Response to Comments

Manuscript number: NHESS-2021-126
Title: Pressure-forced meteotsunami occurrences in the eastern Yellow Sea over the past decade (2010–2019): monitoring guidelines
Authors: Myung-Seok Kim, Seung-Buhm Woo, Hyunmin Eom, and Sung Hyup You
Journal: Natural Hazards and Earth System Sciences

- Reviewer #2:

The manuscript "Pressure-forced meteotsunami occurrences in the eastern Yellow Sea over the past decade (2010-2019): monitoring guidelines" by Kim et al. represent a worthy addition to the meteotsunami research of the eastern Yellow Sea, and I conditionally suggest it for publication. My main concern is the quality of the English language which is rather poor. The manuscript MUST be proofread by either a native speaker with knowledge on the subject or someone with much better working knowledge of the language. I will not list any mistakes, but there are some in almost every sentence. I now list some specific comments:

→ As you commented, we will use one more round of English proofing when submitting the revised manuscript. Please also check "Response to Comments (figures, tables, and equations)". Thank you for your comments.

[Abstract]

1. change "which shows a strong seasonal trend." to "revealing a distinct seasonal pattern."
2. list "favorable conditions" which you have found
3. change "the monitoring system" to "the meteotsunami monitoring system"

→ These comments about rephrasing are planned to be modified after the final response.

[1. Introduction]

4. change "forced long waves" to "forced ocean long waves"
5. change "to the pressure disturbance" to "to the atmospheric pressure disturbance"
6. change "waves and their fundamental periods" to "waves and fundamental periods of shelves, bays or harbors".
7. change "at that time remains unknown" to "was unknown at that time

→ These comments about rephrasing are planned to be modified after the final response.

[2. Observation system and pressure jump]

8. Change the title to "Observation system and extraction of meteotsunami generating pressure disturbances" or simply to "Meteotsunami monitoring system"

→ This comment is planned to be modified after the final response.

9. It is implied (around line 115) that various intensities were tested, but no information on the results of these tests is given. Please explain how did you choose the 1.5 hPa/10 min rate. Also, have you tested intensities over shorter time intervals, e.g. XY hPa/5 min? Please discuss.

→ Kim et al. (2021a) explained how they choose the reason of the 10 min rate (Please refer to 2.3 Preliminary caution SMS). When operating the real-time pressure disturbance monitoring system, it was necessary to consider the delayed time for raw pressure data observed at each AWS to be sent to the KMA (Korea Meteorological Administration). The criterion of air pressure jump in the Yellow Sea was based on the observed intensity of air pressure disturbance during the meteotsunamis of accident (Kim et al., 2019). Also, we tested intensities over shorter and longer time intervals (e.g., hPa/5 min & hPa/20 min) as following figure. We applied the same criterion (red line) of air pressure jump (0.15 hPa/min). Following figure indicates raw pressure data and air pressure disturbances for each time interval at the DH harbor where the largest meteotsunami was detected since 2010 (meteotsunami of accident: 26/04/2011). The shorter the interval of the rate, the more sensitive it is, but from the point of view of real-time monitoring system operation, it was decided to be 10 min rate.

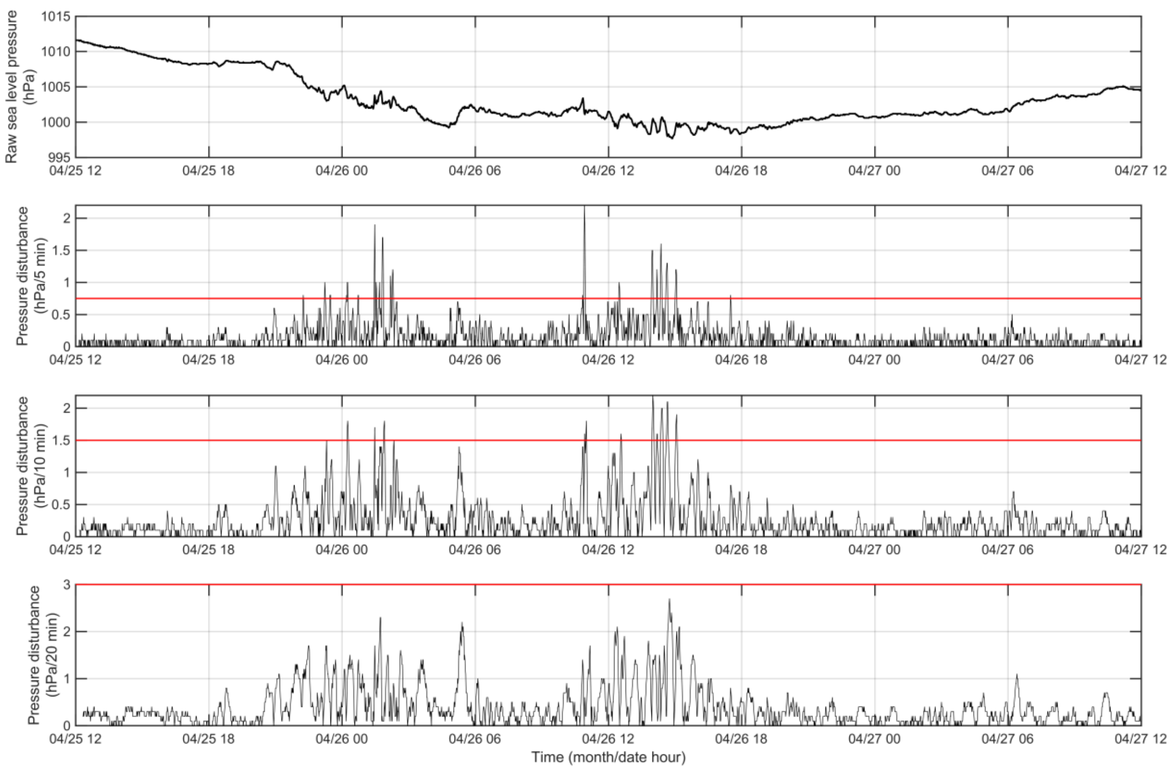


Figure: Raw pressure data and air pressure disturbances for each time interval (5, 10, and 20 min rate of pressure change) at the DH AWS during 25-27 April 2011.

