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Abstract

This study examines the long-term wave data observed along the coastline of the Sea of Japan. The focus was mainly placed on the wave climate at Wajima Port, which is located on the outer coast of the Noto Peninsula in Ishikawa Prefecture. The wave characteristics at Wajima were first compared with those at Kanazawa, which is located relatively close (90 km) to Wajima. The wave climate at Wajima and Kanazawa indicated similar features in terms of wave height and period. The influence of Noto Peninsula was substantial only in terms of the incoming wave direction. While neither a statistically significant trend nor jump was found for the long-term variation of annual wave height at these sites, an increasing trend and an abrupt jump around 1990 have been detected in the long-term variation of wave periods at Kanazawa. The wave periods in July have significantly increased at both Wajima and Kanazawa. The wave properties were then compared with those at Rumoi and Hamada Port, which are respectively located 830 km and 510 km away from Wajima. Over a long stretch of the Sea of Japan coast covering Rumoi, Wajima, Kanazawa, and Hamada, wave climate indicated similar and significant seasonal changes. The difference in the properties of significant waves around these four sites was about 10 %. Significant wave height and period correlated very well with second order polynomials at each site. In contrast, wave directions along the coastline indicated significant differences. At Rumoi and Hamada, neither significant trends nor jumps in long-term annual wave periods were detected. The statistical test revealed that the long-term increasing trends and abrupt jumps of wave period in summer were intrinsic to the waves at Wajima and Kanazawa, located in the central coastal areas adjacent to the Sea of Japan.

Key Words: long-term variation, NOWPHAS dataset, regional comparison, Sea of Japan, wave climate

I. Introduction

More than 2,300 km coastline on the Japanese archipelago is faced to the Sea of Japan, which is a marginal sea of the western Pacific Ocean between the Asian mainland, the Japanese archipelago and Sakhalin. Recently, there has been a wide variety of coastal problems along the coastline such as severe damages and inundation induced by violent winter waves and swells, retreat of shoreline, deposition of sediment in ports, destruction of coastal ecosystems, and others. Furthermore, the future climate change is expected to place significant influence on wave characteristics such as wave height, period and incoming direction that can

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induce further adverse impact on coastal areas (Komar *et al.*, 2009; Mori *et al.*, 2009). In order to cope with these issues a deep physical understanding on the regional wave characteristics is essentially important as basic engineering data.

The wave observation along the Sea of Japan coast was started since the early 1970s by the NOWPHAS (Nationwide Ocean Wave information network for Ports and HArborS) project by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (Nagai *et al.*, 1994). From around 1980, JMA (Japan Meteorological Agency) has also started the wave measurements on the Sea of Japan coast. On the basis of these measurements several studies have been conducted on the wave climate along the Sea of Japan coast. Kobune *et al.* (1988) examined the NOWPHAS data during 1970 to 1984 all over Japan. Their study included 6 sites along the Sea of Japan coast (Rumoi, Sedana, Fukaura, Hazikizaki, Wajima and Hamada). They showed that the seasonal variation of significant wave height and period is remarkable along the Sea of Japan coast. The monthly-averaged significant wave height is largest in winter around 2 m and smallest in summer around 0.5 m. The annual mean wave height is slightly larger than 1 m. The corresponding wave period is around 7 s in winter and around 5 s in summer. The annual mean is 5 to 6 s. The correlation between the wave height and period is strong along the Sea of Japan coast compared with that in the coasts facing to the Pacific Ocean. The offshore wave slope approaches 0.03 to 0.04 as the wave height becomes large. By the end of the 20th century, Nagai (1997) summarized the observed wave characteristics obtained from the NOWPHAS system over 25 years. The analysis included 8 sites (Rumoi, Fukaura, Sakata, Wajima, Kanazawa, Tottori, Hamada and Ainoshima) on the Sea of Japan coast. Shimizu *et al.* (2006) extended the analysis over 35 years in which waves at Rumoi, Sakata, Kanazawa and Hamada sites were examined. The study indicated that there was no significant trend in the annually-averaged significant wave height until 2004. Yamaguchi *et al.* (2007) examined the wave data obtained by the NOWPHAS and JMA over more than two decades along the whole Japanese Coast. Their analysis included 13 sites on the Sea of Japan side (Rumoi, Sedana, Matsumae, Fukaura, Atsumi, Wajima, Kanazawa, Kyougamisaki, Tottori, Kashima, Hamada, Ainoshima and Fukuejima). They examined the existence of jumps and trends for significant wave height and period. On the Sea of Japan side, an increasing jump was observed for the significant wave height and period in summer. An increasing trend in wave period was also observed in summer. Mase *et al.* (2009) investigated the long-term variability of annual large waves (maximum and top three or five average) at 9 sites along the Sea of Japan coast (Rumoi, Sedana, Fukaura, Sakata, Wajima, Kanazawa, Fukui, Tottori and Hamada). They pointed out that the height of episodic waves generated by winter monsoon pattern has increased in these 30 years. Seki *et al.* (2011, 2012) examined the NOWPHAS measurements over 40 years along the whole Japanese Coast. On the Sea of Japan side, wave characteristics at 9 sites (Rumoi, Fukaura, Sakata, Wajima, Kanazawa, Tottori, Hamada, Ainoshima and Ioujima) were investigated. Significant wave height and period in spring and summer indicated an increasing trend at several locations along the Sea of Japan coast.

Located in the middle of the Sea of Japan coast, Ishikawa Prefecture has also been suffering from various coastal problems, including the progress of severe coastal erosion, frequent occurrence of rip current accidents, reduction of coastal habitats, and others. In order to obtain a deep physical understanding of the variation in wave properties at Ishikawa Prefecture, the authors have recently investigated the long-term variation of wave characteristics at Kanazawa Port during 1971 to 2012 (Nguyen and Yuhi, 2015). The results indicated that the annually-mean wave period abruptly increased around 1990. The increase of monthly-averaged wave period was most significant in July. In this study, the authors extend the previous analysis and further examine the long-term wave characteristics along the coastline of Ishikawa Prefecture. First the wave characteristics observed at Wajima is examined and compared with that at Kanazawa (Nguyen and Yuhi, 2015). Based on the local comparison of wave climate the influence of Noto Peninsula is discussed. Secondly, the wave climate at Wajima is compared with that of Rumoi and Hamada that are located far (830 and 510 km) from Wajima on the northern and southern part of the Sea of Japan. On the basis of the comparison of regional wave characteristics along the Sea of Japan coast, intrinsic features of wave climate on the coastline of Ishikawa Prefecture are explored.

II. Datasets and Methods

1) Field Site and Datasets

NOWPHAS is the wave observation network and analysis system around the Japanese coastal area. Along the Sea of Japan coast, the wave characteristics have been measured from the early 1970s by this project, and at present the number of NOWPHAS observation sites has reached more than 20. Among them, the wave analysis in this study was conducted at the following four sites: Rumoi Port, Wajima Port, Kanazawa Port and Hamada Port. The locations of the stations are shown in Fig. 1. The site numbers, names, type of instruments, water depth of measurements, periods of analysis are summarized in Table 1. Since the records comprise of more than 30 years at these sites, it is considered to be sufficiently long for the inspection of the regional wave climates and their long-term changes.

The observation data includes mean, significant, and 1/10 wave height and period. The measurement of wave direction at Rumoi, Wajima, Kanazawa, and Hamada started respectively from 1996, 1991, 2004 and 2004. Namely the length of wave direction data is not sufficiently long for the analysis of long-term variation. The statistical data processing had been performed in time intervals of 2 hours from the start of observations until the end of the 20th century. After that, the data processing has been conducted every 20 minutes. In this study, the time intervals of 2 hours were used. Numbers of data over the observed durations at the four sites are presented in Table 2.

Fig. 1 Location of observation sites.

Table 1 List of wave measurement and analyzed period.

