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REMOTE SENSING ANALYSIS OF COLD WATER TEMPORAL AND SPATIAL VARIABILITY IN THE EAST SEA

Suk Yoon[1] and Hyun Yang[123]

Key words: Cold water, remote sensing, satellite data, sea surface temperature.

ABSTRACT

In this study, we monitored temporal and spatial variability in summer cold water events in the East Sea of Korea. We defined cold water as seawater that is ≥ 5°C colder than the surrounding area. When cold water expands or changes in propagation direction, the National Institute of Fisheries Science (NIFS) of Korea issues a cold water upwelling warning to prevent aquafarm damage. To understand cold water effects, we analyzed the causes of continuous and strong cold water events, and propagation thereof, using satellite and *in situ* data for summer to autumn in the period 2011–2019. To investigate the cold water life cycle, we used satellite-derived sea surface temperature (SST) data collected by the National Oceanic and Atmospheric Administration (NOAA) satellites Aqua and Terra, as well as *in situ* ocean surface current and wind data. Our results showed that cold water zones tend to expand in early summer and contract in late summer. The cycle of cold water expansion and contraction was repeated several times due to cold water events.

I. INTRODUCTION

Cold water events, i.e., when the water temperature is ≥ 5°C lower than the surrounding area, occur yearly in summer off the eastern coast of South Korea. The National Institute of Fisheries Science (NIFS) of Korea issues cold water warnings when cold water zones expand or change direction, or when the water temperature decreases by ≥ 5°C. Alerts are issued when the water temperature decreases by ≥ 10°C.

The influence of the North Korean Cold Water (NKCW), which has relatively low salinity and high dissolved oxygen content, is one cause of such cold water events (Kim and Kim, 1983; Lee and Na, 1985). Cold water was reported when southwesterly winds of 3 or 4 m/s persisted for at least 7 and 3 days, respectively; however, the main cause of cold water events is unseasonably low water temperatures throughout the entire sea water mass (Suh et al., 2001).

Upwelling cold water creates conditions favorable for fishing ground formation, where low-temperature bottom water containing abundant nutrients rises and promotes plankton reproduction (Knauss, 1998; Yoo and Park, 2009). However, cold water upwelling off the eastern coast of South Korea also kills fish and algae through abrupt daily changes in water temperature (3–5°C) in coastal fish farms (Han et al., 1995). Rapid changes in water temperature can alter physiological conditions, disrupt homeostasis, and affect life activities in fish (Chang et al., 1999). Cold water events cause frequent ship accidents due to sea fog (Han et al., 1995). For these reasons, the spatiotemporal distribution of cold water events off the eastern coast of Korea has been analyzed using satellite and measurement data (Suh et al., 2001). The correlation between cold water events and chlorophyll distribution has also been examined (Yoo and Park, 2009). However, few studies have analyzed the effects of cold water events on environmental conditions (Yoon and Yang, 2016). A 10-year survey of cold water events, including their causes and movement, reported that NIFS issued the most warnings and alerts in 2013. In the present study, we analyzed the locations, time periods, and effects of cold water events from 2011 to 2019. The results of this study on cold water events should facilitate the management of fishing grounds and improve maritime safety.

II. STUDY AREA AND DATA

The conditions of the East Sea exhibits are complex; its southern half is affected by the Tsushima Current, whereas its northern half is affected by cold currents. In many parts of the East Sea, such as the coastal waters off Pohang, strong cold water events occur in summer every year.

Sea surface temperature (SST) data, which are important for

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Table 1. Satellite and *in situ* data used in this study. AVHRR, Advanced Very High Resolution Radiometer; KMA, Korea Meteorological Administration; KOSC, Korea Ocean Satellite Center; NOAA, National Oceanic and Atmospheric Administration; MODIS, Moderate Resolution Imaging Spectroradiometer; SST, sea surface temperature.