- Kim, M.-S., Kim, H., Eom, H.-M., Yoo, S.-H., Woo, S.-B., 2019. Occurrence of hazardous meteotsunamis coupled with pressure disturbance traveling in the Yellow Sea, Korea. J. Coast. Res. 91, 71–75. https://doi.org/10.2112/si91-015.1

- Kim, M.-S., Eom, H., You, S.-H., Woo, S.-B., 2021a. Real-time pressure disturbance monitoring system in the Yellow Sea: pilot test during the period of March to April 2018. Nat. Hazards. https://doi.org/10.1007/s11069-020-04245-9

[3. Classification of pressure-forced meteotsunami dates]

10. change the title; "dates" were not pressure-forced; sea levels were pressure forced or meteotsunami; perhaps: "Classification of pressure-forced" meteotsunami events

→ This comment is planned to be modified after the final response.

11. "which means the inverted barometer response" - no, the inverted barometer response is ~1cm/hPa - what you have here is much stronger - so, this means "resonant effect between the propagating air pressure disturbance and long ocean waves"!

→ This comment about rephrasing is planned to be modified after the final response.

12. "phase relationship between pressure jump and high-frequency sea level.." - what "phase relationship"? "In-phase, out-of-phase, almost simultaneous appearance"?

→ We intended similar timing of occurrence. We will rephase the expression of "phase relationship" to "timing".

13. What kind of filter did you use? Please state and give an appropriate reference.

→ We used the wavelet filter that Torrence and Compo (1998) suggested. This filter has the advantage over traditional filtering in that it can be used to isolate single events that have a broad power spectrum or multiple events that have varying frequency.

- Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. Bull. Am. Meteorol. Soc. 79, 61–78. https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

14. Figure 3. and accompanied analysis/text - I like this idea for extracting the extremes. However, since the events are almost symmetric around zero I would consider looking at the wave heights instead of at amplitudes and extracting the events in a similar way.

→ As you commented, the meteotsunami events were re-analyzed using wave height rather than amplitude. Please check the modified figures and tables.

15. Figure 4. It is not clear from this Figure what was excluded "Sample data collection: 68% (1 sigma)." I suggest writing "Exclusion of dates with less than 68% of available data" - sigma is a strange variable to use when it comes to a number of data.

→ This comment is planned to be modified after the final response.

16. change "was controlled in the first" to "was removed in the first"

→ This comment is planned to be modified after the final response.

17. You say that you removed daily mean from daily samples. That is not really necessary if you filtered the data as well, and you have, as I understand?

→ As you commented, demean from each daily sample is not necessary. The process flow diagram (Figure 4) will be modified after the final response.

[4. Pressure-forced meteotsunami occurrences]

18. Table 2. Mark the strongest amplitude of each event with bold letters, or underline. So, in the first row that would be 33.3 at MS station...

→ As you commented, we modified the table. Please check the modified table.

19. Line 234-235. Discuss here or in discussion (better in discussion) why do you think that meteotsunamis are more common during March-May

→ We will discuss the possible reason of the meteotsunami seasonality in discussion. Please refer to 28th comment.

20. Figure 6. Think about adding some strength parameter to this Figure - for example, for each month try plotting median height at stations at which it was recorded.

→ As you commented, we modified the figure. Please check the modified figure.

21. Line 240. change "The spatial vulnerability" to "The spatial spread" or "The spatial pattern".

→ This comment is planned to be modified after the final response.

22. Figure 7. Instead of showing a total number of events, show the number of events per year - this way, the effect of shortness of time series will be removed.

→ As you commented, we modified the figure. Please check the modified figure.

23. In your list (line 260) condition (3) is the same as condition (2) but stronger - remove the condition (2).

→ This comment is planned to be modified after the final response.

24. Figure 8. I like the idea

→ Thank you for your encouragement.

25. Figure 9. I suggest adding another column in which filtered air pressure time series are shown, starting at the top with the northern stations, and ending, at the bottom with the southern stations - or another way around.

→ As you commented, we will add the filtered air pressure time series from the starting and ending.

26. It is not clear how were speed and direction of propagation assessed? From radar images or from air pressure data? Please explain. If from the radar data, confirm it with air pressure data.

→ The propagation patterns of the classified 42 meteotsunami events were analyzed as follows:

(1) The intensity and movement of rain rate exceeding 5 mm/h were confirmed by visual inspection (Kim et al., 2021a).

(2) Arrival time list and isochrone map of air pressure jump were estimated in the area where the high rain rate propagated (Figure 9).

(3) Direction and speed were assessed using the three points of AWSs based on the explicit formula suggested by Šepić et al. (2009). Equations are specified in Response to Comments (figures, tables, and equations).

- Kim, M.-S., Eom, H., You, S.-H., Woo, S.-B., 2021a. Real-time pressure disturbance monitoring system in the Yellow Sea: pilot test during the period of March to April 2018. Nat. Hazards. https://doi.org/10.1007/s11069-020-04245-9

- Šepić, J., Denis, L., Vilibić, I., 2009. Real-time procedure for detection of a meteotsunami within an early tsunami warning system. Phys. Chem. Earth 34, 1023–1031. https://doi.org/10.1016/j.pce.2009.08.006

27. Figure 11. I like the idea of this Figure as well.

→ Thank you for your encouragement.

[5. Discussion]

28. Please discuss reasons why do you suppose meteotsunamis are most common from March to May.

→ We will discuss possible connection between the following synoptic patterns and meteotsunami occurrences based on previous results (Kim et al., 2016, 2017). According to previous results, the spring season (March to May) in the Korean peninsula has the seasonal characteristics of a migratory anticyclone and an extratropical depression generated in the Tibet and Mongolian plateau passing through the Yellow Sea every three or four days. The spatial distribution of the atmospheric pressure system generally increases the potential atmospheric instability in the Yellow Sea. Atmospheric instability (e.g., pressure jump, low-level jet), which can lead to fluctuations of the sea level, often increase when a cold front in an extratropical depression passes through the Yellow Sea.