Site No.	Site Name	Instrument type	Water depth (m)	Observed periods (Year. Month)		Analyzed period (Year. Month)
				Start	End	
1	Rumoi	SRW	12.0	1970. 01	1978. 01	1978.02 ~ 2013.12
		USW	27.0	1978. 02	1981. 04	
		USW	49.8	1981. 04	1995. 09	
		DWDM	49.8	1995. 09	now	
2	Wajima	USW	52.0	1979. 01	1995. 08	1979.01 ~ 2012.12
		CWD	27.0	1990. 08	1995. 08	
		DWDM	52.0	1995. 09	now	
3	Kanazawa	USW	20.0	1970. 01	1971. 05	1970.01 ~ 2012.12
		USW	20.2	1971. 11	2003. 07	
		DWDM	21.1	2003. 07	now	
4	Hamada	USW	51.1	1974. 03	2003. 08	1974.03 ~2013.12
		DWDM	50.1	2003. 08	now	

(SRW: Step-type Wave Gauge; USW: Ultrasonic-type Wave Gauge; CWD: Ultrasonic-type Current meter; DWDM: Doppler-type Wave Directional Meter)

Table 2 Number of wave data at the four sites.

Site No	Site name	Total data	Missing data	Percentage of missing data (%)
1	Rumoi	153408	13260	8.643617021
2	Wajima	149028	19537	13.10961698
3	Kanazawa	176064	27174	15.43416031
4	Hamada	166536	40105	24.08188019

2) Method of Analysis

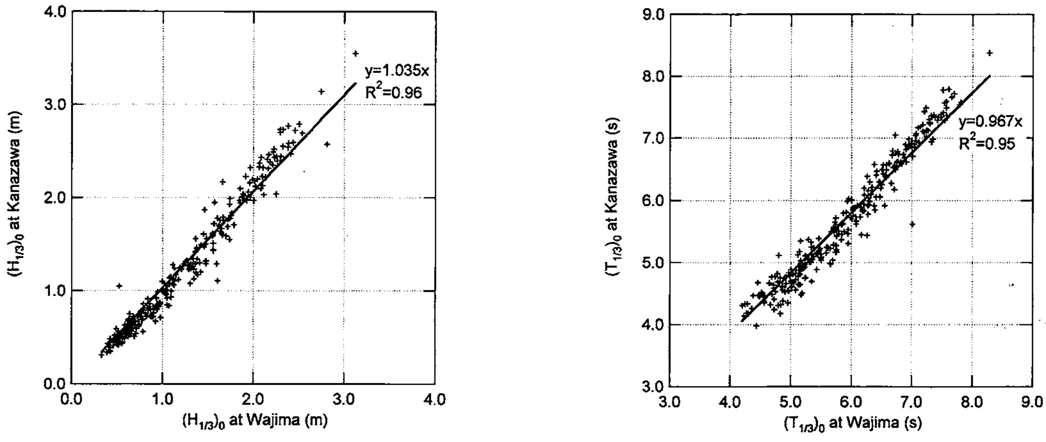
In general, the measured records include both normal values and abnormal values. Preliminarily, the acquisition rate of wave data for each year as well as each month was computed as a ratio between the number of normal data and the total number of data. When the acquisition rate was less than 70 %, the data for the year or the month was omitted. Initially, wave heights were converted into corresponding deep water values based on the linear wave (shoaling) theory. Firstly, the monthly-mean properties were computed for the significant wave height and period for each month. Then these values were further averaged over the study period in order to clarify the seasonal variation and relation between them. The corresponding wave slopes were also examined. On the basis of the aforementioned analysis, the similarities and differences among the stations were examined. Secondly, the seasonal variation of incoming wave direction has been analyzed as well. In seasonal comparison, the whole year was divided into 4 seasons: spring: from March to May; summer: from June to August; autumn: from September to November and winter: from December to the following February. Thirdly, the long-term variations of wave characteristics were examined. At the beginning, the long-term variation of annually-mean, maximum, and top 1 % (quantified as the 99 % quantile of wave height records) of significant wave properties were calculated and compared. The long-term variations of monthly-mean values were then examined. After that, the monthly-mean properties were analyzed separately before and after 1990 to examine the changes of observed wave characteristics. Fourthly, the Mann-Kendall (Kendall, 1938) and Lepage tests (Lepage, 1971) have been conducted in order to detect the significant trend or jump in the long-term variations at each station.

In the analysis, the focus is mainly placed on the wave climate at the coastline of Ishikawa Prefecture, which is located on the middle north of the Honshu island of Japan. For this purpose, wave climate observed at Wajima Port was investigated in detail and compared with the corresponding wave properties at Kanazawa Port. Through the local comparison the influence of Noto Peninsula is discussed. Next, overall comparison along the Sea of Japan coast was carried out. The wave at Rumoi, Wajima, and Hamada Port located at the north, middle, and south part of the Sea of Japan coast were analyzed to understand the regional dependence of wave climate and to clarify the intrinsic features observed at the coastline of Ishikawa Prefecture.

III. Wave Climate around the Coastlines of Ishikawa Prefecture

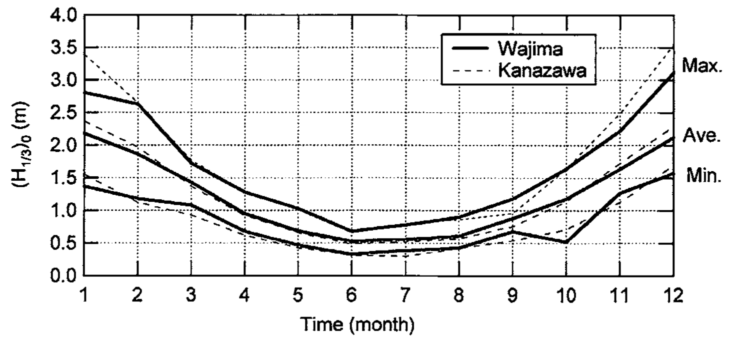
1) Seasonal Variation

Along the Japanese coast, it is generally known that the seasonal variation of waves on the Sea of Japan side is more significant than that on the opposite side facing to the western Pacific Ocean. On the overall, the seasonal variation in wave characteristics at both Wajima and Kanazawa indicated similar features to the previous studies (*e.g.* Kobune, 1988). Waves are the smallest during summer and the largest in winter due to the strong East Asian winter monsoon. In spring and autumn, waves are the medium. Since the Wajima and Kanazawa sites are located relatively close to each other (90 km), the wave properties at these sites are strongly correlated in wave height and period. The correlation between monthly-averaged values of significant wave heights and periods at Wajima and Kanazawa were examined as shown in Fig. 2. The figures illustrate that the values at these two sites can be linearly correlated very well. On average, the wave height at Wajima is approximately 3 to 4 % smaller than that at Kanazawa, while the wave period at Wajima is 3 to 4 % larger than that at Kanazawa. Figure 3 shows the comparison of seasonal variation in monthly-mean wave characteristics at Wajima and Kanazawa, including the average, maximum, and minimum values during the observation period. Wave heights in winter at Wajima are slightly smaller than that at Kanazawa. In contrast, wave periods at Wajima are slightly larger than that at Kanazawa. Figure 3 (a) clearly illustrates that, although the differences in wave heights at both sites in spring, summer and autumn are not clear, wave heights at Wajima in winter are 6.0 to 12.0 % smaller than that at Kanazawa. On the contrary, Fig. 3 (b) shows that wave period at Wajima are always 3.5 to 4.2 % larger than that at Kanazawa. The

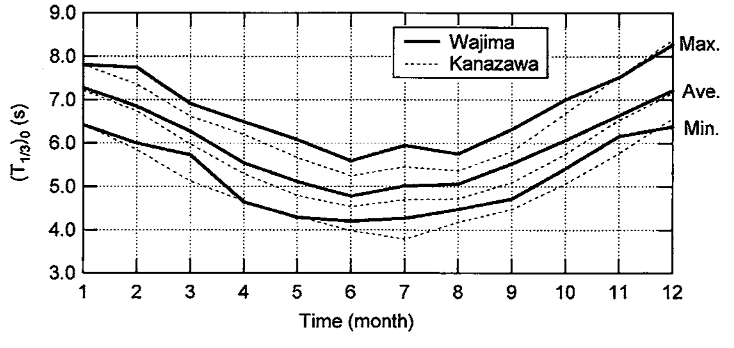


(a) Wave height (b) Wave period

Fig. 2 Correlation between monthly-averaged significant wave properties at Wajima and Kanazawa.