	Satellite SST data		Buoy data			
	AVHRR/NOAA-18, 19	MODIS/ Aqua, Terra	Buoy name	Ullungdo	Donghae	Pohang
Spatial resolution	1 km		Latitude (N)	36.35°N	35.34°N	37.45°N
Temporal resolution per day	1–2 times					
Band	Thermal		Longitude (E)	36.35°N	129.84°E	131.11°E
Orbit	Polar					
Acquisition time	2 days					
Source	KOSC		Source	KMA		

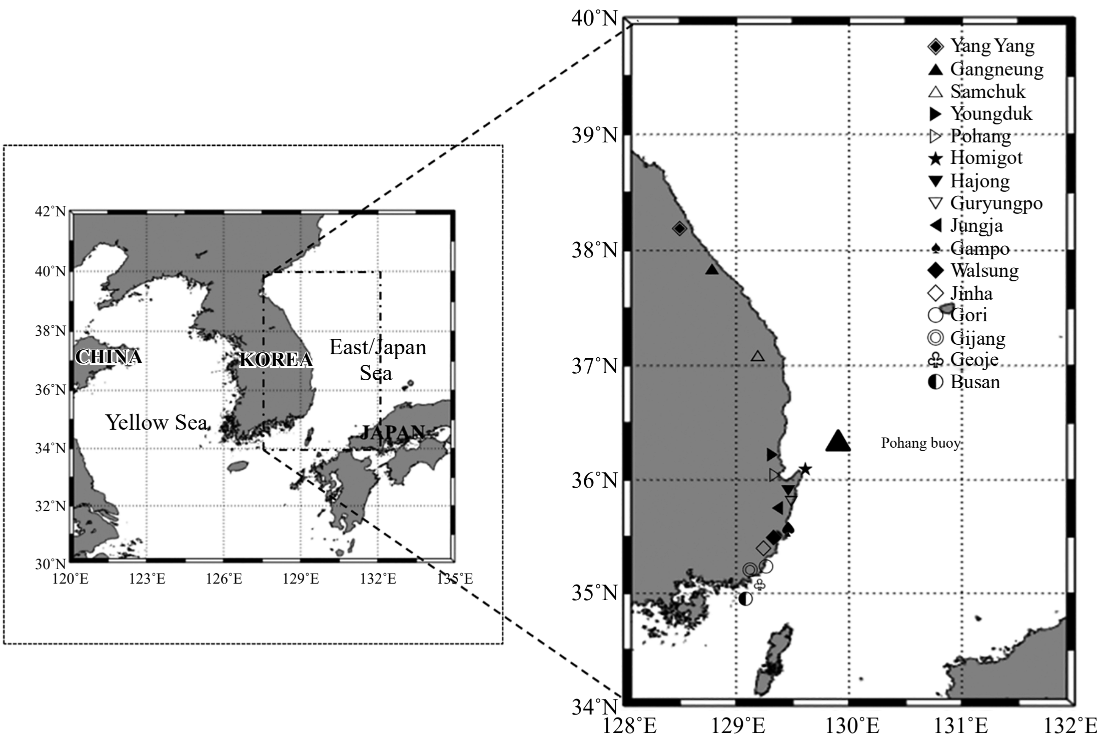

Fig. 1. Study area in the East Sea.

analyzing cold water spatiotemporal distribution, were compared with buoy data for Pohang (Figure 1) to verify our results. The East Korea Warm Current (EKWC) flows along the eastern coast of the Korean Peninsula. Coastal upwelling occurs periodically in the southern coastal waters of the East Sea (Kim et al., 2008), mainly due to southward movement of the NKCW, upwelling, or typhoons (Kim and Kim, 1983; Yoo and Park, 2009). Off the Korean Peninsula, cold waters occur mainly along the east coast, and is seen off the coast of Gijang, Ulsan, and Gampo from late June to August. We analyzed the spatiotemporal distribution and movement of cold water zones using satellite and *in situ* buoy data, mainly collected off the eastern coast (Figure 1).