- Kim, H., Kim, M.-S., Lee, H.-J., Woo, S.-B., Kim, Y.-K., 2016. Seasonal characteristics and mechanisms of meteo-tsunamis on the west coast of Korean Peninsula. J. Coast. Res. 75, 1147–1151. https://doi.org/10.2112/SI75-230.1

- Kim, H., Kim, M.-S., Kim, Y.-K., Yoo, S.-H., Lee, H.-J., 2017. Numerical weather prediction for mitigating the fatal loss by the meteo-tsunami incidence on the west coast of Korean Peninsula. J. Coast. Res. 79, 119–123. https://doi.org/10.2112/SI79-025.1

29. Please give a point-by-point schematic (perhaps a figure) on how the meteotsunami warning system will be designed: Thus e.g., constant monitoring of air pressure, an automatic warning to personal when air pressure rate of change surpasses a given threshold at one of the beacon stations, careful examination of all air pressure stations, determination of speed and direction as soon as possible, issuing a warning. As a final note, I compliment the authors for the nice research and figures.

→ We are planning the following meteotsunami warning system. The conceptual diagram will be prepared after the final response.

(1) The existing meteotsunami warning system is operated based on the following characteristics (Kim et al., 2021a):

- Observation system is organized with the 89 AWSs (17 AWSs in caution zone and 72 AWSs in waring zone).
- Air pressure disturbances exceeding 1.5 hPa/10 min are regarded as air pressure jumps that can generate the meteotsunamis in the Yellow Sea.
- The meteotsunami alerts are divided into two levels (preliminary caution SMS and propagation SMS).

(2) It is planned to utilized radar image and outer-located harbor tide gauges (AH, EC, WD, DH, and MS) as additional observation system. The meteotsunami alerts will be divided into three levels (preliminary caution SMS, propagation SMS, and warning SMS):

- The temporal and spatial variability of air pressure jumps in the open sea will be tracked with the radar image.
- Favorable conditions (speed and direction) for the generation of extreme meteotsunami events were examined in this study. When sending the 2nd SMS (propagation SMS), it is planned to include warning level (high-moderate-low) based on the speed and direction of air pressure jumps.
- If the peak-to-trough wave height at one tide gauge among the five tide gauges exceeds the meteotsunami limit (20 cm and 4 sigma) and dominant period bands of the waves are less than 30 min, it is suggested to send a warning SMS (3rd SMS: extreme level). The prior two SMSs are sent through proxy-based assessment. The

last warning SMS will be sent based on resonant waves directly observed at each beacon tide gauge after sending the two SMSs.

- Kim, M.-S., Eom, H., You, S.-H., Woo, S.-B., 2021a. Real-time pressure disturbance monitoring system in the Yellow Sea: pilot test during the period of March to April 2018. Nat. Hazards. https://doi.org/10.1007/s11069-020-04245-9

Response to Comments (figures, tables, and equations)

We have significantly revised our results according to your advice. The major revision can be summarized as follows:

(1) Classification of the meteotsunami events

Maximum amplitude → maximum peak-to-trough height
Absolute threshold → combined threshold criterion based on four-sigma value and absolute wave height of 20 cm

(2) Meteotsunami occurrences

Yearly and monthly strength parameter of the meteotsunamis were added using the box-plots. Spatial pattern of the meteotsunamis were estimated based on the number of events per year (2d histogram).

(3) Classification of the extreme meteotsunami events considering only occurrence rate

Average amplitude, meteotsunami occurred-tide gauges of more than six, and occurrence rate of more than 50% → meteotsunami occurred-tide gauges of more than six and occurrence rate of more than 50%

(4) Propagation patterns of air pressure jumps on the meteotsuanmi events

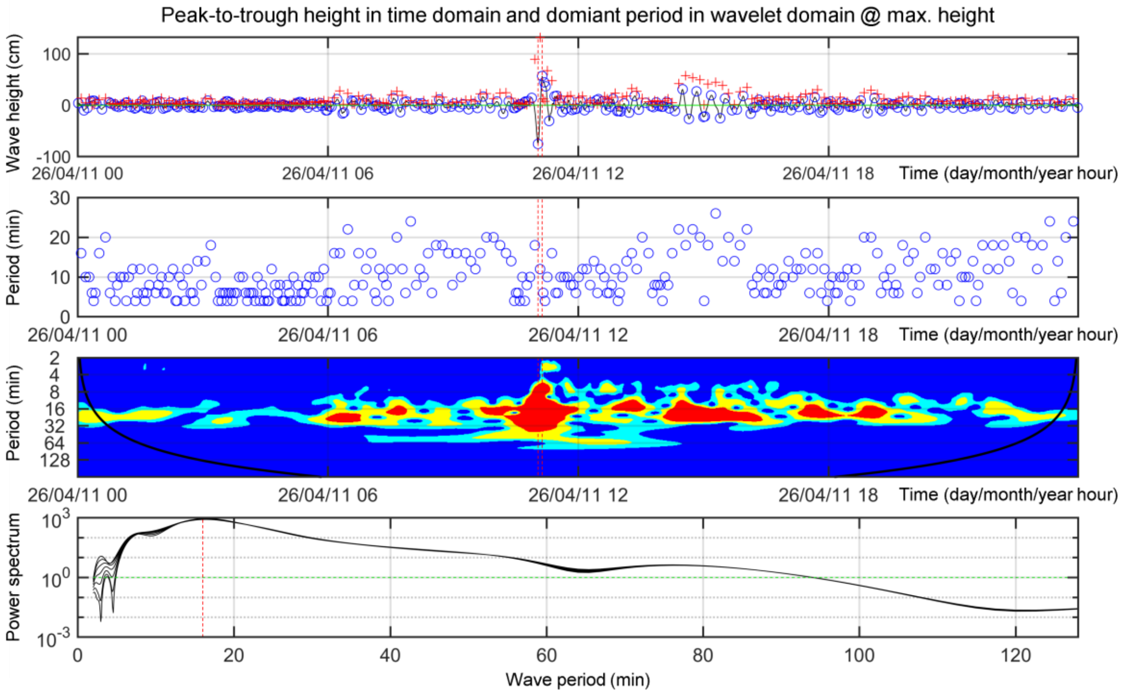
Radar image analysis through visual inspection + linear speed and direction using 2 AWS → radar image analysis through visual inspection + pressure tendency method using 3 AWS (Šepić et al., 2009)

