Long –term variation of wave characteristics at the Kaetsu Coast, Japan and regional comparison of wave climate along Japan coastline

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Dissertation

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A dissertation submitted in partial fulfillment of the requirements for the Degree of Doctor of Engineering

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Abstract

This study investigates the long-term variation in wave characteristics measured at ten NOWPHAS's stations around Japanese coastline for the last four decades. In the first part of the research, long-term wave data observed at the Kanazawa Port, Ishikawa, Japan are investigated in order to clarify the long-term as well as the seasonal characteristics in significant wave properties. On the overall, the seasonal variation in wave height, period, and direction is shown to be significant. The monthly-mean wave height and period are correlated with second order polynomials very well. For the long-term variation, the annual mean of significant wave height indicates no significant trends. On the contrary, the Lepage statistical tests detect an abrupt increase in the annual mean of significant wave period around 1990. In relation to these changes, the long-term variation in monthly-mean wave characteristics shows that the wave slope becomes smaller in the last two decades. The Mann-Kendall statistical tests demonstrate that the monthly-mean wave height and period in July have significantly increased during the study duration. Several attempts have been made to correlate these features with climate change.

The second part of the research investigates the seasonal variability of wave characteristics and related morphological indices at the Kaetsu Coast, Ishikawa, Japan based on the long-term wave data observed at Kanazawa Port in duration 1971-2012. First, the seasonal variation of wave energy flux is investigated in combination with the directional distribution. Most of the incoming wave energy is concentrated on winter, in which high waves from the WNW, NW, and NNW direction frequently attack the coastline. Second, the characteristics of wave breaking in the nearshore, breaker height and depth, are examined. Related morphological indices such as the closure depth and Sunamura index are also estimated. The seasonal variation of these properties indicate common pattern, in which the values are highest in winter, medium in spring and autumn, and lowest in summer. The cumulative probability of breaker depths varies significantly from season to season. The estimated closure depth also indicates distinct seasonal changes. These results indicate that the cross-shore width of significant morphological change is substantially variable in time. The estimations of Sunamura indices suggest that the shoreline is advanced during summer, while the recessions of shoreline generally occur in other seasons. The transitions from recessions to advances of the shoreline are deduced to occur in March, from advances to recessions in

September. Third, the analysis of infragravity waves is conducted. The patterns of the daily as well as monthly variation of infragravity wave heights are similar to that of wind waves. A strong linear correlation exists between the heights of infragravity and wind waves.

The third part of the research makes a comparison of long-term wave data observed along the coastline facing to the Sea of Japan. The focus is mainly placed on the wave climate at Wajima Port, which is located on the outer coast of Noto Peninsula, Ishikawa Prefecture, Japan. The wave characteristics at Wajima are first compared with those at Kanazawa, which is located relatively close (90 km) to Wajima. The wave climates at Wajima and Kanazawa indicate similar features on wave height and period. The influence of Noto Peninsula is substantial only for the incoming wave direction. While neither statistically significant trend nor jump is found for the long-term variation of annual wave height at these sites, an increasing trend and an abrupt jump around 1990 are detected in the long-term variation of annual wave period at Kanazawa. The wave periods in July have significantly increased at both Wajima and Kanazawa. The wave properties are then compared with those at Rumoi and Hamada Port, that are located far (830 and 510 km) from Wajima. Over a long stretch of the Sea of Japan coast covering Rumoi, Wajima, Kanazawa, and Hamada, wave climates indicate similar and significant seasonal changes. The difference in the properties of significant waves around these four sites is about 10%. Significant wave height and period are correlated very well with second order polynomials at each site. In contrast, wave direction along the coastline indicate significant differences. At Rumoi and Hamada, neither significant trend nor jump in long-term annual wave period is detected. The statistical tests reveal that 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.

In term of the fourth, this part of the research investigates long-term wave data obtained at six observed sites facing to the Pacific Ocean coastline of Japan, which are Tomakomai, Hachinohe, Onahama, Kashima, Shionomisaki, and Shibushi. On the overall, the seasonal variation of wave climates along this coastline are not significant. Waves in autumn and spring are just slightly larger than that in other seasons. The differences in variations of significant wave height from site to site are considerable. The significant wave heights at the central sites of the coastline are the highest. As far north and south, the mean of significant wave height decreases as much. The statistical tests reveal that long-term trends and abrupt jumps concentrate in wave period at the north sites of the coastline (Tomakomai and Hachinohe). Mann-Kendall tests for annual mean of long-term wave period indicate increasing trends at 1% significant level at both of the north sites. Lepage tests with sample size of 10 years also detect abrupt jumps at 1% significant level in annual mean of long-term wave period around 1990 at these north sites. Namely, the long-term increasing trends and abrupt jumps of wave period in winter, summer and autumn are also intrinsic to the waves at the north sites. Increasing trends at 1% significant level are detected in winter and summer at Tomakomai, in summer and autumn at Hachinohe. Several climate indices express light impacts on these increasing trends of wave period at the north sites.

The final part of this research further analyzes the wave period in July in duration 1971-2012 at Kanazawa port and compared with the following features: Various climate indices; observed, and reanalysis meteorological factors. The results shows that, the occurrence probability of larger waves in the second duration (1991-2012) is more than 50% higher than that in the first duration (1971-1990). Both observed and reanalysis wind speed data express similar patterns to the wave periods. The statistical tests of the mean and maximum observed wind speed indicate increasing trends during the study duration. The Lepage tests with sample size of 15 years also detect abrupt jumps at 1% significant level around 1990 for these factors. For the reanalysis wind speed data, although the Mann-Kendall test indicates no significant increasing trends, the Lepage test with sample size of 15 years detect an abrupt jump significant at 1% level around 1991.

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CHAPTER 1. INTRODUCTION

1. Background

It is estimated that ocean water covers more than 70% of the Earth's surface. As a result, the oceans play an important role in the social and economic development of the world. The importance of the oceans can be seen through many aspects such as human trade, travel, mineral extraction, power generation and others. However, the oceans are also the potential factors that trigger a variety of devastating disasters such as violent tsunami waves, storm surges induced by hurricanes, typhoons, cyclones, and others. One of the most important portions relating to the oceans is coastal areas that play a vital role in the development of the world as well as human being. For example, the population in many of the world's major cities lying on coastal areas is extremely crowded. It is estimated that, in 2003, the population density of coastal cities in the world is about 15 million people per 1 km of the sea coast and the predicted number reaches to double by 2025 (Creel, 2003). The most important features that directly control and influence coastal areas are wave characteristics. Waves are essentially important natural features for related marine engineering such as fishery, the design of coastal construction, prevention of coastal disasters and others. The generated motion of waves perform a vital role in transporting energy around the globe and shaping the coastlines.

Generally, waves are generated on the free surface of oceans, seas, lakes, rivers, canals or even on small ponds. Waves in the oceans can travel thousands of miles before reaching the shoreline. Waves start from small ripples, as the time proceeds wave height can reach up to 34 m (Masselink et al., 2003). The sizes of the waves are influenced by some factors as follows: the strength of the wind; the distance in which the wind blows (fetch); and the length of the gust (duration). According to the theory of Phillips (1957), the wave is first created by a random distribution of normal pressure acting on the water from the wind. The water surface is initially at rest and the generation of wave is initiated by adding turbulent wind flows and then, by the fluctuations of the wind, normal pressure acting on the water surface. This pressure fluctuation induces normal and tangential stresses to the surface water, and generates wave behavior on the water surface. Wave characteristics are different in deep and shallow water because of the presence of seabed. On the ocean surface, a wide variety of wavelengths are generated and interfere. As waves disperse away from the fetch, they become more regular sized and spaced. This is because the speed of a wave in open water is closely related to its wavelength. The different groups of waves move at different speeds and therefore are naturally sorted by wavelength: the largest, fastest-moving waves at the fore, the smaller, slower-moving ones behind. As they propagate across the open ocean, wind-generated waves maintain a constant speed, which is unaffected by depth until they reach shallow water. In shallow water, even before they break, the waves start to feel the ocean floor, and hence start transferring some of their energy. Just beyond the breakpoint, the distortion of the wave shape makes the near-bed water motions favor an onshore direction, which causes sediments to migrate towards the shore. When approaching shoreline waves transfer their energy to this area. Every coastal-protection projects must investigate wave characteristics to figure out the most appropriate solution for coastal construction. Moreover, around the world ocean waves present various changing trends in different areas. Furthermore, the climate change is expected to place significant influence on long-term trends of wave characteristics such as wave height, period and incoming direction that can induce further adverse impact on coastal areas (Komar et al., 2009; Mori et al., 2009). Accordingly, many scientists all over the world have placed great interests on the variation of long-term wave characteristics in order to examine the relation between these two phenomena.

Japan is surrounded by seas with approximately 37,000 km of coastline. Coastal areas play a critical role in economic and social developments in this country. In general, Japanese coast on the side facing to the Sea of Japan is hardly influenced by tide because of the low variation in tidal range here. The average tidal range around the Sea of Japan coastline is just about 0.3m. On the side facing to the Pacific Ocean, the tidal range is about 2 m. The dominant force acting on surrounding Japanese coasts is wave climate. Therefore, since 1970 NOWPHAS (Nationwide Ocean Wave information network for Ports and HArborS), which is a observation project on wave characteristics around the country by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (Nagai et al., 1994). Moreover, for the time scale of several decades, the influence of climate change is also expected to cause further impacts on the Japanese coastal zone as well. There have been many coastal researches which are in relation with the development of industrial area, the protection of coastal regions and some other purposes. Especially, Japanese scientists have spent their great efforts and time on solving coastal problems in order to promote the nationwide coastal development and to extend the coastal protection works against devastating waves.

In order to clarify the coastal risks around this region as well as provide basic engineering information, physical understanding about variations of waves is essentially important. Accordingly, this thesis intensively explores the long-term variation of wave characteristics around Japan based on the observed dataset of the NOWPHAS.

2. Previous Researches

2.1. Wave characteristics along the Sea of Japan coastline

The wave observation along the Sea of Japan coast was started since the early 1970s by the NOWPHAS. 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-mean 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 thirteen 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 nine 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.

2.2. Wave characteristics along the Pacific Ocean coastline

Previously, Shimizu et al. (2006) indicated that there was no significance trends in annual mean of significant wave height along the Pacific coastline, until 2004. However, several distinguishing features of wave climates have been detected in some other studies conducted along this coastline. Based on 10 years of observed data and 10 years of hindcast on wave climates, Okada et al. (1998) revealed that the wave height had shown an increasing trend in duration 1975-1994 at most of the stations along the Pacific coast of Japan. The averaged increasing rate among these stations is 0.6cm/year. Seki et al. (2011 and 2012) examined the long-term trend of wave characteristics on Japanese coast over the last 40 years. The results showed that significant wave height and period indicated increasing trends at some locations along the Pacific coastline. The annual mean of significant wave height increased at Mutsuogawara, Hitachinaka, and Nakagusukuwan. The increase of annual mean of significant wave period is concentrated on the northern sites of the coastline (Tomakomai, Hachinohe, Onahama, and Hitachinaka). Moreover, Shimada (2014) investigated summer wave height variability at this area and showed that significant decreasing trends in significant wave height were found in the south of northern Japan in August.

3. Objective

The first objective of this study is to quantify the long-term variation in wave characteristics for the last four decades measured at ten NOWPHAS's observed sites, which are located around Japanese coastline. The specific objectives of the present investigation are to: (i) analyze the monthly-mean wave properties averaged over the observation period in order to clarify the characteristics of seasonal variation; (ii) investigates the correlation between the significant wave height and period at the sites along the Sea of Japan; (iii) examine the long-term variations in annual- and monthly-mean wave properties on decadal time scales. The Mann-Kendall and the Lepage tests are then employed to detect increasing or decreasing trends in the measured dataset. These tests also clarify the significant level of the detected trends.

The second objective of this study is to investigates the characteristics of wave forcing and related morphological indices at the Kaetsu Coast, Ishikawa, Japan based on the wave data observed at the Kanazawa Port. The aim is to understand the following characteristics: (i) the seasonal distribution of wave energy flux relating to incoming wave direction; (ii) the characteristics of nearshore waves and related morphological indices that include breaker height and depth, closure depth, and Sunamura index; (iii) the characteristics of infragravity waves.

The third objective of this study is to quantify the relationship between climate change phenomenon and the variation of the long-term wave characteristics around Japanese coastline. It aims to clarify the following: (i) the correlation between the significant changes in variation of wave properties and various climate indices; (ii) the relationship between the variation of several meteorological factors, which include measured and reanalysis data, over the study duration and the significant changes of the wave properties. The Mann-Kendall and Lepage tests are also applied for trend tests of the aforementioned meteorological factors. In order to achieve these goals, comparative analyses of the data are conducted.

CHAPTER 2. METHOD OF ANALYSIS

1. Study area

This study investigates the long-term variation in wave characteristics for the last four decades measured at ten NOWPHAS's observed sites around Japanese coastline, in which four sites are located along the Sea of Japan coast and six sites are along the Pacific Ocean coast. Among four observation sites along the coastline of Sea of Japan, Kanazawa and Wajima sites have been selected for the wave analysis at northern Kaetsu coast. The others are Rumoi and Hamada that are located far (830 and 510 km) from Kanazawa or Wajima on the northern and southern part of the Sea of Japan.

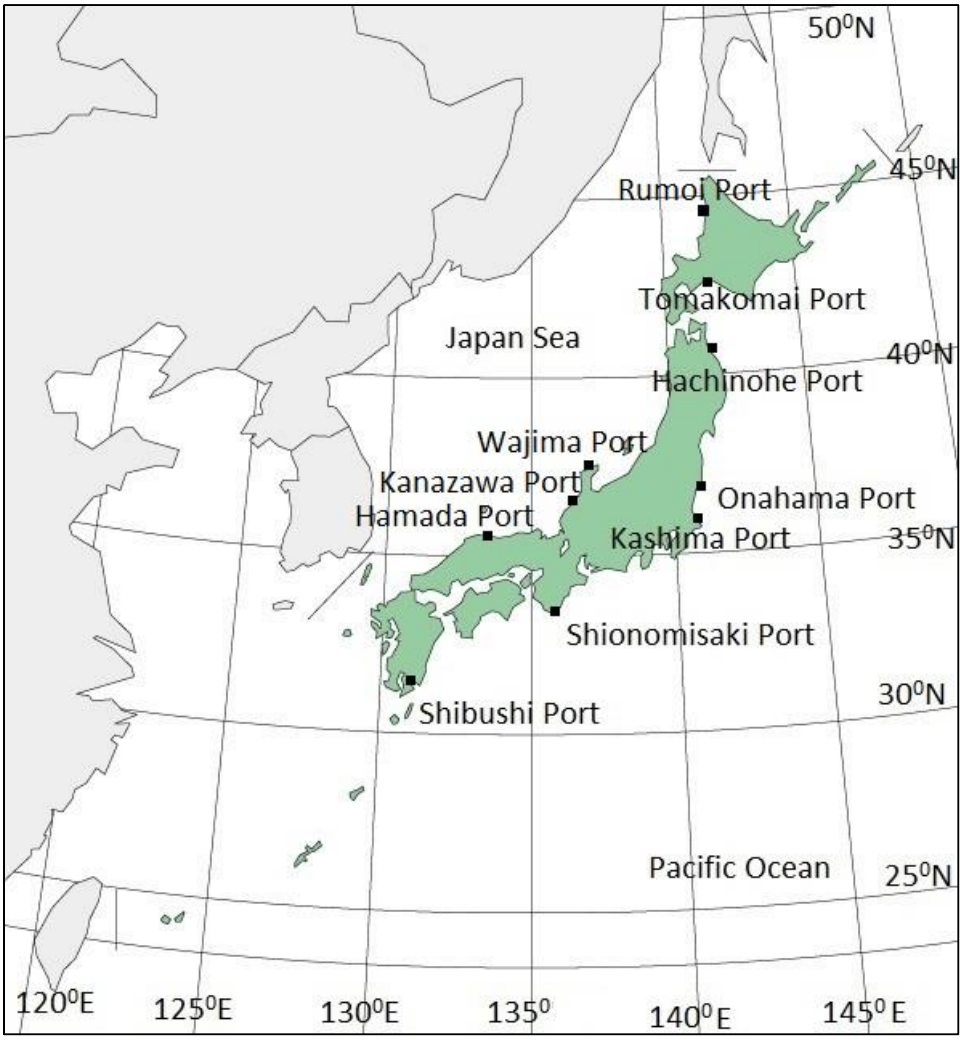


Figure 2.1 Location of research area

On the other side of the coast, six observed sites have been selected to represent three regional parts along the Pacific Ocean coastline, in which Tomakomai and Hachinohe sites are located at the north part, Onahama and Kashima represent the middle part, and the representative sites for the south part are Shionomisaki and Shibushi. The locations of the observed sites are shown in Figure 2.1. The site numbers, names, types and water depth of instruments setting, the periods of analysis data are summarized in Table 2.1.

Table 2.1 Wave measurement and analyzed period

Area	Site No	Site Name	Instrument type	Water depth (m)	Observed periods (Year. Month)		Analyzed period (Year. Month)
					Start	End	
Along the Sea of Japan coast	1	Rumoi	SRW	12	1970. 01	1978. 01	1978.02 ~ 2013.12
			USW	27	1978. 02	1981. 04	
			USW	49.8	1981. 04	1995. 09	
			DWDM	49.8	1995. 09	now	
	2	Wajima	USW	52	1979. 01	1995. 08	1979.01 ~ 2012.12
			CWD	27	1990. 08	1995. 08	
			DWDM	52	1995. 09	now	
	3	Kanazawa	USW	20	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	
Along Pacific Ocean coast	5	Tomakomai	SRW	13.3	1970.01	1977.12	1978.01 ~ 2013.12
			USW	24.5	1978.01	1981.12	
			USW	50.7	1982.03	1996.03	
			DWDM	50.7	1996.03	now	
	6	Hachinohe	PW	16.7	1971.03	1973.03	1973.03 ~ 2013.12
			USW	21.0	1973.03	1988.11	
			USW, CWD	27.7	1988.11	now	
	7	Onahama	USW	20.0	1980.01	1986.03	1980.01 ~ 2013.12
			USW, CDW	20.0	1987.03	2002.11	
			DWDM	23.8	2002.11	now	
	8	Kashima	USW	22.0	1972.04	1982.05	1972.04 ~ 2013.12
			USW	24.0	1984.03	now	
			CDW	24.0	1989.03	now	
	9	Shionomisaki	PW	12.8	1970.08	1986.11	1987.01 ~ 2013.12
			USW	54.7	1987.01	1997.08	
			DWDM	54.7	1998.08	now	
	10	Shibushi	USW	36.2	1980.04	now	1980.04 ~ 2013.12
			CWD	36.2	1991.11	now	

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

2. Datasets

2.1. NOWPHAS dataset

NOWPHAS is the wave observation network and analysis system around the Japanese coastaline. The wave characteristics have been measured from the early 1970s by this project. The number of observation sites of NOWPHAS has reached up to 61 until 2012 (Seki et al, 2012). In this research, datasets in duration of the last four decades at ten observed sites around Japan have been chosen. Since the record comprises more than 40 years, it is considered to be sufficiently long for the inspection of long-term changes. Five types of instruments,PW (Pressure-type Wave Gauge); SRW (Step-type Wave Gauge); USW (Ultrasonic-type Wave Gauge); CWD (Ultrasonic-type Current meter); and DWDM (Doppler-type Wave Directional Meter) have been used for the measurements at the sites

The observation data includes mean, significant, and 1/10 wave height and period. The measurement of wave direction at the Sea of Japan coastal sites (Rumoi, Wajima, Kanazawa, and Hamada) started respectively from 1996, 1991, 2004 and 2004. At Pacific Ocean coastal sites (Tomakomai, Hachinohe, Onahama, Kashima, Shionomisaki, and Shibushi) they started from 1997, 1992, 1992, 1991, 1994 and 2000, respectively. 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.

