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High Waves in the West Coast of Korea during Winter Season Generated by Excessively Developed Low Pressure

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Abstract

Characteristics of the high waves arriving on the west coast of Korea are intensively examined based on the analysis of long-term coastal wave observation data obtained at multiple locations as well as some available meteorological data. It was clarified that the rapid drop of the atmospheric pressures during the development and evolution of the extra-tropical cyclone is the chief reason for the occurrence of high waves in the Yellow Sea. Directly influenced by this meteorological phenomenon, very strong winds tend to blow extensively over the entire sea region and evoke generation of high waves. Since the wave field is predominantly governed by the local wind field, the temporal variation of wave height and period is very closely related to that of the wind speed. Hence, characteristics of the high waves appeared in the Korean west coast are found to be wind waves rather than swell

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Keywords: High waves; Winter storm; Extra-tropical cyclone; Yellow Sea; Wave monitoring

1. Introduction

On the west coast of Korea, considerably high waves occasionally appear in winter season influenced by extremely strong winds driven by well-developed extra-tropical cyclone. Several researchers have examined the phenomenon of the high wave events occurred in the Yellow Sea and arrived on the west coast of Korea (e.g. Ryu and Kim, 2004; Go et al., 2006; Chong and Seol, 2007), but characteristics of the high waves are yet sufficiently investigated due to lack of long-term wave monitoring data along the western coastline of Korea. According to the previous studies,

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large-height wave events are likely to appear when the mid-latitude extra-tropical low pressure system is excessively developed in the Yellow Sea. Stormy sea condition with significant wave height greater than 3 m on the west coast of Korea is observed more than several times during every winter season. As the casualties and property damage attributed to the high waves are reported almost every year, it is necessary to improve understanding of the characteristics of high waves in order to better predict its occurrence and arrival on the coast.

The Korea Institute of Ocean Science and Technology (KIOST) has continuously observed nearshore wave climate at multiple stations along the west coast of Korea during recent several years. These wave monitoring data are valuable as there had been little continuous long-term wave observation program around this region. In this paper, the observation data of the high waves are analyzed together with the meteorological data available during the wave events, particularly focusing on clarification of the intrinsic characteristics of the high waves.

2. Analysis of the observed wave data

The coastal waves were measured at the five locations along the west coast of Korea shown in Fig. 1, where pressure-type wave gauges were deployed on the sea bottom. Information about the geographical coordinate, the water depth, and data availability of each wave station is presented in Table 1. The pressure gauges recorded the raw wave data at a sampling rate of 2 Hz. For each measuring instrument, the wave spectrum was calculated from the spectrum of water pressure by using the transfer function between the wave pressure and the water surface elevation, by using the first 2048 data points during every 30 minutes.

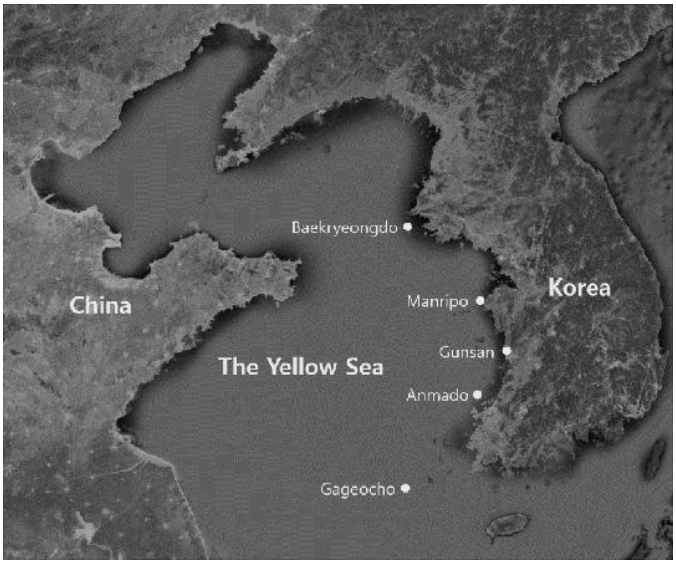

Fig. 1. Location map of the field measurement stations.

Table 1. Information on the five wave measurement stations.