III. METHODS

We analyzed satellite and measured environmental data for summer cold water events in from the period 2011 to 2019. We analyzed the spatiotemporal movement of cold water zones using SST data obtained from the Advanced Very High Resolution Radiometer (AVHRR), National Oceanic and Atmospheric Administration (NOAA), and Moderate Resolution Imaging Spectroradiometer (MODIS) satellites Aqua and Terra (Salomonson et al., 1990). We also analyzed Archiving,

Table 2. Cold water alert (O) and warning (V) events reported by the National Institute of Fisheries Science (NIFS) from June 27 to August 12, 2013.

Location	Latitude (N)	Longitude (E)	June 29	July 9	July 15–16	July 24	July 29	August 11	August 15
Homigot	36.075°	129.54°	–	O	O	V	–	–	–
Yongdeok	36.41°	129.44°	V	O	O	V	–	–	–
Pohang	36.01°	129.40°	–	O	O	V	V	–	–
Uljin	36.80°	129.27°	V	–	–	V	–	–	–
Gijang	35.27°	129.25°	–	O	O	V	V	–	–
Gampo	35.80°	129.50°	–	O	O	V	V	–	–
Ullgi	35.49°	129.44°	–	O	V	V	V	–	–
Busan	35.19°	129.25°	–	–	–	V	V	–	–
Geoje	34.84°	128.74°	–	–	O	–	–	–	–
Total events (alert/warning) 12/16			0/2	6/0	6/1	0/8	0/5	0/0	0/0

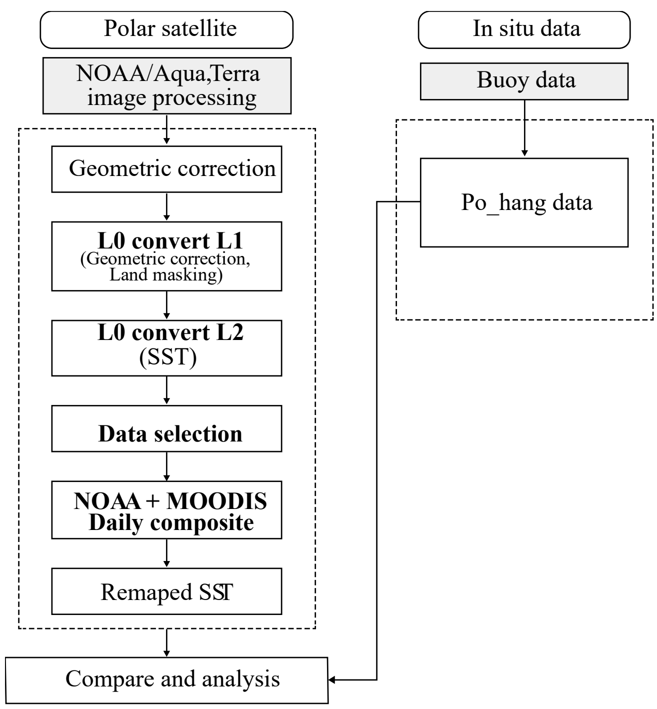

Fig. 2. Satellite image processing procedure.

Validation and Interpretation of Satellite Oceanographic (AVISO) geostrophic current (Cummins and Freeland, 2007) and wind direction and speed data, to determine their influence on cold water movement. Buoy data were used to verify satellite SST values and analyze environmental effects. Figure 2 shows the satellite image processing procedure, and Table 1 describes the data used in this study.

IV. RESULTS

4.1 Spatiotemporal changes in strong cold water events in 2013

To observe the distribution and movement of cold water zones, we analyzed SST image data from late June to mid-August in 2013 (Figure 3). To verify the accuracy of the cold water distribution shown in Table 2, we compared these results with warnings and alerts issued by the NIFS during the same period, and found good agreement.

