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Discussions

Characteristics of high waves observed at multiple stations along the east coast of Korea

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Abstract

In recent several years, extremely high waves occasionally visited the Korean coast of the East Sea and caused severe coastal disasters almost every winter season. In this paper, characteristics of such high waves are reported by analyzing wave records collected at multiple stations along the Korean east coast. Meteorological data obtained at relevant weather stations were also used in the analysis. The reason for appearance of the high waves was identified as the strong northeasters due to extra-tropical low pressure systems that had been rapidly developing in the East Sea. The general mechanism concerning the formation and spatial evolution of such strong low pressure systems was more clearly understood through the synthetic analysis of the wave and meteorological data. In particular, the influence of spatio-temporal features of the low pressure system on the resulting characteristics of the high waves was described in more detail in this study. Since the overall wave direction was northeast also, the first wave arrival time on the coastline became later for a wave station whose latitude is lower. At present, however, the arrival time of such high waves on the coast as well as their intrinsic characteristics such as wave height and period are not satisfactorily predicted by the daily weather forecast. Hence, it is necessary to enhance predictability of the high waves by investigating developmental mechanisms of the strong low pressure system in winter season more thoroughly.

1 Introduction

During past several years, the Korean east coast has experienced exceptionally high storm waves several times in winter season. Taking a few examples, the significant wave height reached its maximum of 9.69 m near Sokcho harbor on 21 October 2006, which was the maximum wave height ever observed on the east coast of Korea (Jeong et al., 2007). More recently, on the first day of year 2011, unusually high waves of H_s = 6.71 m visited Jukbyeon port. Besides these records, appearances of winter storm waves of higher than 5 m once or more times every year became common in recent years. These storm waves caused severe casualties, damage to coastal structures, and extensive beach erosion along the east coast of the Korean peninsula, which have rarely been occurred until very recently. Although it is not clearly certain whether higher waves are more frequently coming to the coastal waters, due to the lack of available long term data of continuously monitoring waves around this area, some long-lived local citizens testify that such an unusually high waves scarcely appeared in the past. Indeed, the scale of human death toll and property damage attributed to the high waves keeps increasing trend during the recent decades.

In particular, repeated loss of human lives due to the outbreak of huge waves has gradually been becoming public concern. Almost every year, human casualties are occuring due to suddenly appearing large waves at the beaches, coastal roads, or the navigating ships. In particular, most of the casualties at coastal zones occurred under mild rather than wild weather conditions so that people were unlikely to be wary of the risk of sudden wave appearance. Meanwhile, similar appearances of the abnormally high waves and accompanying coastal damage in winter season were also repeatedly reported on the west coast of Japan, or the other side of the East Sea. The most remarkable event in recent decades occurred on 24 February 2008, highlighted by the peak significant wave height of 9.92 m at Toyama bay and consequent severe damage of coastal facilities around the bay (Nagai et al., 2009; Mase et al., 2009; Lee et al., 2010).

Several researchers have studied the generation mechanism and characteristics of the winter storm waves in the East Sea (Kitaide, 1952; Isozaki, 1971; Isozaki and Yoshio, 1972; Jeong et al., 2009; Kim and Lee, 2010; Oh et al., 2010). According to them, such severe storms are likely to appear when the sea surface experiences continuously blowing strong northeasters, which are generated by an exceptionally well-developed extra-tropical low pressure system staying around Hokkaido, near the northeastern boundary of the East Sea. Due to the long fetch distance from the low pressure system to the coasts of Korea and Japan, a thousand kilometers or more,

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the waves can become developed if the strong wind fields continue several days over the sea. Unless there are any other focused wind events during the wave propagation to the coastal zone, characteristics of the waves are likely to be those of long-period swells. However, the waves occasionally face varying weather conditions that may significantly influence the original wave characteristics. Hence, the wave field at its arrival on the coast is often presumed to be a combined sea, or a mixture of swell and wind waves. Indeed, the term "swell-like waves" is widely used among the researchers, news reporters, and local citizens, although the word carries rather vague connotation.

As described in Oh et al. (2010), the heights of such high waves often exceed 4 to 5 m and their spectra are rather wide-banded, whereas the swells coming to the Korean east coast are typically smaller than 3 m and follow narrow-banded wave spectrum. Meanwhile, the significant wave periods of the high waves mostly range between 10 to 15 s, which are apparently longer than typical wave period of windsea. In this respect, the waves appearing in winter season, having comparatively longer period ($T_s > 9$ s) and larger height ($H_s > 3$ m), are widely called as swell-like waves in Korea. If strong wind fields driven by a low pressure system are formed close to the coastal zone, the corresponding wave characteristics tend to be similar to those of wind waves, but if they are located rather longer distance from the coastline, the incoming waves are more likely to be dominated by swells. As the low pressure system evolves and moves across the East sea, however, the wind fields over the sea are also subject to some spatio-temporal changes. Hence, the nature of swell-like waves is neither solely governed by swell or windsea in most cases, for which explicit decomposition of both components from the wave record is not always simple.

At the present, the occurrence of such high swell-like waves on the Korean east coast is only roughly predicted in the daily weather forecast. Hence, it is required to improve understanding of the detailed generation mechanism of the high waves in order to accurately predict its arrival on the coast. As a fundamental step towards this, Korea Institute of Ocean Science and Technology (KIOST) has continuously monitored nearshore wave climate at multiple locations along the Korean east coast during recent

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several years. These wave monitoring data are very precious because there had previously been no intensive wave observation program solely focused on the high waves on the Korean east coast. This paper presents the principal monitoring results of the abnormally high wave phenomena during the field observation period, particularly focusing on the intrinsic characteristics of the waves.

2 Observed high swell-like waves

2.1 Wave observation at multiple stations

The coastal waves were measured at nine locations along the east coast of Korea as shown in Fig. 1. At each measurement station, a pressure type wave gauge was deployed on the sea bottom. The water depths at the measurement stations varied between 13.0 and 18.5 m as shown in Table 1. Considering that the typical significant wave period of the high waves ranges from 9 to 14 s, most of the waves measured at the stations tend to be intermediate depth waves. The values of relative depth kh computed from the wave observation data are in the range from 0.5 and 1.0. As the bathymetric contours in this area are straight and parallel to the shoreline, the incoming waves may experience refraction, shoaling and possible breaking when they feel the sea bottom, but amplification of wave height due to wave focusing rarely occurs. Also, relatively steep bathymetric gradient allows propagation of waves from the offshore to the nearshore without undergoing strong wave breaking. Hence, the significant wave height observed at the wave station is not so much different from the one at the offshore in most cases.

The pressure sensors at the nine stations were not installed at the same time, but the number of active measurement stations has increased year by year with slight adjustments in the sensor specification and the method of data acquisition. Since around the year 2008, continuous wave observation has been carried out at the whole locations shown in Fig. 1. Moreover, two more devices for identifying wave direction were added very recently to the above wave observation network: a Directional Wave Rider (DWR) buoy was installed adjacent to the pressure gauge at Jukbyeon in March 2009, while an Acoustic WAve and Current profiler (AWAC) at Sokcho in December 2010, respectively.

The raw wave data were acquired at the sampling rate of 2 Hz, except the buoy that adopted 1.28 Hz rate. For each measuring instrument, the wave spectra were obtained every 30 min by using the first 2048 data points within the time segment. Then, the corresponding significant wave height (H_s) was estimated using the zeroth moment of the spectrum (m_0) as $H_s = (m_0)^{1/2}$. The values of H_s were also computed from the zero-upcrossing method by taking the mean of the highest one-third waves during the same time segment and the agreement was fairly good in general when they were compared with the corresponding spectral estimates. For the wave period, meanwhile, the significant wave period T_s estimated from the zero-upcrossing method was used in the analysis as the quantity displayed the temporal changes of wave period more effectively rather than some other parameters such as the peak period (T_p) or the mean period (T_m) derived from the wave spectrum. The value of T_p was unreasonably estimated sometimes especially when the wave height was relatively small, whereas T_m was less sensitive to the steep rise or subtle change of wave period than T_s.

2.2 High waves on 1 January 2011

As an exemplary observation record of high waves, the time series of H_s at nine stations during the high wave events occurred on 31 December 2010 to 04 January 2011 are shown in Fig. 2. Rapid increase of wave heights on the first day of year 2011 is clearly displayed in the figure. The wave height reached to its maximum at 01:00 LT at the most northern station, Daejin, while it appeared 7 h later at the most southern station, Jinha. In general, the wave height first started to increase at the stations of high latitudes. The largest wave height during the time period shown in Fig. 2 was 6.71 m, which

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was measured at 09:30 1 January at Jukbyeon station. Almost similar maximum wave heights of 6.70 m were observed at Gangneung station.