(a) Wave height



(b) Wave period

Fig. 3 Comparison of seasonal variation in monthly-mean wave properties at Wajima and Kanazawa.

discrepancies are clear in spring, summer and autumn while it is small in winter.

Next, the relationship between the monthly-averaged significant wave height and period at Wajima and Kanazawa were considered and compared, for the averaged and the maximum values during the study period (Fig. 4). In the figures, the regression results and several curves corresponding to typical wave slope (H_0/L_0) were also included. Commonly at both sites, wave slope in winter are larger than that in summer. Generally, for both averaged and maximum values, the wave at Wajima are not as steep as that at Kanazawa. In particular, Fig. 4 (a) illustrates that in both sites, the monthly-averaged values of wave height and period are strongly interdependent. They can be correlated very well with the following second order polynomials.

At Wajima with correlation coefficient of R^2=0.996:

$$H_{1/3} = 0.08T_{1/3}{}^2 - 0.31T_{1/3} + 0.11. \qquad (1)$$

At Kanazawa with correlation coefficient of R^2=0.998 (Nguyen and Yuhi, 2015):

$$H_{1/3} = 0.09T_{1/3}{}^2 - 0.35T_{1/3} + 0.25. \qquad (2)$$

Similarly, the maximum values of monthly-mean wave height and period (Fig. 4 (b)) can be closely correlated with the following second order polynomial. At Wajima with correlation coefficient of R^2=0.987:

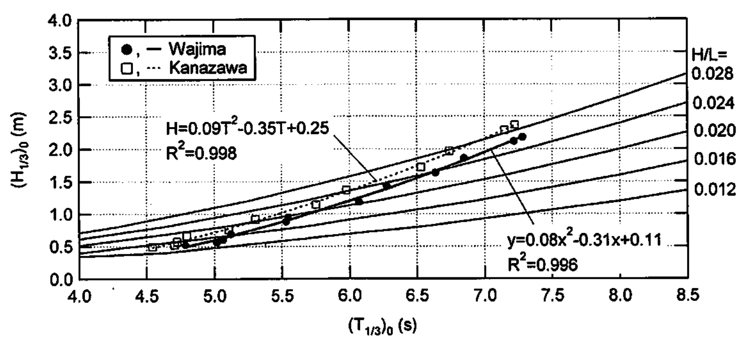
$$H_{1/3} = 0.15T_{1/3}{}^2 - 1.14T_{1/3} + 2.37. \qquad (3)$$

At Kanazawa with correlation coefficient of R^2=0.973:

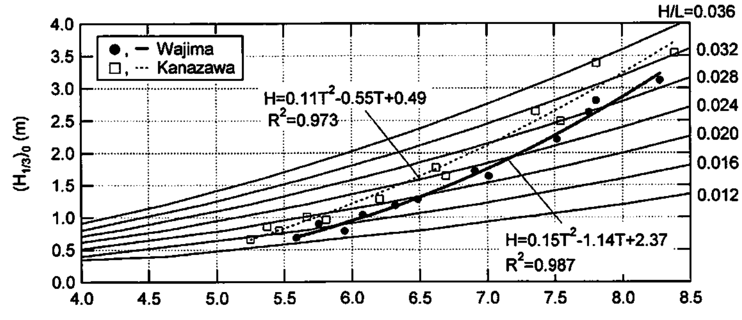
$$H_{1/3} = 0.11T_{1/3}{}^2 - 0.55T_{1/3} + 0.49. \qquad (4)$$

Since the difference between Wajima and Kanazawa is small in the above results, it is deduced that the effects of the Noto Peninsula are small on the wave height and period.

In contrast to the wave height and period, the wave direction at these two sites indicate substantially different features. Figure 5 compares the incoming wave direction relating to wave period, at Wajima and



(a) Average height and period



(b) Maximum height and period

Fig. 4 Comparison of the relationships between monthly-mean wave height and period at Wajima and Kanazawa.

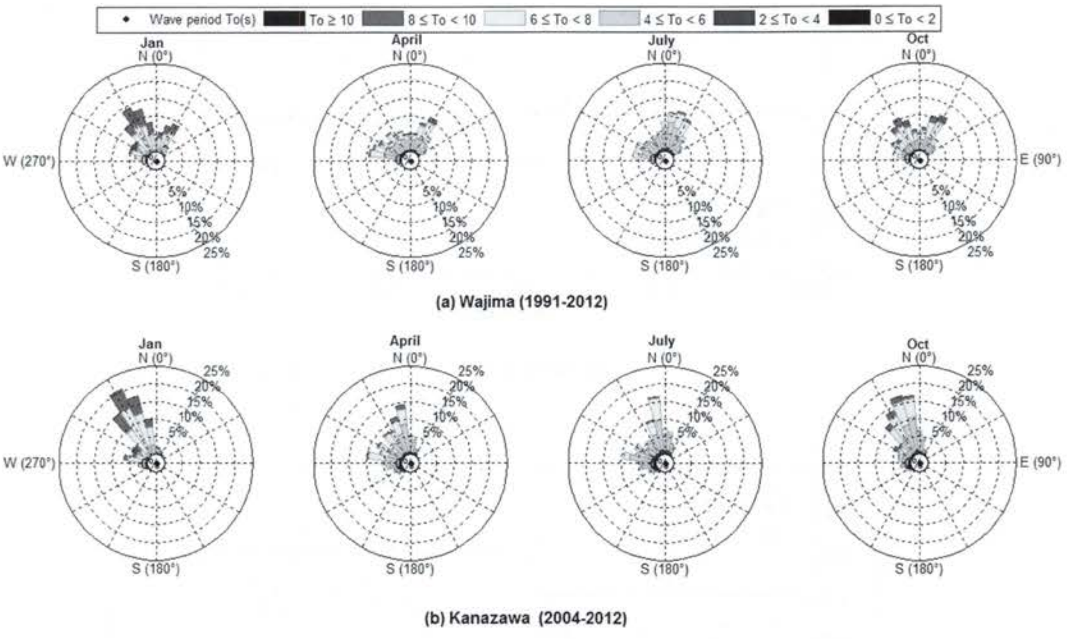


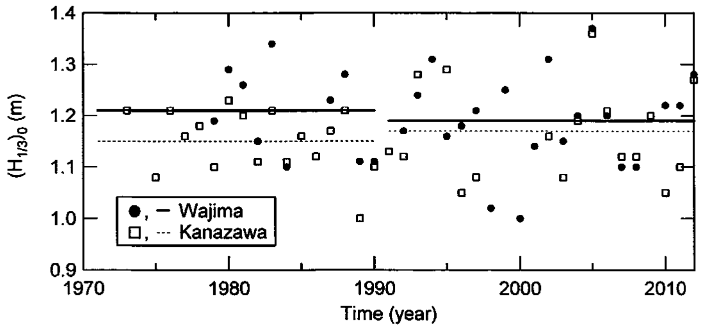
Fig. 5 Incoming wave direction and wave periods in the four seasons at Wajima and Kanazawa.