Station	Latitude	Longitude	Water depth (m)	Data availability		
				Dec.2005	Nov.2008	Jan.2009
Baekryeongdo	37°59′08.9″N	124°37’34.5″E	15.0	○	○	○
Manripo	36°47′50.1″N	126°08’09.1″E	8.0		○	○
Gunsan	35°58′44.9″N	126°29’24.2″E	14.0	○		
Anmado	35°23′78.9″N	126°05’27.1″E	12.5	○	○	○
Gageocho	33°56′31.8″N	124°35’39.0″E	16.5	○	○	○

Among the available wave data, three high wave events that occurred in December 2005, November 2008, and January 2009 are selected for the analysis in this study as they showed distinct dissimilarity as well as similarity with respect to detailed processes of wave growth and decay patterns. Figs. 2 to 4 shows the time series of the significant wave heights and periods observed at all the available measurement stations during the three wave events, respectively.

In case of December 2005, abrupt increase of wave height and period is observed at all measurement stations around 23:00 3rd December 2005, which clearly indicates the arrival of high waves on the coast. As shown in the figure, the rising time of H_s is almost the same among the wave stations. In this study, the condition of $dH_s/dt \geqq 0.6$ m/hr and $H_s \geqq 0.8$ m is used to detect the rising time of the significant wave height. Such a feature of rapid increase of wave height at multiple stations at the same time shown in Fig. 2 implies that the wave field is chiefly governed by wind sea rather than swell. The maximum significant wave height during the wave event was 6.42 m observed at Gageocho. After reaching to the peak value, the wave height gradually decreased over two more days. Similar pattern was also observed for the significant wave period, showing sudden increase of T_s along with the arrival of high waves at the wave observation stations. The maximum significant wave period during the wave event was 10.7 s observed at Gageocho.

The time series of H_s and T_s for the high wave event in November 2008 are shown in Fig. 3. In this case, the variation patterns of wave height and period showed discrepancy from those in December 2005 as two subsequent growths and decays of wave height are displayed. The reason for this type of temporal evolution of H_s and T_s is ascribed to the development and movement of two separate low pressure systems over the Yellow Sea during the high wave event, more detailed analysis of which is described in the following. Compared to the record of high waves shown in the previous figure, the wave height and period quickly dropped after the two peaks appeared on 27th and 29th November respectively, indicating relatively short duration time of strong wind field over the sea. The rising time of H_s, associated with the first arrival of the high waves on the coast, was not the same but different among the stations, ranging from 02:00 (at Manripo station) to 09:00 (at Anmado station) on 27th November.

Similar time series plot for the high wave event in January 2009 is shown in Fig. 4. Similarly as the case in December 2005, wave height and period suddenly increased to the peak and then gradually decreased at all the measurement stations. In this case also, the rising time of H_s showed slight difference among the stations, which was 14:30 on 22nd January at Baekyreongdo, while 22:00 on the same day at the other three stations.

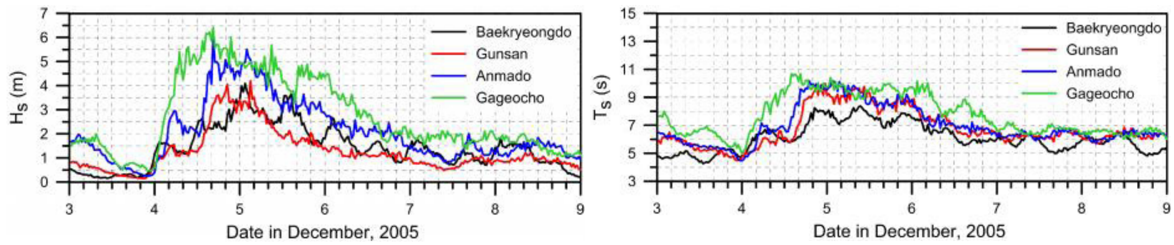

Fig. 2. Time series of H_s and T_s of the high waves during 3rd to 8th December 2005.

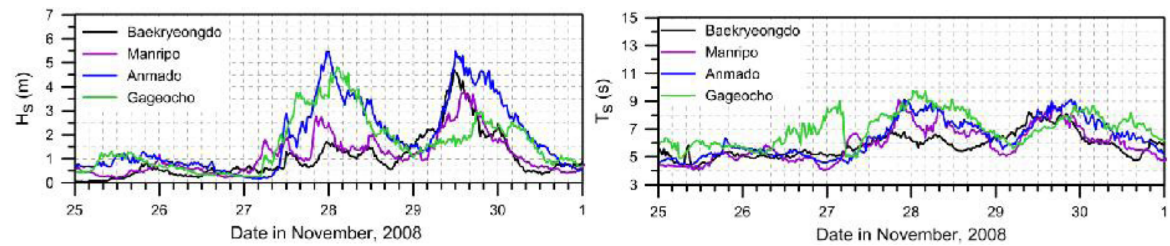

Fig. 3. Time series of H_s and T_s of the high waves during 25th to 30th November 2008.

