and

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there were many casualties reported along the east coast of Korea due to the leisure activities in clear local weather condition.

In this study, we revisit the abnormal storm waves in February 2008 and investigate the potential extreme "Yorimawari Waves" in the Toyama Bay by means of statistical analysis and numerical experiments with the WRF-WAVEWATCH III system.

DATA AND METHODS

Data

A weather chart showing the meteorological condition at 12:00 UTC 23 February 2008 is presented in Fig. 2. The Low A system generated west of Korean peninsula over the Yellow Sea at 06:00 UTC 22 February moved rapidly eastward at 12:00 UTC on the same day. Afterward, it continued to move eastward slowly over the ES, strengthening in central pressure from 1008 hPa to 992 hPa within 12 hrs. For a day from 00:00 UTC 23 to 00:00 UTC 24 February, the Low A system stayed near Hokkaido and strengthened further. Another Low B system was also developed southeast of Honshu and moved northeastward until it neared the other low system. Due to these meteorological conditions, westerly and northwesterly winds were dominant during the slow movement of the Low A over the ES on 22 February, while strong north and northeasterly winds of about 20 m/s were blowing dominantly on 23 and 24 February (Fig. 3).

The observed wave characteristics from Korea Hydraulic and Oceanographic Administration (KHOA) in Korea and Nationwide Ocean Wave information network for Port and HAbourS (NOWPHAS), in Japan are presented in Table 1. From the observed wave characteristics and winds, it is found that the coastal damages around the Toyama Bay are caused by storm-induced swells (Lee et al., 2010).

Table 1 Observed maximum wave heights, periods and time in February 2008 due to a developed low. Data are from NOWPHAS, Japan (JP), and KHOA, Korea (KR).

Station	Wave height (m)	Wave period (s)	Time (UTC)
Naoetsu, JP	6.4	10.2	10:00 23
Toyama, JP	9.92	16.2	07:00 24
Fushiki-Toyama, JP	4.22	14.2	05:00 24
Wajima, JP	7.73	13.2	03:00 24
Anmok, KR	5.5	14.17	11:00 24

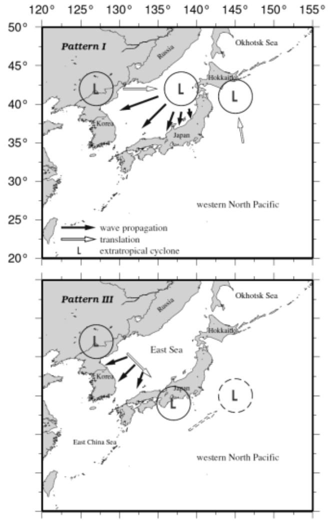

Fig. 1 Three movement patterns of low pressure systems that cause the abnormal storm waves in ES based on literature reviews.

Statistical analysis

In order to estimate the potential extreme storm waves in the Toyama Bay, we investigate the two factors affecting the wind wave growth, such as wind intensity and duration, by statistical analysis. The other factor, fetch, is not considered in the analysis since the observed swell directions is NNE dominant in the Toyama Bay. Thus the fetch is somehow pre-determined.

Wind duration

In the work of Tsuchiya et al. (1991), the following extreme value analysis (EVA) was performed for the abnormal storm waves in the ES:

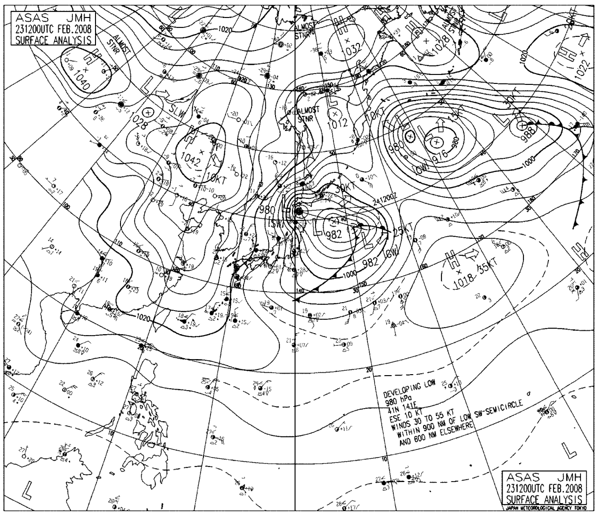

Fig. 2 Weather chart at 12:00 UTC 23 February 2008 depicting the long north-south trough of pressure gradient between the Low A and a high over the Siberia.