Similar to the trends of H_s, the significant wave period also increased and then decreased monotonously around the first day of year 2011 as shown in Fig. 3. Contrary to the time series of H_s shown in Fig. 2, however, the rapid rise in the magnitude of the quantity was less apparent in case of T_s. This was mainly because of the relatively long significant wave period of approximately 8 to 10 s, before the further increase of wave period up to approximately 12 to 13 s on 1 January, influenced by precedent swell waves. For most of the other high wave events, an abrupt jump was more clearly recognized with the first passage of high waves since the wave period before the arrival of high waves was much shorter, typically around from 5 to 6 s (see the top two panels in Fig. 5 to appear later).

2.3 Comparison of three high wave event records

From the continuous observation and subsequent analysis during many years, it became obvious that the general features of the onset and continuation of the each high waves show apparent distinction among them. In order to highlight such a difference in the temporal change of wave heights and periods, time series of H_s and T_s obtained during two more high wave events were presented in Figs. 4 and 5 for the comparison with the data shown in Figs. 2 and 3. For the clarity of the comparison, only the wave records obtained at the four stations of Sokcho, Mukho, Hupo, and Jinha, which almost covers the whole east coastline of Korea with an almost equivalent spatial interval in latitude, are displayed in the figures.

A similarity among the three cases is the sequential rise of wave height, starting from the most northern station followed one after another at the next southern stations. As clearly seen in Fig. 4, rising time of the wave height gradually fell behind with the decrease in the latitude of the measurement station. This implies that the waves might have propagated from northward direction for all the cases.

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Meanwhile, the maximum wave heights in the three cases showed marked difference among them. On 23 October 2006, exceptionally high waves greater than 9 m were observed at relatively northerly located stations of Sokcho and Mukho. The 9.69 m wave record at Sokcho at 11:00, 23 October was and is still the largest significant wave height observed on the east coastline of Korea. In contrast, the maximum heights on 24 February 2008 as well as 01 January 2011 were not as high as the one in October 2006, 5.06 m and 6.04 m respectively, at the stations of Mukho. Another difference among the three time series is the overall trend of H_s during the high waves. In case of October 2006 and January 2011, the wave height rapidly increased and monotonously decreased over more than two days. In case of February 2008, however, the wave height further increased on 24 February after the first jump on the previous day so that showed double-peaked pattern as seen in the figure.

Further difference found in Fig. 4 is the intervals between arrival times of the high waves at the four stations. In the top figure, the high waves started to visit Sokcho at 17:00, 22 October 2006, while they arrived at Jinha approximately 22 h late. In contrast, the gap in arrival time of the high waves between the two stations (Sokcho and Jinha) was only approximately half in January 2011 and one-third in February 2008, respectively.

The corresponding time series of T_s shown in Fig. 5 also displayed similar difference among the three wave events as with those of H_s. In general, the significant wave period increased along with the arrival of high waves and then gradually decreased after the peaks, but the detailed patterns of change in T_s appeared differently each other. Compared to the other two cases, the value of T_s increased exceptionally sharply in the top panel of Fig. 5. The time series in the middle panel is characterized with the rise of T_s in double times, which is related to the double-peaked pattern of the corresponding time series of H_s. The noticeable feature in the last panel is the little temporal gap in arrival times at different measurement stations.

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3 Some characteristics of the high swell-like waves

3.1 Spatial difference in wave appearance and growth

As shown in the above, temporal gaps in the onset of high waves among the measurement stations showed apparent discrepancy depending on each wave record. Moreover, the spatial distributions of the maximum wave height along the stations were also not the same for the three wave events. Since these two features are fundamental factors in estimating the source region and propagation direction of the high waves, they were investigated in more detail by utilizing all the available wave data for the three cases as explained in the following.

In Fig. 6, the two time instances at the steep initial rise and peak of the wave height detected at each measurement station are displayed as the left and right ends of the corresponding bar graphs, respectively. Hence, the horizontal length of each bar graph stands for the time span from the first appearance of the high waves to the reaching of maximum wave height. In the figure, the abscissa indicates the time elapsed measured from the first arrival of the high waves at any of the nine stations, which were typically observed at the most northern available stations. As shown in Fig. 6, the first arrival time of the high waves was more delayed in general if the latitude of a station was lower. The same trend was also found in the appearance of maximum wave height along the measurement stations. These features imply that the high waves came from northern side as mentioned earlier. For the three wave events, temporal gaps in the first appearance of the high waves between the most northern and southern stations were 22, 13, and 7 h respectively, showing marked discrepancies.

Meanwhile, the time span from the initial rise to the arrival of peak wave was 16.3 h on average in October 2006. The corresponding mean duration time for the waves in February 2008 was 8.6 h, much shorter compared to the previous case, when it was calculated by excluding data from the two lowest stations (Yangpo and Jinha). At those stations, the first peak appearance times were rather ambiguously estimated as the decreasing and re-increasing trend after the first peak was not clearly found as

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at the rest of the stations. Meanwhile, the average time interval from the first wave appearance and reaching to the second peak was 38.4 h. Finally, in case of the high waves occurred in January 2011, it took only 7.4 h on average for the reaching of maximum height after the initial arrival of the high waves.

Figure 7 shows the maximum significant wave heights at the measurement stations during the three high wave occurrences. In case of February 2008, two maximum values at each station corresponding to the double peaks in wave height are presented in the figure. Although a general similarity in the spatial distribution of the maximum height is not found among the three cases, it is clear that the highest height in a single wave event is typically observed between Sokcho and Jukbyeon stations, or the central part of the Korean east coast.

3.2 Wave direction

The direction of high waves occurred in January 2011 was monitored using a AWAC at Sokcho and a DWR buoy at Jukbyeon, respectively. Figure 8 shows the recorded wave direction at the two stations. As opposed to the rapid increase and subsequent decrease in wave height for five days shown in Fig. 2, the wave directions at the two stations changed very little within the narrow range from east to northeast. This implies that the wave field during the five days was wholly governed by a single dominant wave phenomenon. Meanwhile, the mean wave direction to the north was 54.6° at Jukbyeon whereas a slightly more eastward value of 67.4° was obtained at Sokcho. Since the wave angle at the station of higher latitude was more inclined to the east direction, it is possible to presume that source region of the high waves might be placed at a northeastern area from the both stations.

3.3 Wave spectra

Figure 9 shows the wave spectra that are corresponding to the maximum wave height during the three high wave events in October 2006, February 2008, and January 2011.

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Although the spectral magnitudes were different depending on the cases, the overall shape of the wave spectra were almost the same in spite of the difference in observation stations and time periods. This implies that the general shape of wave spectrum, formed by the high waves occurring on the east coast of Korea, would be always similar to those shown in Fig. 9. For all the cases, the spectral peak frequency was in the range of $f = 0.07 \sim 0.08$ Hz, equivalent to peak wave period of $12 \sim 14$ s. Although it is not shown in the figure, investigating temporal change of the wave spectrum revealed that the spectral energy growth during the high swell event was particularly concentrated over the peak frequency bands. Meanwhile, the secondary spectral peak also appeared at $f = 0.15$ Hz for all the cases, which could be a result of self-wave interaction activated under strong wind forcing. Overall, the spectral energy of the secondary peak was one order of magnitude smaller than that of the first peak.

4 Analysis of the meteorological condition

4.1 Meteorological data

In order to assist the investigation of the generation mechanism of the high waves, the meteorological data provided by the Korean Meteorological Agency (KMA) were used in the analysis. First, the weather charts around the Korean peninsula during the occurrence of high waves were collected. In addition, the data of mean wind speed and direction were gathered at the weather stations that are closest to each of the nine wave measurement locations shown in Fig. 1, respectively. All the weather stations are located at inland locations that are very close to the coastline. KMA provides the weather chart every three hours, while the mean wind data are produced at every one hour interval. They estimate the mean wind speed and direction by taking the average of the corresponding instantaneous values during the first ten minutes every hour. Since the vertical distance of the anemometer from the earth surface is not the same among the weather stations, the mean wind speed at each station was converted to the value at 10 m above the earth surface by assuming a logarithmic profile of it.