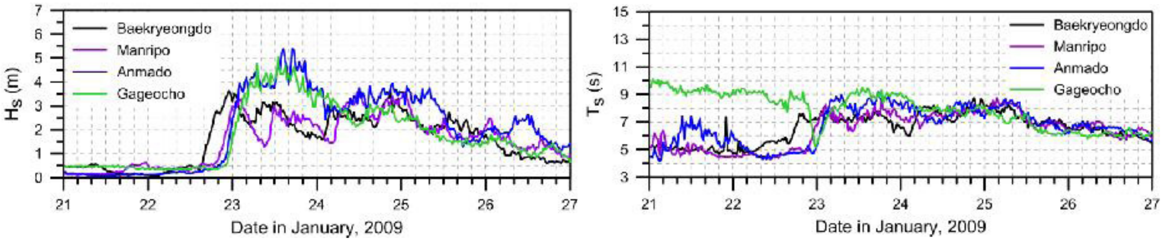

Fig. 4. Time series of H_s and T_s of the high waves during 21st to 26th January 2009.

3. Analysis of the weather chart and wind data

In order to examine the detailed correspondence of the appearance of high waves with the meteorological condition, the weather chart and wind observation data provided by the Korean Meteorological Agency (KMA) were used in the analysis. The weather charts around the Korea and the wind data acquired at the weather station nearest to each of the wave measurement locations were collected for the instances of the three high wave events. The weather chart is officially released every three hours by KMA, while the mean wind speed and direction at each weather station are produced at every one hour interval. The wind data are provided by taking the average of the instantaneous winds 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 is converted to the value at 10 m above the earth surface by assuming a logarithmic profile of it. In addition, wind datasets provided by ECMWF (the European Centre for Medium-Range Weather Forecasts) are also used in the analysis of meteorological condition during the high wave event.

During the time period of the high waves on the west coast of Korea, there existed at least one strong low pressure system over the Yellow Sea. The low pressure was originally generated inland of China and then moved eastward into the sea, while developing its strength by absorbing vapors provided by the ocean surface. In some atmospheric situations favorable to rapid development of the low pressures, it is excessively developed so as to be comparable to a small- or medium-size typhoon. In such a case, strong baroclinic gradient is formed around the Yellow Sea, which makes strong wind fields and subsequent high wave phenomenon over the sea eventually.

Development of the low pressure during the high wave in December 2005 is shown in the weather chart of Fig. 5. It is clearly seen that one extra-tropical cyclone is located in the East Sea, close to the west coastline of Japan. The cyclone was originally formed inland of China and then crossed the Yellow Sea to arrive the present position shown in the figure. Influenced by the existence of the low pressure system, very narrow isobaric contour lines are formed over the Yellow Sea, making steep gradient of the atmospheric pressures favorable to the formation of strong wind field. Indeed, mean wind speed at that time instant was almost comparable to 20 m/s all over the Yellow Sea as shown in the ECMWF wind field (the right panel of Fig. 5). The figure shows that wind direction was mostly north to northwest along the western coastline of Korea.

For the high wave event in November 2008, similar weather chart showing the atmospheric pressures at the earth surface as well as the corresponding ECMWF wind field are presented in Fig. 6. As shown in the figure, the overall shape of the weather chart is very similar as that shown in the previous figure: a low pressure system has been located near the Japan and narrow isobaric contour lines were formed around the extra-tropical cyclone, resulting in steep pressure gradient over the Yellow Sea. In this case, however, the contours of the isobaric lines within the continental region show significant dissimilarity with those in the previous figure. Probably influenced by such a discrepancy in the neighboring meteorological condition, the wind fields over the Yellow Sea in Fig. 6 show apparent difference from the one shown in the previous figure: the wind speed was significantly smaller as approximately 10 m/s while the wind direction mostly headed to the east. Due to this feature, the significant wave height during the high wave in November 2008 might be relatively smaller than the value observed in December 2005.

Fig. 7 shows the weather chart and ECMWF wind field during the high wave event in January 2009. Although the location of the low pressure is different from the two precedent cases, narrow isobaric contour lines are also formed across the Yellow Sea, making a condition associated with strong wind blow over the sea. As shown in the

ECMWF wind field, strong northwesterly winds heading to the western coast of Korea are prevailing at that time, which should provide favorable situation for the development of high waves.