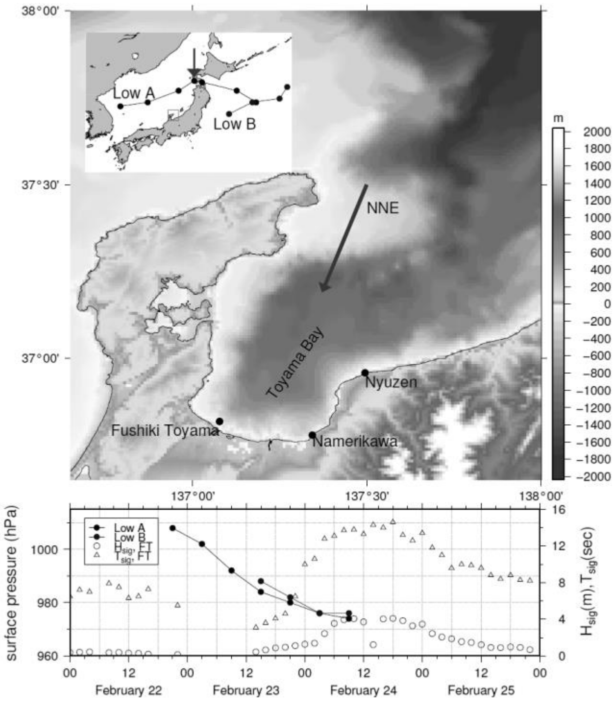

Fig. 3 Tracks of low pressures and observed wave direction (upper panel) and the pressure variations of lows in time together with observed H_s and T_s at Fushiki Toyama buoy (lower panel).

a) Observed wave characteristics over 4 m at four sites along the Japan coast facing the ES are collected from October to March for 10 yrs from 1980 to 1989.

b) The related data of the track, transition time, and central pressure from the responsible corresponding lows are also collected based on weather charts.

c) Then, apply the EVA to those data collected fitting to the Gumbel distribution.

Table 2 exhibits the result of EVA in terms of transition time, which is related with and proportional to the wind duration induced by a moving low. In the following numerical experiments, the result is referred in the experiment scenarios.

Wind intensity

In terms of extreme wind intensity condition, we compare the two events between the low in February 2008 and the one in April 2012, because the low in April 2012 is the most intensified one ever observed in extratropical cyclones in the ES. The analysis is conducted as follows:

a) Calculate the average increment rate of wind speeds due to the low in 2012 compared to those by the low in 2008. The wind speeds used are obtained from 20 AMEDAS stations which observed the highest winds during the passage of the lows

b) Calculate the average increment rate of wind speeds based on the empirical formula for wind-pressure relationship. The minimum pressure observed in 24 February 2008 is 980 hPa, while it is 962 hPa in 3 April 2012. The difference of minimum pressure between the two events is 18 hPa. According to Knaff and Zehr (2007), the wind speed by the low in February 2008 can be intensified further about 20 m/s following the empirical formula of wind-pressure relation in case the low in February 2008 get intensified down to 962 hPa.

c) Then, we choose the larger increment rate of wind speed between the two results obtained above for the following numerical experiments.

Numerical models and their configurations

The atmosphere-wave modeling system consists of the following components: the Advanced Research Weather Research and Forecasting (WRF) model (v 3.2) (Skamarock et al., 2008) for the atmosphere, the third generation wind-wave model WAVEWATCH III (WW 3) v 3.14 (Tolman, 2009) for the waves.