4.2 Development and evolution of strong low pressure system

In order to understand principal meteorological features associated with the high waves which occurred in January 2011, the weather charts during the time period of high wave occurrence were investigated. Figure 10 shows three weather charts corresponding to two and one days before and just on the day of first wave arrival on the Korean east coast. At 9:00 on 30 December 2010, a low pressure system was formed in the central lower region of East Sea as can be seen in the top panel of Fig. 10. During the next 24 h, the center of the low pressure system moved eastward across the Japan's main island, with its central atmospheric pressure dropping by 14 hPa. Then, the central atmospheric pressure further dropped to 972 hPa when it moved more east off the Japan islands at 9:00 on 1st January 2011. As shown in the middle and bottom panels of Fig. 10, the spatial distance between the isobaric lines across the East Sea is very narrow in the contour maps of the atmospheric pressure field. This implies that the pressure gradient was very steep perpendicular to the isobaric lines, which might be closely associated with the strong wind blows and resulting generation of high waves over the sea. The contour maps of the atmospheric pressure indicate that wind might blow from the northeast direction as wind fields are typically formed along the isobaric lines clockwise to the low pressure center. Such strong northeasters blowing over the East Sea in winter season have been designated as Donghae twisters in Korea (Chung, 1996).

Although Fig. 10 shows only the weather charts at only three instants during the occurrence of high waves in January 2011, formation of such strong low pressures and resulting steep pressure gradient across the sea was always confirmed during the occurrence of high wave events. Since KMA provides weather charts every three hours, it is possible to investigate the moving path of an individual low pressure by following its central location. In fact, the center of an extra-tropical low pressure system is not

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always easily recognizable because the central location may vary greatly according to the overall pressure field surrounding it. During the high wave events on the Korean east coast, however, central location of the low pressure system can relatively clearly be identified directly from the corresponding weather chart as already shown in Fig. 10. For the three high wave events explained in Figs. 4 and 5, the identified moving trajectories of the low pressures are shown in Fig. 11. In the figure, the location of each circle stands for the central location of the low pressure system, while the numbers in it indicate the time difference measured from the first arrival time of the waves on the Korean east coast. The central locations of the low pressure system were obtained one by one from every single corresponding weather chart by finding the exact center of the circled isobaric lines. Then, the each found location was carefully marked in the map as shown in Fig. 11 referring to the neighboring latitude/longitude lines. Before and during the occurrence of the high waves occurred in October 2006, there existed two low pressure systems around the Yellow Sea, which later combined into one. In February 2008 also, two low pressure systems were developed in the East Sea, but their traces were independent of each other in this case.

A common feature found in Fig. 11 is that the low pressure systems advanced eastward for all the cases. However, the specific location, or latitudes and longitudes of the low pressure centers, associated with the respective wave events, showed significant difference depending on the individual case. For example, the location on the time when first waves arrived on the coastline, or the position of the circle labeled as zero in Fig. 11, was very different among the cases. It was on the west coast of the Korean peninsula for each of the two pressures of October 2006, but on the far east side of the Japan's main island for the low pressure of January 2011. At the time of first rise of wave height in February 2008, the centers of the two low pressures were placed at the northern tip of Hokkaido and west central region of East Sea, respectively. In this respect, there seems to be little consistency in the relationship between the occurrence of high waves and the detailed moving path of corresponding low pressure system.

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4.3 Pressure drop and magnitude of waves

As explained in Fig. 10, the central atmospheric pressure typically drops along with the advance of a low pressure system into the sea. The reason for this tendency is ascribed to the acquisition of more sea vapours, energy source of promoting growth of a low pressure, with its continuous eastward movement toward the Pacific Ocean. Figure 12 shows the change in atmospheric pressure at the center of the low pressure systems associated with the three high wave events. In the figure, the horizontal axis denotes the relative time counted from the first arrival of waves on the coast. It can clearly be seen that the central pressure dropped along with the time passage for all the cases. However, the initiation time and the magnitude of the pressure drop showed some difference depending on the cases. In case of January 2011, the decline of atmospheric pressure started to occur 48 h before the arrival of waves on the coast. Moreover, the total amount of pressure drop during the period that exceeded 30 hPa. In contrast, the pressure decline begins only less than 15 h before the appearance of the first wave for other cases, with smaller magnitudes of pressure drops.

Particularly in October 2006, the central pressure showed comparatively insignificant pressure change, except for some drop of the secondly generated low pressure system that was initiated six hours later than the first wave arrival. This feature is contradictory to the appearance of the highest significant wave height of 9.69 m at Sokcho during that period. In order to find the reason for this mismatch, we examined a series of sequential weather charts during the wave event in October 2006. Through the examination, it was clarified that the weather conditions were favourable for the generation of a strong wind field heading towards Korea because the two low pressures formed at that time moved slowly and stayed half a day around the Yellow Sea and inland of the Korean peninsula, although the pressure drop itself was relatively smaller than those of the two low pressures in February 2008 and January 2011. Moreover, the existence of a strong high pressure system, whose central pressure was greater than 1030 hPa, and located in China's east bound helped the formation of a strong pressure gradient in

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north to south direction toward Korea. In contrast, the reason for comparatively smaller maximum height during the wave events in February 2008 and January 2011, notwithstanding the greater pressure drop in both cases, was ascribed to more eastwardly biased locations of the corresponding low pressure systems far offshore from Korea.

One noteworthy thing is that extremely high waves of 9.92 m, comparable to that observed at Sokcho in October 2006, incurred huge damages along the central northern coast of Japan around Toyama bay on 24 February 2008. At that time, a pair of low pressure systems was developed in the East Sea as shown in Fig. 11, which made strong wind fields heading to the Japanese western coastline and resulting high waves that were observed around Toyama bay. Interestingly, huge waves visited the Korean east coast when the two low pressures were formed around Korea in October 2006 and almost the same wave phenomenon due to another two low pressures was observed on the central northern area of Japanese west coast in February 2008. This implies that independent generation and coincident development of two or more extra-tropical low pressure systems yield a favourable condition for the formation of a large wave field. Eventually, however, the height, direction, and continuation time of waves would be determined by the combination of all the relevant met-ocean conditions, such as the amount of pressure drop, moving trajectory, staying time, and the number of low pressure systems as well as the overall arrangement of neighboring atmospheric pressure field. Therefore, there seems to be no simple direct relationship between the magnitude of waves and the pressure drop of related low pressure system, although the generation and evolution of such a low pressure is always confirmed when a high wave event occurred on the Korean east coast.

4.4 Mean wind speed and direction

Figure 13 presents time histories of mean wind speeds and directions during the three high wave events in October 2006, February 2008, and January 2011. It shows the wind records acquired at the weather stations closest to the wave observation stations where the maximum wave heights were measured respectively. Each data point in

Fig. 13 represents the mean of instantaneous values during the first ten minutes of every hour so that the time interval of wind data was one hour. Relatively high mean wind speeds surpassing 15 $m s^{-1}$ were observed on 23 October 2006 and 1 January 2011. In contrast, the mean wind speeds were substantially smaller than 10 $m s^{-1}$ during 22 to 26 February 2008, which might not be sufficiently strong as to generate the observed high waves. This indirectly implies that the local wind field at the weather stations was not necessarily significant in generating the high waves at that time.

Meanwhile, the wind directions at the weather stations were mostly classified into north to northwest groups during the three wave events. It is noteworthy that the wave direction was mostly northeast as shown in Fig. 8. Hence, northeasters might blow over the far offshore sea of Korea during the high wave events. This fact again confirms that the local wind field itself was not a major source of generating the high waves observed on the Korean east coast.

Then, time series of significant wave height and mean wind speed are plotted together in Fig. 14. The peak of both time series coincided well in October 2006 and January 2011, but this trend was not found in February 2008. In case of October 2006 also, significant wave height started to increase at 17:00 on 22 October before the more sharp increase of wind speed at 03:00 the next day. In this respect, the occurrence of high waves was not directly correlated with the local wind field, although strong local winds affected more rapid increase of wave height during the wave event. Recent human casualties occurred mostly when local wind speeds were not so strong, as in the case of February 2008. As the local weather and wind condition were mild on those days, tourists or fishermen were likely to do their coastal activities without recognizing the danger of sudden appearance of high waves.