Table 2.2 Number of data at the ten sites

Area	Site No	Site name	Total data	Missing data	Percentage of missing data (%)
Along the Sea of Japan coast	1	Rumoi	153,408	13,260	9
	2	Wajima	149,028	19,537	13
	3	Kanazawa	176,064	27,174	15
	4	Hamada	166,536	40,105	24
Along the Pacific Ocean coast	5	Tomakomai	157,788	6,537	4.14
	6	Hachinohe	179,700	24,311	13.53
	7	Onahama	149,028	24,785	16.63
	8	Kashima	175,332	38,183	21.78
	9	Shionomisaki	113,964	10,993	9.65
	10	Shibushi	149,028	15,646	10.50

The measurements include both the normal observed values and the abnormal values(missing data). In this research, the acquisition rate for each measured year as well as each month was computed as a ratio between the number of normal values and the total number of values in that year or month. When the acquisition rate was less than 70%, the relative year or month was omitted in order to maintain the quality of the analysis. When seasonal features are analyzed, each season is defined as follows: spring, from March to May; summer, from June to August; autumn, from September to November; and winter from, December of the previous year to February.

2.2. Climate indices dataset

A climate index is used to describe the state and the changes in the climate system. The first classical climate indices of the atmosphere have been defined already about a hundred years ago, in which North Atlantic Oscillation (NAO) is the first found teleconnection pattern. Climate indices allow a statistical study of variations of the dependent aspects, such as analysis and comparison of time series, trends, and others. This study considers thirteen climate indices to make comparisons with the wave characteristics which have revealed significant changes in the study duration. Most of the climate indices dataset in the analysis are provided by Climate Prediction Center (CPC) of the United State of America through its open access website. Other indices are accessible through the websites of the Japan Meteorological Agency, and the Climate Data Guide. The time series of the data are available for both daily and monthly mean. To understand and predict changes in climate, ocean waves, and to reveal the connection between them, this study uses monthly mean values of various climate indices for comparison with the variation of wave characteristics. The used climate indices and the available websites for downloaded data are shown in Table 2.3.

2.3. ERA-20C dataset

The European Centre for Medium-Range Weather Forecasts (ECMWF), which is a producing and disseminating numerical weather predictions organization, has recently completed the computations of the ERA-20C dataset. This is an atmospheric reanalysis dataset, including the spatial-temporal evolution of the atmosphere and ocean surface wind waves, from January 1900 to December 2010. The assimilation methodology is 24-hour, 4D-Var analysis, with variational bias correction of surface pressure observations. Its final result has covered the longest and mostly global dataset. The continuous 110 year length of the ERA-20C datasets makes it possible to investigate the long-term trend of various features. In this study, the meteorological properties and wind waves (period and direction) dataset in July of duration 1970-2010 have been compared. The reanalysis datasets in this duration, which were retrieved from ERA-20C, include mean period and direction of wind waves, mean speed and direction of 10m above sea level wind, sea level pressure, and sea surface temperature.

Table 2.3 Climate indices dataset

No	Acronyms	Name of indices	Period of available data	Websites
1	NAO	North Atlantic Oscillation	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
2	EA	East Atlantic	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
3	WP	West Pacific	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
4	EPNP	East Pacific-North Pacific	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
5	PNA	Pacific-North American Pattern	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
6	EAWR	East Atlantic/Western Russia	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
7	SCA	Scandinavia	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
8	TNH	Tropical/Northern Hemisphere	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
9	POL	Polar/Eurasian	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
10	PDO	Pacific-Decadal Oscillation	1950-now	https://www.ncdc.noaa.gov/teleconnections/pdo/
11	AO	Arctic Oscillation	1950-now	http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml
12	ENSO	El Nino-Southern Oscillatin	1950-now	http://www.data.jma.go.jp/gmd/cpd/data/elnino/index/soi.html
13	NPI	North Pacific Index	1950-now	https://climatedataguide.ucar.edu/climate-data/north-pacific-np-index-trenberth-and-hurrell-monthly-and-winter

3. Analysis of wind wave characteristics

Wave properties are represented by some parameters as follows: wave height (H); the vertical distance between the crest and the trough; the horizontal distance between successive wave's crests is called a wavelength (L); and the time between successive wave crests is the wave period (T). A very important feature of waves is significant wave, the average of the highest one-third (33%) of waves occurring in a given time. This is adopted because of the importance of larger waves in comparison with the smaller. Significant wave height and period ($H_{1/3}$ and $T_{1/3}$) and the mean or the spectral peak wave period are the essential characteristics relating to this (Ferreira and Guedes Soares 2002, Dong et al., 2013).

Long-term wave characteristics are normally investigated based on a longtime field measured data. They can be figured out by statistical analysis methods. NOWPHAS is the wave observation network and analysis system around the Japanese coastal area. It is administrated and managed since 1970's so that it can provide necessary data for this analysis. The intention of this part is to analyze and clarify the measured wind-wave characteristics in the last four decades based on NOWPHAS observation data, includingsignificant wave heightand period, maximum wave height and period, direction of waves and some other features. The following wave characteristics are investigated: seasonal variation in wave height, period and direction; long-term variation in annual- and monthly mean wave height and period; characteristics of episodic events.

As shown in Table 2.1, wave characteristics have been measured in relatively shallow water areas at the ten sites. Accordingly, wave heights were first converted into corresponding deep water values based on the linear wave (shoaling) theory. The theory uses a velocity potential approach to trace the apparent movement of gravity waves on a fluid surface which is assumed to be incompressible and irrotational. The velocity V=V(u,v,w) at each point satisfies the governing equation for mass conservation, which is called as the continuity equation.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (2.1)$$

In which $u = \frac{\partial \phi}{\partial x}$, $v = \frac{\partial \phi}{\partial y}$, $w = \frac{\partial \phi}{\partial w}$, where ϕ is velocity potential.

By Substituting the velocity potential in the continuity equation (2.1), another equation will be obtained

$$\frac{\partial^2 \phi}{\partial x^2}+\frac{\partial^2 \phi}{\partial y^2}+\frac{\partial^2 \phi}{\partial z^2}=0 \qquad (2.2)$$

Equation (2.2) is called as Laplace equation. The Laplace equation is applied in many fields of physics and engineering. The solutions to this equation therefore vary in different boundary conditions. It is necessary to select an appropriate solution to the particular water wave motion. For a two-dimensional case of water waves, the Laplace equation is expressed as

$$\frac{\partial^2 \phi}{\partial x^2}+\frac{\partial^2 \phi}{\partial z^2}=0 \qquad (2.3)$$

In order to solve the Laplace equation, appropriate boundary conditions need to be provided. In terms of two-dimensional water waves, the boundary conditions are specified at the bottom boundary, the free-surface boundary, and the side boundaries. The free-surface boundary condition includes the kinematic free-surface boundary condition and the dynamic free-surface boundary condition. At the side boundaries, for water waves which are considered to be periodic in space and time, the periodic boundary condition is applied. The Laplace equation with the linearized boundary conditions can be solved with the technique of separation of variables. The velocity potential can be expressed in terms of *H*, *δ*, *h*, and *k* as follows

$$\phi = \frac{H\sigma}{2k}\frac{\cosh k(h+z)}{\sinh(kh)}\sin(kx-\sigma t) \tag{2.4a}$$

where *H* is wave height, *g* is gravity acceleration, *k* is the wave number, σ is the angular frequency of the wave, h is water depth. The corresponding water surface elevation $z=\eta(x,t)$ is expressed as

$$\eta(x,t) = \frac{H}{2}\cos(kx-\sigma t) \tag{2.4b}$$

By applying kinematic free-surface boundary condition, the relationship between σ and *k* will be established as

$$\sigma^2 = gk \tanh kh \tag{2.5}$$

In addition, a propagating wave will travel a distance of one wavelength *L* in one wave period *T*, and recalling that $\sigma=2\pi/T$ and $k=2\pi/L$, the celerity of wave propagation *C* can be expressed as follows

$$C^2 = \frac{L^2}{T^2} = \frac{g}{k}\tanh kh \tag{2.6}$$

Similarly, the wavelength can be obtained via the following equation

$$L = \frac{g}{2\pi}T^2 \tanh\frac{2\pi h}{L} \tag{2.7}$$

In order to demonstrate the relationship of wave characteristics in deep and shallow water area, another features of wave need to be considered, that are group velocity, C_g, and wave energy *P*.

$$C_g = nC \tag{2.8}$$

where *n* is a parameter which is defined as $n = 0.5(1+\frac{2kh}{\sinh 2kh})$

$$P = EnC \tag{2.9}$$

in which E is the total energy of wave per unit width of surface area

$$E=(1/8)(\rho g H^2) \tag{2.10}$$

Under the assumption of no energy losses or inputs, the energy conservation equation is obtained as follows

$$(EC_g) = (EC_g)_0 \tag{2.11}$$

(EC_g) corresponds for energy at the shallow water area, and $(EC_g)_0$ corresponds for energy at the deep-water area. Substituting equations (2.8) and (2.10) into equation (2.11), the relationship between wave heights in deep and shallow water area is obtained as:

$$\frac{H}{H_0} = \sqrt{\frac{1}{2n}\,\frac{C_0}{C}} = K_s \tag{2.12a}$$

K_s is the shoaling coefficient and it can be calculated from linear wave theory as follows:

$$K_s = 1/\sqrt{\tanh kh + kh(1 - tanh^2 kh)} \tag{2.12b}$$

Note that, K_s is a function of water depth and not of wave height. In deep water K_s =1.0. It takes a minimum of 0.91 at h/L_0 approximate 0.15 and as the water depth reduces it increases without limit.

In reality, the wave height is limited by wave breaking. The energy in a wave travels at the group velocity, which is related to the phase velocity by equation (2.8). In shoaling the group velocity changes at a different rate to the phase velocity and there is a corresponding change in wave height. Based on equations (2.12) that is demonstrated from linear wave theory, the wave characteristics in deep water area will be figured out as

$$H_0 = H/K_s \tag{2.13}$$

After converting the deep-water wave heights, the monthly-mean properties were then computed for the significant wave height and period in order to examine the seasonal variation and relation between them. Then, the long-term variation in wave height and period and characteristics of episodic events were considered. The seasonal variation of incoming wave direction in available duration has also been examined. When appropriate, the whole year was divided into four seasons: spring: from March to May; summer: from June to August; autumn: from September to November and winter: from December to next February. The values of annual-mean, maximum, and top 1% (quantified as the 99% quantile of wave height records) significant wave properties were also computed to investigate the long-term variation.

4. Analysis of wave forcing and related morphological indices

4.1. Estimation of potential deep-water wave energy

The wave energy flux of ocean irregular waves is given by the following equation (e.g. Takahashi and Adachi, 1989; Nagai et al. 1998)

$$W = \frac{\rho g^2}{32\pi} H_{rms}^2 T \tag{2.14}$$

where W the wave energy flux per unit length of wave-crest (N or W/m), ρ the water density (1025 kg/m^3), g the acceleration by gravity (9.8 m/s^2), T the wave period (s), and H_{rms} the root-mean-square wave height (m).

If the Rayleigh distribution is assumed, the relation between H_{rms} with deep-water significant wave height H_0 becomes (e.g. Goda (2010))

$$H^2_{rms} \approx \frac{1}{2}(H_{1/3})_0^2 \tag{2.15}$$

The period of component waves is assumed to be the same as the period of significant wave in deep water (Takahashi and Adachi, 1989; Nagai et al. 1998):

$$T = (T_{1/3})_0 \tag{2.16}$$

In combination of equations (2.14), (2.15), and (2.16), the wave energy flux is elucidated as

$$\mathrm{W} = \frac{\rho g^2}{64\pi}(H_{1/3})_0^2 (T_{1/3})_0 \tag{2.17}$$

The averaged wave power in a given time duration (t=0 to t_0) is calculated as follows:

$$WP = \frac{1}{t_0}\int_{t=0}^{t=t_0} W dt \cong \frac{1}{t_0}\frac{\rho g^2}{64\pi}\sum_{n=1}^{N} H_{0,n}{}^2 T_{0,n}\Delta t \tag{2.18a}$$

where the subscript n denotes the n-th value in the wave record, N is the total number of data during the given duration, and Δt is the time interval of each observation ($\Delta t = t_0/N$). In the analysis, the time intervals of statistical data processing (2 hours = 7,200 s) were used for Δt. The value of t_0 was set as the length of each month. The corresponding accumulative wave energy flux during the given duration is

$$E = WP \times t_0 = \int_{t=0}^{t=t_0} W dt \cong \frac{\rho g^2}{64\pi} \sum_{n=1}^{N} H_{0,n}{}^2 T_{0,n} \Delta t \quad (2.18b)$$

The monthly variation and directional distribution of wave power and corresponding accumulative energy fluxes were calculated based on equations (2.18).

4.2. Estimation of breaker heights and depths

In terms of breaking waves, the analysis combined the shoaling wave theory with the breaker height equation proposed by Keulegan and Patterson (1940) to calculate the breaker height (H_b) and depth (h_b) as:

$$H_b = \gamma h_b \quad (2.19)$$

Keulegan and Patterson defined the range of the values of γ between 0.71 and 0.78. It is noted that different researchers demonstrated different ranges of γ; for example, Munk (1949), based on solitary wave theory, showed that γ was approximately 0.78; Thornton and Guza (1982) took a field measurement and determined that the coefficient γ was in the ranges from 0.3 to 1.1; and others. This analysis used the value of 0.8 for γ.

The computation of breaker height and depth has been performed as follows: First, breaking wave heights and water depths were calculated based on the shoaling coefficient (2.13) and the breaking criteria (2.19); monthly variation of breaking wave heights and water depths were then figured out; the cumulative probability of occurrence for breaker heights $p(H_b)$ and depths $p(h_b)$ were estimated to deduce the seasonal variation of the width of the breaker zone. Corresponding cumulative occurrence probability (probability of non-exceedance) for breaker heights $P(H_b)$ and depths $P(h_b)$ were also examined.

$$P(H_b) = \int_0^{H_b} p(H_b) dH \quad (2.20a)$$

$$P(h_b) = \int_0^{h_b} p(h_b) dh \quad (2.20b)$$

4.3. Estimation of closure depths

The inner closure depth is defined as the seaward limit of significant cross-shore sediment transport by waves. On the basis of linear wave theory, Hallermeier (1981) proposed an inner closure depth formula for quartz sand in seawater as:

$$D_s = (2.28 - 10.9\frac{H_0}{L_0})H_0 \tag{2.21}$$

in which H_0 and L_0 are deep wave height and wave length, respectively.

This study uses the equation (2.21) to estimate the closure depth. The seasonal variation of occurrence probability $p(D_s)$ and the cumulative probability $P(D_s)$ at the study area were also analyzed.

4.4. Estimation of Sunamura index

Sunamura and Horikawa (1974) established a classification formula for shoreline changes by means of a non-dimensional parameter C, which has been known as Sunamura index, as following:

$$C = (H_0 / L_0)(\tan\beta)^{0.27}(d_{50} / L_0)^{-0.67} \tag{2.22}$$

in which, $\tan\beta$ is the average beach slope from the initial shoreline up to the critical water depth of sediment movement. d_{50} is the median diameter of sediment in the sea water. Sunamura (1980a) eliminated non-credible data and added new data to define the demarcation value of C of 18 for field observed data between recession and advance of shoreline; when $C > 18$ the shoreline was recessed, while it was advanced when $C < 18$. This research uses the equation (2.22) for the estimation of Sunamura index in order to reveal the seasonal characteristics of shoreline changes at the Kaetsu Coast.

The northern part of the Kaetsu coast is composed of gently sloping beach with fine sand. In this research, accordingly, the values of $\tan\beta = 0.01$ and $d_{50} = 0.18$ mm were used as typical values for the study area.

4.5. Analysis of infragravity waves

Initially, the datasets of infragravity waves were arranged into daily- as well as monthly-mean values. After that, the variations of the daily- and monthly-mean of infragravity wave heights were examined to clarify the seasonal variations. Then, the relation between infragravity wave heights and the significant wave heights in deep water were examined to reveal the connection between them.

5. Statistical tests

In this analysis, the Mann-Kendall tests (Kendall, 1938) and the Lepage tests (Lepage, 1971) have been conducted in order to detect significant trends or jumps in the long-term variations of wave characteristics as well as in necessary climate factors.

5.1. Mann-Kendall test

The Mann-Kendall (MK) test is a non-parametric test to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. The trend may or may not be linear. The null hypothesis H_0 assumes that there is no trend and this is tested against the alternative hypothesis H_1, which assumes that there is a trend. In a procedure of computation, the test considers the time series of N data points and X_i and X_j as two subsets of data where $i = 1,2,3,\ldots, N-1$ and $j = i+1, i+2, i+3, \ldots, N$. The data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values. If a data value from a later time period is higher than a data value from an earlier time period, the statistic S is incremented by 1. In contrast, if the data value from a later time period is lower than a data value sampled earlier, S is decremented by 1. The net result of all such increments and decrements yields the final value of S as following:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \mathrm{sgn}(X_j - X_i) \qquad (2.23)$$

in which X_j and X_i are the annual values in years j and i, $j > i$, respectively, N is the length of the dataset (number of years).

$$sgn(X_j - X_i) = \begin{cases} 1, & if\ X_j > X_i \\ 0, & if\ X_j = X_i \\ -1, & if\ X_j < X_i \end{cases} \qquad (2.24)$$

If $N < 10$, the value of $|S|$ is compared directly to the theoretical distribution of S derived by Mann and Kendall. The two tailed test is used. At certain probability level H_0 is rejected in favor of H_1 if the absolute value of S equals or exceeds a specified value $S_{\alpha/2}$, where $S_{\alpha/2}$ is the smallest S which has the probability less than $\alpha/2$ to appear in case of no trend. A positive/negative value of S indicates an upward/downward trend.