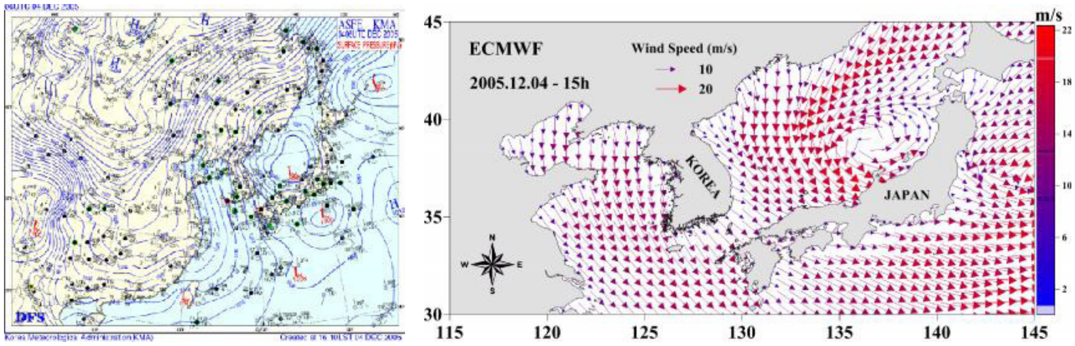

Fig. 5. Weather chart and ECMWF wind field around Korea at 15:00 4th December 2005.

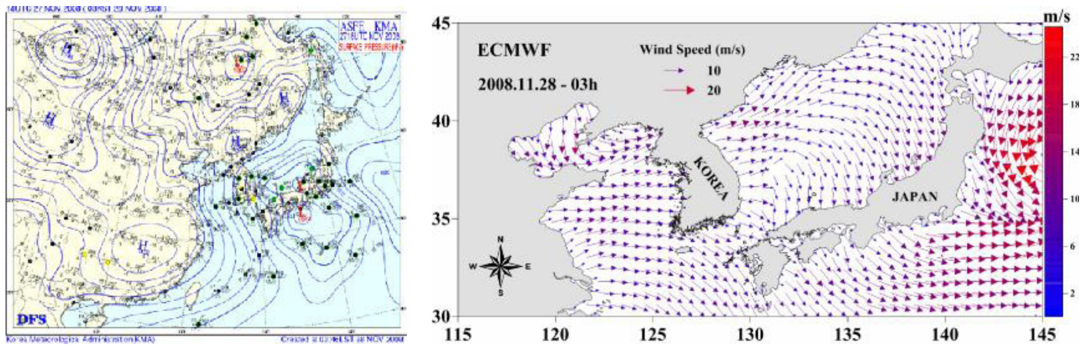

Fig. 6. Weather chart and ECMWF wind field around Korea at 03:00 28th November 2008.

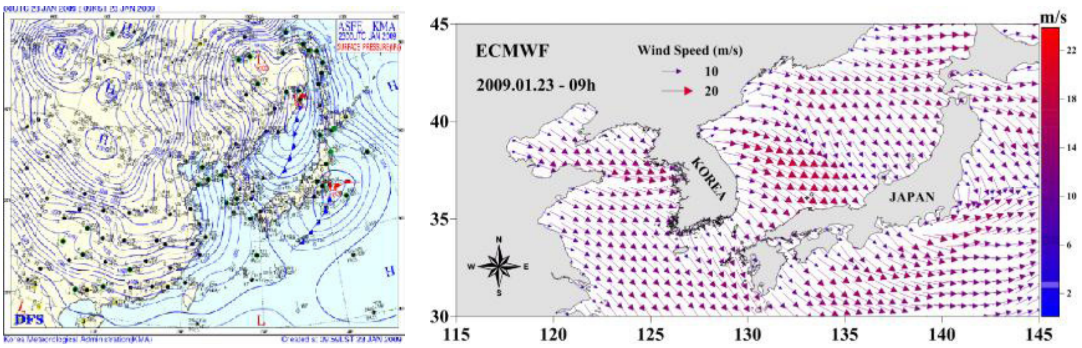

Fig. 7. Weather chart and ECMWF wind field around Korea at 09:00 23rd January 2009.