WRF is a 3D non-hydrostatic mesoscale model developed at National Center for Atmospheric Research (NCAR) based on non-hydrostatic, compressible form of governing equations in spherical and sigma coordinates with physical processes such as precipitation physics, planetary boundary layer (PBL) processes and atmospheric radiation processes incorporated by a number of physics parameterizations. The present study adopts an interactive grid nesting with three domains with horizontal resolutions of 27, 9 and 3 km, respectively. The WRF computation is carried out for 120 hrs from 00:00 UTC 22 February to 00:00 UTC 27 February 2008. The model topography for the chosen domain regions is obtained from the U.S. Geological Survey (USGS) topography database. A Four-Dimensional Data Assimilation (FDDA) technique is also applied to all of the domains in the wind, temperature and mixing ratio fields every six hours.

WW3 (v 3.14) is a full-spectral third-generation wind wave model developed at the Marine Modeling and Analysis Branch (MMAB) of the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP) and freely available from NCEP. The WW3 model is applied to the storm wave simulations for the same periods with the same configuration of three nesting domains as the WRF simulation to account for the accurate swell propagation. The bathymetry for the wave simulations is taken from the GEBCO 30 arc-sec database. The external forcing is imposed from the simulated winds from the WRF model. In the last version (v3.14) of the energy balance equation of WW3 used in this study, the depth-induced wave energy dissipation term (Battjes and Janssen, 1978) is incorporated for the wave propagation in shallow water environment, which is the same formula adapted in the

Simulating Waves Nearshore (SWAN) model (Booij et al., 2004). Therefore, the shallow water dynamics in the surf zone are expressed properly. In WW3, three package-like wind input and dissipation terms are available as follows: (1) The input-dissipation source terms of WAM cycle 3, which is based on Snyder et al. (1981) and Komen et al. (1984), (2) The input-dissipation package by Tolman and Chalikov (1996), which is based on Chalikov and Belevich (1993) and Chalikov (1995) for wind input and on Tolman and Chalikov (1996) for low- and high-frequency dissipation consitutents, (3) The input-dissipation source terms based on the modified wave growth theory (Janssen, 1991) and the WAM4-type dissipation term with combination of a saturation-based term (Bidlot et al., 2005).

Based on the numerical experiments of Lee (2013b) for evaluating the WW3 performance in terms of wind input and dissipation source terms, the WAM4-type input-dissipation package shows the best performance for the abnormal storm waves in October 2005 and October 2006. Therefore, the WAM4-type wind input and whitecapping dissipation terms are used together with the discrete interaction approximation nonlinear wave-wave interactions (Hasselmann et al., 1985). The frequency increment factor (X_ω), the first frequency (ω_0), the number of frequencies and the directions for all of the simulations are set as 1.1, 0.04118 Hz, 25 and 36, respectively. The initial and boundary conditions for domains 2 and 3 are imposed from the mother domains, while the zero start (with the initial spectral densities of 0) is applied for domain 1 in the WW3 simulations.

Table 2 Computed transition time of a low from the extreme value analysis of low pressures (reproduced from Table 3 in Tsuchiya et al. (1991)).

Return period (yr)	Transition time (hr)
30	58.6
50	63.5
100	70.2
250	79.1
500	85.8

Table 3 Configurations of numerical experiments for wave modeling depicting the different external forcing conditions for wind intensities and durations.

Run	Wind intensity (%)	Wind duration (hr)
A	100	Hindcast
B	160	Hindcast
C	160	A + 6
D	160	A + 12
E	160	A + 18

Numerical experiments

Table 3 represents the scenarios of numerical experiments conducted for estimating the extreme storm waves, Yorimawari Waves, in the Toyama Bay. Based on the extreme conditions on wind intensity and duration, five numerical experiments for wave modeling are conducted with different external forcings for wind intensities and durations. With respect to the wind duration, it is extended 6, 12 and 18 hrs from the real condition of which the low pressure stagnated near Hokkaido. For wind intensity, two conditions are considered with real and 1.6 times intensified winds. The downward red arrow in the sub-plot of the upper panel in Fig. 3 indicates the location of the low for the extension of wind duration.

