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Occurrence of Hazardous Meteotsunamis Coupled with Pressure Disturbance Traveling in the Yellow Sea, Korea

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ABSTRACT

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Several unexpected abnormal waves occurred near the west coast of Korea on March 31, 2007, May 4, 2008, April 26, 2011, and caused enormous damage to property and human lives. None of the events reported at the time were noticeably large, such as earthquakes or typhoons. However, in all reported events, it was observed that sea-level pressure disturbances combined with clusters of the atmospheric instability were propagated from China to the west coast of Korea. After these atmospheric disturbances were observed along the coast, significant meteorological tsunamis were also observed at tidal stations near the accident site. On the hazardous meteotsunami dates, arrival time and duration of the high-frequency sea-level oscillations were correlated with the pressure disturbance and high rain rate. To analyze the interaction between the pressure disturbance and the following sea-level oscillations, their propagation characteristics were also compared. As a result, they traveled to the eastward crossing over the Yellow Sea with coupled propagation on the dates of the accident. This process made the sea-level fluctuated by rapid pressure changes and amplified by Proudman resonance in a specific range of depth.

ADDITIONAL INDEX WORDS: *Abnormal waves, pressure disturbances, coupled propagation.*

INTRODUCTION

Meteotunami is similar to tsunami and storm surge but characterized as a different type of hazardous phenomenon. Period of the signal during meteotsunami has a typical period range from a few minutes to a few hours, which is similar to the tsunami (Monserrat, S. *et al*., 2006). Also, both resulting signal pattern is characterized by localized peaks and attenuate non-periodically. Unlike the tsunami, which is caused by seismic or volcanic activity, meteotsunami is generated by atmospheric disturbances. Storm, a category of other surges, is similar to a tsunami in that it is induced by atmospheric disturbance, but it is categorized as a different phenomenon mainly due to its different temporal and spatial scales. The meteotsunami is locally known as "Rissaga" in the Balearic Islands (Spain), "Marrobbio" in Sicily (Italy), "Milghuba" in Malta, and "Abiki" in Japan. In Korea, it is called "Abnormal wave" due to the characteristic of the sudden occurrence in the coastal area.

The dates of hazardous meteotsunamis having the meteo-tsunami related casualties and property damage were on 31 March 2007, 4 May 2008, and 26 April 2011. Meteotsunami case on 31 March 2007 is known as the case that recorded the largest amplitude and oscillated the longest so far. In addition to the deaths of four people, the property damage caused by flooding, ship loss, vehicle flooding, and damage to farms amounted to about 2,245 million won (Yoon and Eom, 2013). Jukdo (Figure 1, JD) was struck by sudden meteorological tsunamis on Sunday 4 May 2008 which caused the most human casualties (9 dead and 15 injured) in the reported case. Accident scenes that the several people were swept away by unexpected waves were captured in the surveillance videos (Figure 2). At 10:55 KST on 26 April 2011, tsunami-like sea-level oscillations occurred and they caused many of the farms and vessels located in the harbor to be damaged.

The study of meteotunamis in the Yellow Sea has been focused on March 31, 2007, which was the largest wave observed. Kim *et al*. (2014) suggested that a cold front with low pressure crossed the Yellow Sea several times, and the meteotsunamis arrived during the unstable meteorological condition on 31 March 2007. Choi *et al*. (2008) and Eom *et al*. (2012) analyzed the growth process and amplification of the abnormal waves through 1-D and 2-D ocean modeling in ideal conditions. On May 4, 2008, the case occurred only in the local area, unlike the case on March 31, 2007. The exact cause of the human casualty has not been determined. Through analysis of the CCTV image recorded at the time of the accident, Yoo *et al*. (2010) quantitatively derived the characteristics of the abnormal waves (maximum wave height, period, speed) at the point of accident occurrence. Choi and Lee (2009) reported that the pressure jump was detected in the Yellow Sea during the meteotsunami, but it was not powerful enough to cause the accident, and there could be other causes for the amplification of the abnormal waves. The event of 26 April 2011 has not been studied yet.