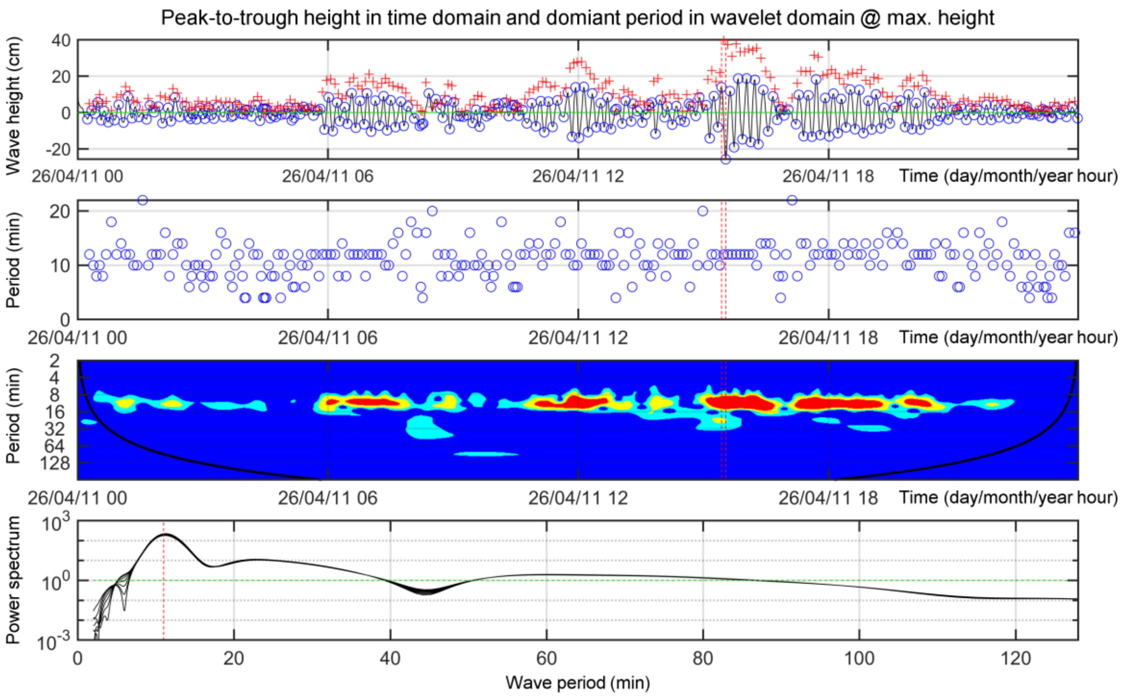
(5) Local amplifications in multiple harbors

Scatter diagram of dominant period of detected waves and maximum wave height was added.

The following figures and tables will be significantly polished to improve the readability after the final response.

[Figure 2: The 3rd and 4th panel in following figure will be added in prior Figure 2] Wave height and dominant period of the meteotsunamis during 26/04/2011 meteotsunami event at the DH (upper) and EC (lower) tide gauge. The 1st panel: peak-to-trough height of the filtered sea level in time domain. The 2nd panel: approximated wave period in the time domain. The 3rd panel: wavelet analysis. The 4th panel: distribution of wavelet power spectrum when the maximum wave height observed.



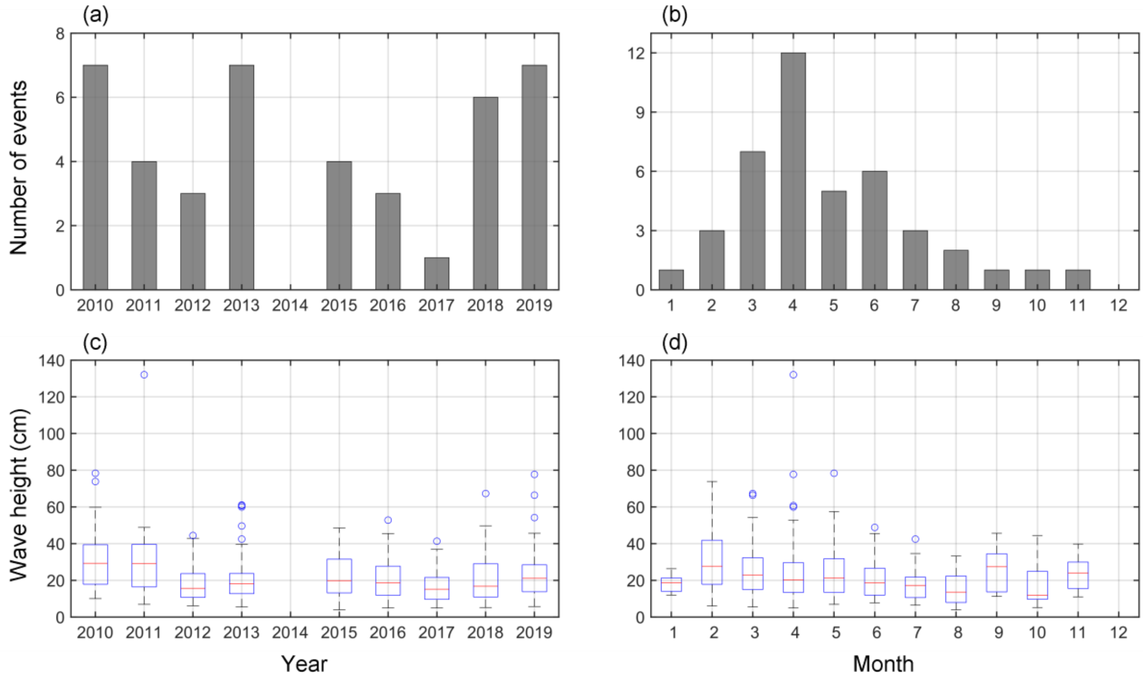


[Table 2: modified] Daily maximum wave height (cm) during 42 meteotsunami events. The reported events since 2010 are denoted by superscript. The strongest intensity of each event are marked by underlined and bold text. The events are indicated as Day/Month/Year.