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5 Emergence and propagation of high swell-like waves

5.1 Estimation of the source region of waves

If a wave field is solely composed of swell components, it is possible to estimate the source region of waves based on the difference in propagation speeds of the wave components related to different spectral frequencies (Earle et al., 1984). Assuming a swell wave starts its propagation at time t_0 and reaches a location at time t_a after traveling a distance D, the relationship between the three parameters is given as follows:

$$t_0 = t_a + \frac{D}{g/4\pi f} \quad (1)$$

where g is the gravitational acceleration and f is the wave frequency. After differentiating Eq. (1) and rearranging with respect to D we obtain

$$D = \frac{g}{4\pi}\left(\frac{t_2 - t_1}{f_2 - f_1}\right) \quad (2)$$

where t_1 and t_2 denote the arrival time of wave components corresponding to f_1 and f_2, respectively. Hence, the traveling distance D can be estimated if there exists a discrepancy between the arrival times of wave components having different frequencies. Then, the initiation time of swell propagation t_0 is also known by inserting D into the Eq. (1).

By using the above method, values of D and t_0 were evaluated for the three high wave events shown in Figs. 4 and 5. For the wave records at Sokcho where high waves arrive first among the four stations shown in the two figures, the time series of three individual wave components $f = 0.070$, 0.078, and 0.086 Hz were plotted together as shown in Fig. 15. The three frequencies correspond to significant wave period of 11 to 13.5 s. For the maximum wave spectra for the three wave events, the spectral peak frequency mostly coincided with one of the three above frequencies. In the figure, only the result for the high waves that occurred in February 2008 is provided because the second rise of wave height during the wave event was adequate for applying the method of Earle et al. (1984), while the rest two high wave events in October 2006 and January 2011 were found to be not applicable to the analysis method.

In Fig. 15 it is recognized that spectral energies of the three wave components start to increase almost simultaneously at the first rising of wave height at 02:00 23 February. The dashed line at this time shown in the figure is plotted by connecting and extending the initial rising times of the three wave components. The line is almost vertical as there is no significant difference in the rising times among them. In such a condition, it is not possible to estimate D and t_0 because D goes to infinity as $f_2 - f_1$ is almost zero in Eq. (1). In contrast, apparent discrepancy is found between the starting times of the three wave components during further increase of spectral densities in the evening of 23 February. The spectral energy at the lowest frequency component ($f = 0.070$ Hz) first starts to increase at 20:00, 23 February. The rising of spectral energy occurs two and half hours later for the wave component of $f = 0.078$ Hz, while it occurs six and half hours later for the one $f = 0.086$ Hz. In this condition, the dotted line connecting the corresponding rising times is not vertical but inclined as shown in the figure so that estimation of D and t_0 is possible. After simple calculation, those values were evaluated as $D = 965$ km and $t_0 = 16{:}00$, 22 February. Considering that the dominant wave direction during high wave occurrences on the Korean east coast is usually northeast as shown in Fig. 8, the source region of the waves arriving after the evening of 23 February is conjectured to be the sea waters between the Russia's east end and the Japanese Hokkaido island. In the weather chart at 15:00, 22 February, indeed, the center of the low pressure system was located very close to the estimated source region, indicating formation of strong wind fields around this area.

As the characteristics shown in Fig. 15 were quite different at the first and second rises of spectral densities, the evolution of wave spectra after the two time instances was compared each other. Then, it was found that the spectral energy increased over almost all the frequency ranges of the wave spectra in the former case. However, the

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augmentation of spectral energy was limited to comparatively narrow frequency bands around the peak frequency in the latter case. Such a contrast indicates that an intrinsic wave growth mechanism would show distinct dissimilarities for the two time periods. Since a swell wave is generally represented as a peaked narrow wave spectrum, the characteristics of waves observed after the evening of 23 February would be predominantly governed by long-travelled swell. In contrast, the earlier wave growth from daybreak was supposed to be a result of local windsea development occurring near the wave station since the wave energy was enhanced not only for the peak frequency ranges but also for the relatively lower and higher frequencies demonstrating active wind action on the wave field.

Meanwhile, Fig. 16 shows the time series of wave steepness at Sokcho station during the high wave event in February 2008. It can be clearly seen that values of the wave steepness rapidly increase from daybreak of 23 February along with the first rising of wave height, similarly as in augmentation of spectral energy at that time shown in Fig. 15. In contrast, such a steep increase of the wave steepness is not found around the time of the second increase in spectral energy after the evening of 23 February. In that period, the wave steepness continuously decreases in spite of the increase in wave height. This discrepancy might be ascribed to the aforementioned difference in dominance of wave field by either windsea or swell during the two time periods. It is noteworthy that the high waves observed in October 2006 and January 2011 also had similar patterns as in Figs. 15 and 16, with respect to the evolution of wave spectra as well as the variation of wave steepness associated with the first wave growth in February 2008.

5.2 Discussions on the estimation of wave source region

The generation of high swell-like waves and their propagation to the Korean east coast can be qualitatively understood from the analysis of wave observation data together with corresponding meteorological condition during the wave occurrence. Furthermore, quantitative evaluation of the source region and the initial time of wave development can be made by using the method suggested by Earle et al. (1984). However, this method is only applicable to a swell-dominating wave field as it is basically based on the wave dispersion principle. Indeed, the source region of high waves that appeared in October 2006 and January 2011 could not be estimated using this method because the corresponding wave spectral features were similar to those of wind waves. The reason for the inability to make use of Earle et al. (1984)'s method for windsea is that wave components having different frequencies may not freely propagate according to their unique dispersion characteristics but be forced to travel under the influence of continuous wind action (Hasselmann, 1962).

Another limitation in the estimation of wave source region based on the method of Earle et al. (1984) is that it intrinsically assumes a point source fixed at a specific spatial position during the whole time of swell propagation to a certain location. This kind of ideal swell propagating condition can scarcely be met in the real field condition as a low pressure system will move as shown in Fig. 11 and accordingly the corresponding wind fields also might vary as time elapses. In this respect, the swell arriving at a certain observation point is more likely to be a combination of some waves generated under different spatio-temporal source regions. Despite this restriction in the use of Earle et al. (1984)'s method, the estimation result of wave source region for the second increase in wave height of February 2008 somehow well matched with the meteorological evidences showing formation of strong wind fields over the estimated source region. In order to obtain more reliable estimation results, however, it is necessary to conduct numerical simulations using available wave models to track back the course of wave propagation from the source region and to directly relate the meteorological condition to the wave fields observed on the coast.

6 Summary and conclusions

In recent years, visiting of high waves in winter season became common on the east coast of Korean peninsula. Public concerns are growing as the high waves have caused human casualties, damage of ships and coastal structures, and serious beach erosion along the coastline. In this paper, records of the high waves that occurred on the first day of 2011 were presented, with supplementary data of two other previous big wave events in October 2006 and February 2008. The New Year wave was monitored at nine measuring stations simultaneously along the east coast. By analyzing these wave data with the corresponding meteorological data, major characteristics of these waves were clarified in some detail.

The reason for the appearance of the high waves was found to be due to the long-lasting strong wind fields directing toward Korean east coast, which was formed as a result of the low pressure trough in the vicinity of the extra-tropical low pressure system that advances to East Sea from the China inland with decreasing central pressure. Not only the pressure drop during the movement but also other factors in meteorological condition such as moving trajectory and staying time of the low pressure system together with arrangement of neighboring atmospheric pressure field were found to have importance in determining characteristics of waves. The observed maximum significant wave heights exceeded 5 m as shown in the three wave records in October 2006, February 2008, and January 2011, and the outbreak of such a high waves once or more is highly probable in the East Sea during every winter season. Therefore, it is necessary to be more prepared by enhancing predictability of the high waves, based on the understanding of the detailed mechanism of the rapid growth of the low pressure system and developing efficient operational wave prediction system not too late.

Acknowledgements. This work was supported by the research projects (PM57300 and PE98941) of Korea Institute of Ocean Science and Technology. The authors are grateful to late Yoshimi Goda, professor Emeritus of Yokohama National University, who encouraged publishing this work when the earlier study was presented in the 2nd CDIT-KORDI Workshop held in Tokyo, Japan on 10 October 2010.

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Table 1. Geographic coordinates and water depths of the measurement stations.

Station	Latitude	Longitude	Water depth (m)
Daejin	38.521° N	128.427° E	17.5
Sokcho	38.208° N	128.617° E	18.5
Gangneung	37.798° N	128.929° E	13.0
Mukho	37.548° N	129.125° E	15.0
Jukbyeon	37.060° N	129.433° E	18.0
Hupo	36.700° N	129.484° E	15.0
Weolpo	36.212° N	129.398° E	17.4
Yangpo	35.886° N	129.539° E	17.8
Jinha	35.387° N	129.361° E	18.0

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Fig. 1. Location map of the wave measurement stations.