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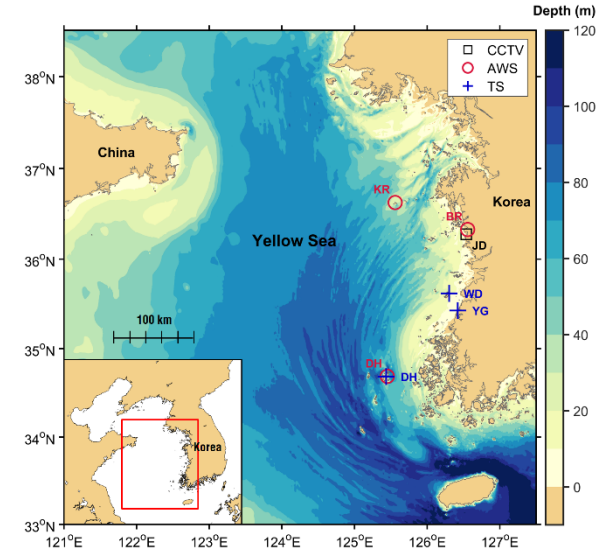


Figure 1. Maps showing bathymetry and locations of CCTV, AWS (Automatic Weather System), and TS (Tidal Station) used to analyze the meteotsunami case in the Yellow Sea. Black square marks the CCTV installed near the meteotsunami damaged area (JD: JukDo). Red circles indicate KMA (Korea Meteorological Administration) AWS (KR: KyukRyulbeedo, BR: BoRyeong, DH: DaeHeuksando). Blue cross markers represent KHOA (Korea Hydrographic and Oceanographic Agency) TS (WD: WiDo, YG: YeongGwang, DH: DaeHeuksando).



Figure 2. CCTV images which captured (a) the propagation of sudden waves (red rectangle) on 4 May 2008 (12:37:51 KST, M-20s), and (b) significant human casualties (red dashed circle) on 4 May 2008 (12:38:11 KST, M: time of the accident due to the Meteotsunami in JD).

When considering the meteotsunami research in the Yellow Sea which has been performed to date, much of the prior research was mainly focused on analyzing the cause of each meteotunami case. Still, there remains the meteotsunami case which has not been analyzed, and the similar characteristics for the meteotsunamis have not yet been studied. The primary goal of this study is to analyze the common cause and the amplification process of the significant sea-level oscillations which were observed in the reported meteotsunamis.

METHODS

To examine the interaction between the pressure disturbance and the resulting the sea-level oscillations during the meteotsunami cases, we analyzed 1-min sampling sea-level pressure in AWS and 1-min sampling tide level in tidal stations located near the accident zone (Figure 1).

Rapid pressure jump can be detected based on an analysis of the rate of change of air pressure (Sepic' *et al.*, 2011). The rate of sea-level pressure surpassing 1.2-1.5 hPa/10-min in the Yellow Sea has been considered as pressure disturbance in KMA. In our study, the criterion of the pressure disturbance was rigorously determined as 1.5 hPa/10-min over the region (Figure 4 red lines). The same criterion was applied over the Yellow Sea since the magnitude of the pressure disturbance is not dependent on observation points.

The tsunami frequency range (for periods of 2-min to 2-hour) about 99% of the energy of background oscillations is related meteorological forcing (Monserrat *et al.*, 2006). High-frequency oscillations have been filtered by the wavelet decomposition (Torrence and Compo, 1998) with a cut-off period of 2-hour. As the magnitude of the meteotsunami is dependent on the location of each observation point (Monserrat, S., 2006), the relative criterion of the meteotsunami was determined as 3-sigma value of the amplitude (Figure 3 red lines; YG: 47.3 cm, (b) WD: 8.6 cm, (c) DH: 18.7 cm) in the tsunami frequency band for 1-day before and after the meteotsunamis (Kim *et al.*, 2017). The duration of time the pressure disturbances and the meteotsunamis lasted was calculated as the periods exceeding each criterion.

To estimate the source location and propagation direction of the atmospheric instability related to the pressure disturbances, we analyzed the leading clusters which exceed 20 mm/hr in the 10-min interval radar images by visual inspection (Figure 5).