In case of $N \geq 10$, the statistic S is approximately normally distributed and the variance (σ^2) for the S-statistic is defined as:

$$\sigma^2 = \frac{N(N-1)(2N+5) - \sum t_i(i)(i-1)(2i+5)}{18} \tag{2.25}$$

in which t_i denotes the number of ties to extent i. The summation term in the numerator is used only if the data series contains tied values. The standard test statistic Z_s is calculated as follows:

$$Z_s = \begin{cases} \frac{S-1}{\sigma} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sigma} & if\ S < 0 \end{cases} \tag{2.26}$$

The test statistic Z_s is used a measure of significance of trend. In fact, this test statistic is used to test the null hypothesis, H_0. If $|Z_s|$ is greater than $Z_{\alpha/2}$, where α represents the chosen significant level (5% with $Z_{0.025}$ = 1.960; 1% with $Z_{0.005}$ = 2.576) then the null hypothesis is invalid implying that the trend is significant.

In this research, Mann-Kendall tests is conducted by a modified computaional program which uses Kendall's tau (τ) for the detection of trends of dataset. τ is defined on the ranks of the data as follows:

$$\tau = 4\left(\sum_{i=1}^{N} N_i / [N\,(N-1)]\right) - 1 \tag{2.27}$$

Kendall's τ always take values between -1 and +1. Detection of significant level trends can be examined by comparing τ and $\tau_{g(i)}$

$$\tau_{g(i)} = \pm\, t_{g(i)}\ [(4N+10)/(9N(N-1)]^{1/2} \tag{2.28}$$

in which $t_{g(i)}$ is the t-value for two-sided t-test. For i=1,N, the values of τ and $\tau_{g(i)}$ is calculated and then the significant level of test trends will be figured out by comparing them.

5.2. Lepage test

The Lepage test statistic is a combination of the Wilcoxon-Mann-Whitney and the Ansari-Bradley test statistics. It is a non-parametric test that investigates significant differences between two samples, even if the distributions of the parent populations are unknown. The definition of Lepage test (*HK*) is as follows:

$$HK=\{W-E(W)\}^2/\ V(W)+\{A-E(A)\}^2/V(A) \tag{2.29}$$

In (2.29)

$$W=\sum_{i=1}^{n_1+n_2} iu_i;$$

$$E(W)=\frac{1}{2}n_1(n_1+n_2+1);$$

$$V(W)=\frac{1}{12}n_1n_2(n_1+n_2+1).$$

Here, for $\{x=x_1, x_2,\ldots.., x_n\}$ and $\{y=y_1, y_2,\ldots\ldots..,y_n\}$, if a i_{th} smallest sample belongs to x, u_i=1, belongs to y, u_i=0.

When the size of each sample is equal to or greater than ten, the *HK* follows the chi-square distribution with two degrees of freedom. In such cases, when *HK* exeeds 4.210, (5.991), (9.210), the difference between two samples is judged at 10%, (5%), (1%) significant level, respectively. In this research, a computational program was developed to apply the Lepage statistical tests on procedure of jump detection. Only the differences at 5% and 1% significant levels were considered.

6. Comparison with climate indices and some meteorological factors

For the time scale of several decades, the influence of climate change is expected to have placed substantial impacts on the coastal zone. In order to investigate the relation between long-term variation of wave characteristics and climate change phenomena, some climate indices and several regional meteorological factors were examined to make comparisons with wave characteristics which have significant changes. For the change at northern Kaetsu area at the Sea of Japan coast, the year-to-year variation of several climate indices, including the Arctic Oscillation (AO), El Nino-Southern Oscillation (ENSO), Western Pacific (WP), and North Pacific Index (NPI) were investigated. The number of typhoons passing through the Sea of Japan area in July was examined. The impacts of El nino and La nina phenomena in study duration were considered as well. In addition, some observed meteorological data including wind velocity, sea level pressure, and air temperature in the area were taken into account. Finally, the mean of wind waves, 10m above sea level wind, sea level pressure, and sea surface temperature retrieved from ERA-20C datasets were also investigated. For the changes at northern Pacific Ocean side, monthly mean of all existed climate indices, including the WP, AO, ENSO, NPI, East Atlantic (EA), East Atlantic/Western Russia (EAWR), East Pacific-North Pacific (EP-NP), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Pacific/North American (PNA), Polar/ Eurasia Pattern (POL), and Scandinavia (SCAND) were divided into seasonally- and yearly-mean to make comparisons.

CHAPTER 3. LONG-TERM VARIATION OF WAVE CHARACTERISTICS ON THE KAETSU COAST, Ishikawa, JAPAN

1. Introduction

Kaetsu Coast is located on the middle north coast of Japan (Figure 2.1). The coastline includes approximately 75 km alongshore stretch and has a general NNE-SW orientation. This area has been suffering from various problems. The coast has experienced serious erosion for a long time under the combined influence of the persistent attack of high winter waves and human-related activities. On the northern area, the rip current accidents have frequently occurred in summer at the Uchinada district. Long-term reduction of coastal habitats is reported at Hakui area. For the time scale of several decades, the influence of climate change is also expected, that may cause further impacts on the coastal zone. In order to cope with these problems, physical understanding of long-term external forces is essentially important as basic engineering information.

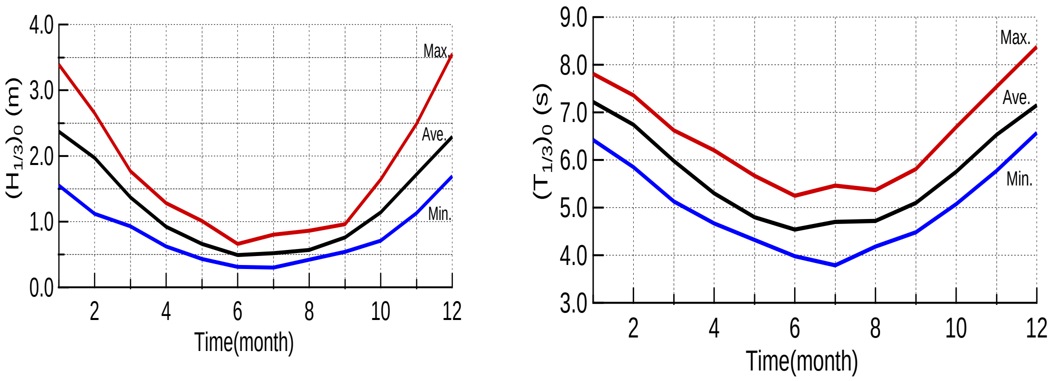
Among the natural forces acting on Kaetsu Coast, the influence of wave action is considered to be dominant, because this area is micro tidal with maximum tidal range of 0.4 m. Accordingly, this part of the study investigates the long-term variation in wave characteristics for the last four decades observed at Kanazawa Port, which is located at the middle of the coast. First, the monthly-mean wave properties averaged over the observation period are examined in order to clarify the characteristics of seasonal variation. The correlation between the significant wave height and period are investigated. The long-term variations in annual- or monthly-mean wave properties are then examined on decadal time scales. Two kinds of statistical test are conducted in order to detect significant changes. For the typical changes in monthly-mean wave properties, comparisons have been made with several climate indices and incoming wave direction.

2. Seasonal variation in wave height, period and direction

2.1. Monthly-mean wave characteristics

On the overall, the seasonal variation in wave characteristics at the Kaetsu Coast is significant, which is known as a distinguishing feature of the Sea of Japan coast. Generally, wave conditions are really calm during summer. On the contrary, the wave climate becomes violent in the winter season due to the strong East Asian winter monsoon. In spring and autumn, waves are the medium. Figures 3.1 show the seasonal variation in monthly-mean wave height and period, including the average, maximum, and minimum values in duration 1971-2012. The figures clearly illustrate that the wave heights and periods are the highest in winter, medium in spring and autumn and the lowest in summer. The mean heights of significant wave in summer are around 0.5 m, while they are greater than approximately 2 m in winter: the significant wave height in winter is approximately 4 times larger than in summer. In spring and autumn season, wave height is in the range 0.5 to 1.5m.

The seasonal variation of wave period is quite similar to wave height variation. The significant waves in winter have longer period and the mean values are around 7 s, while waves in summer have smaller period around 4.5 s. The significant wave periods in winter are around 1.5 times those of the summer. In spring and autumn, the wave period is in the range 4.5 to 6.5s. On July, the curve for average values is slightly distorted. This is related to a long-term change, which will be discussed later.



(a) Wave height **(b)** Wave period

Figures 3.1 Seasonal variation in Monthly-mean wave properties

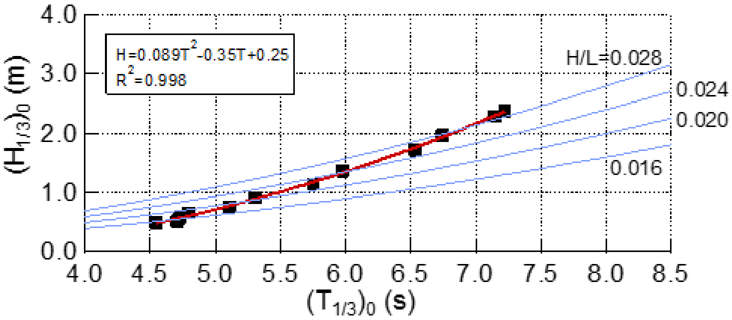
The maximum and minimum values of monthly-mean wave height and period indicate essentially the same patterns of variation. The strength of year-to-year variation in the same month can be inspected from the range of the data, which is defined as the difference between the maximum and minimum values. The figures clearly show that the range of wave height becomes larger in winter and smaller in summer, while the seasonal variation in the data range of wave period is weak.

Figures 3.2 show the relationship between the monthly-mean significant wave height and period, for (a) the average and (b) the maximum values during the observation period. In the figure, the regression results and several curves corresponding to typical wave slope (H_0/L_0) are also included.

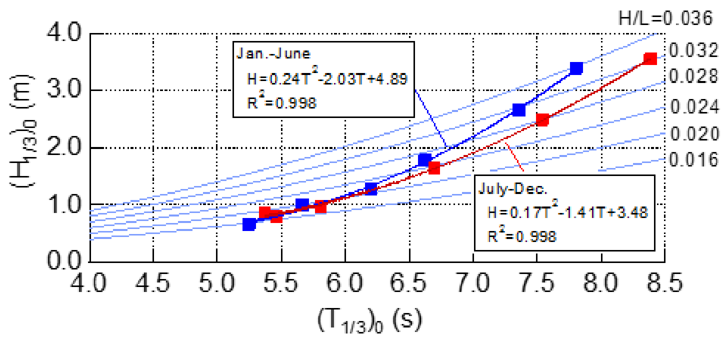
It is clearly shown in Figure . 3.2(a) that the mean values of wave height and period are strongly interdependent. They can be correlated very well with the following second order polynomial with the correlation coefficient of R^2=0.998:

$$H_{1/3} = 0.089 T_{1/3}{}^2 - 0.35 T_{1/3} + 0.25 \quad (3.1)$$

Waves in winter are steeper than in summer. For the mean values, the wave slope in summer is asymptotic to 0.016, while wave slope in winter becomes steeper (approximately 0.028).



(a) Average height and period



(b) Maximum height and period

Figures 3.2 Relationship between monthly-mean wave characteristics (1971-2012)

Similarly, the maximum values of monthly-mean wave height and period are closely correlated (Figure .3.2(b)), but the resulting curves are slightly different for January-June and July-December duration.

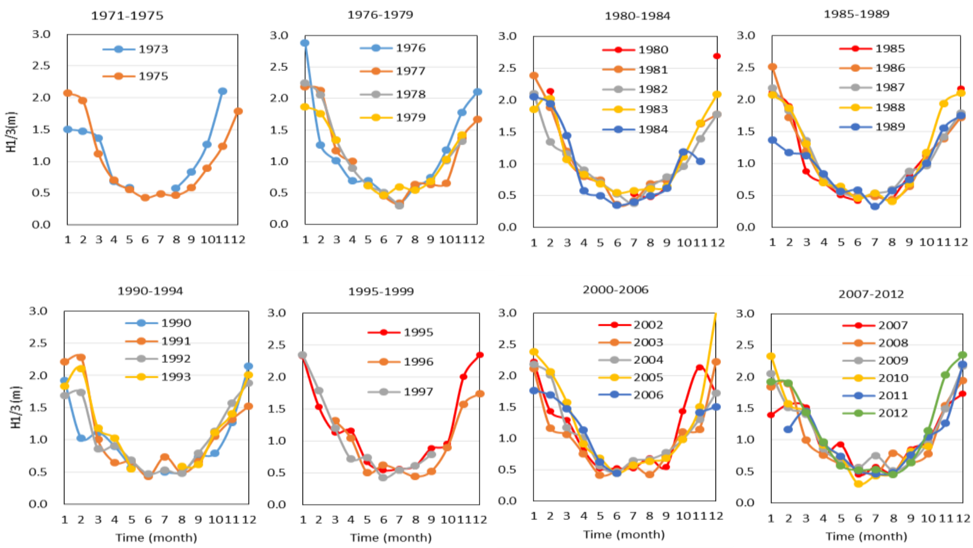
$$H_{1/3} = 0.24{T_{1/3}}^2 - 2.03T_{1/3} + 4.89 \quad (3.2a)$$

(from January to June)

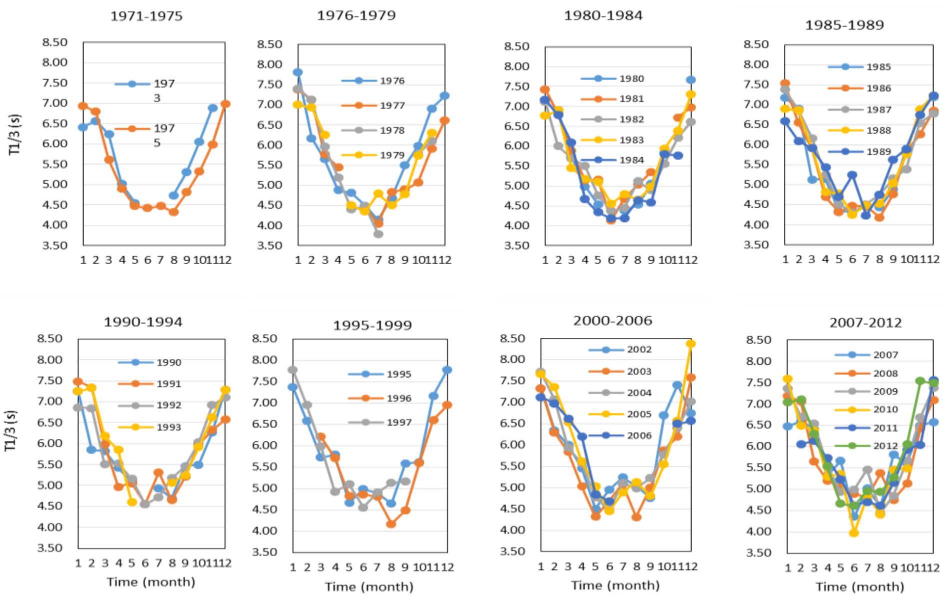
$$H_{1/3} = 0.17{T_{1/3}}^2 - 1.41T_{1/3} + 3.48 \quad (3.2b)$$

(from July to December)

The correlation coefficients are R^2=0.998 for both cases. The corresponding range of wave slope is from 0.016 to 0.036, which is wider than that of the average values. Interestingly, with the same value of wave period, wave slope in duration of January to June is steeper than in July to December.



(a) Wave height

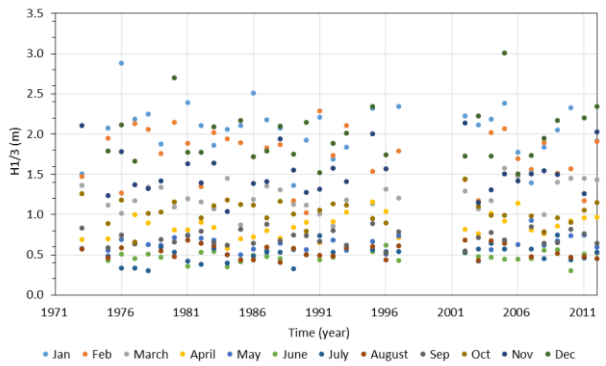


(b) Wave period

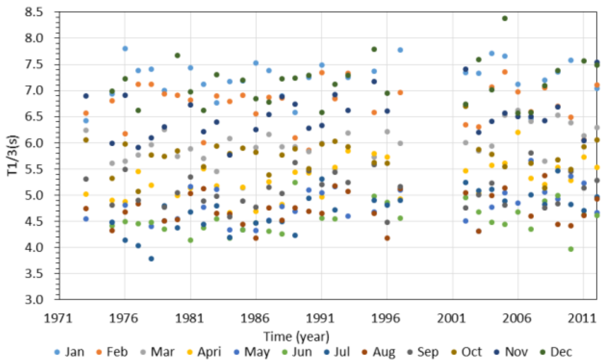
Figures 3.3 Monthly-mean wave characteristics in period 1971-2012

Figure 3.3 shows the monthly-mean wave characteristics for each year in measured duration from 1971 to 2012. In the figure, years and months that have an acquisition rate below 70% are ignored in order to suppress the influence of data errors. The figure illustrates that monthly-mean wave characteristics are largest in December 2005 and lowest in July 1978 with the values of 3.01m and 0.3m for wave height and 8.38s, 3.79s for wave period, respectively.

Figure 3.4 describes the variation of monthly-mean wave characteristics with time. This figure onece again illustrates that the values of wave characteristics on December 2005 and July 1978 are respectively the highest and lowest values. In addition, the figure also illustrates that the top three highest significant wave heights are 3.01m, 2.88m, and 2.70m appeared on December 2005, January 1976, and December 1980, respectively, while the three largest values of significant wave periods are 8.38s, 7.81s, and 7.79s occurred on December 2005, January 1976, and December 1995, respectively. This demonstrates that when a wave height reaches to the maximum value, the relating wave period may not reach the maximum one.



(a) Wave height



(b) Wave period

Figures 3.4 Long-term variation in monthly-mean wave characteristics

2.2. Statistics relationship between significant wave heights and periods

Figures 3.5 show the statistical relationship between significant wave height and period in the observed duration 1971-2012. In the analysis, the significant wave heights are divided into 8 levels from 1 m to 8 m. The significant wave periods are arranged into 9 levels from 2 s to 18 s. The number of waves that occurred in each range is counted to make the contour plots. In all the cases of dataset, the plots of significant wave heights and periods are restricted in the range of 0.5 m to 5.5 m and 2 s to 12 s, respectively.