Kanazawa, in January, April, July, and October that are representative for winter, spring, summer, and autumn, respectively. At Wajima, waves in winter have longer wave period and approach the coast mainly from the NNW and NNE direction. In spring, dominant wave direction is the NWW and NNE. In addition, the number of waves with long period decreases. In summer, waves approach the coast, mainly from the NNE and NWW direction. The wave periods are the shortest. In autumn, incoming waves are mainly from the NNW and NNE directions. The wave period in autumn is longer than that of summer. In conclusion, over the whole year waves maintain two dominant directions, one of which is always the NNE direction. In winter and autumn the NNW direction is added as the other dominant direction. In spring and summer the other dominant direction moves to the NWW. According to Nguyen and Yuhi (2015), on the other hand, the dominant wave direction at Kanazawa is the NNW in spring, autumn, and winter, and the NNW and NWW in summer. Although the location of Wajima is relatively close to Kanazawa (90 km), the overall results on wave direction at these sites indicated significant differences. This is because the Kanazawa site is located behind the Noto Peninsula and is sheltered from the NNE incoming waves. Namely, the influence of Noto Peninsula is strong on wave direction.

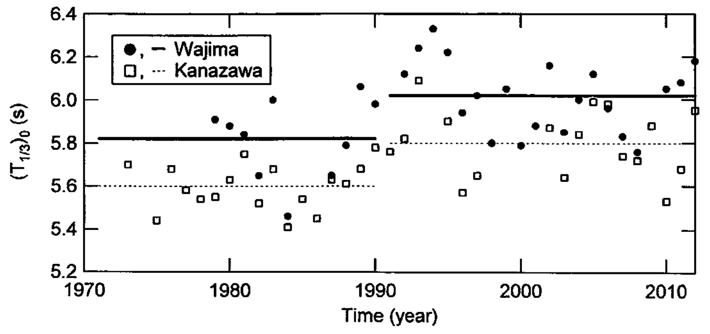
2) Long-term Variation

The long-term variation of annually-mean wave height showed generally common features at these sites. Figure 6 (a) compares the variation in annually-mean significant wave height at Wajima and Kanazawa. The significant wave height at both sites fluctuate between 1.0 and 1.4 m. The statistical tests demonstrated that, in both Wajima and Kanazawa, neither a trend nor a jump exists in the long-term variation of wave height. This is consistent with the analysis by Shimizu *et al.*, (2006) based on the observation around Japan over 35 years. In addition, when observed wave characteristics are analyzed separately by 1990, the following changes have been found. At Wajima, the annual averaged value in duration after 1990 slightly decreases to 1.19 m from the value of 1.21 m in the duration before 1990. In contrast, at Kanazawa, that value slightly increased from 1.15 m to 1.17 m in these periods. After 1990, the scatters of data are nearly the same in both sites, in which the standard deviations are 0.09 m, while the data is more scattered at Wajima, (0.08 m), in comparison with that at Kanazawa, (0.06 m) before 1990.

The long-term variations at these sites are also similar for annually-mean wave period. According to Fig. 6 (b), the annually-mean significant wave period at both Wajima and Kanazawa in the duration after 1990 have



(a) Wave height



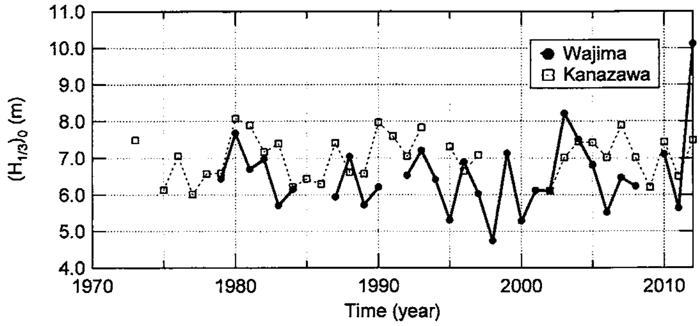
(b) Wave period

Fig. 6 Long-term variation in annually-mean significant wave characteristics at Wajima and Kanazawa.

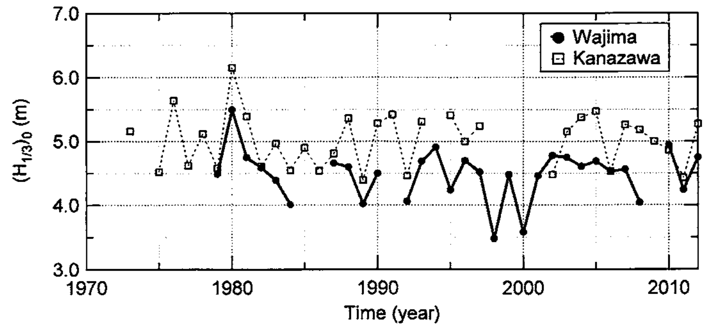
noticeably increased. At Wajima, it increased to 6.02 s from 5.82 s in the former duration. But the statistical tests indicate that this increase is not statistically significant. The wave period fluctuates between 5.46 and 6.33 s. The corresponding standard deviations in the 1st and second duration are 0.18 s and 0.16 s, respectively; the values in the former duration are more scattered.

At Kanazawa, Nguyen and Yuhi (2015) indicated the following wave characteristics: wave period increased from 5.6 to 5.8 s in the two durations; the Mann-Kendall test showed an increasing trend in annual wave period significant at the 1 % level; the Lepage statistics with the sample size of 15 years also detected an abrupt jump in the annually-mean significant wave period around 1990 at the 1 % significance level. It is noted that this result is in agreement with the observation by Seki *et al.*, (2012) and Yamaguchi *et al.*, (2007). The significant wave period fluctuates between 5.41 and 6.09 s, and the standard deviations in the first duration and second duration are 0.11 s and 0.15 s, respectively. In summary, the long-term variations of annually-mean wave height at Wajima and Kanazawa are similar. However, the variation at Wajima is less statistically significant than at Kanazawa.

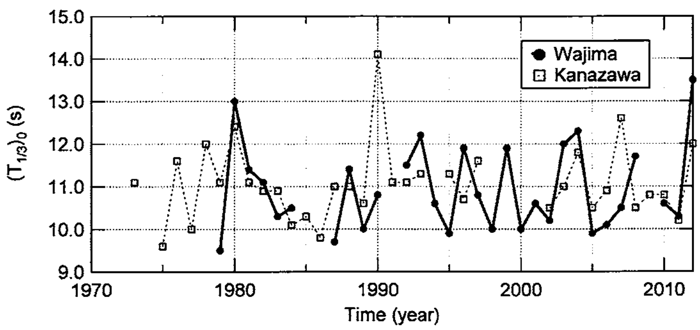
In order to clarify the characteristics of episodic waves, the annually maximum and top 1 % of significant wave characteristics at Wajima and Kanazawa were compared in Fig. 7. The figures illustrate that the maximum wave heights and periods fluctuate in a wide range and the values at Wajima are almost always smaller than that at Kanazawa. Figures 7 (a) and 7 (b) demonstrates that, in Wajima, the maximum wave height reached up to 10.12 m at 2012. In 1980, top 1 % of significant wave height recorded the highest value of 5.5 m. At Kanazawa, the maximum significant wave height reached up to 8.08 m at 1980. In the same year, top 1 % of significant wave height recorded the highest value of 6.15 m. In Fig. 7(c), it is shown that the maximum of the significant wave period at Wajima and Kanazawa was 13.5 s in 2012 and 14.1 s in 1990, respectively. The statistical test indicated no significant trends or jumps at both sites for these episodic waves.



(a) Height of maximum significant waves



(b) Height of top 1% of significant waves

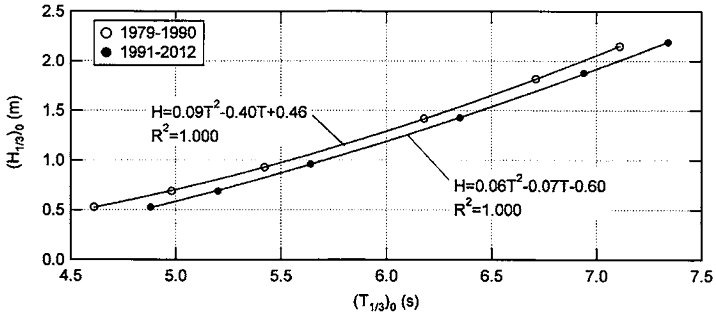


(C) Period of maximum significant waves

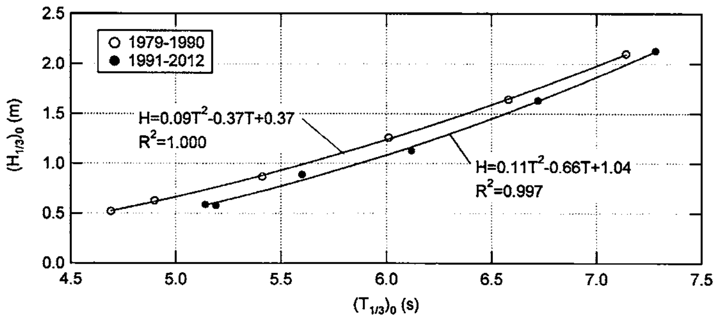
Fig. 7　Long-term variation in episodic wave characteristics at Wajima and Kanazawa.