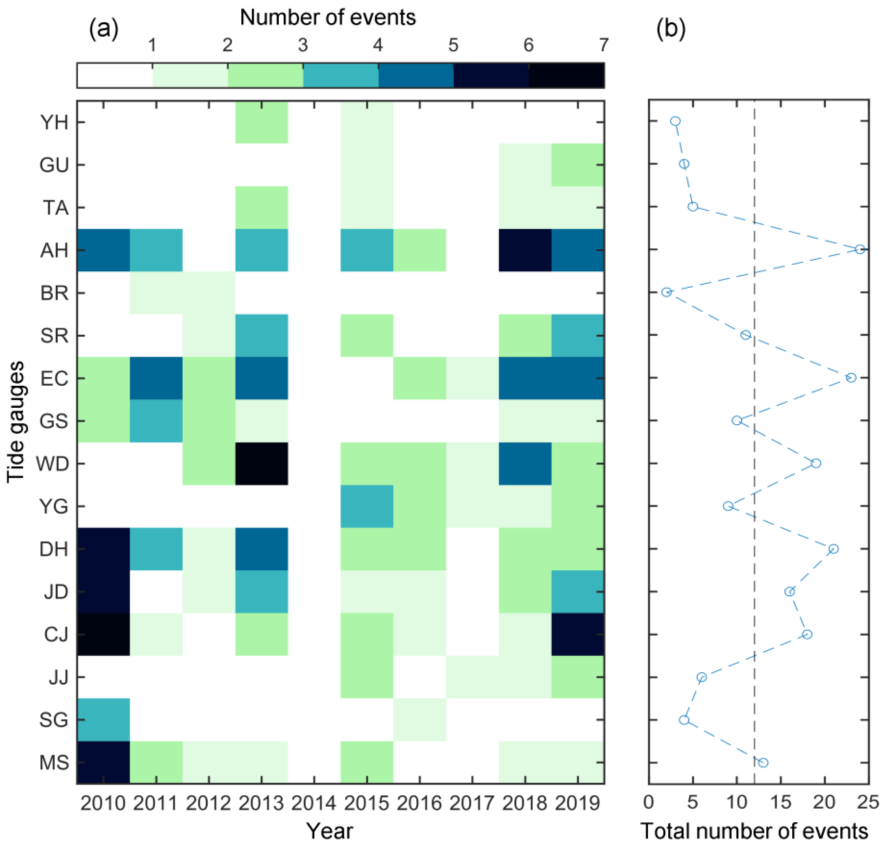
Event date	Lat. A			Lat. B			Lat. C				Lat. D			Lat. E		
	YH	GU	TA	AH	BR	SR	EC	GS	WD	YG	DH	JD	CJ	JJ	SG	MS
10/02/2010	-	-	-	30.6	17.8	-	-	42.2	-	-	43.1	24.6	33.5	-	-	**59.8**
11/02/2010	-	-	-	28.4	11.6	-	-	17.9	-	-	40.9	27.1	49.8	-	53.2	**73.9**
01/03/2010	-	-	-	28.3	-	-	34.9	-	-	-	37.7	24.7	**51.5**	-	-	39.4
03/03/2010	-	-	-	11.4	-	-	15.3	-	-	-	21.6	17.2	21.0	-	**53.3**	37.2
22/03/2010	-	-	-	16.4	-	-	13.9	10.1	-	-	31.5	**36.0**	31.6	-	19.7	24.1
21/04/2010	-	-	-	30.3	-	-	30.2	**33.3**	-	-	24.1	12.2	16.7	-	-	14.9
24/05/2010	-	-	-	-	-	-	19.9	10.5	-	-	**78.4**	28.1	43.1	-	57.5	38.7
26/04/2011[a]	-	-	-	21.3	11.2	-	39.6	18.0	-	-	**132.1**	-	41.8	-	-	46.3
30/04/2011	-	-	-	36.1	20.5	-	41.3	25.9	-	-	**43.1**	16.3	20.2	-	-	38.4
21/05/2011	-	-	-	37.0	-	-	**46.2**	30.6	-	-	24.6	6.9	8.4	-	-	12.0
08/06/2011	-	-	-	36.5	-	-	**48.9**	36.8	-	-	35.6	7.7	11.9	-	27.7	16.4
03/04/2012	9.3	6.1	12.5	13.9	8.3	15.1	13.7	11.7	-	-	27.9	26.7	-	-	42.9	**44.4**
05/07/2012	-	10.1	10.0	-	21.8	29.1	29.7	**31.4**	24.3	-	19.4	8.2	-	-	9.4	17.7
06/07/2012	-	11.3	19.8	-	15.7	14.3	**25.7**	20.5	20.3	-	17.4	10.7	10.7	-	10.5	19.3
20/01/2013	20.8	14.9	**26.3**	23.6	-	12.7	18.2	-	19.4	-	21.7	12.0	13.1	-	15.9	19.2
03/02/2013	6.8	7.8	6.0	15.6	-	14.4	21.2	-	29.4	-	36.0	27.7	23.6	-	22.3	**61.0**
10/03/2013	16.3	–	9.0	–	5.5	13.2	17.5	–	23.7	–	**31.3**	21.6	18.2	–	18.1	29.5
14/04/2013	10.3	15.7	21.5	–	12.1	60.0	**60.7**	19.1	49.6	–	34.2	23.1	21.0	–	–	26.0
29/04/2013	13.3	14.0	15.9	22.3	8.5	25.7	**39.7**	14.8	33.1	–	21.9	8.9	8.9	–	–	11.6
03/07/2013	8.7	6.5	7.5	29.5	–	21.7	17.4	15.7	**42.5**	–	34.6	10.1	15.8	–	10.8	17.1
10/08/2013	**25.8**	–	19.5	–	–	17.0	23.0	20.4	25.1	–	–	7.2	–	–	7.1	5.5
04/04/2015[b]	10.2	16.1	17.7	**48.5**	–	29.5	–	–	20.5	35.3	35.8	20.1	21.7	17.7	29.0	40.1
12/05/2015	–	33.5	13.7	31.4	–	29.0	–	–	32.9	31.6	34.5	18.6	23.6	20.7	**39.2**	19.6
13/06/2015	21.0	18.8	24.1	**38.4**	–	9.8	12.2	–	15.1	22.3	15.2	13.5	9.8	9.3	–	20.9
11/08/2015	5.2	–	4.0	11.2	–	13.6	11.6	4.3	18.2	32.0	17.5	12.8	10.1	31.8	12.1	**33.2**
16/04/2016[b]	5.0	–	6.5	–	5.2	–	11.5	–	11.9	21.1	20.2	25.4	27.6	–	**52.8**	25.8
15/06/2016	12.9	20.5	13.9	**34.4**	11.1	16.3	22.7	–	28.0	30.5	32.6	–	10.9	–	11.8	–
24/06/2016	11.9	11.3	14.7	36.7	–	18.6	26.3	12.8	29.8	44.3	**45.5**	16.5	–	12.4	11.7	22.2
18/04/2017	9.2	15.1	–	–	5.0	15.2	20.7	–	21.8	36.9	–	6.1	–	**41.3**	18.1	11.1
04/03/2018[c]	13.4	–	13.2	33.0	–	–	34.3	45.0	49.7	**67.3**	48.4	25.0	–	–	17.7	34.4
10/04/2018[c]	15.6	–	10.6	**38.2**	–	–	29.6	–	22.2	–	–	8.0	8.6	–	10.5	–
16/05/2018	11.1	13.2	11.2	**32.0**	–	21.2	22.4	–	18.8	–	16.7	7.2	–	–	7.1	9.3
17/05/2018[b]	13.5	24.0	21.2	**35.9**	–	15.5	17.0	15.4	25.6	–	31.7	8.6	15.1	–	10.7	–
09/06/2018	–	–	–	22.2	–	24.6	28.4	–	**32.9**	–	–	11.7	15.0	–	11.5	–
06/10/2018	9.8	–	5.6	17.4	5.2	8.1	10.8	9.7	11.8	13.6	10.4	21.9	25.9	**44.5**	40.0	31.3
20/03/2019[b]	7.9	13.2	14.8	29.1	–	25.5	–	–	–	54.2	**66.4**	28.7	29.8	22.2	25.7	–
30/03/2019	7.6	**35.1**	12.3	21.0	–	11.5	12.0	–	20.8	26.5	29.1	10.3	15.2	11.9	23.6	18.2
07/04/2019	12.8	6.5	5.7	–	–	16.3	18.1	–	14.8	20.2	24.0	22.1	30.3	22.4	30.1	**77.7**
09/04/2019[b]	11.0	19.4	14.7	**31.1**	–	19.5	28.3	–	–	26.4	16.2	15.8	21.6	16.2	23.2	–
06/06/2019	10.7	8.4	8.9	–	–	16.8	24.1	24.8	–	**25.8**	23.3	–	21.2	–	11.8	13.8
07/09/2019	11.2	–	–	**45.6**	–	20.5	31.4	12.8	–	23.4	13.7	34.5	34.3	–	38.8	–
10/11/2019	16.0	29.8	24.3	38.7	–	23.9	29.0	–	30.3	**39.8**	24.1	14.2	–	11.0	11.8	16.0