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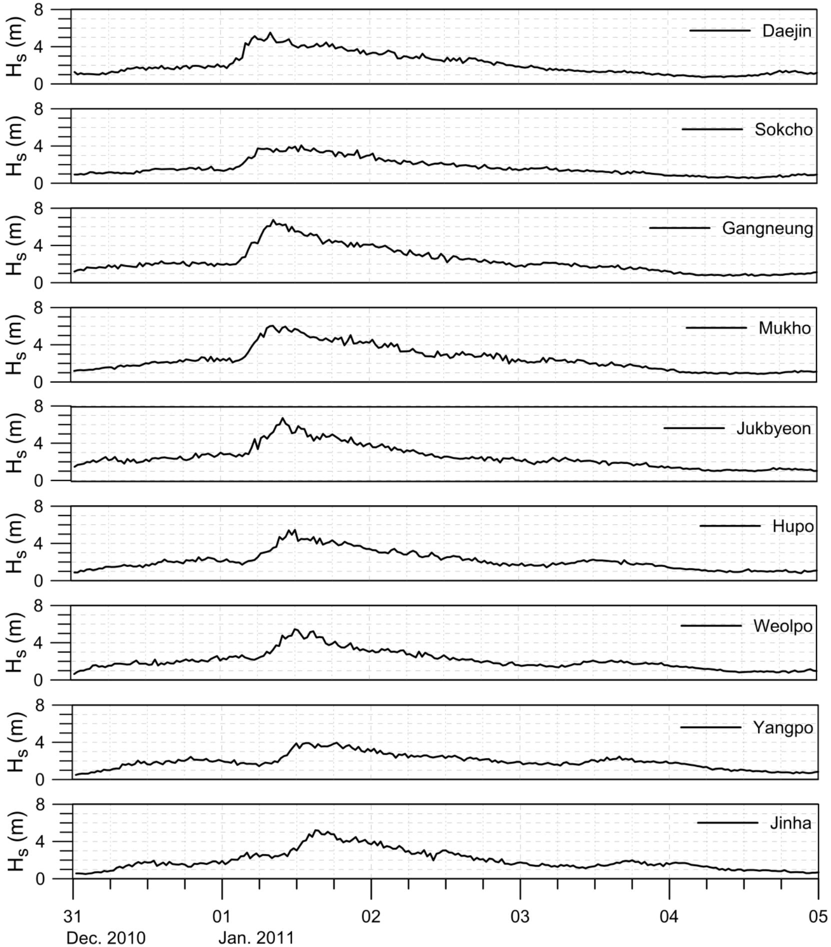

Fig. 2. Time histories of H_s from 31 December 2010 to 4 January 2011 observed at the nine measurement stations.

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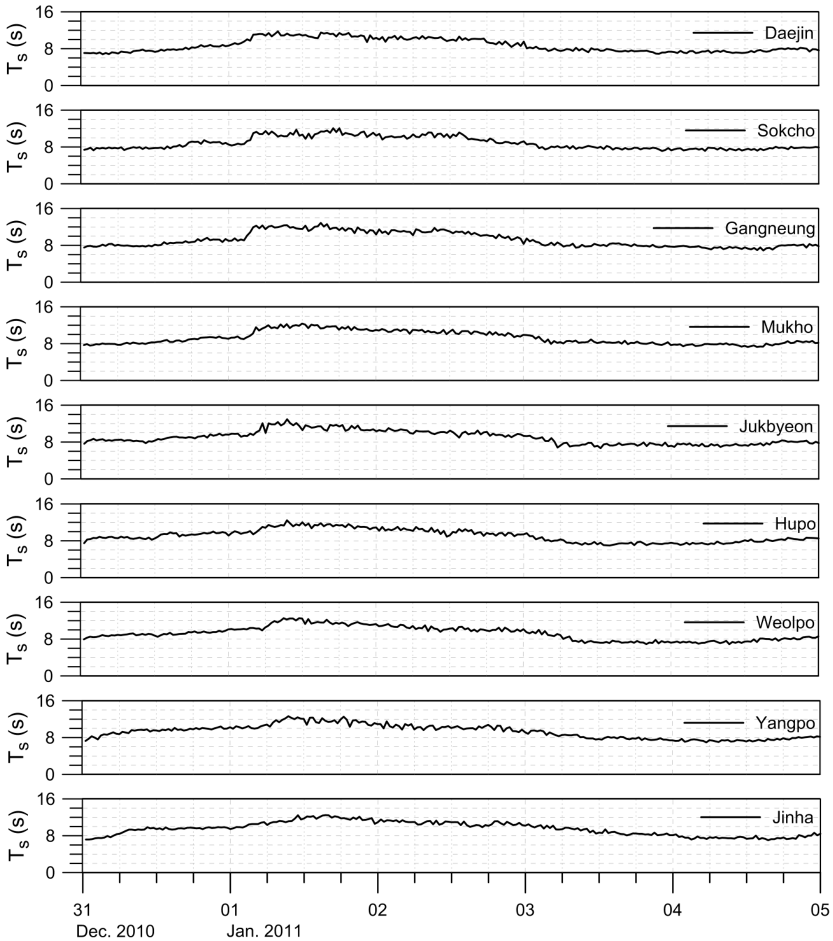

Fig. 3. Time histories of T_s from 31 December 2010 to 4 January 2011 observed at the nine measurement stations.

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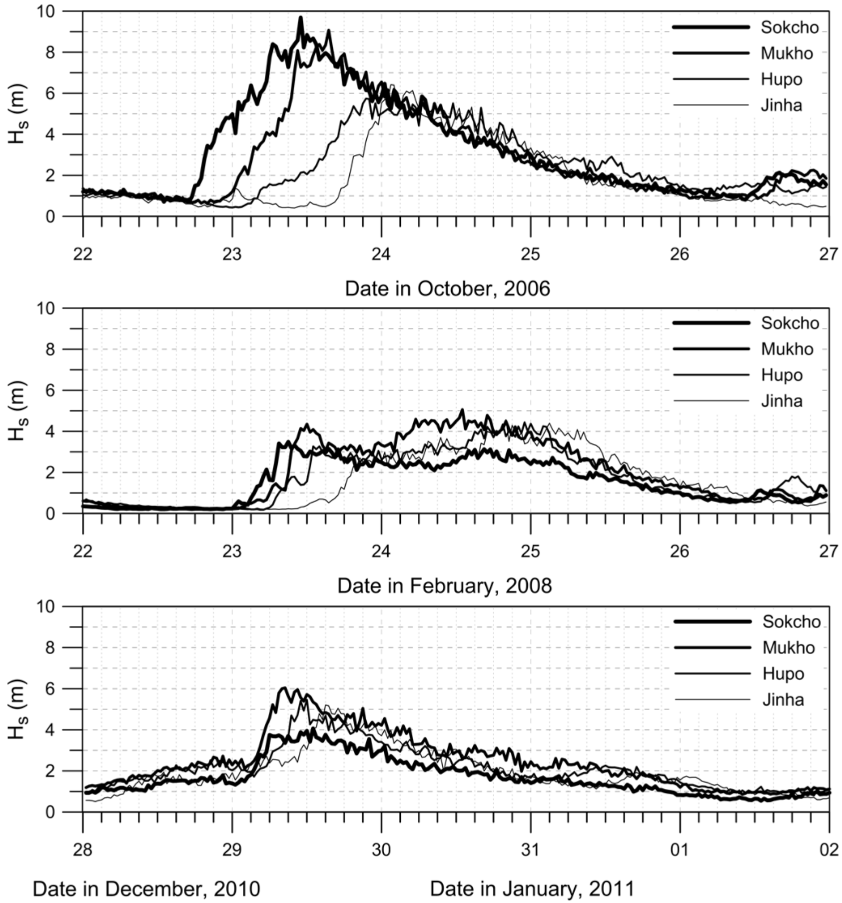

Fig. 4. Comparison of change in H_s at the four measurement stations for the three different high wave events.