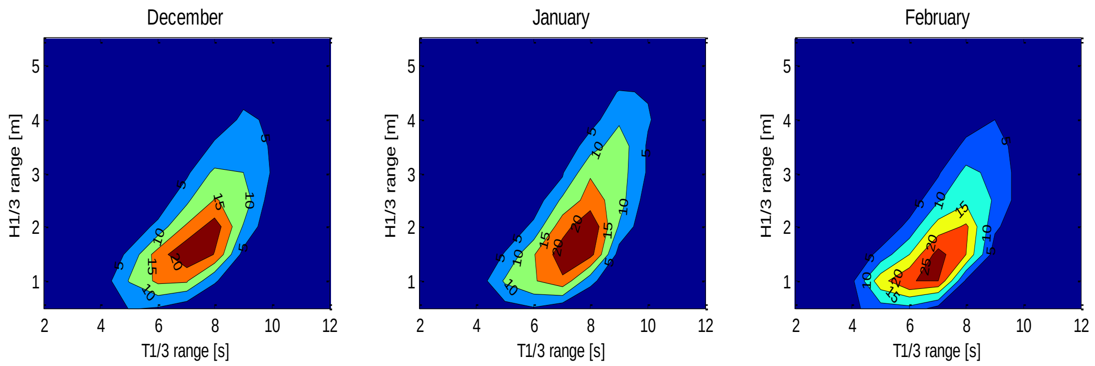
Figure 3.5(a) shows the relationship in the winter season. The wave periods are mainly from 4 s to 10 s and wave heights are from 0.5 m to 4.5 m. Figure 3.5(b) corresponds to the spring season, in which wave periods are mostly in the range of 3 s to 9 s and wave height in the range of 0.5 m to 3 m. Figure 3.5(c) represents the summer season, where almost of the wave heights are less than 2 m and wave periods are less than 8 s. Figure 3.5(d) shows the relationship in the autumn. Here, the number of wave heights in the range of 0.5 m to 4 m and wave periods in the range of 4s to 10s increase significantly in comparison with summer season.

3. Seasonal variation in wave direction

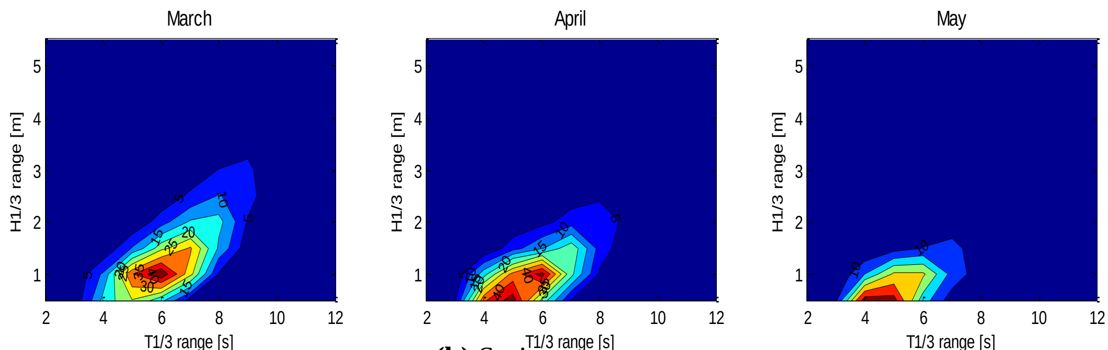
Wave direction is measured from 2004 to 2012. The average values are calculated to examine the seasonal trend in the following figures. In all months, the waves did not approach the direction between 40^o to 210^o because this is the land direction. Wave height and period are also included to analyze the seasonal variation of the relation between wave direction and wave heights or periods.

3.1. Seasonal wave direction relating to wave height

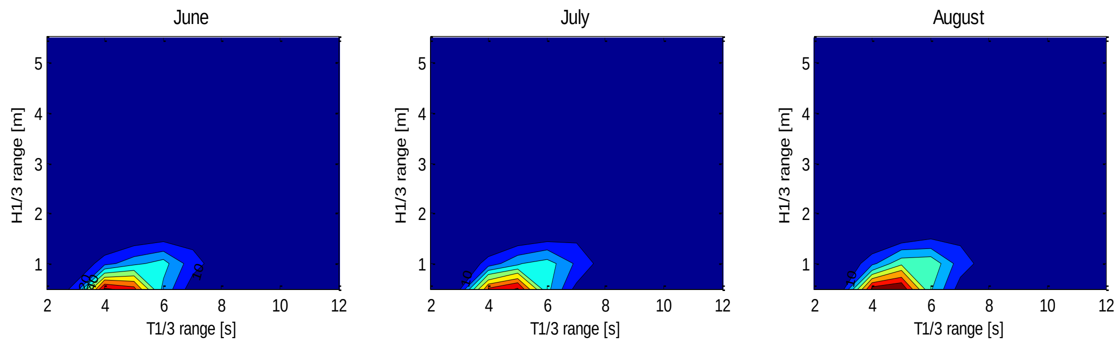
This part analyzes wave directions relating to wave heights. In the analysis, wave directions are arranged into 36 levels corresponding to the directional degree from 0^0 to 359^0. The wave heights that relate to wave direction are divided into 5 categories of height as follows: 0-0.99m, 1-1.99m, 2-2.99m, 3-3.99m, and higher than 4m. Figure 3.6 shows the average wave direction relating to wave height in duration 2004-2012. In general, waves in the winter season are high and approach the shoreline from NNW direction. In particular, wave direction is dominated by NNW direction (from 315° to 359°) in the winter season. The number of high waves is also remarkable. In spring, wave direction is still dominated by NNW but the dominant direction slightly moves to the West direction (270° to 315°).



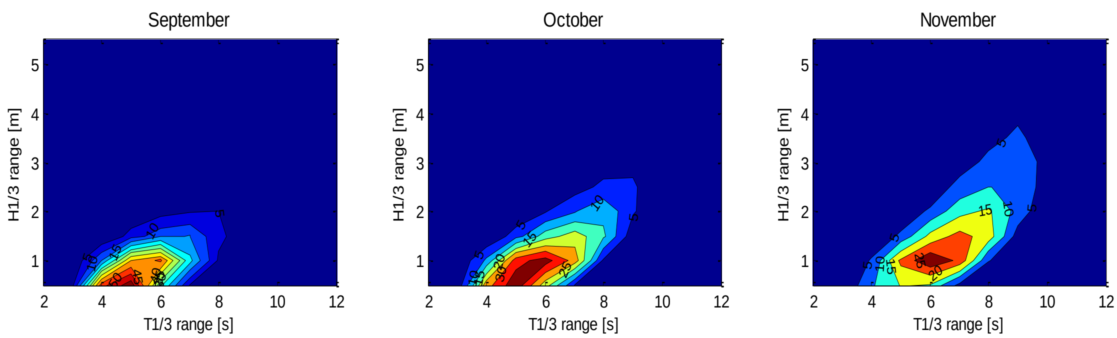
(a) Winter season



(b) Spring season



(c) Summer season



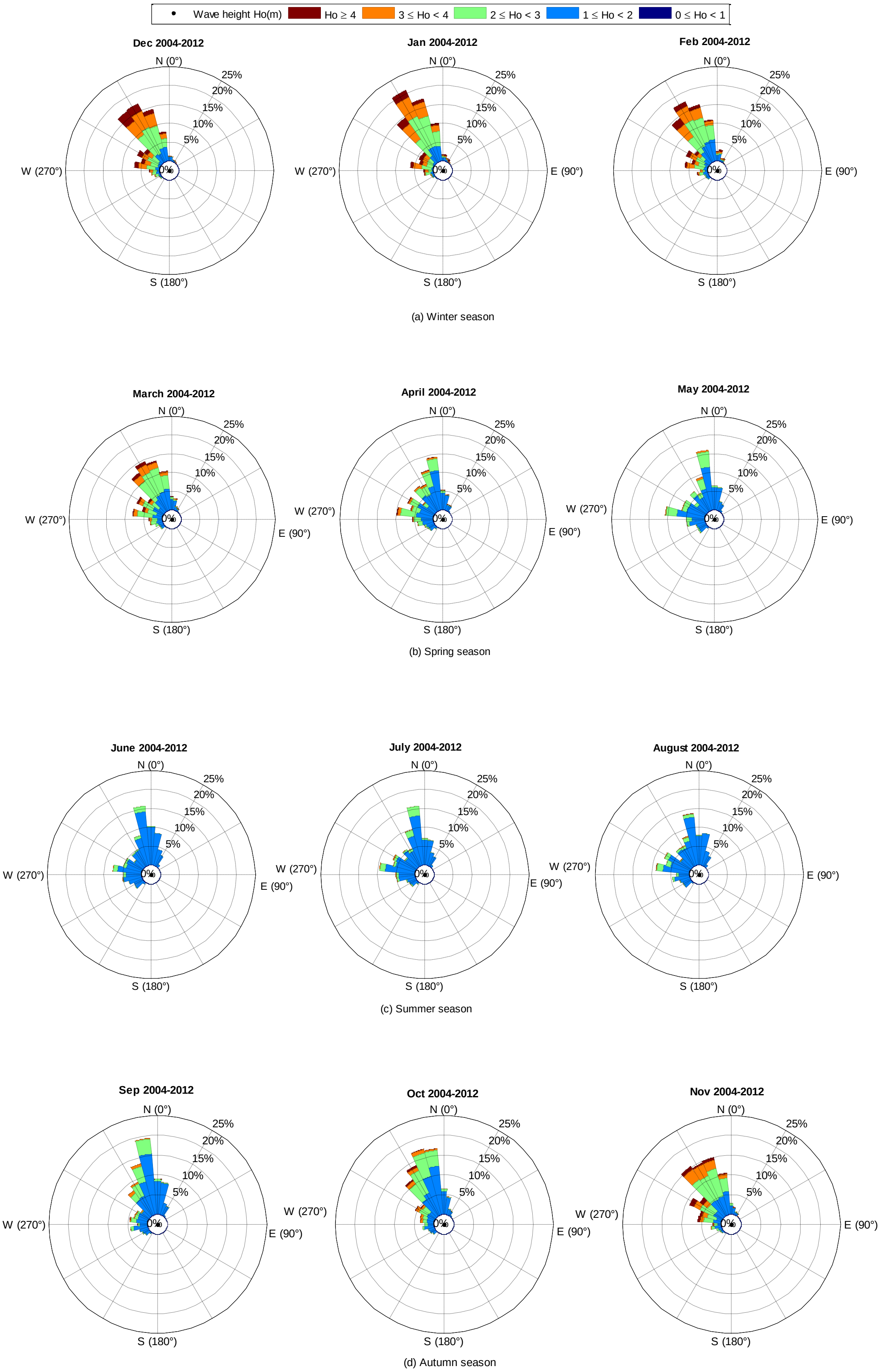
(d) Autumn season

Figures 3.5 The statistical relationship between significant wave height and period

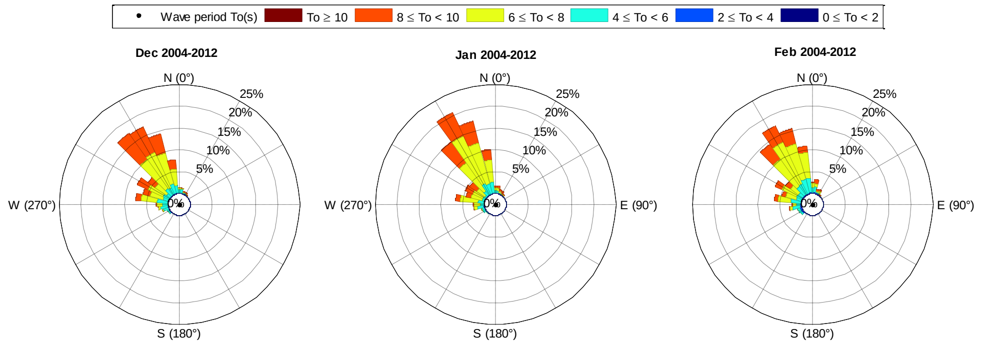
The number of high waves is decreased in comparison with that of the winter season. In summer, waves approach the shoreline mainly from both NNW (315^o to 359^o) and WNW (270^o to 314^o) direction. The number of waves in WNW direction significantly increases in comparison with that of the winter season. The wave heights are mostly less than 1m. This once again demonstrates that in summer season wave is calm. In autumn, waves approach the shoreline mainly from the NNW (315^o to 359^o) and the WNW (270^o to 314^o) direction. But the number of waves that approach shoreline in WNW direction have slightly decreased in comparison with that of the summer season. The wave height is higher than that of summer.

3.2. Seasonal wave direction relating to wave period

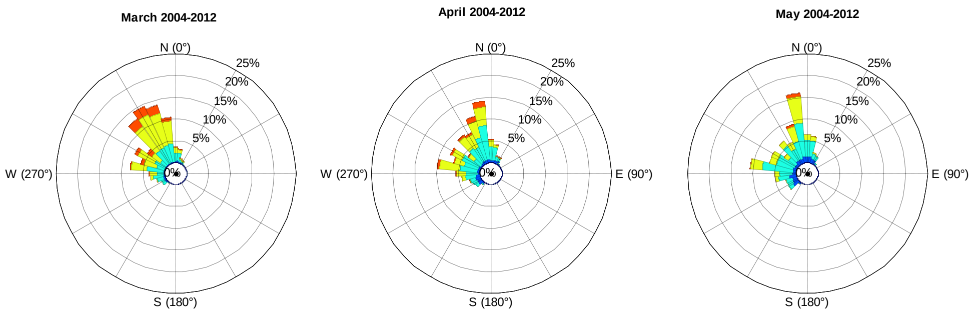
In this part, the wave periods that relate to wave direction are divided up into 6 categories of sizes as follows: 0-1.99s, 2-3.99s, 4-5.99s, 6-7.99s, 8-9.99s, and larger than 10s. Figure 3.7 shows the average wave direction relating to the wave period in duration 2004-2012. Here, the results of wave directions are the same with that of the analysis above. Waves approach the shoreline mainly from the NNW direction in winter season and NNW and WNW directions in summer season. In terms of wave period, the number of large wave periods is remarkable in winter season. In spring, the number of large wave periods is decreased in comparison with that of the winter season. In summer, wave periods are the lowest and mostly less than 6s. In autumn, the wave periods start to increase in comparison with that of summer seasons. In conclusion, waves in winter season generally have large periods and approach the shoreline from the NNW direction. As the time proceeds, the wave period decreases and the wave direction becomes spread out in summer season.



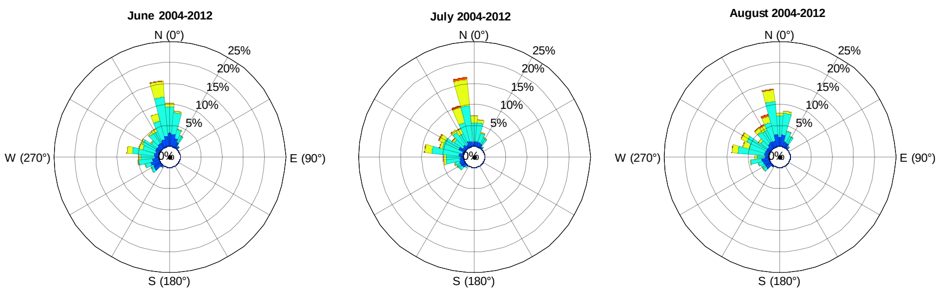
Figures 3.6 Wave direction relating to wave height in duration 2004-2012



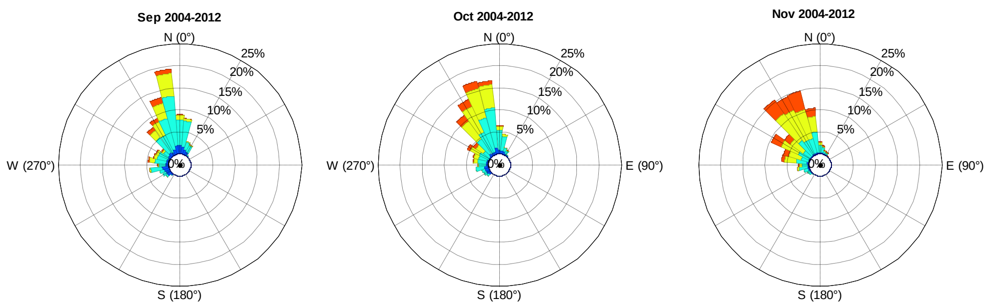
(a) Winter season



(b) Spring season



(c) Summer season



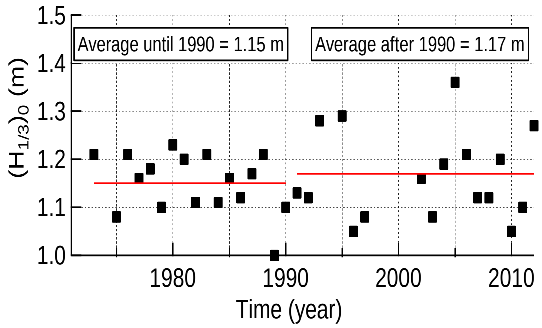
(d) Autumn season

Figures 3.7 Wave direction relating to the wave period in duration 2004-2012

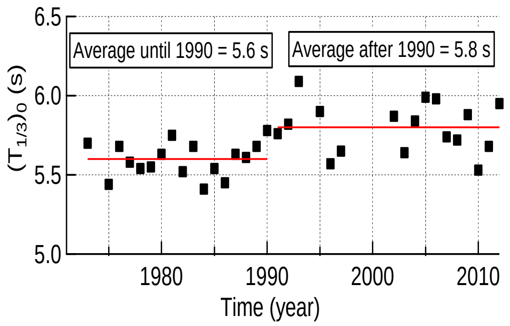
4. Long-term variation in wave height and period

4.1. Annual mean of wave height and period

Next, the long-term trends of variation in significant wave properties were analyzed in duration 1971-2012. Figure 3.8(a) shows the variation in annual-mean significant wave height. The figure illustrates that the significant wave height fluctuates between 1.00 and 1.36m. The statistical tests demonstrated that neither a trend nor a jump exists in the long-term variation. This is consistent with the analysis by Shimizu et al. (2006) based on the observation around Japan over 35 years. A close inspection of Figure 3.8(a) indicates that the data is more scattered recently: the standard deviation in the last two decades (0.09 m) has substantially increased compared with that in the first two decades (0.06 m). According to Figure 3.8(b), in contrast, the annual-mean significant wave period in the last two decades has noticeably increased to 5.8 s from the value in the former period (5.6 s). The Mann-Kendall test showed an increasing trend in wave period significant at the 1% level. The Lepage statistics with the sample size of 15 years also detected an abrupt jump in the annual-mean significant wave period around 1990 at the 1% significant level. 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 6.09s, and the standard deviations in the first two decades and last two decades have a noticeable discrepancy as well, in which the values are 0.11 s and 0.15 s, respectively.