a: destructive event, b: event revealed by KMA internal reports, c: event captured by KMA real–time monitoring system.

[Figure 6: modified] Temporal meteotsunami occurrences between 2010 and 2019: (a-b) number of events per year and month, (c-d) distribution of wave height according to year and month.



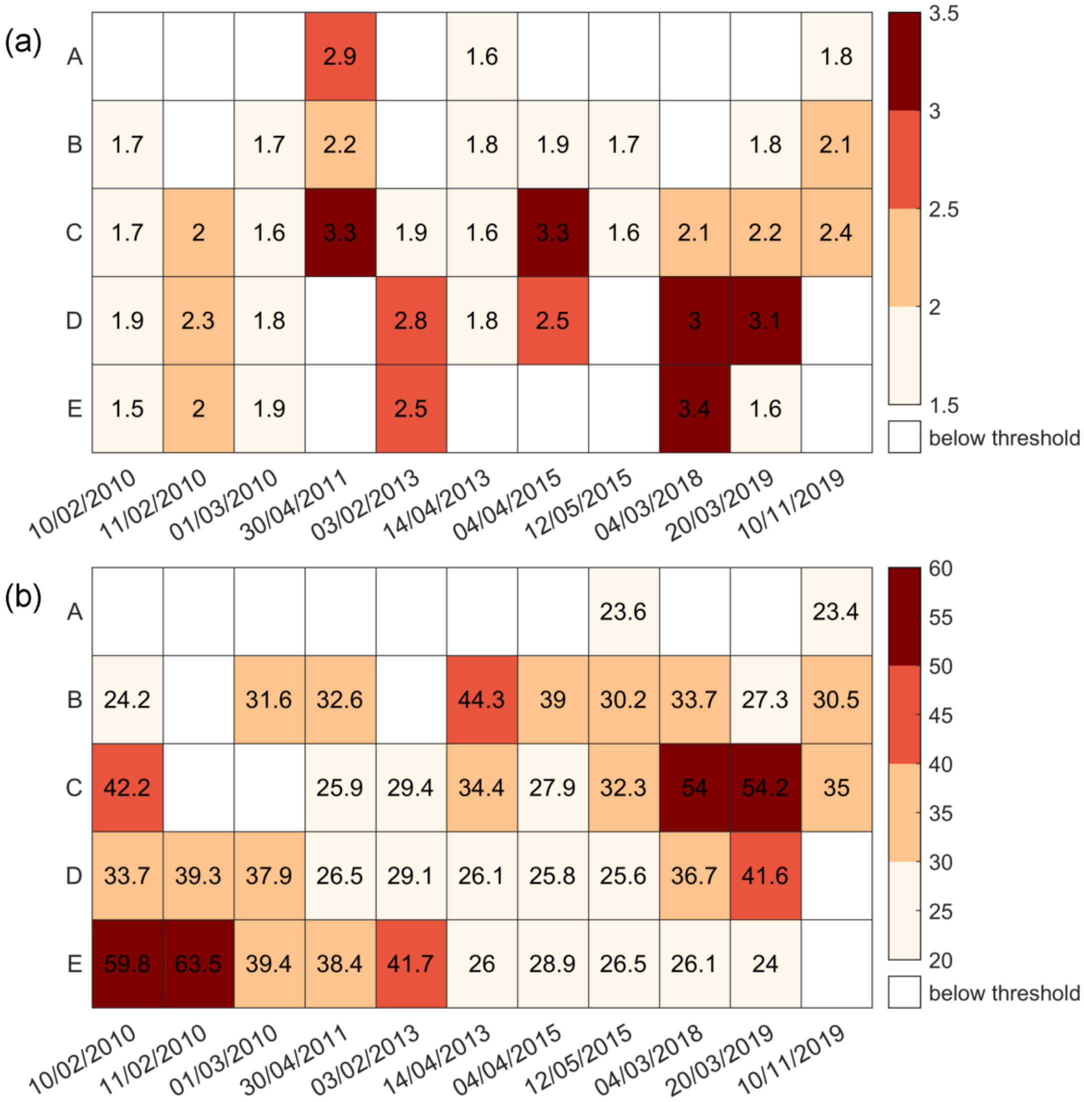
[Figure 7: modified] Spatial meteotsunami occurrences between 2010 and 2019: (a) number of events at each tide gauge per year, (b) total number of events at each tide gauge.