Next, the long-term variation in monthly-averaged wave height and period were examined. Figure 8 shows the relationship between the monthly- mean significant wave height and period at Wajima, which were averaged over 2 different durations: before 1990 and after 1990. The variation of wave heights between the first and the second duration are not significant in general. In contrast, wave periods in the second duration are always greater than that in the first duration. In particular, the wave periods in July have significantly increased from 4.69 s to 5.19 s. Generally similar changes were reported by Nguyen and Yuhi (2015) for Kanazawa.

In order to detect the long-term increasing/ decreasing trend in monthly-mean wave height and period, the Mann-Kendall statistic tests have been conducted at Wajima. For the wave height, the statistics indicated no clear trends. For the wave period, the Mann-Kendall tests demonstrated that there has been an increasing trend in January significant at the 5 % level, and in July at the 1 % level. At Kanazawa, increasing trends with 5 % significance level in April and July have been detected for wave height. For wave period at



(a) From January to June



(b) From July to December

Fig. 8 Comparison of relationship between monthly-mean wave characteris-tics before and after 1990 at Wajima.

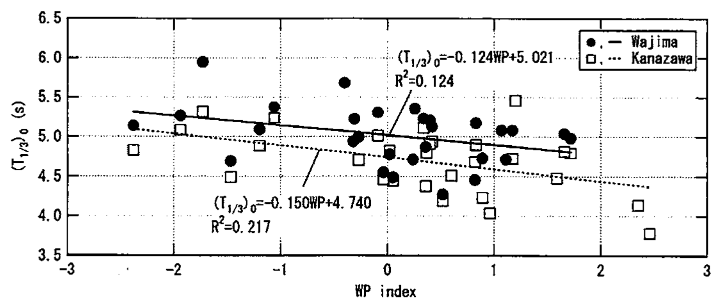


Fig. 9 Relationship between monthly-mean wave period and Western Pacific index in July at Wajima and Kanazawa.

Kanazawa, increasing trends have been significant at the 1 % level in March, April and July, and an increasing trend at the 5 % level has been detected in May. Some previous studies for Kanazawa have pointed out the existence of an increasing trend in wave period during spring (Seki *et al.*, 2012) and summer (Seki *et al.*, 2012; Yamaguchi *et al.*, 2007). The present results are consistent with them.

In order to deduce the possible cause of the change in July at both sites. The year-to-year variation of wave period in July was compared with several climate indices, including the Arctic Oscillation (AO), El Nino-Southern Oscillation (ENSO), Western Pacific (WP), North Pacific Index (NPI), and Zonal Index (ZI). While other climate indices express almost no correlations, the WP index seems to have weak negative correlations with the values at Wajima and Kanazawa as shown in Fig. 9.

IV. Overall Comparison along the Sea of Japan Coast

1) Seasonal Variation

Wave climates in Rumoi and Hamada also have significant seasonal changes like in Wajima and

Kanazawa (Fig. 10). Waves are the highest in winter, the smallest in summer and the medium in spring and autumn. The mean heights of significant wave in summer are around 0.5 m at Rumoi and 0.6 m at Hamada, while in winter they are around 1.6 m, and 1.8 m, respectively. The mean values of the significant wave period in winter are around 6.2 s at Rumoi, 6.9 s at Hamada, while waves in the summer have the smaller period around 4 and 4.5 s at Rumoi and Hamada, respectively. In general, the difference in the values of significant waves around these sites is about 10 %. On average the significant wave height at Hamada is about 4.0 % higher than that of Rumoi but more than 5.0 % lower than that at Wajima. The wave period at Wajima is more than 9.0 % higher than that at Rumoi, but almost 1.5 % lower than that at Hamada. Close inspection revealed that the order of magnitude of wave values at these sites have certain changes in different season. In spring, summer and autumn waves are the largest at Hamada, the lowest at Rumoi, and the medium at Wajima. However, in winter, the order of magnitude of the waves is Wajima, Hamada and Rumoi.

The relationship of monthly-averaged wave height and period at the above 3 sites is then investigated. Figure 11 compares the relationship between the monthly-averaged significant wave height and period, at Rumoi, Wajima, and Hamada. The regression results and several curves corresponding to the typical wave slope (H_0/L_0) were also included. The relation between wave height and period are qualitatively similar among these sites. In common, wave height and period are strongly interdependent. They can be correlated very well with the second order polynomials with high correlation coefficients. Quantitatively, the averaged-values of wave period and height at Hamada are the largest, the values at Rumoi are the lowest and the values at Wajima are the medium. Waves seem to be steeper at the north and flatten at the south part of the coastline. Waves at Rumoi are the steepest, in which the maximum wave slope reached up to 0.03. They are the medium at Wajima with the wave slope in the range from 0.016 to 0.026. The lowest wave slope occurred at Hamada with the

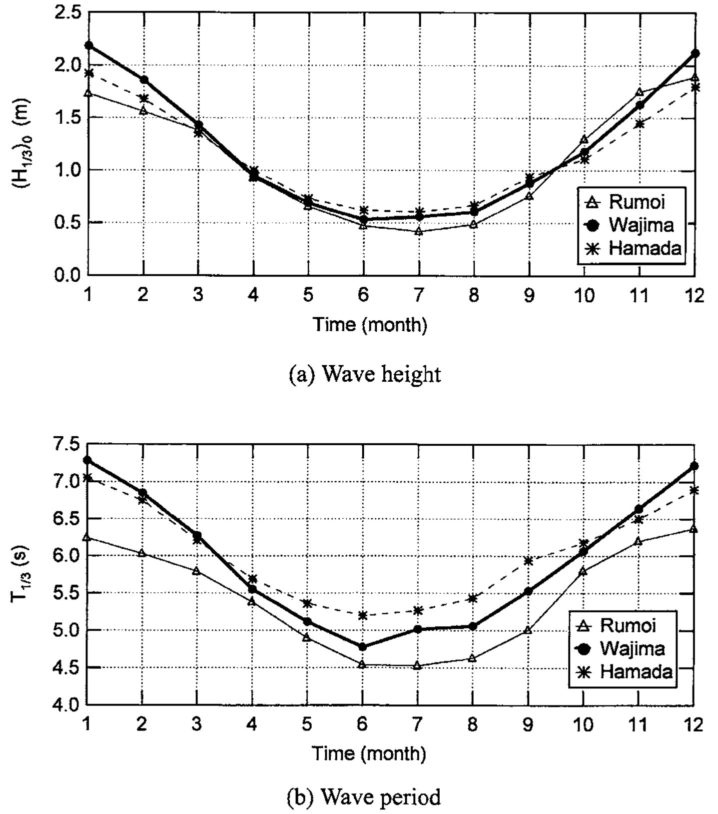


Fig. 10 Comparison of seasonal variation in monthly-mean wave properties at Rumoi, Wajima and Hamada.