RESULTS AND DISCUSSION

Meteorological Tsunamis

The meteotsunamis on 31 March 2007 propagated all over the west coast of Korea when the tide level rose the maximum (Figure 3a). About 2.5 m, the largest ever wave height of the reported meteotsunami wave heights in the Yellow Sea recoded at YG tidal station, and the sea-level oscillations lasted for about 8-hour with the 3-sigma value of the meteotsunami amplitude. It can be presumed that the magnitude of the wave height was amplified as the incoming waves propagated into the direction of a breakwater located in front of the tidal station.

On 4 May 2008 at 11:46 KST, the first significant tide level residual was detected at WD tidal station, about 75 km south-southwest away from the Jukdo (JD) where the casualty occurred (Figure 1, Figure 3b). The maximum amplitude of 18.1 cm was analyzed, 52-min before the time of the casualties in the CCTV deployed at JD when assuming time synchronization between WD tidal station and the (Figure 2b, Figure 3b, Table 1). The high-frequency sea-level oscillations from -14.1 to 18.1 cm propagated toward north-northeast with 23.1 m/s speed, and caused the considerable human loss at JD.

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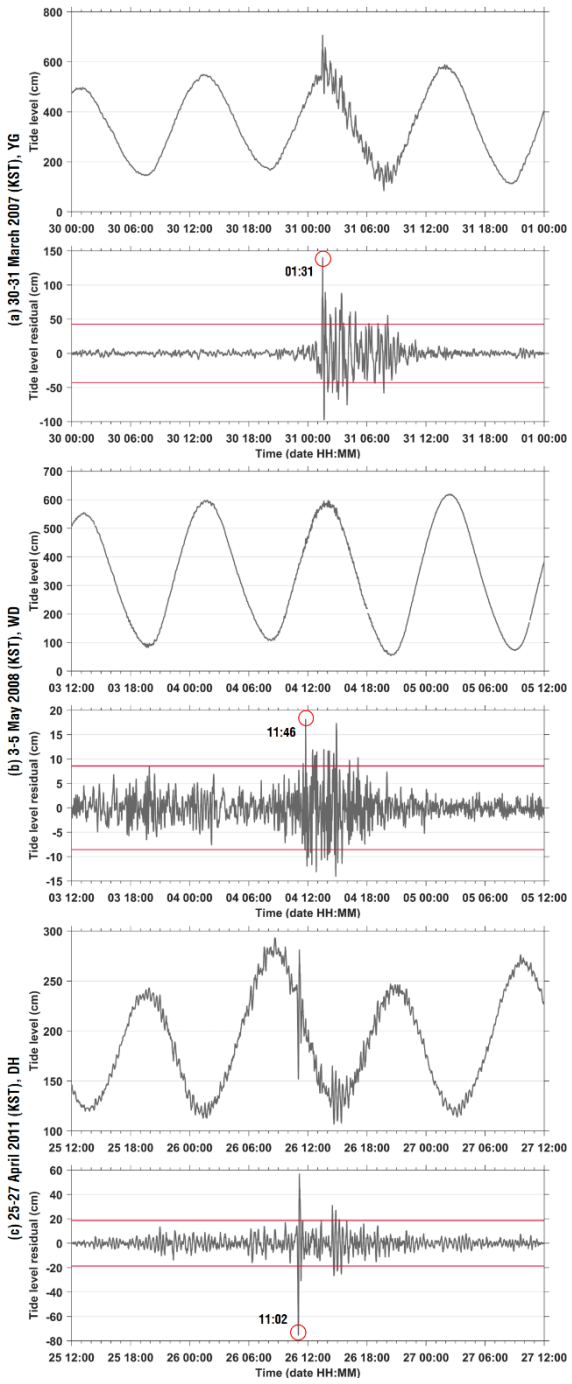


Figure 3. Raw tide level and 2-h high pass filtered tide level from the tidal stations located near the damaged area during the reported meteotsunamis of (a) 30-31 March 2007 (YG), (b) 3-5 May 2008 (WD), and (c) 25-27 April 2011 (DH). Red circles represent meteotsunami arrival time when the amplitude of tide level residual was the maximum. Red lines indicate the 3-sigma limits of the wave amplitude in each tidal station.