On July 16, cold water alerts were issued for Gampo, Gijang, Yongdeok, Pohang, Homigot, and Geoje. The analysis image for this date (Figure 3A1) shows that cold water zones were diminished off the central coast of the East Sea but remained large on the southern coast. Cold water zones initially stretched from the central part of the East Sea (near Dokdo) to the northern part, and their width decreased to approximately 30 km during this period. On July 24, cold water warnings were issued for Gampo, Ulgi, Gijang, Oryukdo, Pohang, Homigot, and Uljin. Figure 3B1 shows that the cold water zones became narrower in width on this date. On July 29, cold water warnings were issued for Gampo, Ulgi, Gijang, Oryukdo, and Pohang. Figure 3C1 shows that weak cold waters remained off the southern coast of the East Sea, and were not detected in coastal areas such as Uljin, Yongdeok, and Homigot. The occurrence of cold water events was confirmed through analysis of satellite-based SST images.

4.2 Long-term spatiotemporal changes in cold water zones

Next, we analyzed cold water alert and warning events from 2011 to 2019 (Table 3). Cold water alerts and warnings, which began in 2013, were issued in July and August of 2013, June and July of 2014 and 2016, July and August of 2017, June and

Table 3. Cold water alerts and warning events reported by the NIFS from 2011 to 2019.

Year	Alert total	Warning total	May	June	July	August
			Alert/warning			
2011	–	–	–	–	–	–
2012	–	–	–	–	–	–
2013	12	16	–	–	0/2	12/14
2014	0	20	–	0/3	0/17	–
2015	0	1	–	–	–	–
2016	0	6	–	0/1	0/5	–
2017	0	10	–	–	0/8	0/4
2018	2	13	–	1/11	–	1/2
2019	0	19	0/10	0/4	0/3	0/2