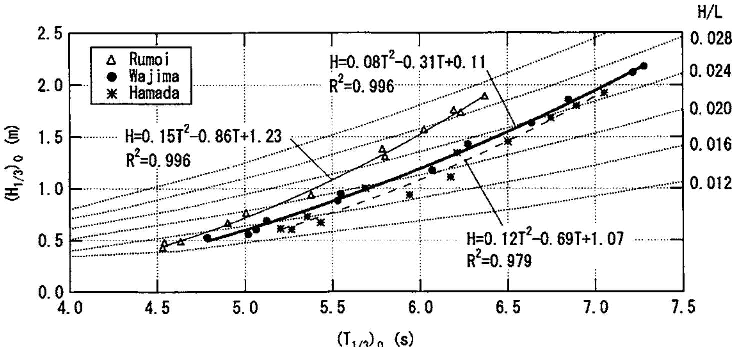


Fig. 11 Comparison of the relationship between monthly-mean wave height and period at Rumoi, Wajima, and Hamada.

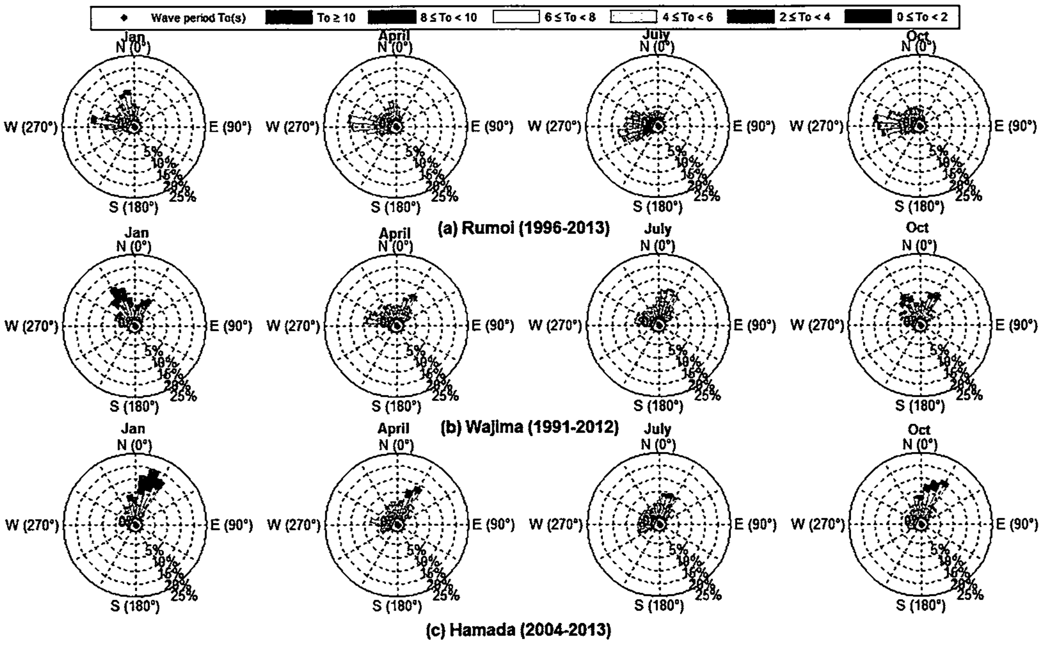


Fig. 12 Incoming wave direction and wave periods in the four seasons at Rumoi, Wajima, and Hamada.

value of 0.013.

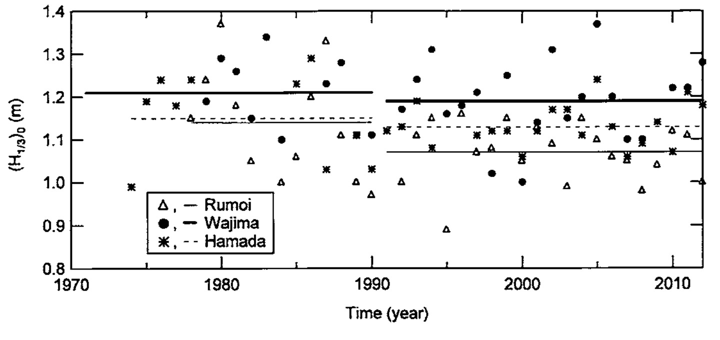
Wave direction along the coastline indicated significant differences. Figure 12 compares the incoming wave direction relating to wave period, at Rumoi, Wajima and Hamada, in typical months, which represent for winter, spring, summer and autumn seasons. While the seasonal variations of wave period at Rumoi and Hamada are also the same with that at Wajima, the variation of wave direction at each site is different from the others. At Rumoi, waves in winter approach the coast mainly from the NNW and NWW direction. In spring, summer, and autumn dominant wave directions are the SWW and NWW. At Hamada, throughout the year waves mainly approach shoreline from the NNE direction. These differences are considered to be mainly related to the orientation of the coastlines at these sites: the shoreline at Rumoi, Wajima, and Hamada has the N-S, NE-SW, and E-W direction, respectively. Moreover, located at the north-eastern part of the Japan Sea, Rumoi could be impacted by the waves from the south-western side with long fetch distance. In contrast, at Hamada the longest fetch of wave evolution is in the direction from the north to the south. These differences may contribute to the discrepancies in wave direction at Rumoi and Hamada.

2) Long-term Variation

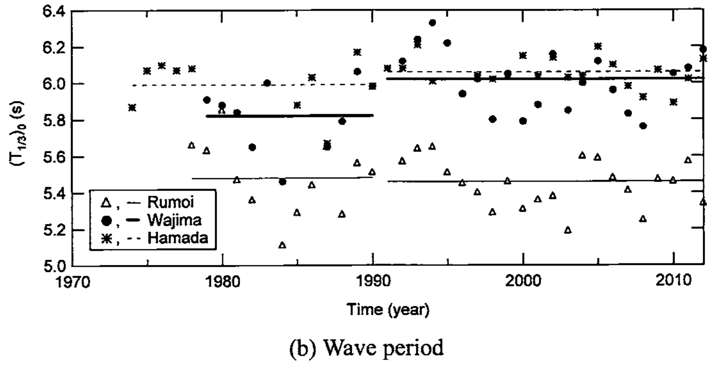
The long-term variation in annual significant wave properties along the Sea of Japan showed some different features. Figure 13 compares the long-term variation in annually-mean of significant waves at Rumoi, Wajima and Hamada. For wave heights, the figure illustrates that, significant wave height at Wajima is generally the highest in comparison with those of other sites. At Rumoi the annually-averaged value is smaller than that at Hamada. Moreover, at Rumoi, the range of the data is greater than that at Hamada. The minimum and maximum values are 0.89 m, 1.37 m at Rumoi and 0.99 m, 1.29 m at Hamada. In addition, the Mann-Kendall tests for the long-term variation of wave height demonstrated a decreasing trend at 5 % significant level at Rumoi, but the Lepage test indicated no abrupt jumps here. In contrast, at Hamada, although the Mann-Kendall test has shown no significant trends, the Lepage test with sample size of 10 years indicated an abrupt jump at 1 % significance level around 1991. According to Fig. 13 (b), the annual-mean significant wave period at Hamada is 6.04 s, which is larger than that of Wajima and Rumoi, 5.95 s and 5.47 s, respectively. Similar to Wajima, at both Rumoi and Hamada, the statistical tests indicated no significant trends or jumps in long-term wave period.

To clarify the long-term differences in the regional variation, wave characteristics of the 4 sites are compared together in Tables 3 and 4. The tables show that, except for the long-term averaged mean of significant wave height in autumn, the long-term mean at the northern part of the coast are always smaller than that at the southern part. In contrast, the standard deviations at the north site are always larger than that at the south site, which mean that the data is more scattered at the northern part in comparison with that at the southern. In addition, an increasing trend in the long-term annual wave period at Kanazawa, the middle sites, and a decreasing trend in the long-term annual wave height at Rumoi, the northern site have been found.

The episodic events also vary from the north to the south parts of the study area. Figures 14 (a), (b) and (c) compare the maximum and top 1 % of significant wave at Rumoi and Hamada. Figures 14 (a) and 14 (b) demonstrate that, at Rumoi, the maximum wave height



(a) Wave height



(b) Wave period

Fig. 13 Long-term variation in annually-mean significant wave characteristics at Rumoi, Wajima and Hamada.