When comparing prior two meteotsunami cases, the sea-level oscillations on 26 April 2011 were observed locally at DH tidal station. In contrast to the signals of other tidal stations attenuated for several hours, the sudden fluctuations with the wave height of 1.3 m (-75.3-56.8 cm) at DH tidal station sharply attenuated to an amplitude of less than 3-sigma in just 20-min (Figure 3c, Table 1). It is possible to identify the influence of the local topography of DH tidal station located in a semi-closed harbor of approximately 800 m radius. In all the reported meteotsunami events, the magnitude, attenuation, and duration of the sea-level oscillations were also heavily dependent on each location of the tidal stations.

Pressure Disturbances

The significant sea-level pressure oscillations of about 4.1 hPa/10-min first arrived at KR AWS at 00:38 KST 31 March 2007 (Figure 4a1, Table 1). The duration of the pressure disturbances was approximately 8-hour, which is almost the same as the duration of the tsunamis on 31 March 2007 because the pressure disturbances surpassing the critical limit in the Yellow Sea continuously propagated at KR and BR AWS (Figure 3a, Figure 4a1, Figure 4a2 shaded region). When the sea-level oscillations were weakened or dissipated over the Yellow Sea, regardless of the pressure disturbances that caused the accident, pressure disturbance of about 1.7 hPa/10-min arrived late at DH AWS (Figure 4a3, Table 1).

At 12:15 KST 4 May 2008, pressure disturbance having the maximum 1.9 hPa/10-min rate of sea-level pressure change arrived at BR AWS located the nearest to the accident areas (Figure 4b2, Table 1). A few minutes after the pressure disturbance arrived at BR AWS located at 5.9 km east from JD, the hazardous meteotsunamis propagated. On the daytime of 4 May 2008 between 12:15 and 12:38 KST, the meteorological tsunami with several minutes of the time lag presumably propagated after the pressure disturbance. Any pressure disturbance was not detected at DH AWS at that time (Figure 4b3).

During the meteotsunamis on 26 April 2011, the continuous pressure disturbances were detected only at DH AWS among the AWS located in the Yellow Sea, and the sea-level pressure oscillations lasted for about 4-hour (Figure 4c3 shaded region, Table 1). The maximum pressure disturbance having a 2.2 hPa/10-min rate of sea-level pressure change generated at 14:00 KST, but the peak of pressure disturbance (1.8 hPa/10-min) closest to the time of the accidents arrived at 11:00 KST. The pressure disturbance followed by the rapid sea-level fluctuations without time lag (Figure 3 red marker, Figure 4c3, Table 1).

Coupled Propagation with Atmospheric Instability

In all the reported events, the cluster of the high rain rate propagated eastward from China during the pressure disturbances in the Yellow Sea (Figure 4, Figure 5). However, the source locations (Shandong, Shanghai, between Shandong and Shanghai) and propagation direction (east, north-northeast, east) of the atmospheric instability were estimated differently in each meteotsunami case.

On the event of 31 March 2007, atmospheric disturbances at the Shandong Peninsula propagated easterly toward the Yellow