(a) Annual-mean wave height

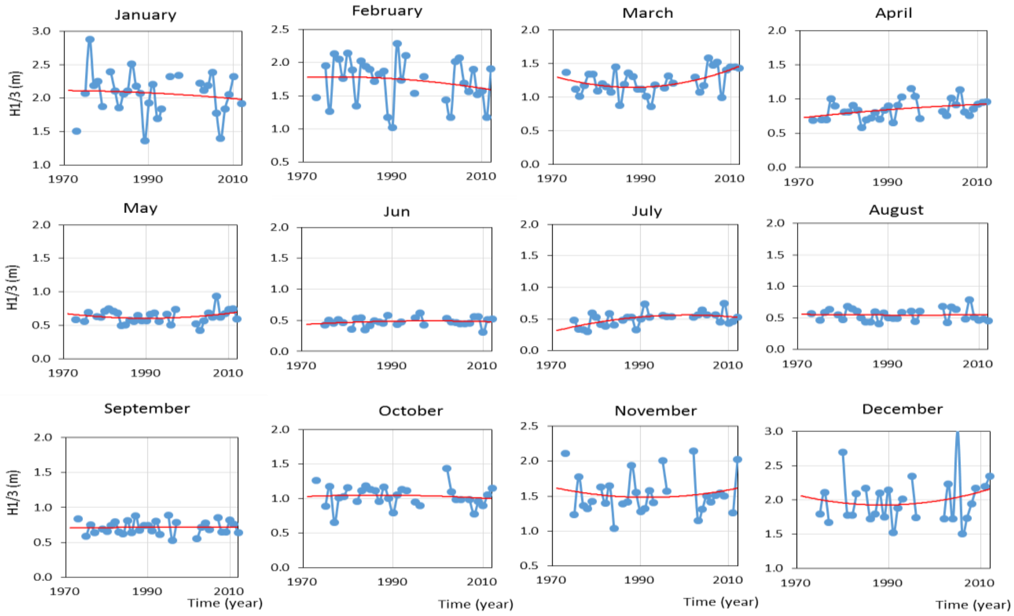


(b) Annual- mean wave period

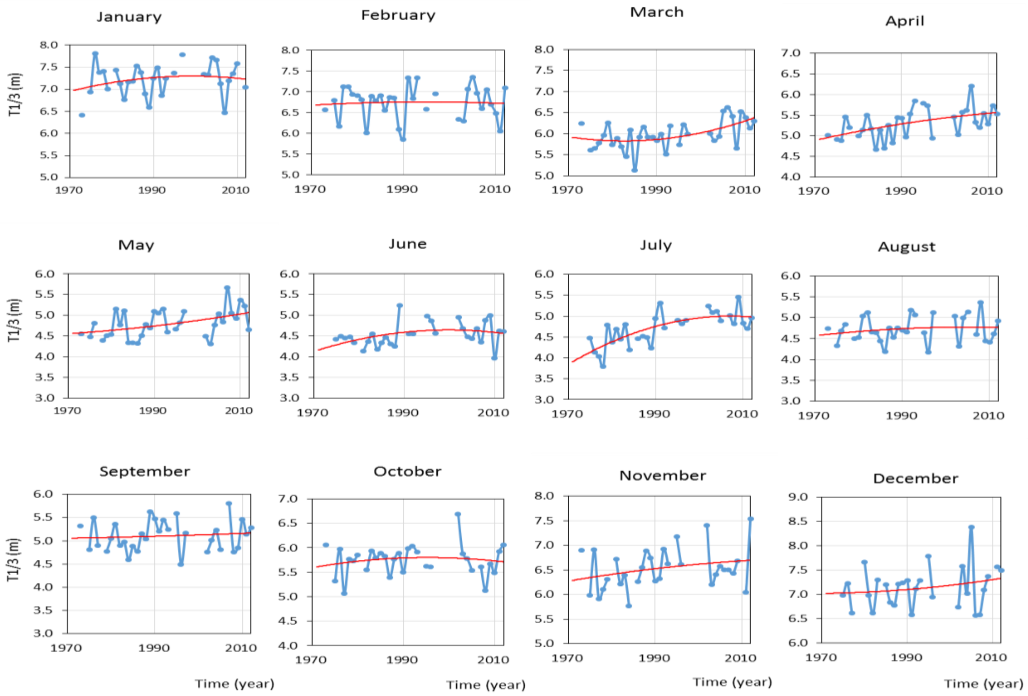
Figures 3.8 Long-term variation of significant wave characteristics

4.2. Monthly-mean of wave height and period

The long-term variation in monthly-mean wave height and period were examined next. Figure 3.9 describes the long-term variation in monthly-mean significant wave characteristics, in which the trends of the data are added, in the duration 1971-2012. In July, wave characteristics seem to have a remarkable increasing trend. This confirms the distorted curve in average significant wave period which was revealed in the Figures 3.1.



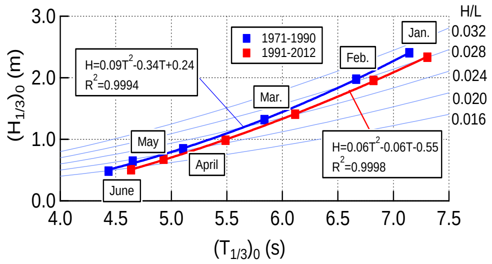
(a) Wave heigh



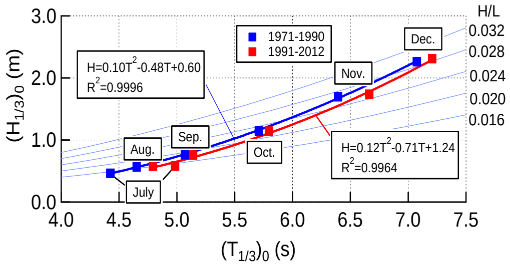
(b) Wave period

Figures 3.9 Monthly wave characteristics (1971-2012)

Figures 3.10 show the relationship between the monthly-mean significant wave height and period, which are averaged over two different durations: from 1971 to 1990 and from 1991 to 2012. The variation of wave heights between the first two decades and the last two decades are not significant in general. In contrast, wave periods in the last two decades are always greater than that in the first two decades. In particular, the wave periods in July have significantly increased from 4.43s in the first two decades to 4.98s in the last two decades.



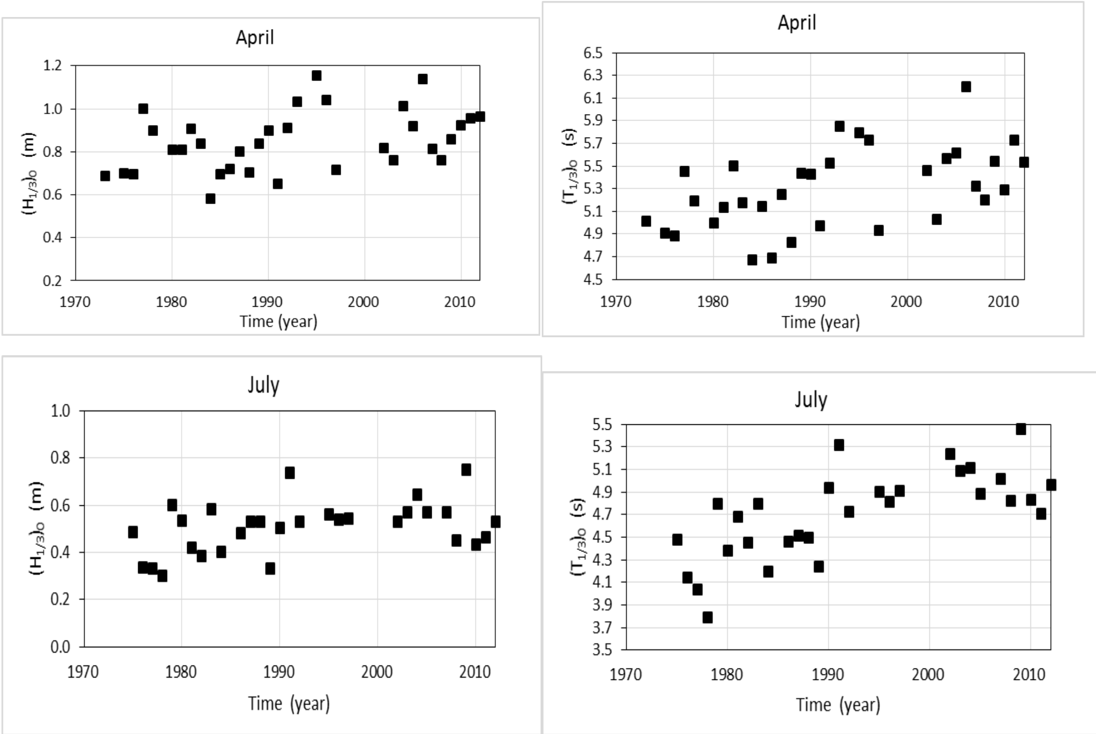
(a) From January to June



(b) From July to December

Figures 3.10 Comparison of the relationship between monthly-mean wave characteristics over two periods

In order to detect the increasing/decreasing trend in monthly-mean wave height and period, the Mann-Kendall statistic tests have been conducted. For the wave height, the statistics indicated an increasing trend of the 5% significance level in April and July. The Mann-Kendall statistics also demonstrated that the wave period in March, April and July have increasing trends significant at the 1% level. The wave period in May also has an increasing trend at the 5% level. The variations in typical months, where significant trend has been detected, are shown in Figures 3.11. A remarkable increasing tendency of wave period in July is recognized. Around the study area, previous related studies have pointed out the existence of an increasing trend in wave period during spring and summer. The present results are consistent with these observations. Moreover the results obtained in the present study clarified that the change in spring are commonly seen from March to May, but the change in summer is concentrated in July.



(a) Wave height **(b)** Wave period

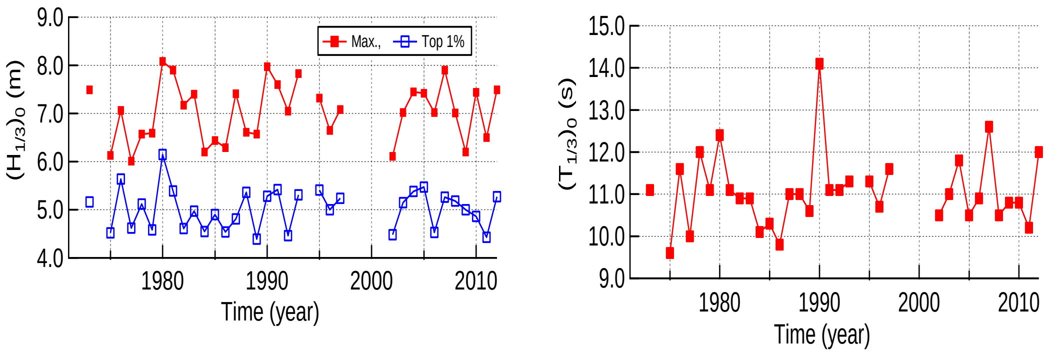
Figures 3.11 Long-term variation of monthly-mean significant wave characteristics in April and July

In order to obtain a further understanding on this distinguishing feature, wave characteristics in July of Wajima Port, which is 90 km northward from Kanazawa Port (Figure .2.1), were investigated. At Wajima, wave data are available from 1979 to 2012. The data have been examined separately by 2 different durations: 1979-1990 and 1991-2012. The results show similar features to Kanazawa site: the wave period in the second duration has an increasing trend in comparison with that in the first duration, while the tendency in wave height variation is not clear. In addition, the variation in wave period is also significant in July: The averaged value in 1979-1990 is 4.69s, while it is 5.19s in 1991-2012. The more detailed analysis about the wave characteristics at Wajima site will be discussed in the next chapter.

5. Characteristics of episodic events

The maximum wave heights and periods fluctuate in a wide range. Figure.3.12(a) demonstrates that 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 Figure .3.12(b), it is shown that the maximum of the significant wave period was 14.1 s at 1990. Mase et al. (2009) mentioned the increasing tendency of maximum wave height around this site. As far as maximum and top 1% values are concerned, however, the statistical tests indicated no significant changes.



(a) Maximum and top 1% waves height **(b)** Period of maximum significant waves

Figures 3.12 Long-term variation in episodic wave characteristics

6. Correlation with climate indices

As mentioned above, the Mann-Kendall and Lepage statistical tests indicated a remarkable increasing tendency of wave period in July. In order to deduce the possible cause of the change, several attempts have been made. First, the year-to-year variation of wave period in July is compared with several climate indices, including the Arctic Oscillation (AO), El Nino-Southern Oscillation (ENSO), Western Pacific (WP), and North Pacific Index (NPI). While other indices have little correlation, WP index expresses a light impact on this change. Figure 3.13 shows the relation between monthly-mean wave period in July and corresponding WP index. The WP index seems to have weak negative correlation with R^2= 0.22.

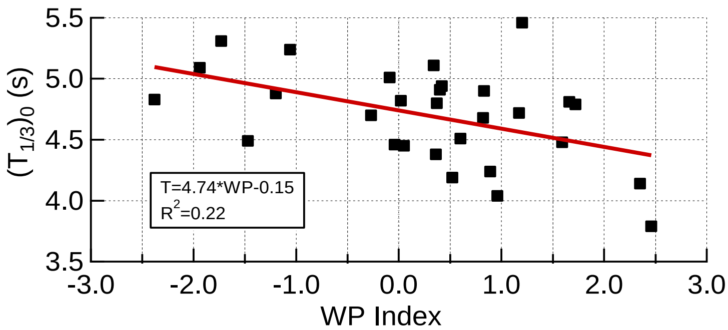
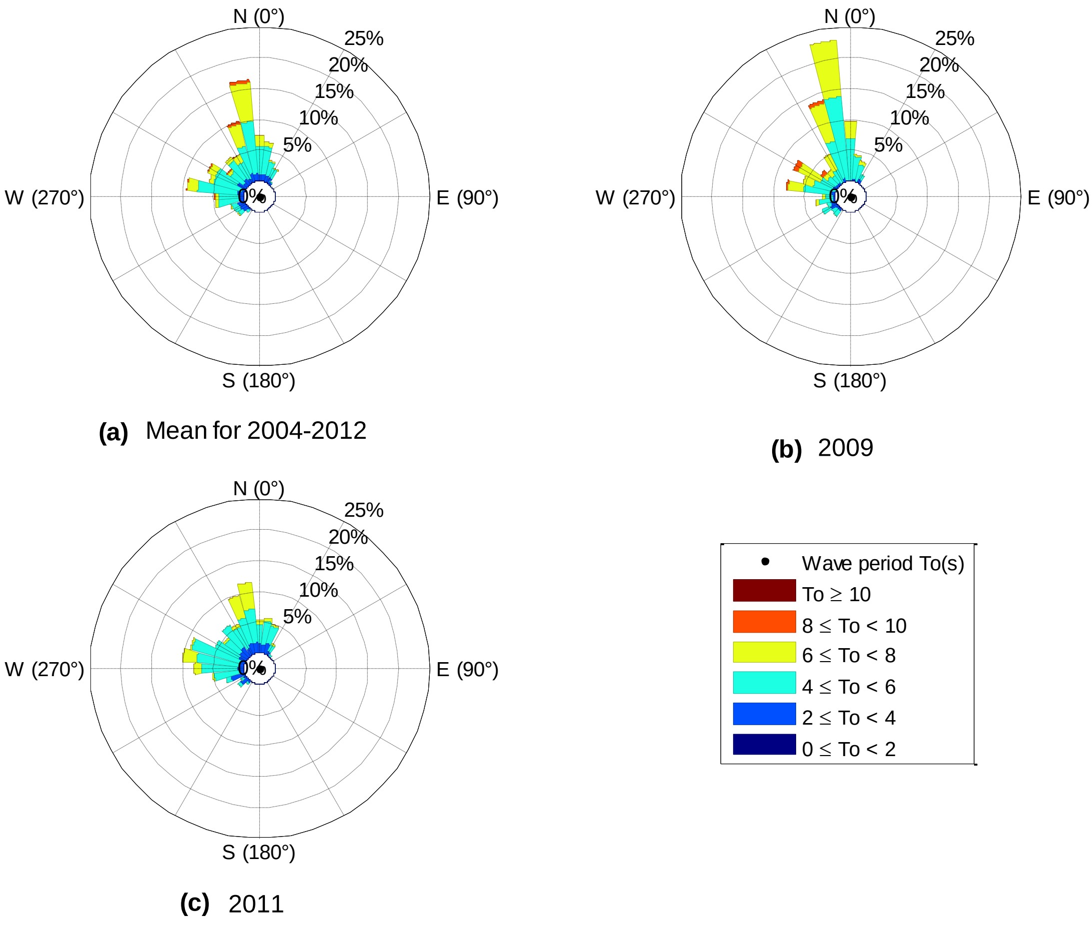


Figure 3.13 Relationship between monthly-mean wave period and Western Pacific index in July

Next, the number of typhoons passing through the Sea of Japan area in July has been examined. The number of typhoons increased in the duration 1991-2012, but the year-to-year change indicated little correlation with wave period variation. Furthermore, several correlation analyses were conducted using the wind data in July based on JRA-55 (the Japanese 55-year Reanalysis) datasets provided by Japan Meteorological Agency. The tendency is, however, not clear. r The correlation between meteorological factors and wave properties are discussed further in detail in Chapter 7.

Finally, the influence of incoming wave direction is discussed based on the recent observation of wave direction. Figure 3.14 compares the distribution of incoming wave direction for the typical years when the wave period is long (2009) and short (2011). The averaged distribution over 2004-2012 is also included. The results imply that when the incoming waves from the NNW are quite dominant, the wave period becomes longer. On the contrary, when the waves from the WNW are equally important the wave period becomes short.



Figures 3.14 Wave direction relating to wave period in July

7. Summary

This part of the study examined the long-term wave data observed at the Kanazawa Port in duration 1971-2012 in order to clarify the long-term as well as the seasonal characteristics in significant wave properties. On the overall, the seasonal variation in wave height, period, and direction were shown to be significant. The monthly-mean wave height and period were correlated with second order polynomials very well. The annual-mean wave period indicated an abrupt increase around 1990. The increase of wave period was most significant in July.

Since the wave characteristics in July could have an impact on the occurrence of rip current accidents, it is important to understand the characteristics of these phenomena and to deduce the possible causes. Future projection is also desirable. For these purposes, more detailed analysis is needed based on the numerical simulation for the wind, wave and current field over the study area.

CHAPTER 4. CHARACTERISTICS OF WAVE FORCING AND RELATED MORPHOLOGICAL INDICES AT THE KAETSU COAST, JAPAN

1. Introduction

The ocean wave statistics play a key role in a variety of coastal projects. An accurate estimation of wave characteristics is of crucial importance, for example, in the planning of countermeasures against wave-induced coastal disasters, the design and management of ports, the utilization of wave energy, the mitigation of accelerated erosion of sandy beaches, the conservation of coastal ecosystem, and others. As a dominant external force on the coastline, the basic information on incident wave characteristics is extremely important to cope with these devastating problems.