RESULTS

Figure 4 exhibits the simulated wind and pressure fields using WRF and the corresponding surface wave fields with WW3 from the experiment run A. The wind fields show northerly winds clearly when the low stagnated near the Hokkaido persistently blowing for almost 24 hrs. The corresponding surface waves illustrate high wind waves over 10 m propagating from north to south. The highest wave group is focused on the northwest of the Toyama Bay. The Sado Island experiences the high waves directly and large coastal damages are occurred. The swell-like waves propagate into the Toyama Bay in NNE direction as observed.

Figures 5 to 9 illustrate the comparisons of wave characteristics between the observed and the computed from the experiment runs A to E, respectively. The hindcast result in Fig. 5 displays slight underestimations both in significant wave height and period. Before the storm waves are propagated into the Toyama Bay at 12:00 UTC 23 February, there seems to be long period waves with small wave heights which is not correctly simulated. Long term spin-up simulation can partly improve the results. The effects of geographical feature of the Toyama Bay such as the bay-scale resonance and coastally trapped waves can also explain the discrepancy between the observed and the computed wave characteristics.

Figure 6 exhibits the comparison of wave characteristics between the observed and the computed. The computed results are from the experiment run B being forced by 1.6 times intensified winds with real duration. Both significant wave height and period are largely increased reaching up to nearly 7 m and 17 sec, respectively.