Table 3 Comparison of annually-mean significant wave properties at the four sites.

(a) Wave period (s)

Site No	Site Name	Annual mean over the study period	Statistical test for long-term trend	Annual mean before 1990	Annual mean after 1990	Standard deviation before 1990	Standard deviation after 1990
1	Rumoi	5.47	No	5.48	5.46	0.19	0.13
2	Wajima	5.95	No	5.82	6.02	0.18	0.16
3	Kanazawa	5.70	Increasing	5.60	5.80	0.11	0.15
4	Hamada	6.04	No	5.99	6.06	0.14	0.08

(b) Wave height (m)

Site No	Site Name	Annual mean over the study period	Statistical test for long-term trend	Annual mean before 1990	Annual mean after 1990	Standard deviation before 1990	Standard deviation after 1990
1	Rumoi	1.10	Decreasing	1.13	1.07	0.12	0.07
2	Wajima	1.20	No	1.21	1.19	0.08	0.09
3	Kanazawa	1.16	No	1.15	1.17	0.06	0.09
4	Hamada	1.14	No	1.15	1.13	0.10	0.05

Table 4 Comparison of seasonal significant wave properties averaged over the study period at the four sites.

(a) Wave period (s)

Site No	Site Name	Mean in Winter	Mean in spring	Mean in summer	Mean in autumn
1	Rumoi	6.21	5.36	4.57	5.67
2	Wajima	7.11	5.65	4.96	6.08
3	Kanazawa	7.04	5.36	4.66	5.80
4	Hamada	7.65	6.58	5.30	6.21

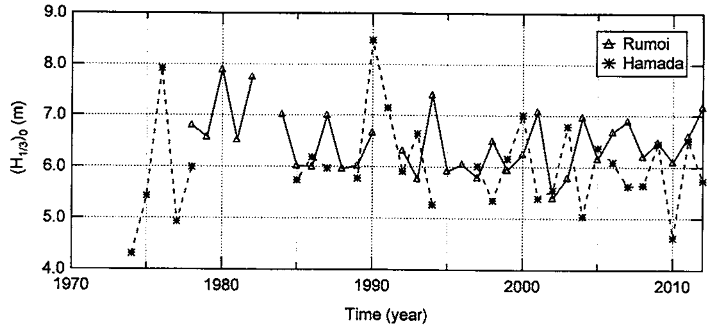
(b) Wave height (m)

Site No	Site Name	Mean in Winter	Mean in spring	Mean in summer	Mean in autumn
1	Rumoi	1.73	0.99	0.46	1.27
2	Wajima	2.05	1.02	0.57	1.23
3	Kanazawa	2.21	0.98	0.53	1.21
4	Hamada	1.80	1.02	0.63	1.17

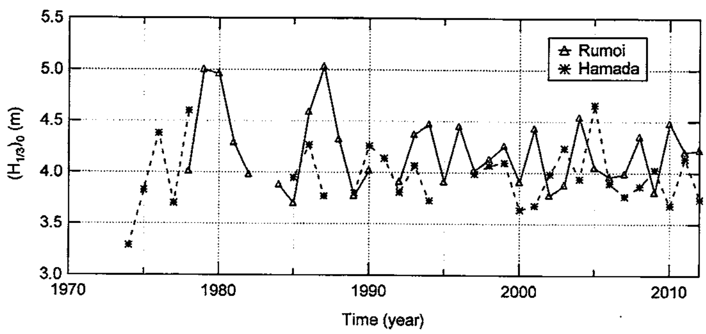
reached up to 7.89 m in 1980. In 1987, top 1 % of significant wave height recorded the highest value of 5.03 m. In Hamada, the maximum significant wave height reached up to 8.47 m at 1990. In 2005, top 1 % of significant wave height recorded the highest value of 4.66 m. Figure 14 (c) shows that the maximum of the significant wave period in Rumoi and Hamada was 12.6 s at 1978 and 11.2 s at 1990, respectively. For long-term annual maximum values, the Mann-Kendall and Lepage tests revealed no significant trends or jumps at Rumoi and Hamada.

Isozaki. (2006) proposed a hypothesis on the existence of negative correlation between the episodic wave characteristics at the middle and north side of the Sea of Japan coast. In order to examine this hypothesis, the year to year variation between the annual maximum significant wave height at Rumoi is compared with those at Wajima and Hamada as shown in Fig. 15. The results revealed that the maximum values at Rumoi and Hamada have little correlation. The episodic wave properties at Rumoi and Wajima seem to have a weak negative correlation when the values at Rumoi are relatively small, but it turns to a positive correlation when the values at Rumoi are large. The correlation coefficients in both cases were small. Hence, the results do not support the assumption by Isozaki (2006).

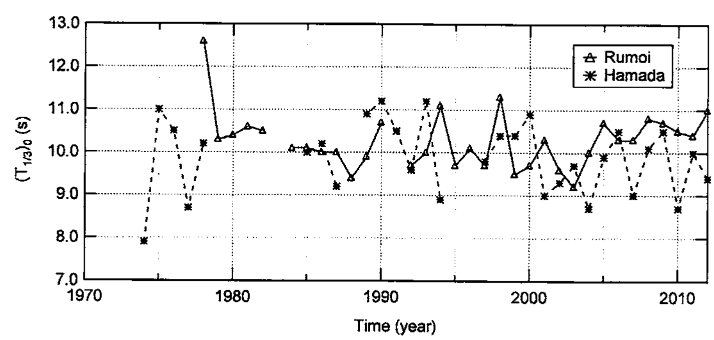
In terms of long-term variation in monthly-averaged wave height and period, comparison has been made on the relationship between the monthly- mean significant wave height and period at Rumoi, Wajima, and Hamada,



(a) Height of maximum significant waves



(b) Height of top 1% of significant waves

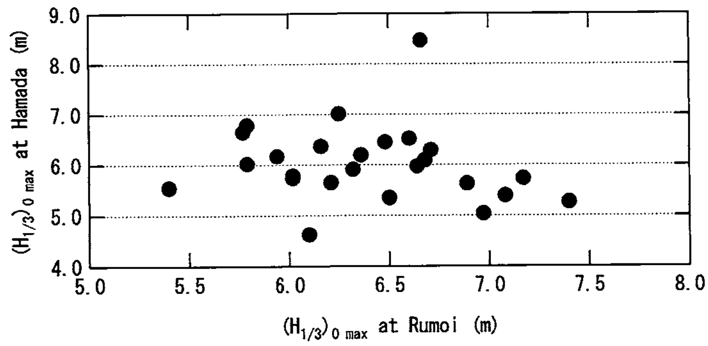


(C) Period of maximum significant waves

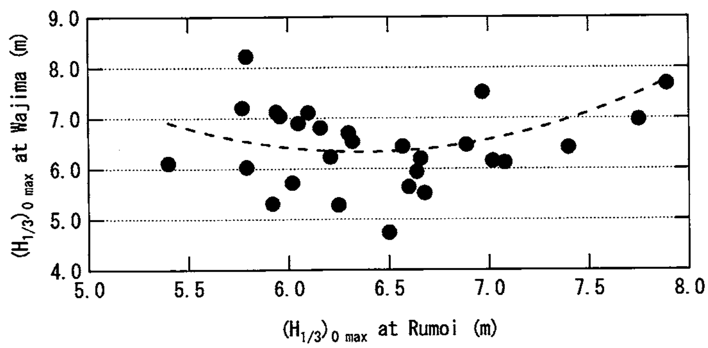
Fig. 14 Long-term variation in episodic wave characteristics at Rumoi and Hamada.

which are averaged over two different durations: before 1990 and after 1990. In general, unlike at Wajima, the differences in values between the first and the second duration at Rumoi and Hamada are not significant for both wave height and period. Especially, in the period from January to June at Romoi, the variation in both duration is quite small. In addition, the Mann-Kendall tests at Rumoi and Hamada showed that, for wave height, the decreasing trends at the 5 % significance level have been detected in October at Rumoi, and in February and August at Hamada. For wave period, while an increasing trend at the 5 % significance level has been detected in March at Rumoi, no clear tendencies have been found at Hamada. For wave periods, the discrepancies of values from the north to the south sites are quite clear, in which the magnitude is in the order of Hamada, Wajima, and Rumoi.