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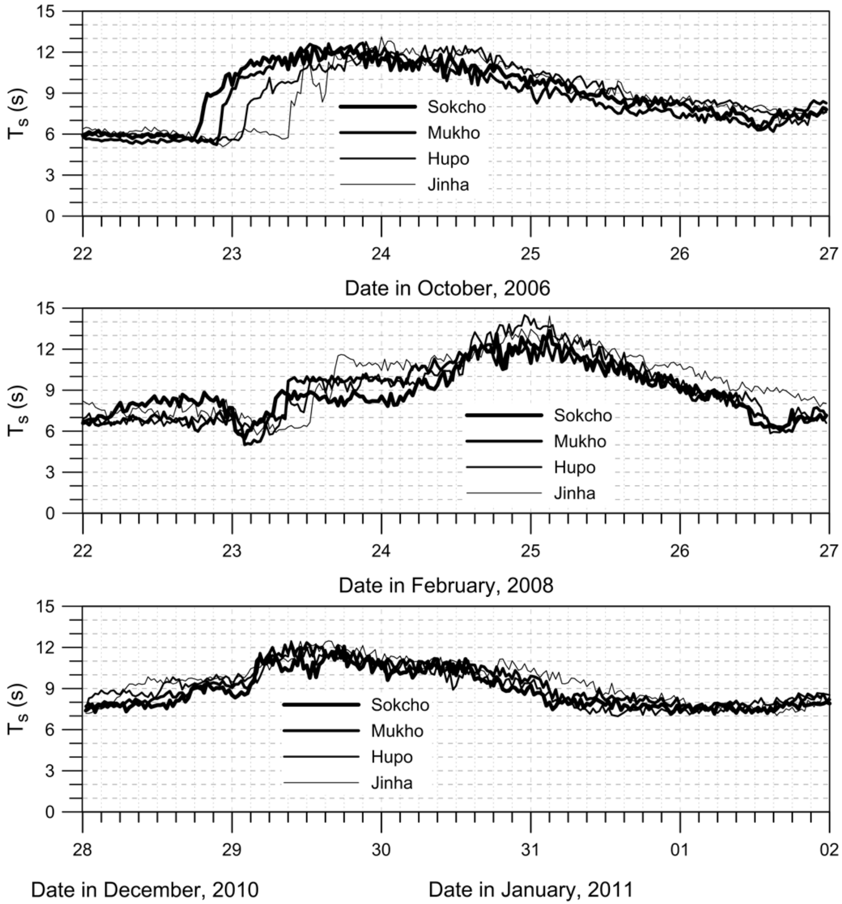

Fig. 5. Comparison of change in T_s at the four measurement stations for the three different high wave events.

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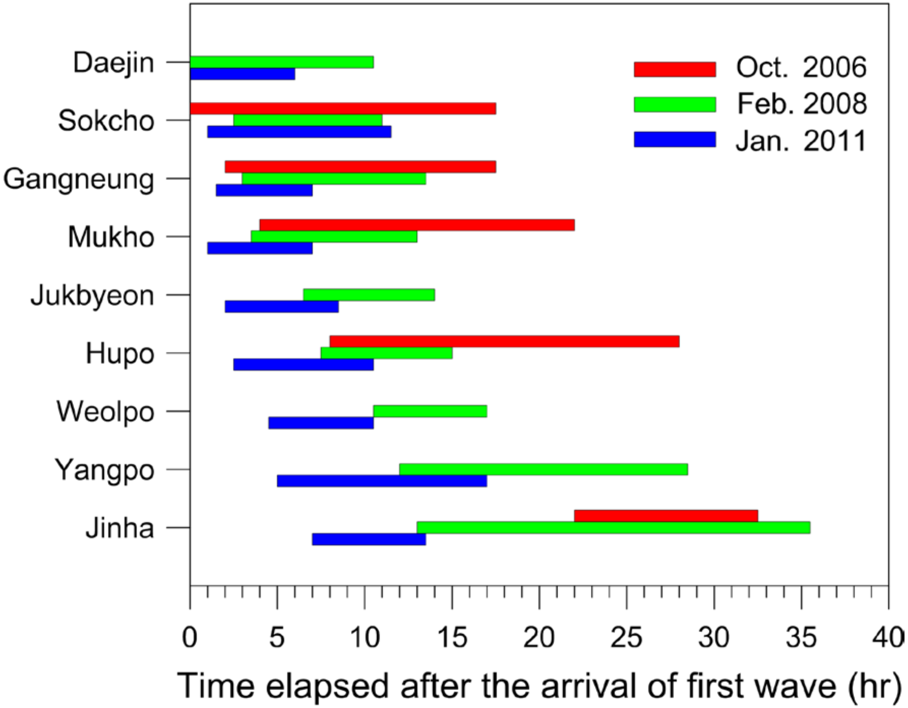

Fig. 6. Temporal duration between the time instances at the first appearance and at the reaching of maximum height at the nine measurement stations.

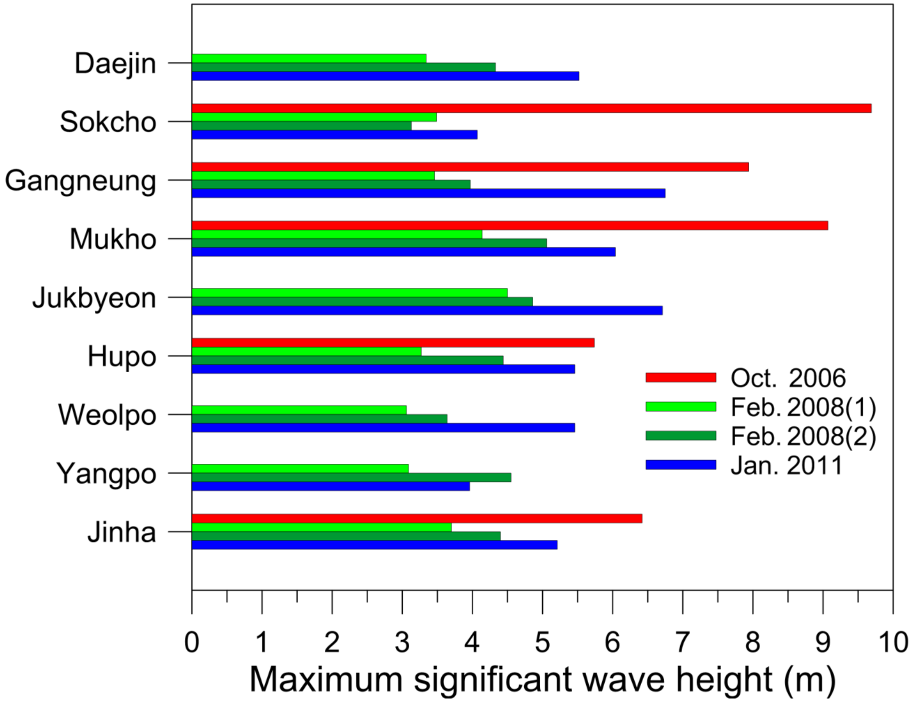

Fig. 7. Maximum significant wave heights observed at the nine measurement stations.

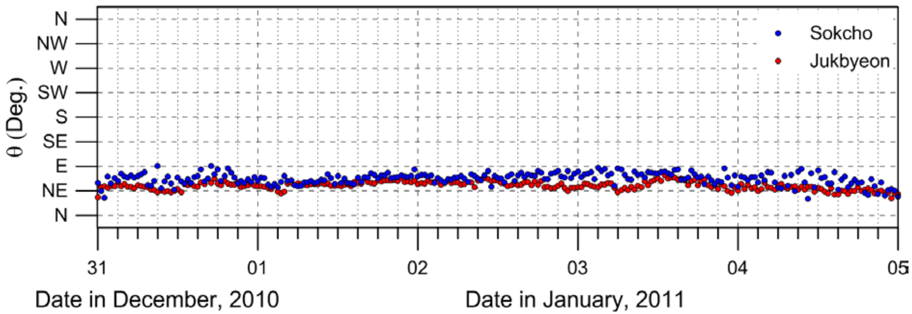

Fig. 8. Time histories of the peak wave direction from 31 December 2010 to 4 January 2011 observed at Sokcho and Jukbyeon stations.