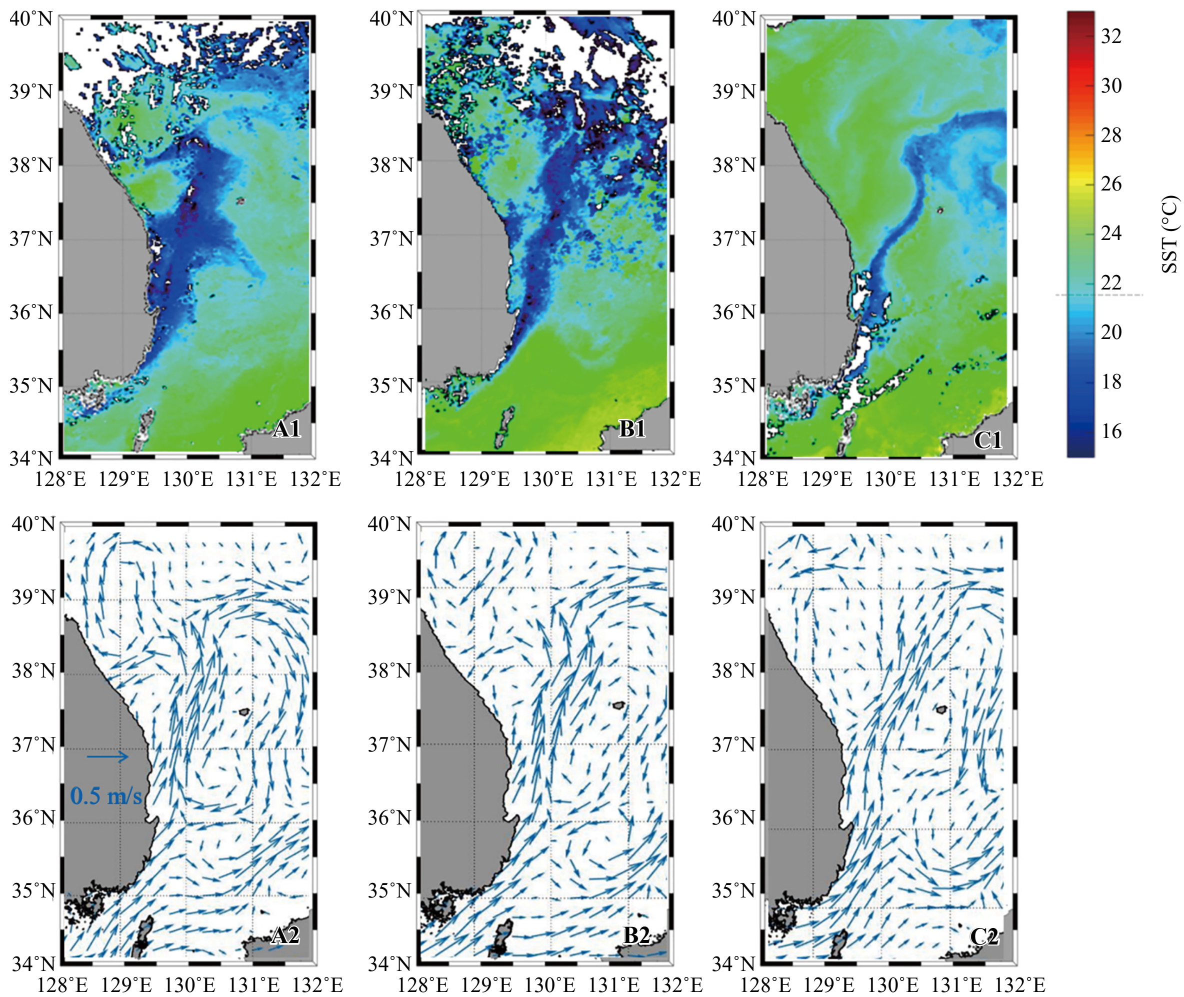

Fig. 3. Daily composite sea surface temperature (SST) images for (A1) July 16, (B1) July 24, (C1) and July 29, 2013, and Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) geotropic current vector images for (A2) July 16, (B2) July 24, (C2) and July 29, 2013.