Some features of long-term trends in monthly-mean wave properties have been found by the Mann-Kendall tests. Table 5 summarizes the long-term trends for monthly-averaged significant wave characteristics at the four sites. The two sites at the middle of the coastlines



(a) Rumoi and Hamada



(b) Rumoi and Wajima

Fig. 15 Year to year variation of maximum significant wave height at Rumoi, Hamada, and Wajima.

Table 5 Summary of the long-term trends for monthly-averaged significant wave characteristics at the four sites.

	Rumoi		Wajima		Kanazawa		Hamada	
Month	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
Jan			△					
Feb								▽
Mar	△				▲			
Apr					▲	△		
May					△			
Jun								
Jul			▲		▲	△		
Aug								▽
Sep								
Oct		▽						
Nov								
Dec								

▲ Increasing trend significant at 1% level;
△ Increasing trend significant at 5% level;
▽ Decreasing trend significant at 5% level.

always have increasing trends especially at Kanazawa. Moreover, most of the detected trends concentrate in spring and summer season. In addition, most of the trends are indicated for significant wave period. In contrast, at both the north and the south sites, some decreasing trends in significant wave height were found. Just one increasing trend was detected in significant wave period in March at Rumoi Port.

A wide variety of abrupt jumps have been detected by the Lepage tests. Tables 6 summarize the years of

Table 6 Years of abrupt jumps detected by the Lepage test for monthly-averaged significant wave characteristics at the four sites with sample size of 10 years.

Month	Rumoi		Wajima		Kanazawa		Hamada	
	$(T_0)_{1/3}$	$(H_0)_{1/3}$	$(T_0)_{1/3}$	$(H_0)_{1/3}$	$(T_0)_{1/3}$	$(H_0)_{1/3}$	$(T_0)_{1/3}$	$(H_0)_{1/3}$
January	1991		1993 1994* 1995* 1996	1995				1989
February	2004	2004						
March	1996 1998		1991 1993		2003	2002 2003		1999
April	1997 1999	1999			1991 1992 1993	1992		
May	1996 1997		1992 1995	1998 2000	1988			
June		1999	1990 1991 1992 1999 2000	1996 1997	1986 1987 1988 * 1989 * 1991			
July			1991* 1992 1993 1995		1987 1988 1989* 1990* 1991* 1992 1995* 1996 1997			
August							2004	
September	1999 2000				1989			
October		2001 2002 2003		1990	2000		2000	
November				1994	1987			1990
December								

(Years with *: significant at 1% level; years without *: significant at 5% level)

abrupt jumps for monthly-averaged significant wave characteristics at the 4 sites with sample size of 10 years and significant at 5 % and 1 % level. With the significant level of 5 % the abrupt jumps have been detected in many years at Rumoi, Wajima, and Kanazawa Port. On the contrary, data at Hamada Port are quite stable during the study period. The jumps were just found in 5 different years. With significance level at 1 %, the abrupt jumps were detected in wave period only at Wajima and Kanazawa. Moreover, the jumps are concentrated in June and July, around the years of 1989-1991.

At areas related to the 4 sites, we have conducted further analysis on the long-term typhoon records, wind speed records and others in order to clarify the possible reasons responsible for the differences. However, factors contributed to the differences of wave characteristics at these 4 sites are quite complicated. At this moment, principal factors contributed to the differences of wave characteristics at these 4 sites are not clear. More detailed analyses are needed in the future research.

V. Summary Remarks

This study examined the long-term wave data observed at the four ports, including Rumoi, Wajima, Kanazawa, and Hamada in order to make a comparison of the long-term as well as the seasonal characteristics in significant wave properties along the Sea of Japan coast.

The local comparison between Wajima and Kanazawa sites indicated several common features in wave characteristics along the coast of Ishikawa Prefecture; the wave characteristics at Wajima mostly have a close relationship with that of Kanazawa. Wave height and period at each site are strongly interdependent and can be correlated very well with the second order polynomials. The statistical tests demonstrated that, in both Wajima and Kanazawa, neither a trend nor a jump exists in the long-term variation of wave height. The wave periods in July have significantly increased at 1 % significant level, at both sites. On the other hand, various different factors between Wajima and Kanazawa were also recognized. Especially, wave direction of these sites demonstrated significant discrepancies. Namely, the effect of the Noto Peninsula is small on wave height and period, but is significant on wave direction. From the statistical tests, neither a trend nor a jump has been found at Wajima on annual wave period, although an increasing trend and an abrupt jump around 1990 were detected at Kanazawa at the 1 % significance level in annual wave period.

On the overall comparison, wave climates at Rumoi and Hamada have significant seasonal changes, qualitatively similar to Wajima and Kanazawa. In general, the difference in the values of significant waves around these sites is about 10 %. Wave height and period can be correlated very well with the second order polynomials. Similar to Wajima, at both Rumoi and Hamada, the statistical tests indicated no significant trends or jumps in long-term annual wave period as well as episodic events of wave height and period. Beside the common features, waves along the coastline indicated regional dependence. Annual wave height at Rumoi is the smallest, Wajima is the highest, and Hamada is the medium. Annual wave period at Rumoi is the smallest, Wajima is the medium, and Hamada is the largest. Moreover, wave direction along the coastline indicated significant differences. The statistical test revealed that at the north (Rumoi) and the south (Hamada) the long-term trends and abrupt jumps are not as clear as those at the middle of the coastline (Wajima and Kanazawa). Namely, the long-term increasing trends and abrupt jumps of wave period in summer are intrinsic to the waves at Wajima and Kanazawa located on the central part of the Sea of Japan.

Although the wave analyses in this study revealed indication of climate change impact on wave characteristics along the Sea of Japan coast during the last 30 to 40 years, it is difficult to provide clear evidence for that. In the future, on the other hand, climate change phenomenon is expected to place stronger impacts on the variation of wave characteristic along Japanese coast (*e.g.* Shimura *et al.*, 2015). In order to clarify the characteristics of such impact, more detailed efforts using wave model prediction is needed.

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日本海沿岸における地域波浪特性の相互比較

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2015年12月16日受理

要　旨

本研究では，日本海沿岸の4地点（留萌，輪島，金沢，浜田）において40年以上に渡って観測された波浪データを解析し，有義波特性の季節変動・長期変動に対する相互比較を行った．解析の主対象は，石川県能登半島外浦に位置する輪島である．まず，輪島における波浪特性を，近隣に位置する金沢の値と比較した．両地点における，波高・周期は強い相関を有し，類似した変動を示した．一方，能登半島による北北東からの波の遮蔽効果により，波向に関しては顕著な相違がみられた．有義波高に関する長期変化では，有意なトレンドやジャンプは検出されなかったが，年平均の有義波周期に関しては金沢において有意な増加トレンドとジャンプが，7月の月平均周期に関しては，両地点で顕著な増加トレンドが検出された．続いて，輪島から北方830kmおよび西方510kmに位置する留萌および浜田における波浪特性を解析し相互比較を行った．解析対象の全4地点において，波高・周期の季節変動特性は類似した傾向を示し，地点間における差は10%程度となった．また，月平均の波高と周期は2次多項式により良く相関づけられた．一方，波向に関しては観測地点により大きな違いがみられた．留萌・浜田においては，年平均および夏季の有義波周期に関して有意なトレンドは検出されず，近年の有義波周期の増加傾向は日本海中央部に特有の現象であることが示唆された．

キーワード：日本海，波候，地域特性比較，長期変動，ナウファスデータ

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