[Table 3: modified] Average intensity and occurrence rate of pressure jump and meteotsunami during extreme meteotsunami events. Extreme meteotsunami event dates are indicated as Day/Month/Year.

Extreme event date	Pressure jump			Meteotsunami		
	Average intensity (hPa/10 min)	Detected AWSs	Occurrence rate (%)	Average intensity (cm)	Detected tide gauges	Occurrence rate (%)
10/02/2010	1.8	28/87	32	36.0	6/7	86
11/02/2010	2.1	28/87	32	37.9	6/8	75
01/03/2010	1.7	46/86	53	36.1	6/6	100
30/04/2011	2.6	40/86	47	30.2	6/8	75
03/02/2013	2.5	29/88	33	22.7	6/12	50
14/04/2013	1.7	27/88	31	29.4	7/12	58
04/04/2015	2.7	49/88	56	26.3	8/13	62
12/05/2015	1.7	12/89	13	27.4	8/12	67
04/03/2018	2.6	32/89	36	34.7	8/11	73
20/03/2019	2.5	47/88	53	28.9	7/11	64
10/11/2019	2.1	34/87	39	23.8	7/13	54

[Figure 8: modified] Heatmap of extreme meteotsunami events: latitude band-averaged intensity of (a) pressure jump and (b) meteotsunami.



[Equation 1-2: added]

The direction θ and speed U of air pressure jumps were estimated using a triangle of AWSs with coordinates (x_1,y_1), (x_2,y_2), and (x_3,y_3). Šepić et al. (2009) suggested that the traveling air pressure jump can be tracked based on the assumption that (i) air pressure jump does not change during its travel over the domain, and (ii) air pressure jump has a constant direction and speed. The propagation pattern is expressed as follows:

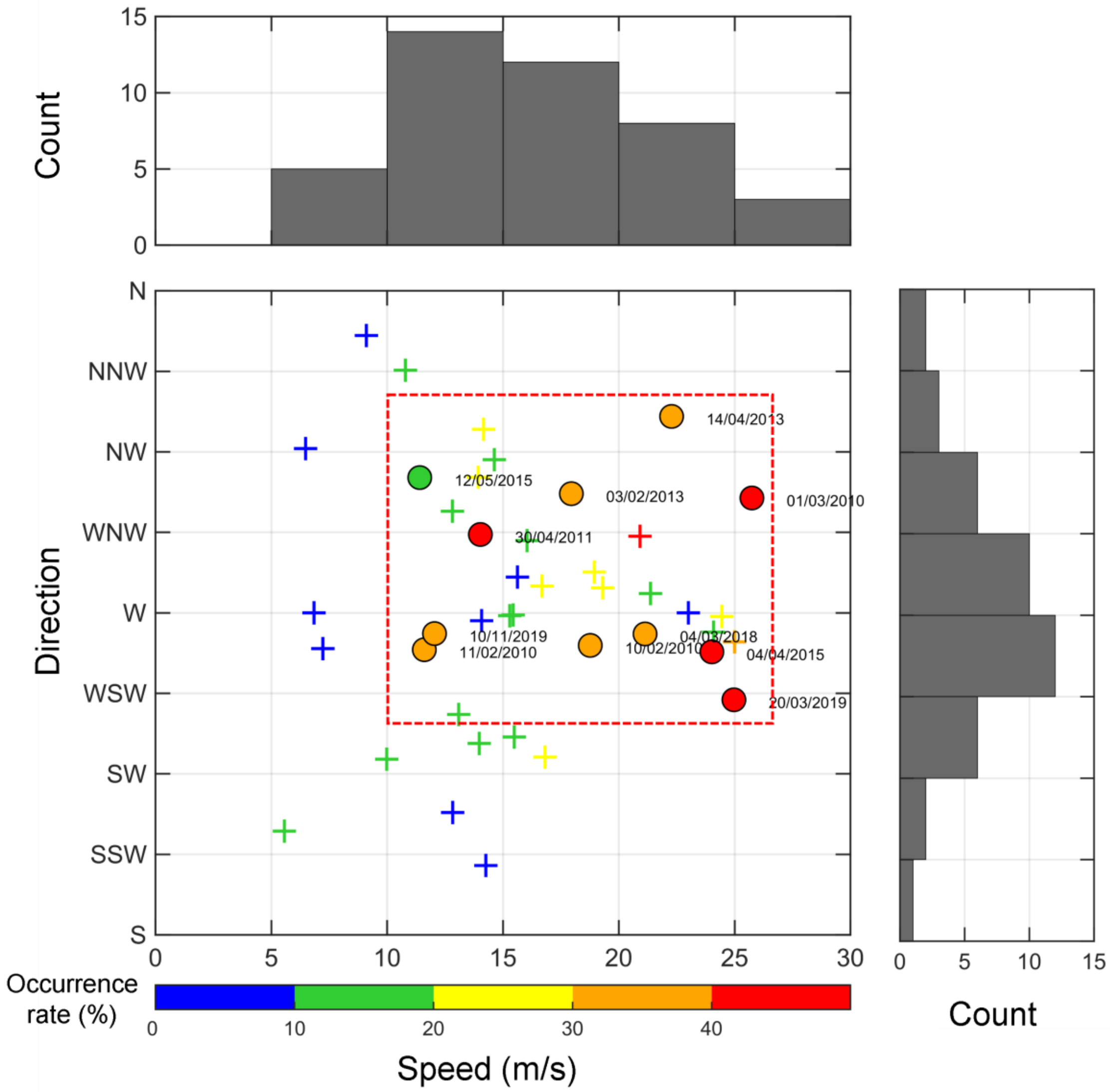
$$tan\theta = a = \frac{\Delta t_{12}\Delta y_{13} - \Delta t_{13}\Delta y_{12}}{\Delta t_{13}\Delta x_{12} - \Delta t_{12}\Delta x_{13}}, \quad (1)$$

$$U = \frac{1}{\Delta t_{12}}\frac{\Delta y_{12} - a\Delta x_{12}}{\sqrt{1+a^2}} = \frac{1}{\Delta t_{13}}\frac{\Delta y_{13} - a\Delta x_{13}}{\sqrt{1+a^2}}, \quad (2)$$