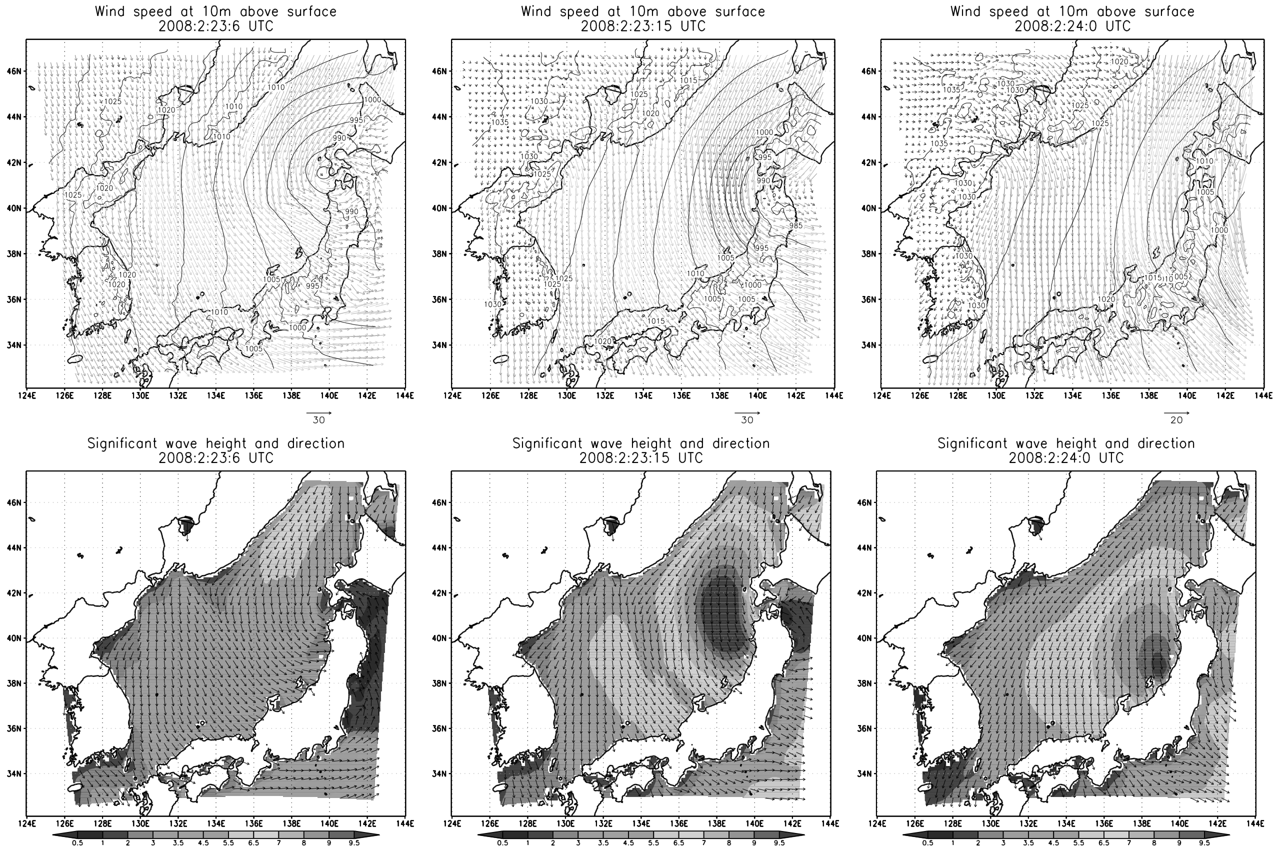

Fig. 4 Simulated wind and pressure (upper panels) using WRF and wave height and direction (lower panels) using WW3 at the given time above the each panel. The results are from the second domain of the experiment run A.

Figure 7 illustrates the same comparison as in Fig. 5, but the computed results are from the experiment run C which uses the external wind forcing enhanced 1.6 times in wind intensity and extended 6 hrs in wind duration. The maximum significant wave height during the simulation period is nearly 7 m and the wave period is nearly 18 sec. As expected from the forcing wind duration, the high storm waves remained longer in the bay.

Figure 8 represents the comparison as in Fig. 5, but the computed results are from the experiment run D. The external wind forcing for run D is same with run C in wind intensity, but the wind duration is extended 6 hrs more from run C. The maximum significant wave height and period are almost same with the run C, but they remained longer in the bay as expected.

The computed results of wave characteristics from the final experiment run E are compared with the observed in Fig. 9. The computed maximum significant wave height is nearly 7 m and wave period is now over 18 sec. The high storm waves over 6 m is now propagating into the bay more than 24 hrs reaching to the Fushiki-Toyama site.

From the all experiment runs, the computed maximum significant wave height and period are 6.78 m and 18.28 sec at the Fushiki-Toyama buoy site.

DISCUSSIONS

In order to estimate the extreme wave characteristics of the storm waves in the Toyama Bay, there are three ways in general:

a) Apply the long-term observed wave characteristics to the EVA to find out the extreme storm wave characteristics for a target return period.

b) Find out the extreme conditions for wind intensity, duration and fetch, and then conduct numerical experiments for wind waves with the extreme conditions for wind forcing.

c) Combine the method a) and b) together. First, investigate the probabilities of extreme wind forcings in terms of wind intensity, duration, and fetch. Then, conduct wind wave modelings with the given extreme meteorological conditions. Finally, apply the resulting wave characteristics to the EVA to obtain the extreme storm wave characteristics.

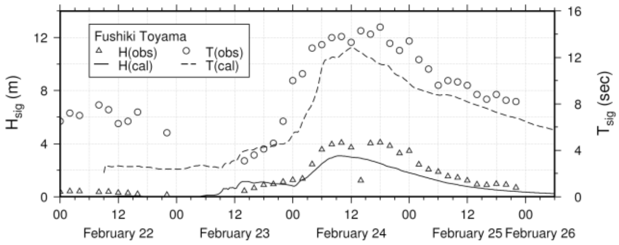

Fig. 5 Comparison of the observed and the computed significant wave heights and periods at Fushiki Toyama. The computed results are from the experiment run A with real wind forcings.

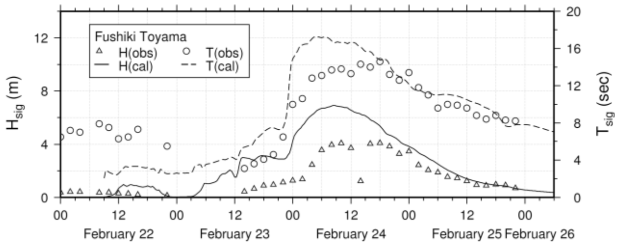

Fig. 6 Same as in Fig. 5. Computed results are from the experiment run B with 1.6 times enhanced wind intensity.