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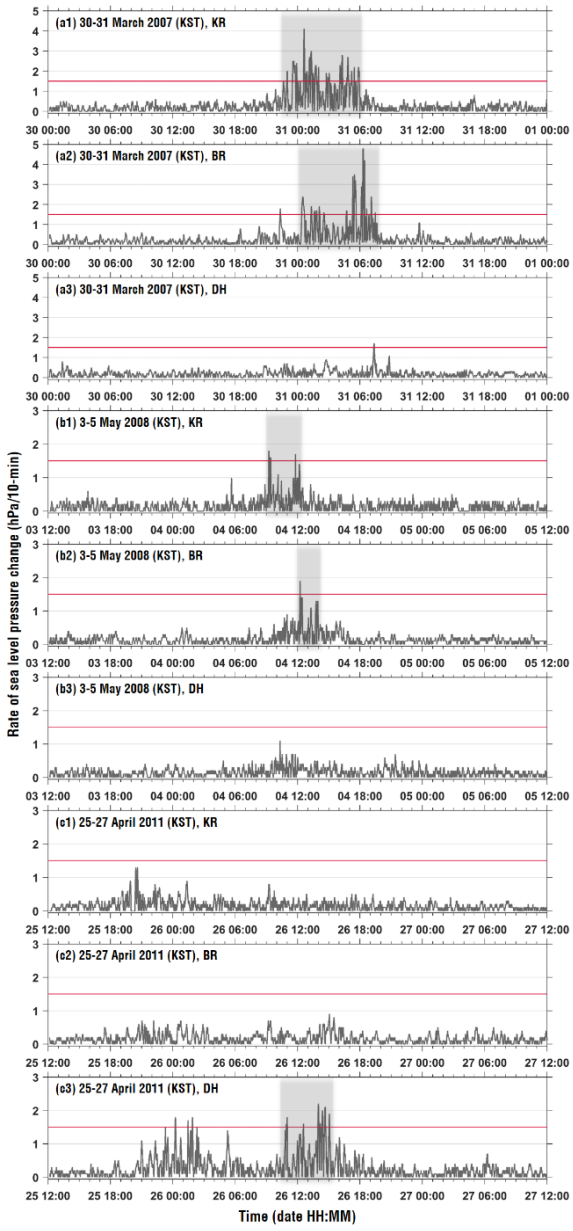


Figure 4. The rate of sea-level pressure change at KR (1), BR (2), and DH (3) AWS during (a) 30-31 March 2007, (b) 3-5 May 2008, and (c) 25-27 April 2011. Red lines represent the limit of the pressure disturbance in the Yellow Sea (1.5 hPa/10-min). Shaded regions indicate the duration of pressure disturbances.

Sea of higher latitude than the latitude at which DH AWS located (Figure 4a1-2, Figure 5a1-2). The meteotsunamis were detected not only at DH tidal station but also other tidal stations throughout the Yellow Sea (Choi *et al*., 2008; Kim *et al*., 2014). Kim et al. (2016) reported that the meteotsunamis due to the harbor resonance after Proudman resonance occurred as the sea-level oscillations entering the DH harbor corresponded with the eigen-period of the DH harbor. During the meteotsunamis, forced waves arrived in most tidal stations of the Yellow Sea where the meteotsunamis coupled with the pressure disturbances propagated, and free waves were observed at DH tidal station where sea-level oscillations propagated after the disturbing force.

Table 1. *Maximum magnitude and arrival time of the meteotsunami and pressure disturbance on each date of the accident.*

Type	Date	Station ID	Maximum magnitude	Arrival time (HH:MM)
Meteo-tsunami (cm)	2007/03/31	YG	140.0	01:31
	2008/05/04	WD	18.1	11:46
	2011/04/26	DH	-75.3	11:02
Pressure disturbance (hPa/10-min)	2007/03/31	KR	4.1	00:38
		BR	4.8	06:18
		DH	1.7	07:20
	2008/05/04	KR	1.8	09:15
		BR	1.9	12:15
		DH	-	-
	2011/04/26	KR	-	-
		BR	-	-
		DH	2.2	14:00

Similar to the propagation pattern of the pressure disturbances, the atmospheric instability near the Shanghai propagated to north-northeast direction toward the accident areas on 4 May 2008 (Figure 4b1-2, Figure 5b1-2). When the leading clusters of high rain rate in the radar images were assumed to be the direction of the pressure disturbances, the distance traveled by the pressure disturbances from KR AWS to BR AWS was approximately 40 km. The time difference of the peak of the maximum pressure disturbance closest to the time of the accidents was 27-min between KR and BR (Figure 4b1-2). Therefore, the pressure disturbance propagated from KR to BR at an average speed of about 24.7 m/s, which approximated to the average speed (23.1 m/s) from WD to JD. The speed of the pressure disturbance near the accident area is approximated to 22.8 m/s, which was derived by Choi *et al*. (2009). The clusters of high rain rate, the pressure disturbance, and the meteotsunamis arrived at JD with the coupled propagation having a time lag, based on the time difference of arrival and the discrepancy of propagation speed between them.