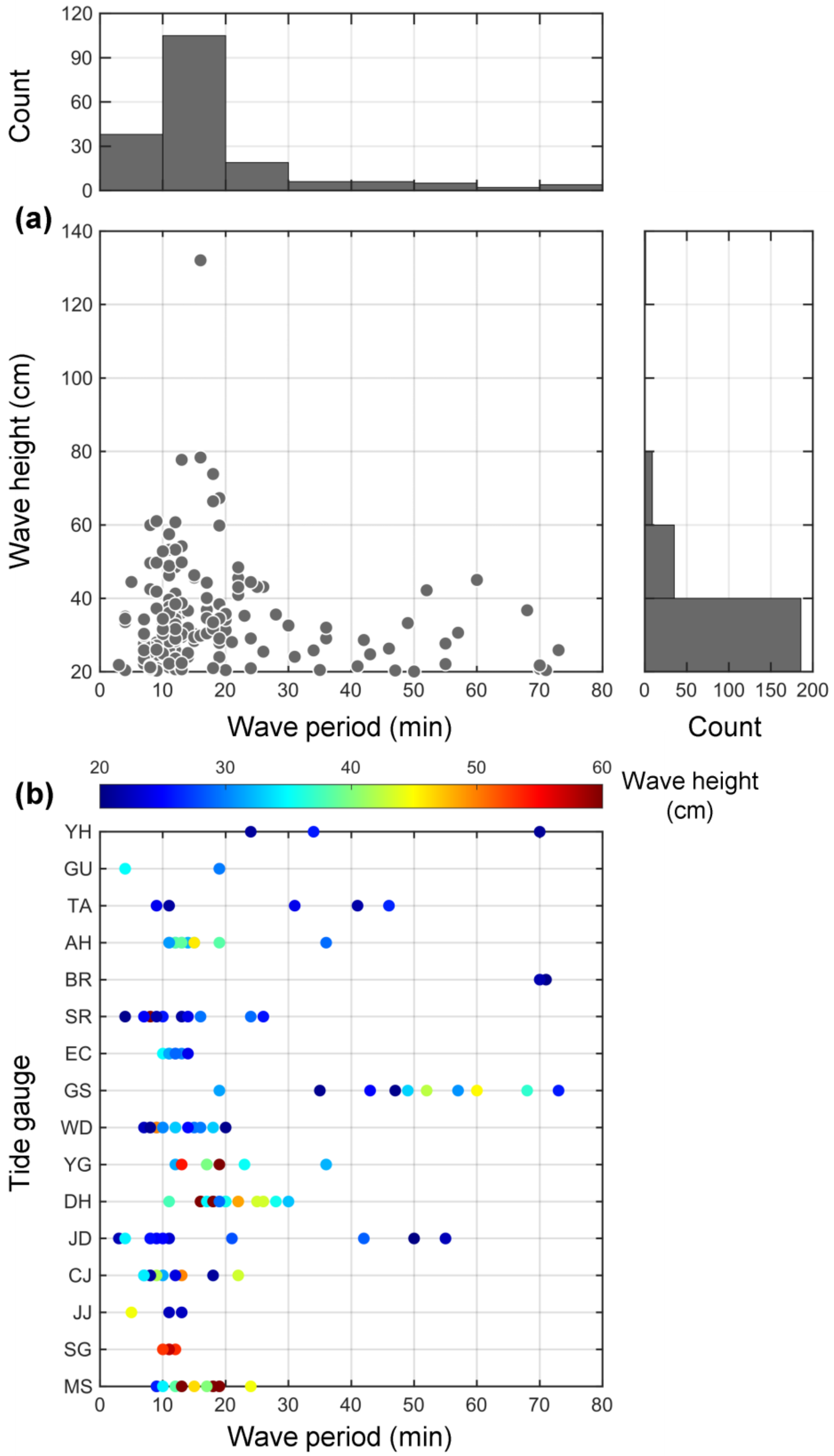
where Δt_{12} and Δt_{13} are the time lags between each AWS; Δx_{12}, Δx_{13}, Δy_{12}, and Δy_{13} are distances between each AWS in the east-west and north-south direction, respectively.

- Šepić, J., Denis, L., Vilibić, I., 2009. Real-time procedure for detection of a meteotsunami within an early tsunami warning system. Phys. Chem. Earth 34, 1023–1031. https://doi.org/10.1016/j.pce.2009.08.006

[Figure 11: modified] Scatter diagram and histograms showing propagation characteristics (speed, direction, and occurrence rate) of air pressure jump on 42 meteotsunami events. Red dashed square encloses dominant range of speed and direction of air pressure jump. Circles mark 11 extreme events classified based on occurrence rate of meteotsunamis. The other 31 events are marked with cross marker. Colors of each marker indicate the occurrence rate of air pressure jumps.



[New Figure] Local amplification of meteotsunamis in semi-closed basins. (a) Scatter diagram of wave period to wave height of the classified 42 meteotsunami events, and histogram. (b) distribution of wave period at each tide gauge.



Other figures and tables will be updated after the final response.

[Figure 1]

[Table 1]

[Figure 3] will be deleted (prior criterion).

[Figure 4] will be modified in the revised manuscript.

[Figure 5] will be modified in the revised manuscript.

[Figure 9] will be modified in the revised manuscript.

[Figure 10] will be modified in the revised manuscript.

[New Figure] indicating the conceptual diagram of the meteotsunami warning system will be added as last figure.

Google Earth satellite images indicating the semi-closed basins in which the tide gauges (red squares) are located will be added as the appendix.