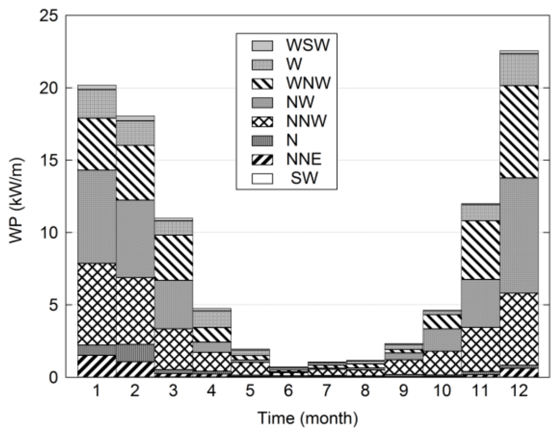
Located on the middle north coast of Japan, the Kaetsu Coast in Ishikawa Prefecture faced to the Sea of Japan. The coastline includes approximately 75 km alongshore stretch and has a general NNE-SW orientation (Figure .2.1). The coast has experienced various problems related to wave and sediment dynamics during the last decades such as the destruction of coastal facilities by violent winter waves, the rapid and severe erosion over the most part of the alongshore stretch; the frequent occurrences of rip current accidents in summer, the reduction of coastal habitats, and others. Since the waves act as the principal driving force of sediment transport and are closely related to morphological change in many of these problems, physical understanding is needed not only for the wave characteristics themselves but also for the influence on morphological responses.

On the wave climate along the Sea of Japan coast, several studies in the last decades demonstrated that the seasonal variation of wave height and period is significant (e.g. Kobune et al. (1988); Nagai (1997); Shimizu (2006); Yamaguchi et al. (2007); Seki et al. (2011,2012). Chapter 3 demonstrated the results of a detailed statistical analysis on the seasonal and long-term variability of wave characteristics at the Kaetsu Coast based on the long-term wave record at Kanazawa Port in duration 1971-2012. The results clarified the characteristics of long-term as well as seasonal variability of wave height, period, and direction at the Kaetsu Coast. The focus was, however, placed on the variation of wave properties at the offshore; the available information is limited for the wave properties in the nearshore area, and the related influence on the sediment transport and morphological changes has not been discussed yet. It is therefore desirable to extend the analysis and further explore the seasonal variability of wave behavior in the nearshore area and to estimate the resulting morphological response to variable wave forcing.

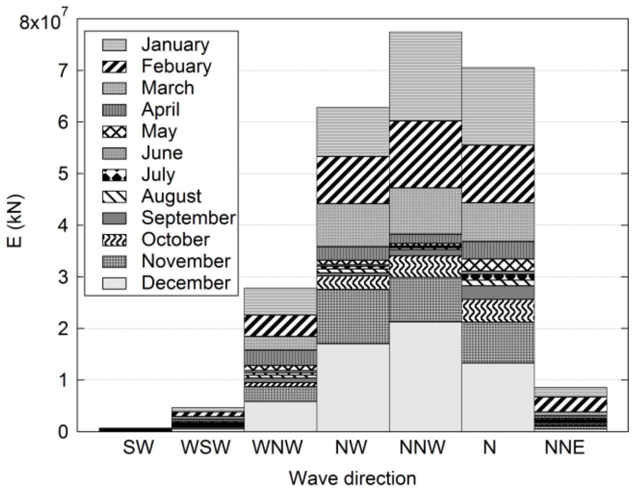
Accordingly, this part further investigates the characteristics of wave forcing and expected morphological responses at the Kaetsu Coast based on the long-term wave data observed at Kanazawa Port in duration 1971-2012. First, as a complementary analysis to Chapter 3, the monthly and seasonal variation of wave energy flux at the offshore area is investigated in combination with the directional distribution to understand the seasonal variability of the magnitude and direction of wave forcing. Second, several kinds of morphological indices that are closely related to incident wave properties are examined in order to deduce the characteristics of morphological response to the seasonally-varying wave conditions. For this purpose, the characteristics of wave breaking in the nearshore region, breaker height and depth, are examined in order to deduce the seasonal variation of the cross-shore width of surf zone where significant morphological changes occur. Moreover related morphological indices such as the closure depth and Sunamura index are estimated to discuss the seaward extent of significant morphological change and the dominant direction of cross-shore sediment movement, respectively. The occurrence probabilities and the probability of non-exceedance of these properties are then computed based on the monthly-mean values. Based on the cumulative probability of breaker depth, closure depths and the Sunamura index the seasonal variation of the width of breaker zone and the advance and recession of shoreline are discussed. Finally, the characteristics of infragravity waves (long-period waves), that is known to strongly affect the swash zone dynamics during high waves (e.g. Guza and Thornton, 1982; Masselink et al. 2003), are investigated to clarify the relation with wind wave characteristics.

2. Energy flux of offshore wind waves

The seasonal and directional variation of wave power, which is defined as the energy flux of the incoming waves per unit time and (alongshore) width, is shown in Figures 4.1. In these figures *WP* indicate the averaged values over 2004-2012. Clearly, the wave power in winter is much larger than that in summer. In winter the wave power is around 20 kW/m, while it is just about 1 kW/m in summer. The values are about 6 kW/m in spring and autumn. The corresponding accumulative energy flux *E* is approximately 1.6×10^8 kN in winter, 8.0×10^6 kN in summer, and 5.0×10^7 kN in each of spring and autumn. The accumulative incoming wave energy flux in winter reaches 60 percent of the total energy. Generally, at Kanazawa Port, the waves approach shoreline from the SW to NNE direction. The annual mean of wave power coming from all of the directions is about 8.2 kW/m. The corresponding annual energy flux is 2.6×10^8 kN. Among them, the WNW, NW, and NNW are the dominant directions of wave incidence in which the wave energies are concentrated. The annual-mean wave power from these dominant directions is 6.6 kW/m and corresponding accumulative wave energy (2.1×10^8 kN) reaches 80 % of the total. It is noted that these dominant directions of wave energy incidence represent the dominant wave direction in winter season.



(a) Monthly variation of wave power



(b) Directional distribution of accumulative energy flux

Figures 4.1 Distribution of incoming wave energy in duration 2004-2012

Next, the year to year variation of wave power was examined. Figures 4.2 show the directional distribution of wave power in two typical years. In 2005 the total wave energy flux over a whole year was the highest (E=3.6×10^8 kN) and in 2007 it was the lowest (E=2.5×10^8 kN). In 2005 the annual mean of wave power is about 11.4 kW/m and the dominant direction of incoming waves is the NW. In 2007 the annual mean of wave power is approximately 7.7 kW/m and the dominant direction of waves slightly moves to the WNW.

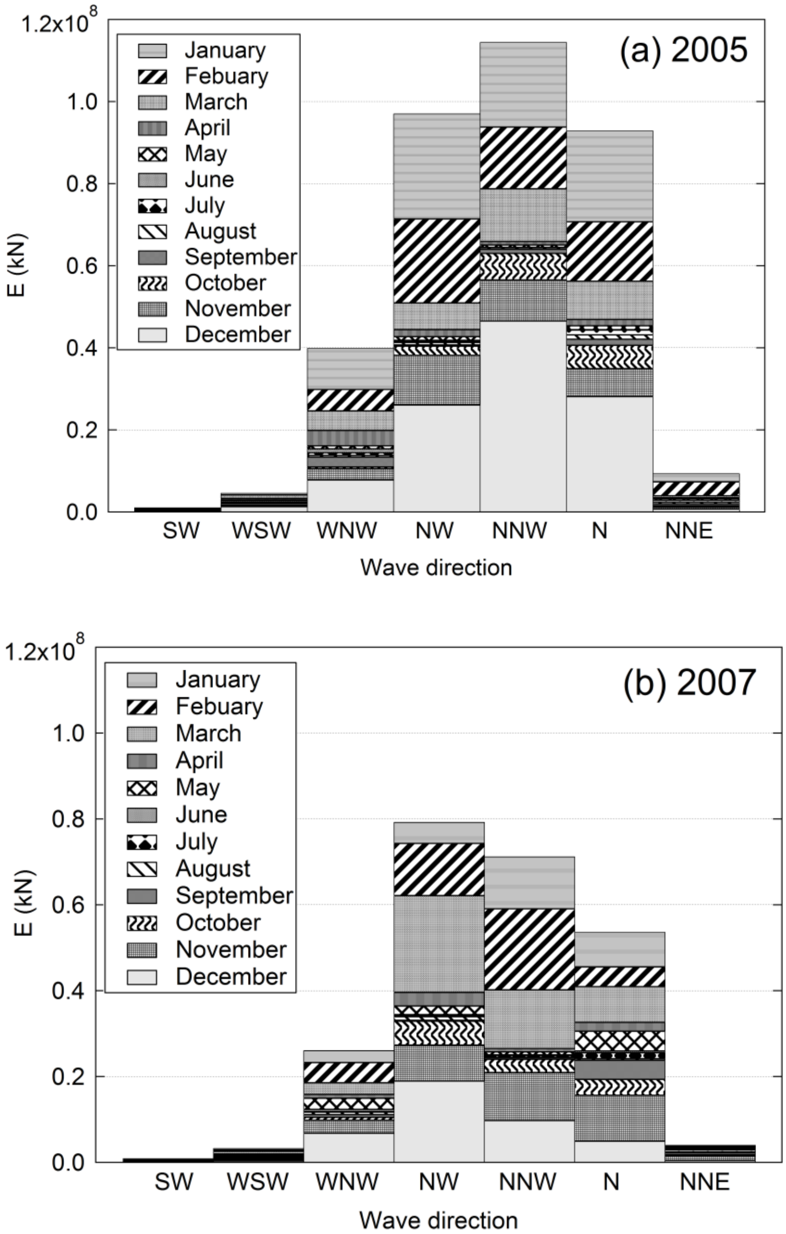


Figure 4.2 Directional distribution of accumulative wave energy flux in two typical years

3. Characteristics of nearshore waves and related morphological indices

3.1. Breaker Heights and Depths

The monthly means of the breaker heights were investigated to examine the seasonal variation of breaker zone where significant morphological change is expected to occur. Figure 4.3 shows the variation in monthly-mean of breaker heights, including the average, maximum, and minimum values in duration 1971-2012. These figures clearly illustrate that the breaker heights are the highest in winter, medium in spring and autumn and the lowest in summer. The average values of breaker heights in summer are around 0.6 m, while they are greater than 2.0 m in winter. In spring and autumn, breaking wave height is in the range 0.6 to 2.0 m. In addition, the mean values correlate very well with the following second order polynomial with a high correlation coefficient (R^2 = 0.99).

$$H_b = 0.06(t\text{-}6.75)^2 + 0.54 \quad (4.1)$$

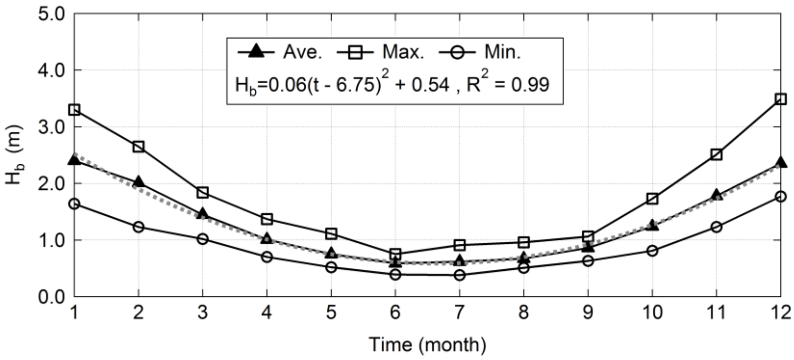


Figure 4.3 Seasonal variation of monthly-mean breaker height at Kanazawa

The seasonal variation of breaker depths at the breaking points is quite similar to breaker height variation as shown in Figure 4.4. The breaker depths in winter are the deepest with the mean values approximately 3.0 m, while in summer they are the shallowest, around 0.8 m. In spring and autumn, the water depths are in the range 1.0 m to 2.0 m. Moreover, the mean values correlate very well with the following second order polynomial, in which the correlation coefficient is similar to that of average breaker height (R^2 = 0.99).

$$h_b = 0.76(t\text{-}6.64)^2 + 0.68 \quad (4.2)$$

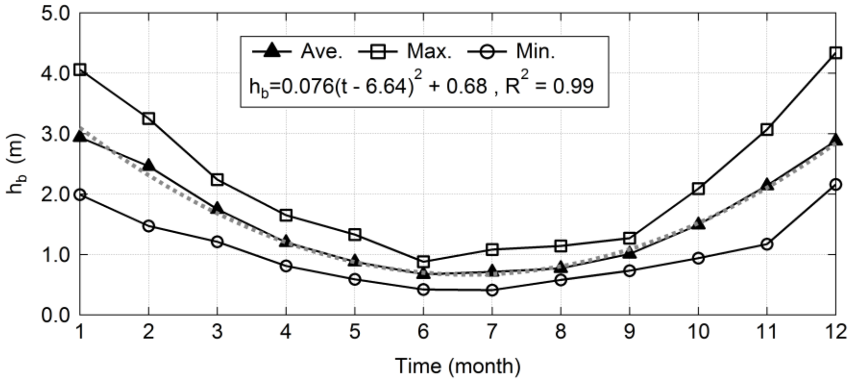


Figure 4.4 Seasonal variation of monthly-mean breaker depth at Kanazawa

The maximum and minimum values of monthly-mean of breaker height and depth indicate essentially the same patterns of variation. The strength of year-to-year variation in the same month can be inspected from the range of the data, which is defined as the difference between the maximum and minimum values. The figures clearly show that the range of both breaker height and breaker depth become larger in winter and smaller in summer. The averaged maximum and minimum values of breaker heights are approximately 3.5 m and 0.4 m, respectively. The averaged maximum value of breaker depth is 4.3 m, while the averaged minimum value is 0.4 m.

Next, the cumulative occurrence probability of breaker depth $P(h_b)$ is investigated for duration 1971-2012 for each season. According to Figure 4.5, in winter season 80 percent of waves break at the area with water depths less than approximately 4.0 m, while in summer this value is just approximately 1.0 m. Namely, in summer the waves break only in the narrow area very close to the shoreline. In the spring and autumn the corresponding water depth is around 2.0 to 2.5 m.

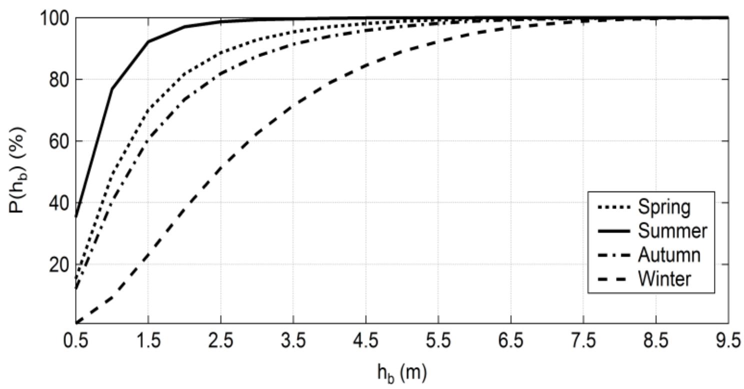


Figure 4.5 Cumulative probability distribution of breaker depth in duration 1971-2012

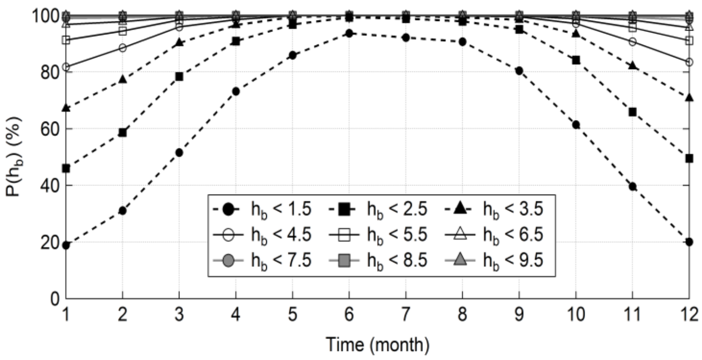


Figure 4.6 Monthly cumulative distribution of breaker depth in duration 1971-2012 at Kanazawa

Figure 4.6 indicates the monthly variation of cumulative occurrence probability of breaker depth in duration 1971-2012. In winter season 10 to 20 percent of waves break at the breaker depths larger than 4.5 m. In summer, the waves do not break at the water depth more than 2.5 m. In spring and autumn the waves break at water areas shallower than 5.5 m. These results indicate that the cross-shore width of surf zone where intensive morphological changes occur is substantially variable in time at the Kaetsu Coast.

3.2. Closure Depths

The cumulative occurrence probability of inner closure depths $P(D_s)$ in duration 1971-2012 at Kanazawa are shown for each season in Figure 4.7. In winter season, the closure depths are estimated to be less than 6.0 m approximately 80 % of time. In contrast, in summer season, the closure depths are less than 2.0 m more than 80 % of time. In spring and autumn, the closure depths are around 3.0 m about 80 % of time.

Next, the monthly variation of cumulative occurrence probability of inner closure depth is examined in Figure 4.8. The figure illustrates that in winter season the inner closure depths are mostly less than 10.0 m. In summer, 4.0 m seems to be the limitation of closure depths. In spring and autumn, most of closure depths are less than 7.0 m.