In contrast with the propagation pattern on 31 March 2007, the atmospheric instability on 26 April 2011 propagated toward the direction of DH only (Figure 5c1-2). When the meteotsunamis arrived, the spatial pattern of the observation stations where the pressure disturbances were detected corresponded to the spatial pattern of the atmospheric instability in the radar images (Figure 3c, Figure 4c1-3, Figure 5c2). At 11:10 KST 26 April 2011, which was the time when the pressure disturbances arrived at DH, the rain rate near DH was relatively higher than the rain rate in other areas. We found that the propagation pattern of atmospheric instability, pressure disturbance, and meteotsunami was correlated with each other, based on the similar spatial pattern and arrival time between them.

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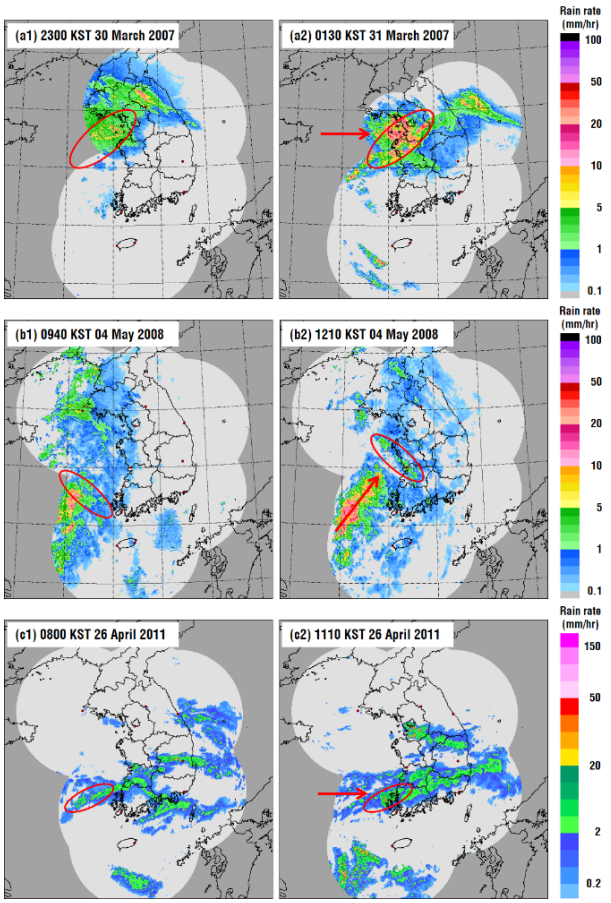


Figure 5. Rain rate of the composite KMA radar images which represents the maximum reflectivity in each column on (a) 31 March 2007, (b) 4 May 2008, and (c) 26 April 2011. Radar images indicate a few hours before (left panel) and during (right panel) the meteotsunamis along the west coast of Korea. Red circles and arrows mark leading clusters of the atmospheric instability which is more than 20 mm/hr and their propagation, respectively.

CONCLUSIONS

The hazardous waves on the dates of the accident were generated by the meteotsunamis in the Yellow Sea coupled with the propagation of atmospheric instability such as rapid pressure changes (1.7-4.8 hPa/10-min) and clusters of high rain rate exceeding 20 mm/hr. Coupled propagation of pressure disturbances and sea-level oscillations with similar arrival time and duration amplified the amplitude of the waves, and thus caused sudden unexpected losses along the west coast of Korea.

In the present, it is hard to ensure the timely warning of the sudden meteotsunamis which propagate with the atmospheric instability because most of the observation points are located on the coast. To detect the coupled propagation in advance, we need at least more than 3 points (located in the northwest, the west, and southwest of the Yellow Sea) of "Meteotsunami safety beacon" installed in the open sea.

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