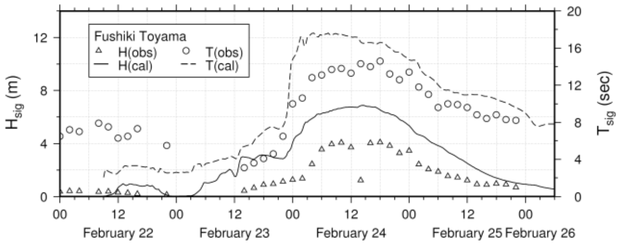

Fig. 7 Same as in Fig. 5. Computed results are from the experiment run C with 1.6 times enhanced wind intensity and 6 hrs extended wind duration.

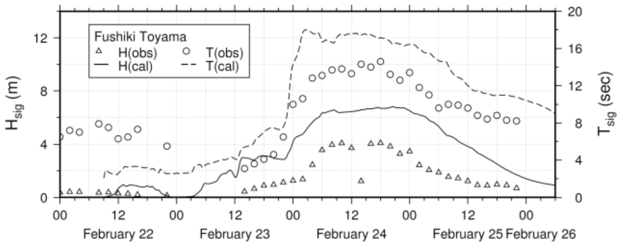

Fig. 8 Same as in Fig. 5. Computed results are from the experiment run D with 1.6 times enhanced wind intensity and 12 hrs extended wind duration.

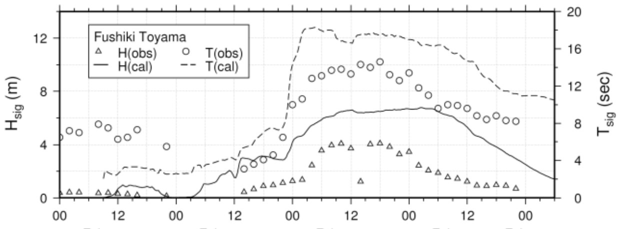

Fig. 9 Same as in Fig. 5. Computed results are from the experiment run E with 1.6 times enhanced wind intensity and 18 hrs extended wind duration.

In the present study, we investigate the extreme wave characteristics by examining the extreme conditions for wind intensity and duration for the event of February 2008. We are not going to state which method is better or not. It could be mentioned, however, the third way might be more physics-based statistical approach by combining meteorological and wave modelings, and statistical modeling.

Unlike the Best track data for tropical cyclones, there is no such historical data archive for the track and central pressure of low pressures (e.g. winter storms and extratropical cyclones) responsible for the abnormal storm waves in the winter ES. To perform the statistical analysis for wind intensity and duration described above, such historical data archive is necessary and have to be established.

As demonstrated in the event of April 2012, the increased supply of latent heat and water vapor could intensify a moving low unprecedentedly rapid. It is mainly due to the extension of the Tsushima Warm Currents. In the future climate, it is feasible that the warmer ocean environment could impact the overlying meteorological conditions, then back to the surface waves. Such potential impacts of climate changes have to be also taken into account for a study of extreme storm waves in the ES.

CONCLUSIONS

In the present study, we investigate the extreme storm waves in the Toyama Bay, Japan, by examining the extreme conditions for wind intensity and duration for the event of February 2008. The wind fetch is more or less pre-determined, therefore it is not considered in the analysis.

In terms of wind intensity, we compare the observed wind speeds due to the lows in February 2008 and in April 2012 to obtain an extreme condition, because the low in April 2012 breaks the records in observed winds and central pressure in its kind of winter storms. With respect to the wind duration, a statistical analysis result for transition time of lows passing over the ES is used to find out the extreme conditions for wind duration.

For the given extreme conditions for wind intensity and duration, numerical experiments are carried out to estimate the extreme storm waves in the Toyama Bay. The resulting significant wave height and period at the Fushiki-Toyama buoy site in the Toyama Bay are 6.78 m and 18.28 sec, respectively.

To improve the extreme storm wave estimation, we discuss and suggest the possible approaches by combining deterministic and statistical methods. Further, the impacts of future warming climate on meteorological conditions and back on surface waves have to be addressed in future works.

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