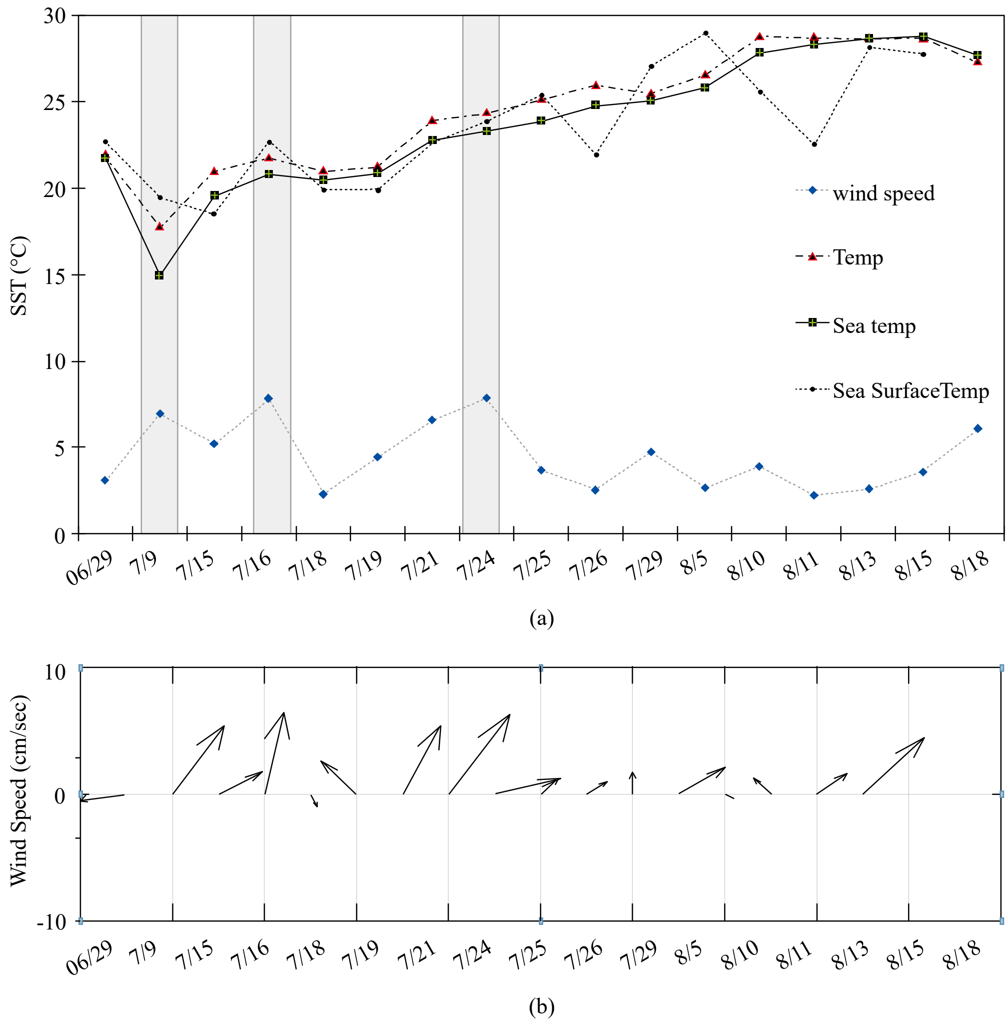

Fig. 4. (a) Comparison of SST (°C) and Pohang buoy data. (b) Wind direction and speed (cm/s) at the Pohang buoy. SST data (°C) were obtained from satellite images

August of 2018, and May of 2019. Further details are provided in Appendix 1.

Cold water areas appear to have expanded over time, being limited to 34–36°N in 2013, versus 34–36°N and ~38°N in 2014, 35°N and 37°N in 2016, 35.5–36.5°N in 2017, 35.5–36.5°N and 37–38°N in 2018, and 35–36.5°N and 37–38°N in 2019. Thus, cold waters have continuously occurred in the central and northern areas of the East Sea during recent years.

4.3 Time series comparison of SST and buoy data for 2013

The analysis results of *in situ* Pohang buoy data and satellite-based SST data are compared in Figure 4. The wind speed buoy data showed that strong cold waters were present on specific dates (Figure 4A),. The southwesterly wind speeds were > 8, < 3, and 8 m/s on July 9, 15, and 16, respectively, and steadily decreased thereafter. From July 21, the wind speed increased again to 6 m/s, and southwesterly winds of > 7 m/s persisted until July 24.

The water temperature was 23°C on June 29, 21°C on July 9, and 23°C from July 15 to 29 (Figure 4A). High water temperatures (> 28°C) were observed from August 5 to the end of the month. Air temperature showed the same pattern as the water temperature, but was 1–2°C higher than water temperature. According to satellite data, the SST was approximately 23°C from late June to early July, decreasing to 18°C on July 15, and then increasing to 20–21°C in the period July 16–19. Water temperature rose to 22°C from July 21 to 24. SST remained high (25°C) from July 25 to 29.

Figure 4B shows that southwesterly winds were dominant. Time series analysis results for the Pohang buoy data revealed strong southerly and southwesterly winds, at > 6–8 m/s on July 9, 15, and 16, when cold water events occurred. Thus, strong winds coincided with the occurrence of significant cold water events. Cold water zones exhibited low SST values, ranging from 18°C to 19°C, and satellite images (Figure 3) showed that cold water zones expanded when strong winds persisted for several days. Strong southwesterly winds (> 7 m/s) lasted until mid-July. Wind speeds decreased to < 5 m/s from late July, after which water and air temperatures continuously increased. From August 10, high air and water temperatures were indicated by both observation and satellite data. Although some low water temperatures were observed, cold water zones generally disappeared from late July onwards.