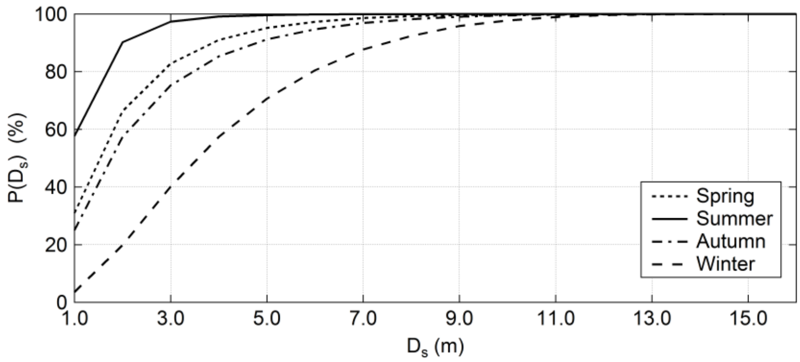


Figure 4.7 Cumulative probability of inner closure depths in duration 1971-2012

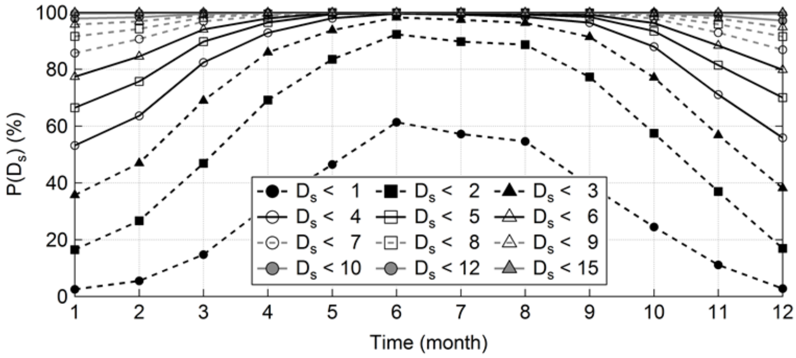


Figure 4.8 Monthly cumulative probability of inner closure depths in duration 1971-2012

3.3. Sunamura Index

The variation of monthly-mean Sunamura index in duration 1971-2012 were investigated. The minimum, mean and maximum values for each month were plotted in Figure 4.9. The Figure illustrates that the values of Sunamura indices are the lowest in summer season, the averaged mean value is around 15. In contrast, in winter season these indices are the highest with the values of larger than 50. In spring and autumn season these indices are the medium, in which the values in the range 18 to 35. Referring to the demarcation value of Sunamura index, it is inferred that during summer season the shoreline is advanced and the recessions of shoreline generally occur in other seasons. The transitions from recessions to advances of the shoreline occur in March, from advances to recessions in September. The minimum and maximum of monthly values are approximately 10 and 64, respectively. In addition, the monthly mean values of Sunamura indices correlate very well with the following second order polynomial with high correlation coefficient (R^2 = 0.99).

$$C = 1.1(t\text{-}6.55)^2 + 15.14 \quad (4.3)$$

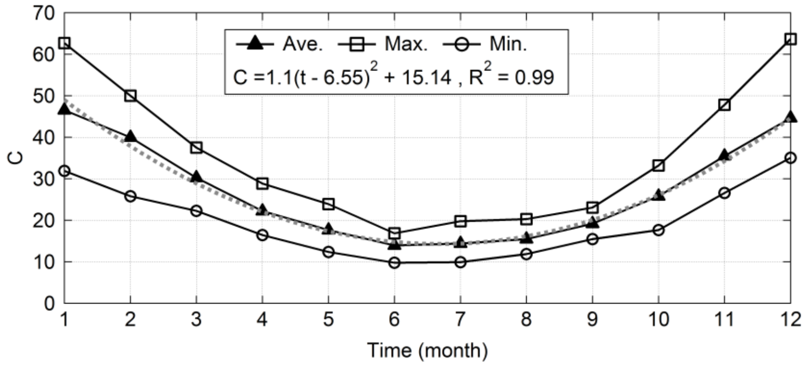


Figure 4.9. Monthly variation of Sunamura index in duration 1971-2012 at Kanazawa

Next, the cumulative occurrence probability of Sunamura index $P(C)$ is examined for each season in Figure 4.10. It shows that in winter most of waves induce recession of the shoreline, in which the percentage for $C > 18$ reaches around 90 %. In contrast, the majority of waves in summer have a role to advance the shoreline. In this season C is less than the threshold value over 70 % of time. In spring and autumn, approximately 50 to 60 percent of waves induce shoreline recession and 50 to 40 percent make the shoreline advance, respectively.

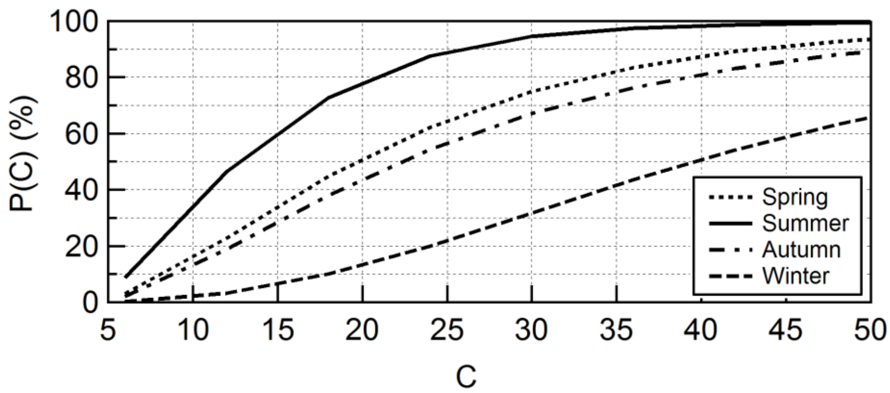


Figure 4.10 Cumulative probability of Sunamura index in duration 1971-2012 at Kanazawa

Next, the monthly variation of occurrence probability corresponding to shoreline advance $P\ (C<=18)$ was rearranged and plotted in Figure 4.11. According to the figure, in June the percentage of Sunamura indices less than 18 is approximately 80 percent of time. This is ten times higher than that in January or December which is just 8 percent. In spring and autumn the rate of change in $P\ (C<=18)$ is large. The probability exceeds 50 percent from May to September. From these results it is deduced that the dominant direction of cross-shore sediment transport is landward during May to September, while it alternates to seaward during October to next March. In April, where *P* (*C*<=18) is approximately 50 %, the net amount of sediment transport in the cross-shore direction is inferred to be small.

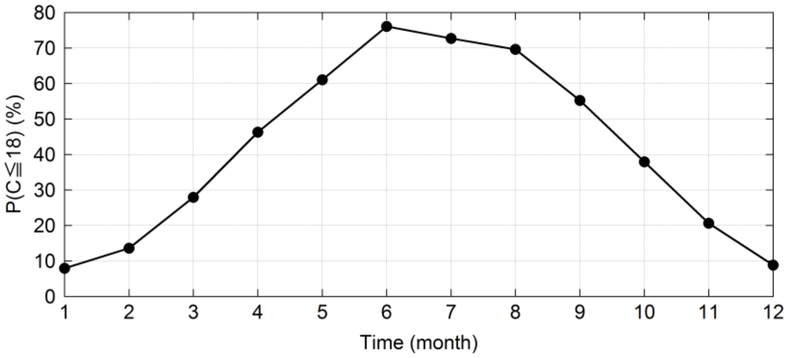


Figure 4.11 Monthly variation of probability for waves with *C*<=18 in duration 1971-2012 at Kanazawa

4. Characteristics of infragravity waves

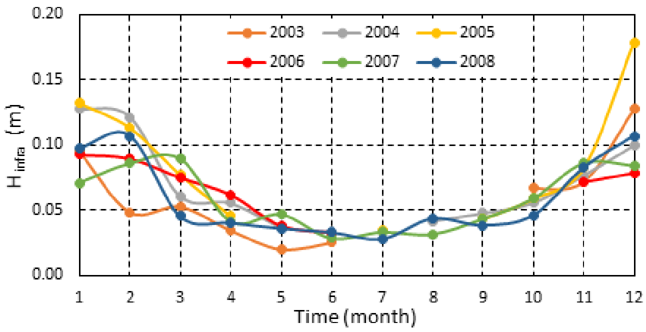
4.1. Seasonal variation

The variation of infragravity waves also have significant seasonal changes like that of wind waves. Figure 4.12 describes the seasonal variation of monthly-mean height of infragravity waves observed at Kanazawa for year by year (Fig.4.12(a)) and the corresponding averaged values (Fig.4.12(b)). The monthly-mean heights averaged over the duration are around 0.030 m in summer, while in winter they are around 0.100 m. The standard deviations were also examined to investigate the scatter of data. The standard deviations in summer are less than 0.01 m, while they are 0.02 to 0.03 m in winter. In the figure, the maximum and minimum values in the same duration are also included. The maximum values of the monthly-mean heights during the observation period are approximately 0.035 and 0.130 m in summer and winter, respectively. The minimum values are around 0.025 m in summer and 0.080 m in winter. The monthly variation of infragravity wave heights in duration 2003 to 2008 can be approximated very well by the following second order polynomial with a correlation coefficient of R^2=0.97. $(H_{infra})_{ave} = 0.003(t - 5.67)^2 + 0.046$ (4.4)

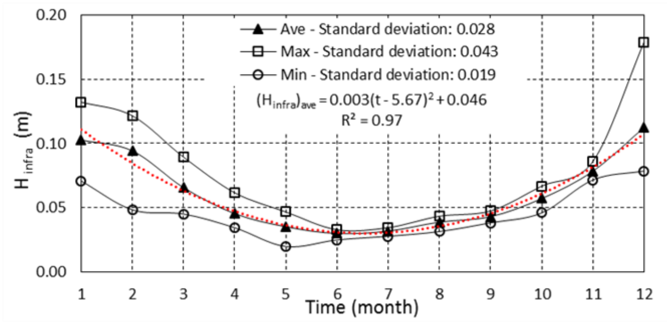
The variation of daily-mean infragravity waves averaged over 2003-2008 are then investigated (Figure 4.13). The daily values in winter are the highest which vary from 0.04 to 0.18m while in summer they are the lowest with the values in range of 0.02 to 0.05 m. The daily values in spring and autumn are the medium, from 0.03 to 0.10 m.

The overall variation in these daily values can be expressed well by the following second order polynomial, in which the correlation coefficient is 0.65.

$$H_{infra} = 3x10^{-6}(t - 166.7)^2 + 0.04 \quad (4.5)$$



(a) Year by year values



(b) Average values

Figure 4.12 Seasonal variation of monthly-mean height of infragravity waves at Kanazawa

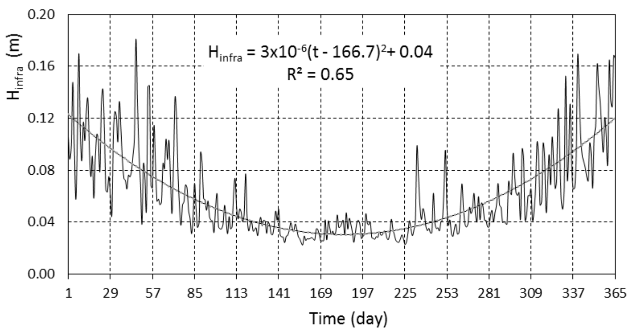


Figure 4.13. Seasonal variation of daily-mean height of infragravity waves at Kanazawa

Next, daily-mean height of infragravity waves are investigated month by month for each year. Figures 4.15 describe the month by month variation of daily means for two typical years (2005 and 2007), in which the average monthly-values in 2005 vary in the widest range (from 0.035 to 0.179m) and the range in 2007 is narrowest (from 0.028 to 0.089 m). The figures illustrate that although the range of average monthly-mean in 2005 is higher than that in 2007, the daily range in 2005 is lower than that in

2007. The daily ranges value in these two years are 0.02-0.39 m in 2005 and 0.02-0.42 m in 2007. The maximum daily values in 2005 and 2007 occur on 05 December and 15 February, respectively.

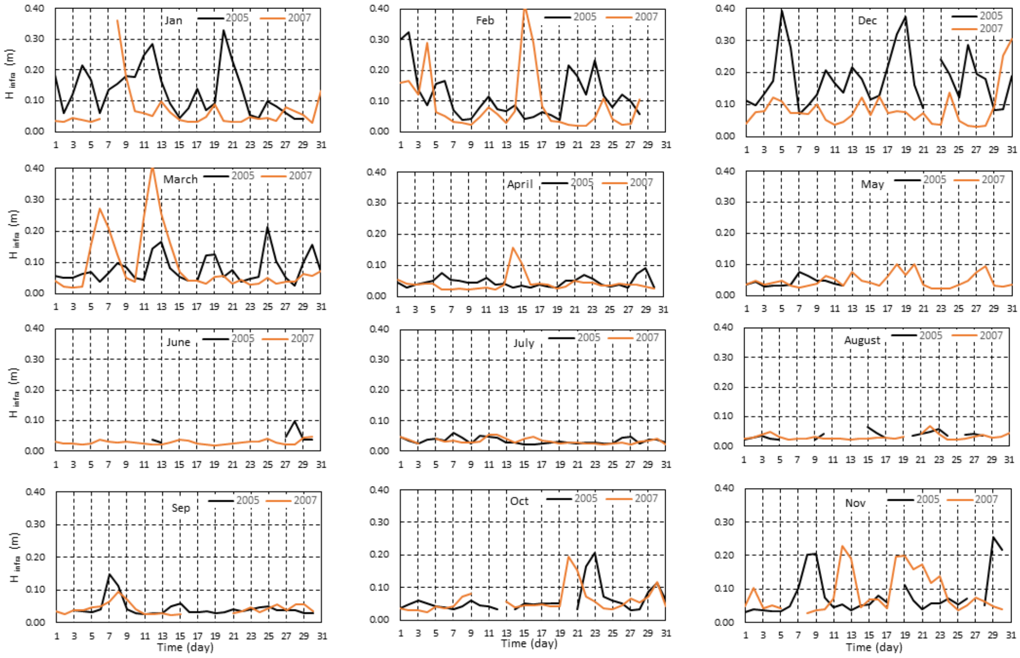


Figure 4.14 Variation of daily-mean height of infragravity waves in 2005 and 2007 at Kanazawa

4.2. Relation with wind waves

The relation between daily-mean of significant wave heights and infragravity wave height are compared for the values in average (Figure 4.15) and in the two typical years (Figures 4.16). The Figures illustrate that patterns of the daily variation of both wind waves and infragravity waves are quite the same. For average values, the daily variatons of wind waves corresponds with the following second order polynomial with higher correlation coefficient (R^2=0.95) in comparison with that of infragravity waves.

$$(H_{1/3})_0 = 6\times10^{-5}(t\text{-}175)^2 + 0.6 \tag{4.6}$$

For typical years, in 2005 the number of days in which infragravity waves are higher than 0.05 m is 153 days and in 2007 it is just 110 days.

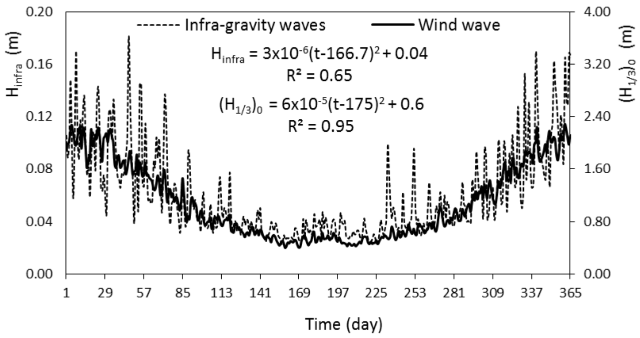
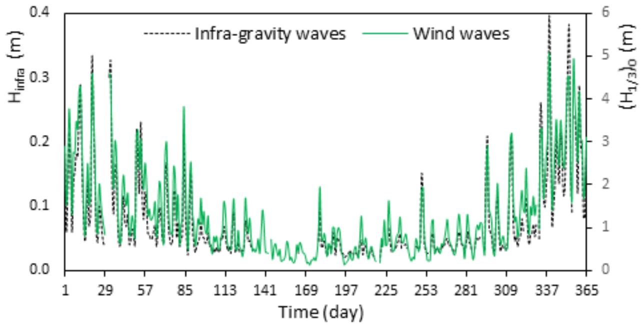
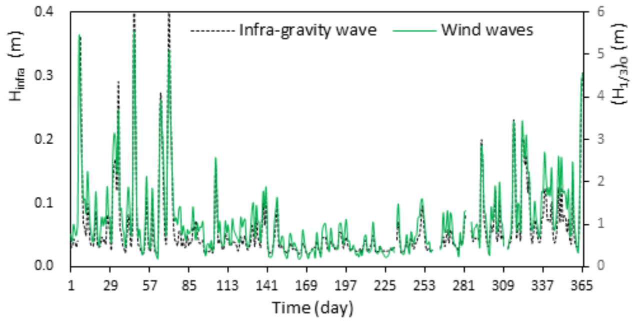


Figure 4.15 Comparison of seasonal variation of daily-mean of infragravity wave heights and significant wind wave heights



(a) 2005



(b) 2007

Figure 4.16 Comparison of seasonal variation of daily-mean of infragravity wave heights and significant wind wave heights for 2005 and 2007

Figure 4.17 compares the seasonal variation of monthly-mean of infragravity wave heights and significant wind wave heights. The error bars are included in the figure to express the standard deviation of the long-term data. The figure illustrates that the pattern of these variations are quite the same. The monthly variatons of wind waves corresponds with the following second order polynomial, in which the correlation coefficient (R^2=0.99) is slightly higher than that of infragravity waves.

$$(H_{1/3})_{0ave} = 0.063(t - 6.63)^2 + 0.36 \tag{4.7}$$

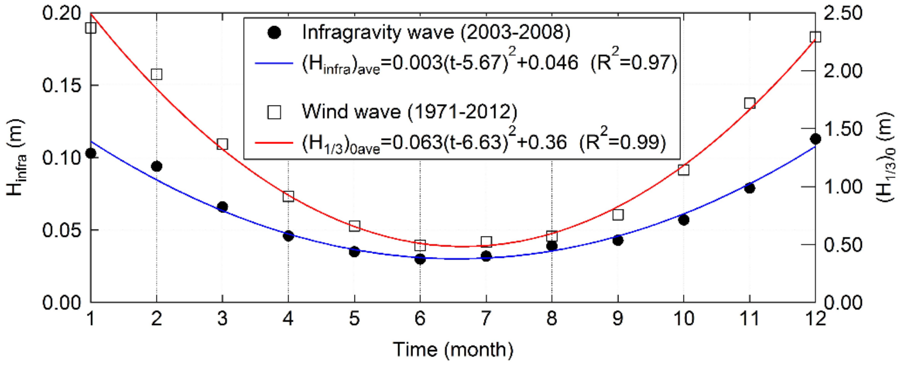


Figure 4.17 Comparison of seasonal variation of monthly-mean of infragravity-wave height and significant wind-wave height

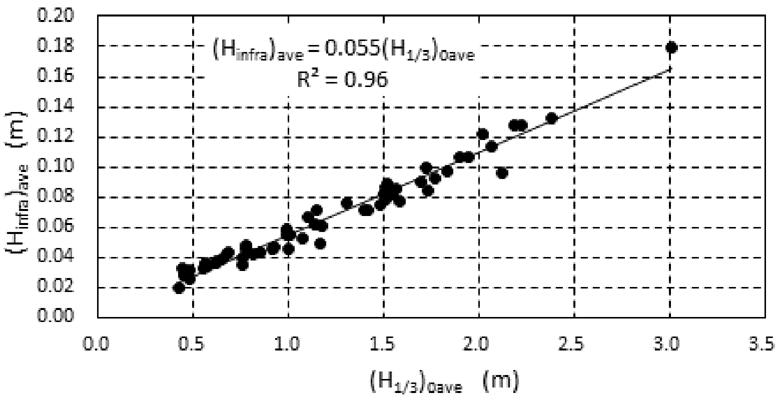


Figure 4.18 Relation between monthly wind wave and infragravity-wave height at Kanazawa in duration 2003-2008

The relation between monthly significant wind waves and infragravity wave heights at Kanazawa in duration 2003-2008 is shown in Figure 4.18. The heights of infragravity waves and wind waves at this site can be linearly correlated very well as the following equation

$$(H_{infra})_{ave} = 0.055(H_{1/3})_{0ave} \tag{4.8}$$

in which the correlation coefficient is very high ($R^2 = 0.96$). On average, the infragravity wave height is approximately 5.5 % of significant wind wave height.