As explained in the three figures above, the excessive development of the low pressure and subsequent formation of strong wind field over the Yellow Sea were always observed during the time period of high wave appearance on the Korean west coast. However, the location and moving trajectories of the low pressures were unique for each wave event. It seems that overall atmospheric conditional structure over the entire sea region, not only the sole development of single or multiple low pressure systems, greatly contributes the formation of specific wind field that enables generation of such high waves.

4. Synthetic analysis of the meteorological and wave data

In order to comprehensively understand the characteristics of the three high waves appeared on the Korean west coast, all the available meteorological and wave data used in this study were put into a single picture together as shown in Figs. 8 to 10, similarly as in Lee (2013) and Oh et al. (2014). In the upper panel of Fig. 8, the moving trajectory of the low pressure formed in December 2005 is graphically displayed. The moving trajectory of a low pressure was detected by following its central location. The central locations of the low pressure system were obtained one by one from every single corresponding weather chart by finding the center of the circled isobaric lines. 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 in hours measured from the first arrival time of the high waves on the Korean west coast.

The temporal variation of central pressure of the extra-tropical cyclone is also presented in the lower panel of Fig. 8, where the time series of mean wind speed (U) as well as the significant wave height (H_s) and period (T_s) at Gageocho are also presented. As the maximum wave height at Gageocho was the largest among the measurement stations, all the physical quantities obtained there were adopted for the plot shown in Fig. 8. For the high waves of November 2008 and January 2009, the data obtained at Anmado were selected for the same reason. Note that the vertical axis on the right hand side of the time series plot corresponds to the magnitude of the significant wave height and period, but half of the mean wind speed. Meanwhile, the vertical axis on the left hand side of the plot is associated with the central pressure (hPa) of the low pressure. It is very clear that the central pressure started to decline in advance of the rise of wave height and period. In addition, the growth and subsequent decay of the mean wind speed coincided fairly well with those of the significant wave height and period. This demonstrates that the local wind field around Gageocho station was the principal factor for generating the high waves in December 2005.

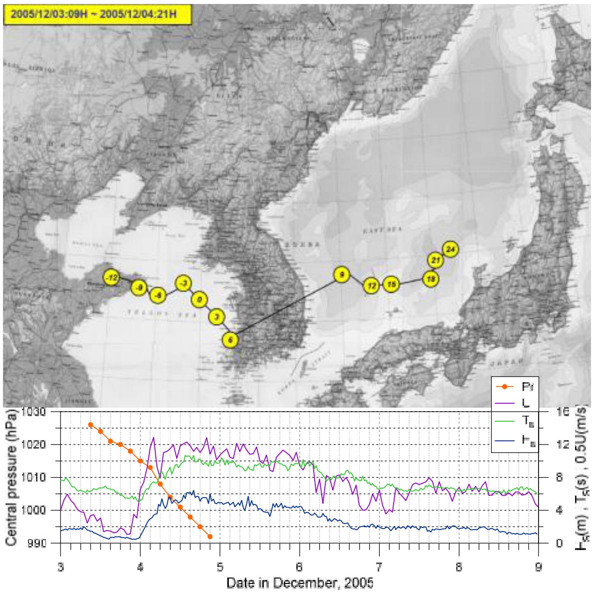

Fig. 8. Trajectory of the extra-tropical cyclone and reduction of its central pressure. Also shown are the time series of wind speed (U), significant wave height (H_s) and period (T_s) measured at Gageocho during the high wave event in December 2005.

Similar analysis was made for the high wave event in November 2008 as presented in Fig 9. In this case also, the local winds and waves at Anmado started to increase with the drop of central pressure of the extra-tropical cyclone, which first marched into the Bohai Sea and then crossed the Yellow Sea and Korea to reach Japan as shown in the figure. The close resemblance among the wind speed, wave height and period during the high wave event is again very clearly recognized. One noteworthy thing in Fig. 9 is that waves grew and declined two times during the wave event. The second wave growth and decay was influenced by the development of another low pressure system in the East Sea, which appeared at the continental shelf region of northern part of Korean peninsula at 03:00 29th November and moved to Hokkaido Island. As displayed in the time series plot of Fig. 9, the central pressure of the low pressure associated with the second wave growth also rapidly dropped within short time period. Relatively quick diminish of H_s in November 2008, compared to the case in December 2005, is probably due to the short duration time of the wind field around the Yellow Sea.