V. DISCUSSION AND CONCLUSION

Cold water events off the east coast of South Korea due to upwelling damage coastal fish farms. Strong cold water events occurred continuously throughout summer 2013. We used SST data provided by the Ocean Satellite Center of the Korea Institute of Ocean Science and Technology, and buoy data including air temperature, water temperature, and wind speed provided by the KMA, to analyze the distribution and movement of cold water zones. First, we compared the analyzed the satellite image data according to the cold water alerts and warnings provided by the NIFS to accurately identify cold water zones, and then confirmed the spatiotemporal distribution patterns of cold water zones through SST satellite image analysis.

Next, we analyzed the influence of ocean surface currents on cold water distribution. The expansion and movement of cold water zones were affected by the magnitude and direction of ocean surface currents, as shown in cold water images. Strong movement of ocean currents occurred around Ulleungdo. Satellite images showed that cold water zones that appeared off the southern coast of the East Sea moved to the northern part of the East Sea along the EKWC, and that cold water zones expanded according to the patterns of strong coastal currents. These findings suggest that it is possible to predict the movement and direction of cold water zones by analyzing ocean surface current flow.

Time series analysis of SST and buoy data showed that strong cold water events were associated with strong southerly and southwesterly winds of 5–8 m/s, and that cold waters expanded for as long as these strong winds persisted. The wind speed decreased to < 5 m/s when cold water zones dissipated. The direction and intensity of wind speed influenced the occurrence of cold water events. Our analysis of temporal changes in cold water distribution showed that cold water events advanced seasonally from July–August to May–June over a long period. Cold water zones expanded from the central East Sea to the northern East Sea in recent years.

The results of this study pertaining to cold water zone movement may improve the management of resources and fishing grounds, which could prevent damage to aquafarms and the fishing industry. Future studies should aim to predict cold water phenomena, and the effects of environmental changes on their occurrence and distribution.

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APPENDIX 1

Table S1. Cold water alert (O) and warning (V) events reported by the National Institute of Fisheries Science (NIFS) from June 27 to August 12, 2014.

Location	Lat. (N)	Lon. (E)	June 27	July 1	July 10	July 29	July 30	August 12
Gangneung	37.75°	128.38°	–	–	–	V	V	Stop V
Samcheok	37.44°	129.18°	V	Stop V	–	V	V	Stop V
Uljin	36.80°	129.27°	V	Stop V	–	–	V	Stop V
Yongdeok	36.41°	129.44°	V	Stop V	–	–	–	Stop V
Homigot	36.075°	129.54°	–	–	–	–	V	Stop V
Pohang	36.01°	129.40°	–	–	–	–	V	Stop V
Gampo	35.80°	129.50°	–	–	V	–	V	–
Ullgi	35.49°	129.44°	–	–	V	–	V	–
Gijang	35.27°	129.25°	–	–	V	–	V	–
Busan	35.19°	129.25°	–	–	V	–	V	–
Geoje	34.84°	128.74°	–	–	V		V	–
2014 Total events (alert/warning) 0/20			0/3 Stop V (3)	0/0	0/5	0/2	0/10	0/0 Stop V (6)

Table S2. Cold water alert (O) and warning (V) events reported by the NIFS from July 11 to August 1, 2016.

Location	Lat. (N)	Lon. (E)	July 11	July 16	June 8	July 12	July 27	August 1
Samcheok	37.44°	129.18°	V	Stop V	V	Stop V	–	–
Jinha	35.83°	129.34°	–	–	–	–	V	Stop V
Ullgi	35.49°	129.44°	–	–	–	–	V	Stop V
Gori	35.31°	129.13°	–	–	–	–	V	Stop V
Gijang	35.27°	129.25°	–	–	–	–	V	Stop V
2016 Total events (alert/warning) 0/6			0/1	0/0 Stop V (1)	0/1	0/0 Stop V (1)	0/4	0/0 Stop V (4)

Table S3. Cold water alert (O) and warning (V) events reported by the NIFS from June 11 to August 27, 2017.