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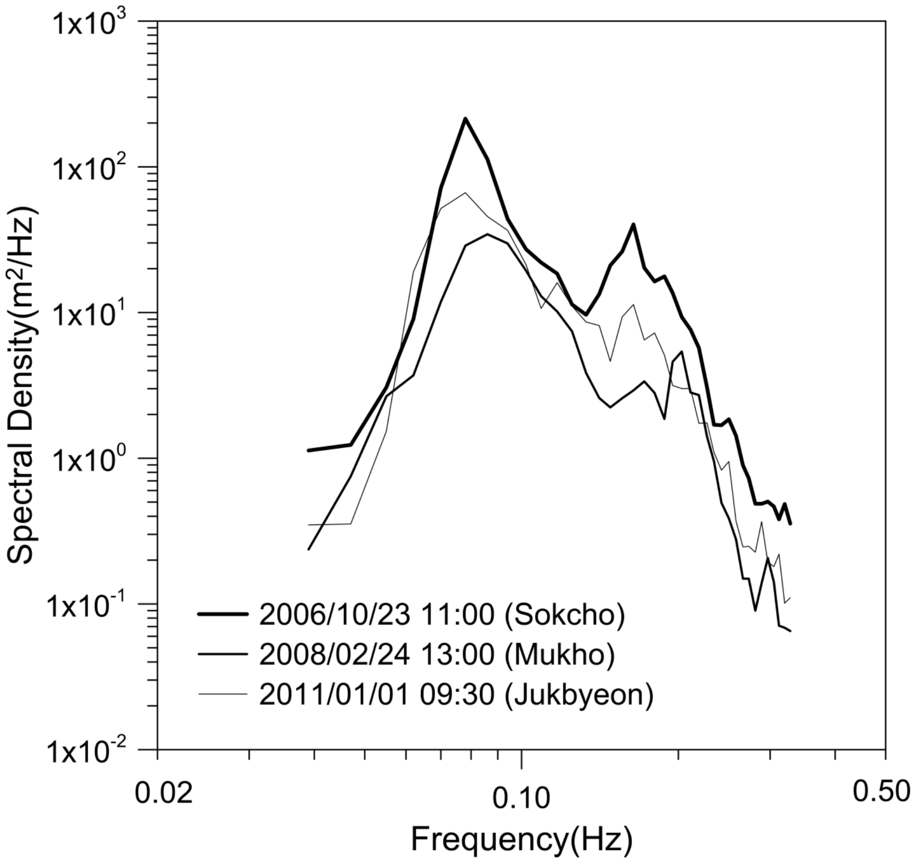

Fig. 9. Wave spectra corresponding to the highest wave height for the three high wave events.

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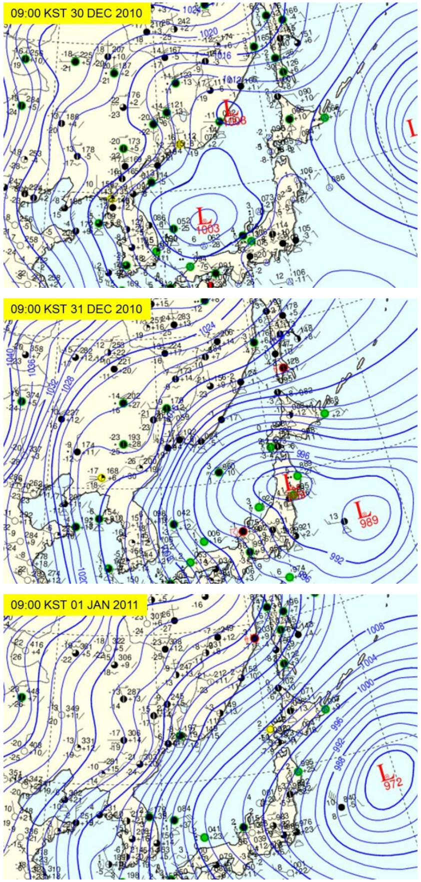

Fig. 10. Three weather charts at 09:00 KST (Korea Standard Time) on 30 and 31 December 2010 and 1 January 2011.

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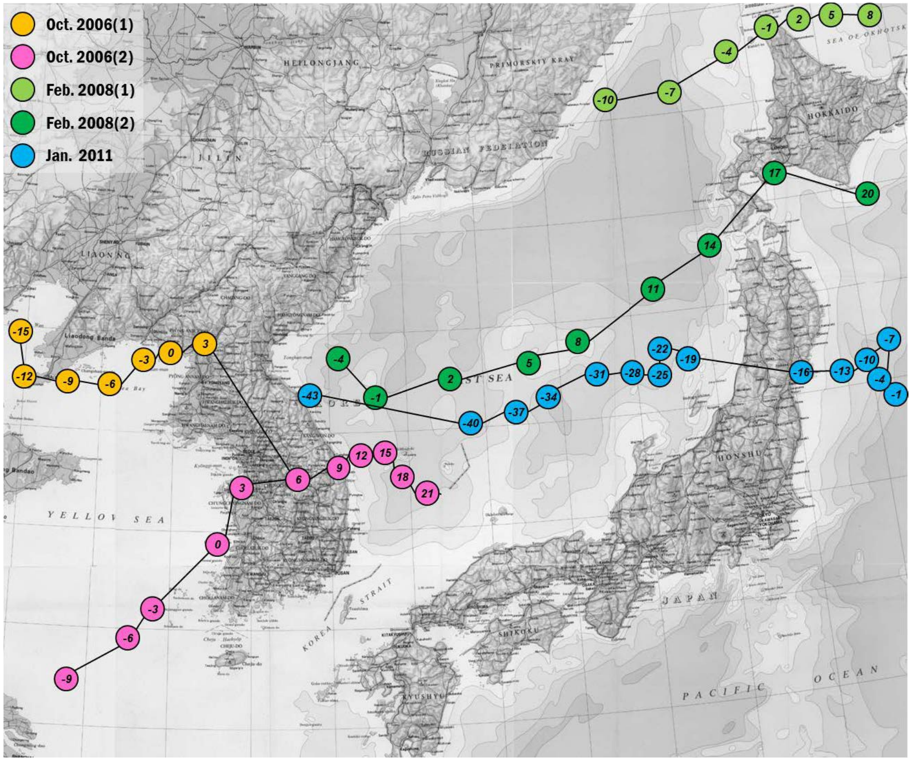

Fig. 11. The paths following the center of the low pressures at the time of the three high wave events.

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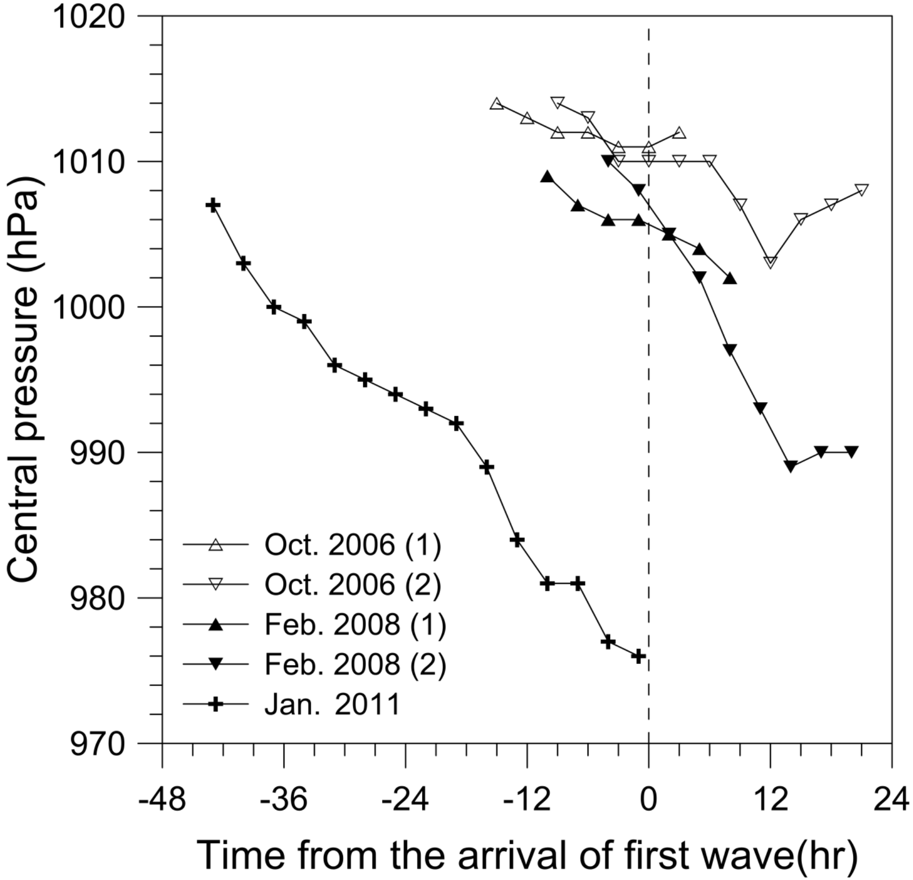

Fig. 12. Variations of atmospheric pressure at the center of the low pressures along with their movement.