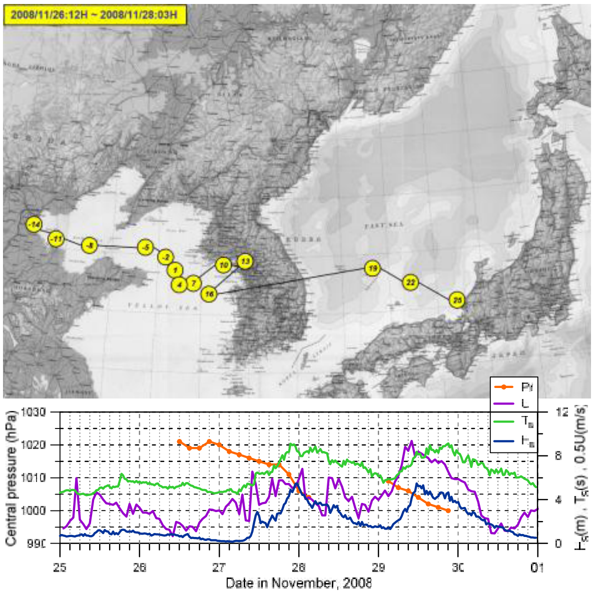

Fig. 9. Same as Fig. 8, but U, H_s, and T_s measured at Anmado during the high wave event in November 2008.

In case of the high waves in January 2009, the general patterns in time seires of the low pressure, the significant wave height and period, and the mean wind speed were very similar as those of December 2005. Especially, the trend in temporal variation of U was remarkably similar as that of H_s, indicating very close correspondence of the observed coastal wave to the wind field around the observation stations. This implies that the high waves were chiefly governed by the sea climate associated with the locally-generated wind rather than swell component from the offshore. Based on the close relationship between the wind and wave field, the main wave direction on the western coastline of Korea at that time was estimated to be west to northwest, similarly as in the ECMWF wind field shown in Fig. 7. Compared to the moving trajectories of the low pressures in December 2005 and November 2008, the central positions of the low pressure shown in Fig. 10 are located by far northern continental region. In spite of the far distance of the moving path of the low pressure from the sea, strong wind field was formed over the Yellow Sea. In this respect, the overall atmospheric condition, rather than the moving path of an extra-tropical cyclone itself, governs the wind and wave fields over the Yellow Sea.

5. Conclusions

The appearance of high waves on the Korean west coast more than several times during winter season is well recognized among the local citizens, navigators, and researchers. However, fundamental characteristics of such high waves are less intensively studied due to the lack of continuous long-term wave monitoring data around the region. In this study, records of such high wave events that had been collected at multiple locations along the Korean west coast are subjected to intensive analysis and major findings from the analysis are presented. During the three high wave events examined in this study, excessive development of extra-tropical cyclone and generation of strong wind field over the entire sea region of the Yellow Sea are clarified as key features determining the characteristics of the high waves. For all the wave events, fairly good agreement was found between the local wind field and the observed waves in terms of the temporal growth and decay patterns, indicating predominant influence of the local wind climate on the characteristics of coastal waves. As the formation of low pressures is very common during winter season around Korea, further investigation on how and when some of the low pressures are especially excessively developed to generate such high waves is required to be carried out in the future, by which more clear understanding of the characteristics of high waves can be obtained.

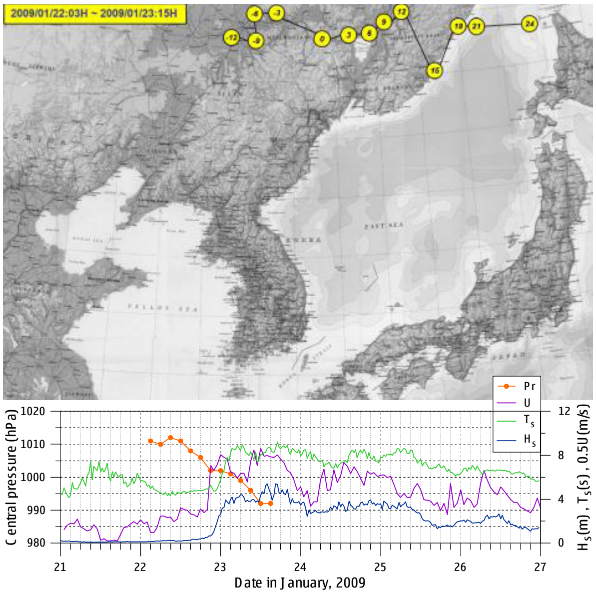

Fig. 10. Same as Fig. 8, but U, H_s, and T_s measured at Anmado during the high wave event in January 2009.

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