Location	Lat. (N)	Lon. (E)	June 11	June 27	August 25	August 26	August 27
Yongdeok	36.41°	129.44°	V	Stop V	–	–	–
Guryungpo	35.98°	129.55°	V	Stop V	–	–	–
Gijang	35.27°	129.25°	–	–	V	V	Stop V
Geoje	34.84°	128.74°	–	–	V	V	Stop V
Jinha	35.83	129.34	V	Stop V	V	–	–
Walsung	35.71	129.48	V	Stop V	–	–	–
Hajong	35.63	129.56	V	Stop V	–	–	–
Jungja	35.48	129.43	V	Stop V	–	–	–
2017 Total events (alert/warning) 0/10			0/6	0/0 Stop V (2)	0/2	0/2	0/0 Stop V (2)

Table S4. Cold water alert (O) and warning (V) events reported by the NIFS from June 14 to September 3, 2018.

Location	Lat. (N)	Lon. (E)	June 14	June 18	June 27	July 4	August 24	August 26	September 1	September 3
Yang Yang	38.09°	128.66°	V	–	–	–	–	–	–	–
Gangneung	37.75°	128.38°	V	–	–	–	–	–	–	–
Samcheok	37.44°	129.18°	V	O	–	–	–	–	–	–
Yongdeok	36.41°	129.44°	–	–	V	Stop V	–	–	–	–
Pohang	36.01°	129.40°	–	–	V	–	V	–	Stop V	–
Guryungpo	35.98°	129.55°	–	–	V	–	–	–	–	–
Jinha	35.83°	129.34°	–	–	V	Stop V	–	–	–	–
Walsung	35.71°	129.48°	–	–	V	Stop V	–	–	–	–
Hajong	35.63°	129.56°	–	–	V	Stop V	–	–	–	–
Jungja	35.48°	129.43°	–	–	V	Stop V	–	–	–	–
Gori	35.31°	129.13°	–	–	V	Stop V	–	–	–	–
Gijang	35.27°	129.25°	–	–	V	Stop V	–	–	–	Stop V
Busan	35.19°	129.25°	–	–	–	–	V	O	–	–
2018 Total events (alert/warning) 2/8			0/3	1/0	0/9	0/0	0/2	1/0	0/0 Stop V (1)	0/0 Stop V (1)

Table S5. Cold water alert (O) and warning (V) events reported by the NIFS from May 20 to August 14, 2019.

Location	Lat. (N)	Lon. (E)	May 20	May 22	May 28	June 10	June 14	June 24	June 26	July 4	July 29	July 31	August 6	August 12	August 14
Yang Yang	38.09°	128.66°	V	Stop V	V	Stop V	V	Stop V	–	–	–	–	–	–	–
Gangneun	37.75°	128.38°	–	–	–	–	–	–	V	Stop V	–	–	–	–	–
Samcheok	37.44°	129.18°	V	Stop V	V	Stop V	V	Stop V	V	–	–	–	–	–	\–
Center of Dondhe	36.75°	129.483°	–	–	–	–	–	–	–	V	–	–	–	–	–
Yongdeok	36.41°	129.44°	V	–	–	–	–	–	–	–	–	V	–	–	–
Pohang	36.01°	129.40°	V	–	–	–	–	–	V	–	V	–	Stop V	V	Stop V
Gijang	35.27°	129.25°	–	–	–	–	–	–	–	–	–	–	Stop V	V	Stop V
2019 Total events (alert/warning) 0/16			0/4	0/0	0/2	0/0	0/2	0/0	0/3	0/1	0/1	0/1	0/0	0/2	0/0