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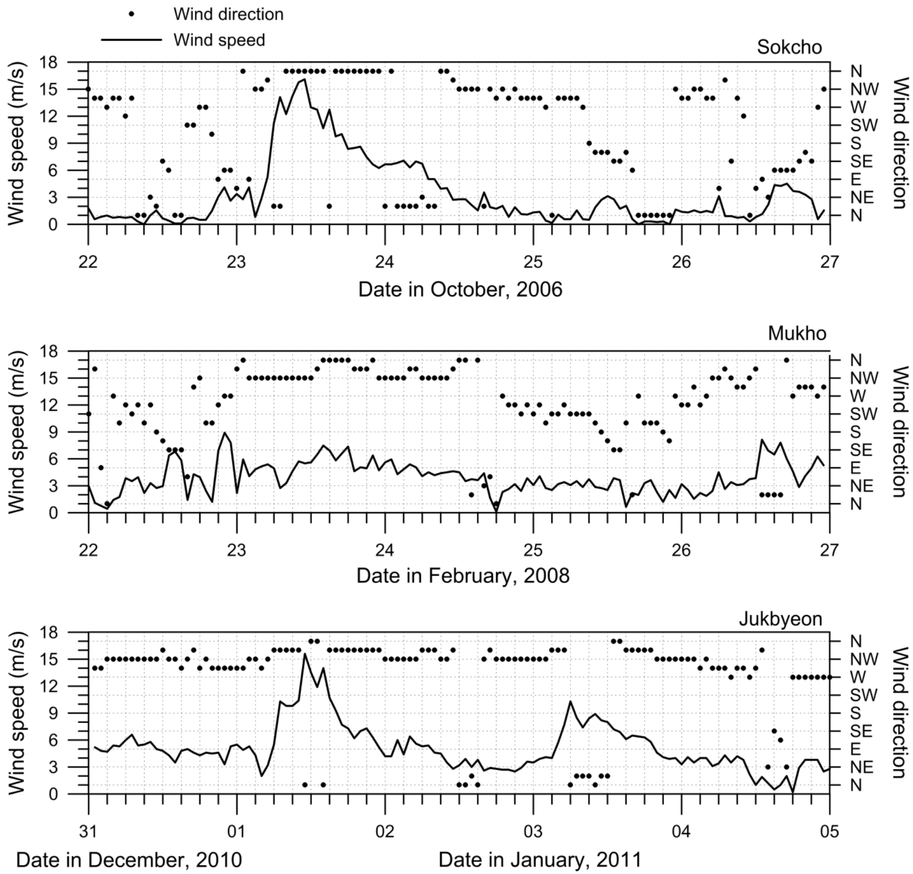

Fig. 13. Temporal variation of wind speeds and directions during the three high wave events.

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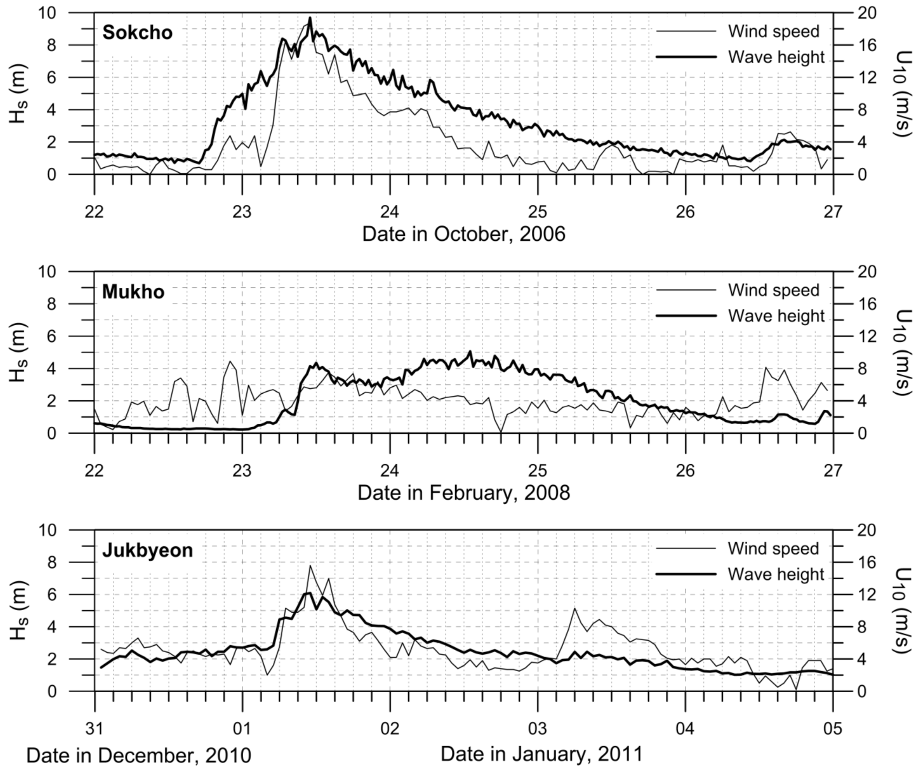

Fig. 14. Comparison of time histories of wind speed and wave height during the three high wave events.

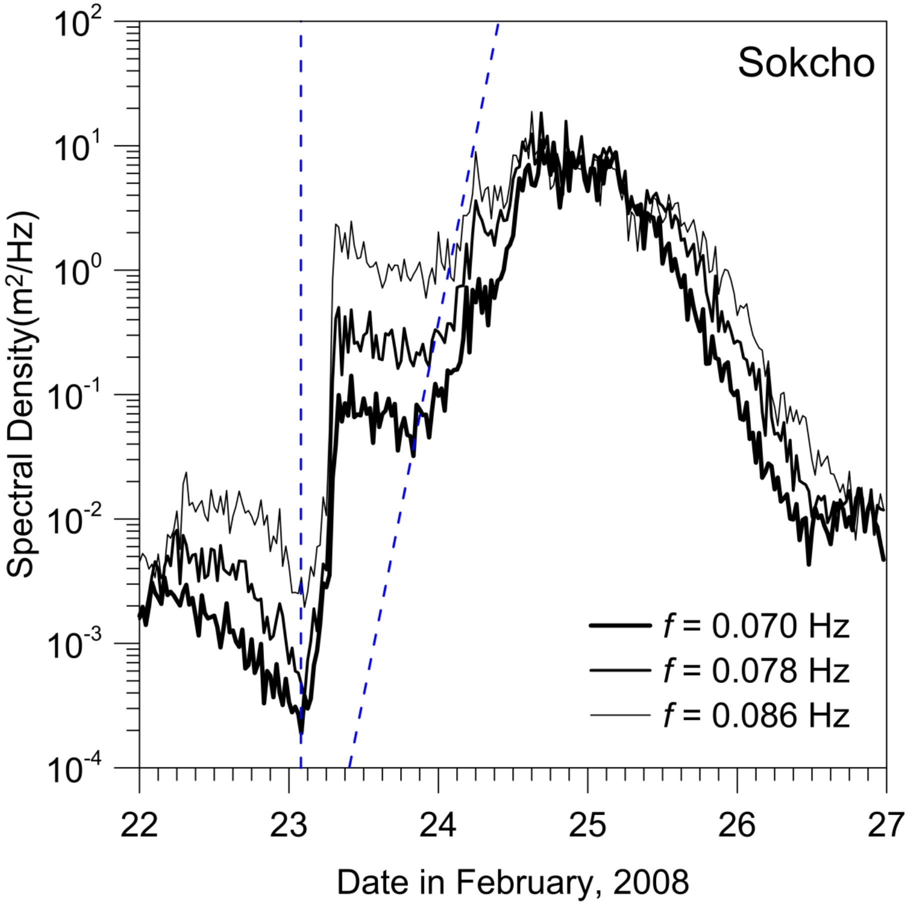

Fig. 15. Time series of spectral densities for the three individual wave components.

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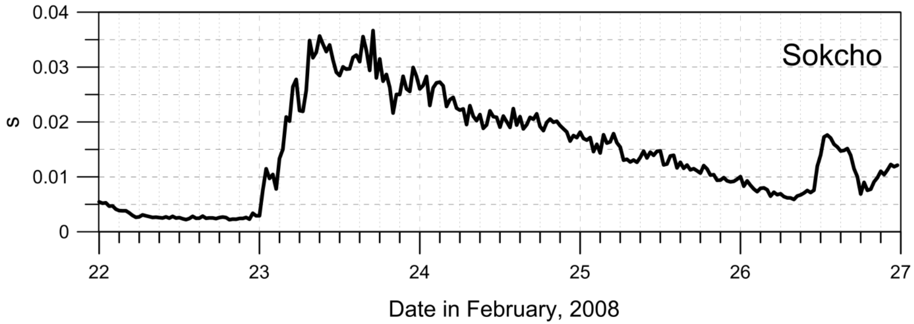

Fig. 16. Temporal variation of wave steepness during the high wave event in February 2008.

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