5. Summary

This part of the study investigated the wave data obtained at Kanazawa Port in duration 1971-2012 in order to clarify the characteristics of deep-water wave energy flux, breaking wave properties (breaker height and depth) in the nearshore, and infragravity waves. In addition, the related morphological parameters (closure depth and Sunamura index) are estimated to deduce the possible influence of wave forcing on the morphological change at the Kaetsu Coast. The seasonal variation of wave energy flux indicated that most of the wave energy is transported during winter season. The directional distribution showed that approximately 80 % of total wave energy incident the coast from the WNW, NW, and NNW direction. The pattern of seasonal variation of breaker height and depth are quite similar. The values are the highest in winter, medium in spring and autumn and the lowest in summer. The cumulative probability distribution of breaker depth indicated that in winter 80 % of waves break at the area with water depths less than 4.0 m, while in summer this water depth is just approximately 1.0 m. In the spring and autumn the water depth of the area at which 80 % of waves break is less than 2.5 m. The cumulative probability of closure depth revealed that over 80 % of time the closure depths are less than 6.0 m in winter, 2.0 m in summer, 3.0 m in spring and autumn. Similar to breaking properties, the monthly mean of Sunamura indices are the lowest in summer, the highest in winter season, and medium in spring and autumn. It was deduced that during summer season the shoreline is advanced and the recessions of shoreline generally occur in other seasons. The transitions from recessions to advances of the shoreline occur in March, from advances to recessions in September. Infragravity waves have the same seasonal pattern with the wind waves. The patterns of the daily as well as monthly variation of infragravity waves are similar to that of wind waves. The heights of infragravity waves and wind waves can be linearly correlated very well.

CHAPTER 5. COMPARISONS OF REGIONAL WAVE CLIMATE ALONG THE SEA OF JAPAN COAST

1. 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 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.

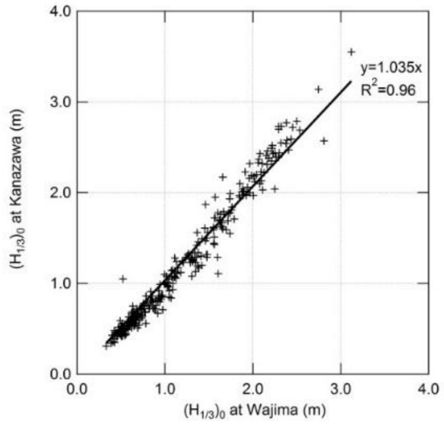
The wave observation along the Sea of Japan coast was started since the early 1970s by the NOWPHAS. From around 1980, JMA (Japan Meteorological Agency) has also started the wave measurements on the Sea of Japan coast. On the basis of these measurements several studies have been conducted on the wave climate along the Sea of Japan coast. Several remarkable features have been demonstrated along a part of this coastline.

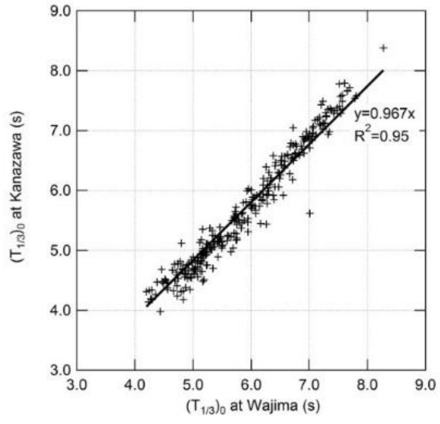
Located in the middle of the Sea of Japan coast, Ishikawa Prefecture has also been suffering from various coastal problems, including the progress of severe coastal erosion, frequent occurrence of rip current accidents, reduction of coastal habitats, and other marine disasters. In order to obtain a deep physical understanding of the variation in wave properties at Ishikawa Prefecture, the long-term variation of wave characteristics at Kanazawa Port during 1971 to 2012 was investigated in Chapter 3. The results indicated that the annual-mean wave period abruptly increased around 1990. The increase of monthly-mean wave period was most significant in July. In this chapter, the analysis is extended by a further investigation of 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. 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.

2. Wave climate around the coastlines of Ishikawa prefecture, Japan

2.1. Seasonal variation of wave characteristics

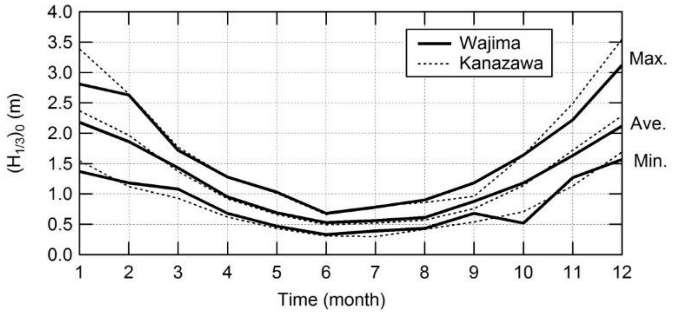
Along the Japanese coast, it is generally known that the seasonal variation of waves on the Sea of Japan side is more significant than that on the opposite side facing to the western Pacific Ocean. On the overall, the seasonal variation in wave characteristics at both Wajima and Kanazawa indicated similar 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 (90km), the wave properties at these sites are strongly correlated in wave height and period. The correlation between monthly-mean values of significant wave heights and periods at Wajima and Kanazawa were examined as shown in Figures 5.1. 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. Figures 5.2 show 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 5.2(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, Figure 5.2 (b) shows that wave period at Wajima are always 3.5 to 4.2% larger than that at Kanazawa. The discrepancies are clear in spring, summer and autumn while it is small in winter.



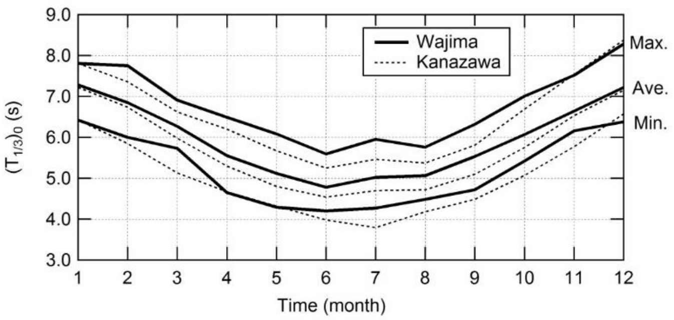


(a) Wave height **(b)** Wave period

Figures 5.1 Correlation between monthly-mean significant wave properties at Wajima and Kanazawa



(a) Wave height



(b) Wave period

Figures 5.2 Comparison of seasonal variation in monthly-mean wave properties at Wajima and Kanazawa

Next, the relationship between the monthly-mean significant wave height and period at Wajima and Kanazawa were considered and compared, for the averaged and the maximum values during the study period (Figure 5.3). 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, Figure .5.3(a) illustrates that in both sites, the monthly-mean 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:

$$H_{1/3} = 0.08{T_{1/3}}^2 - 0.31T_{1/3} + 0.11\,. \tag{5.1}$$

At Kanazawa with correlation coefficient of R^2=0.998:

$$H_{1/3} = 0.09{T_{1/3}}^2 - 0.35T_{1/3} + 0.25. \tag{5.2}$$

Similarly, the maximum values of monthly-mean wave height and period (Figure 5.3(b)) can be closely correlated with the following second order polynomial. At Wajima with correlation coefficient of R^2=0.987:

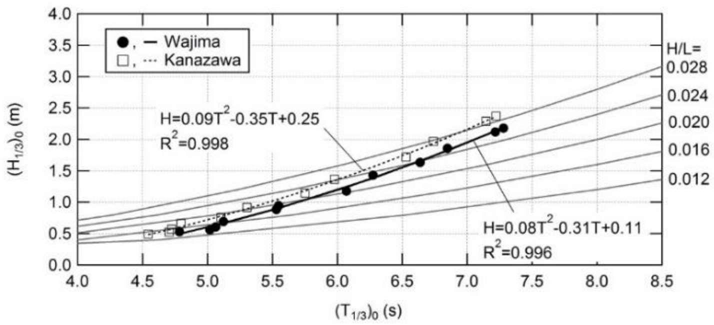
$$H_{1/3} = 0.15{T_{1/3}}^2 - 1.14T_{1/3} + 2.37. \tag{5.3}$$

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

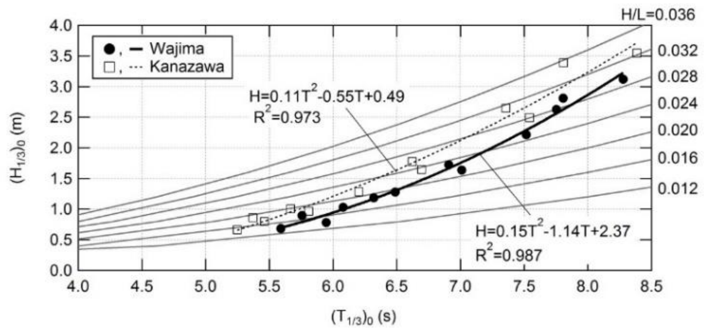
$$H_{1/3} = 0.11{T_{1/3}}^2 - 0.55T_{1/3} + 0.49. \tag{5.4}$$

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 5.4 compares the incoming wave direction relating to wave period, at Wajima and 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 WNW and NNE. In addition, the number of waves with long period decreases. In summer, waves approach the coast, mainly from the NNE and WNW 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 WNW. According to the analysis in Chapter 3, on the other hand, the dominant wave direction at Kanazawa is the NNW in spring, autumn, and winter, and the NNW and WNW 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 by the incoming waves from the NNE. Namely, the influence of Noto Peninsula is strong on wave direction.

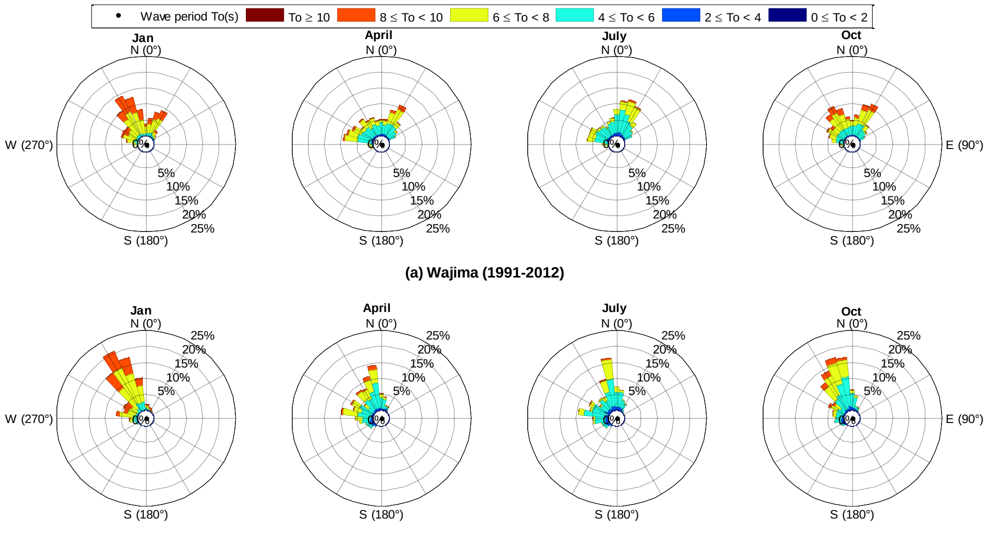


(a) Average height and period



(b) Maximum height and period

Figures 5.3 Comparison of the relationships between monthly-mean wave height and period at Wajima and Kanazawa



Figures 5.4 Incoming wave direction and wave periods in the four seasons at Wajima and Kanazawa

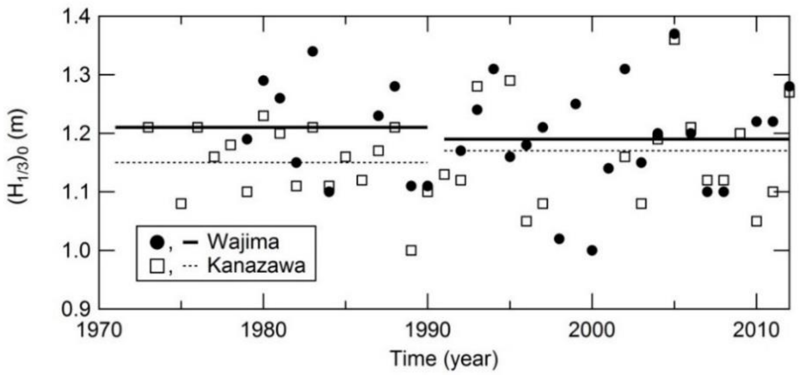
2.2. Long-term variation of wave characteristics

The long-term variation of annual-mean wave height showed generally common features at these sites. Figure 5.5 (a) compares the variation in annual-mean significant wave height at Wajima and Kanazawa. The significant wave height at both sites fluctuate between 1.0 and 1.4m. 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 1.19m from the value of 1.21m in the duration before 1990. In contrast, at Kanazawa, that value slightly increased from 1.15m to 1.17m in these periods. After 1990, the scatters of data are nearly the same in both sites, in which the standard deviations are 0.09m, while the data is more scattered at Wajima, (0.08m), in comparison with that at Kanazawa, (0.06m) before 1990.

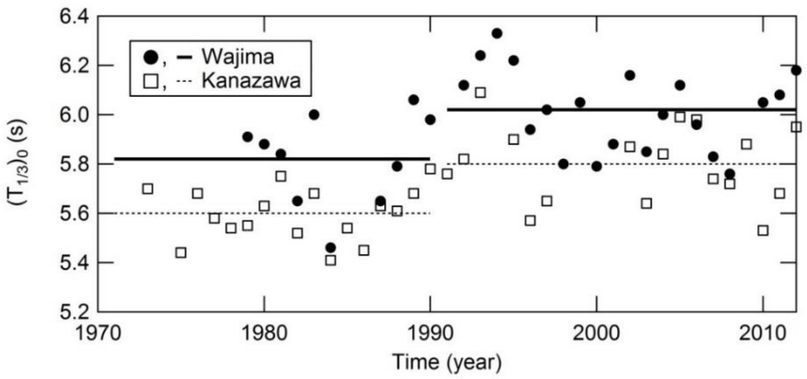
The long-term variations at these sites are also similar for annual-mean wave period. According to Figure .5.5 (b), the annual-mean significant wave period at both Wajima and Kanazawa in the duration after 1990 have noticeably increased. At Wajima, it increased to 6.02s from 5.82s in the former duration. But the statistical tests indicate that this increase is not statistically significant. The wave period fluctuates between

5.46 and 6.33s. The corresponding standard deviations in the first and second duration are 0.18 s and 0.16 s, respectively; the values in the former duration are more scattered.

The result in Chapter 3 indicated the following wave characteristics at Kanazawa: 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 annual-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 6.09s, 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 annual-mean wave height at Wajima and Kanazawa are similar. However, the variation at Wajima is less statistically significant than at Kanazawa.



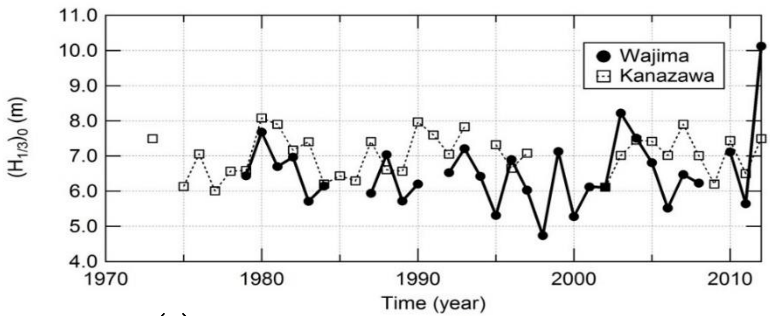
(a) Wave height



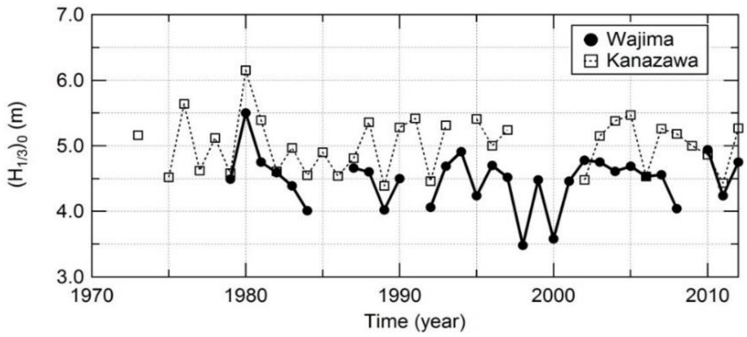
(b) Wave period

Figures 5.5 Long-term variation in annual-mean significant wave characteristics at Wajima and Kanazawa

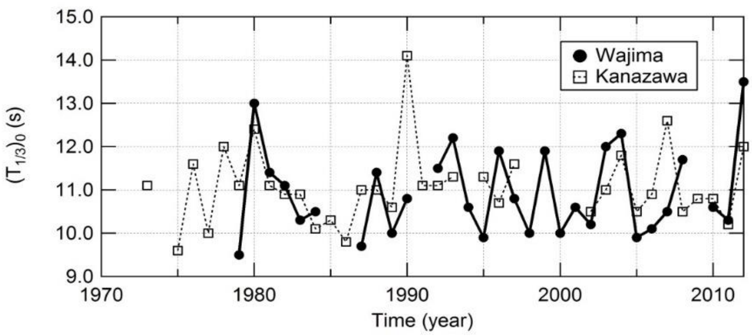
In order to clarify the characteristics of episodic waves, the annual maximum and top 1% of significant wave characteristics at Wajima and Kanazawa were compared in Figures 5.6. The figures illustrate that the maximum wave heights and periods fluctuate in a wide range and the values at Wajima are almost always smaller than that at Kanazawa. Figures 5.6(a) and 5.6(b) demonstrates that, at 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 8.08m at 1980. In the same year, top 1% of significant wave height recorded the highest value of 6.15 m. In Figure . 4.6(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



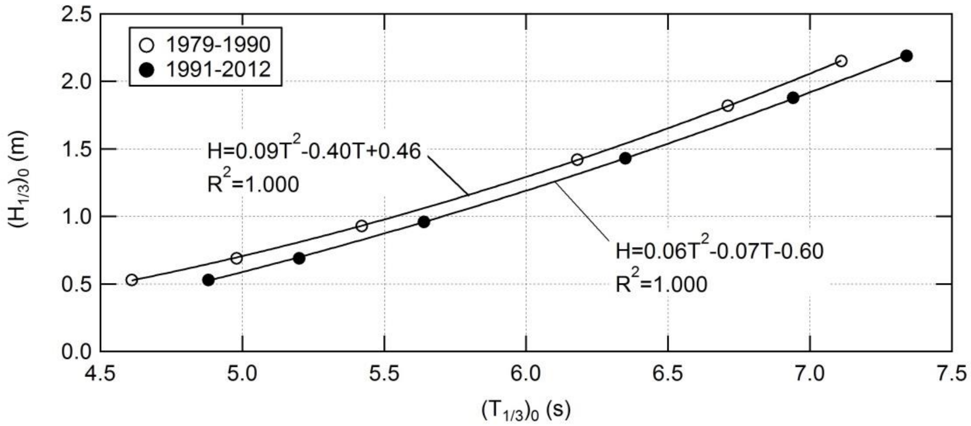
(b) Height of top 1% of significant waves



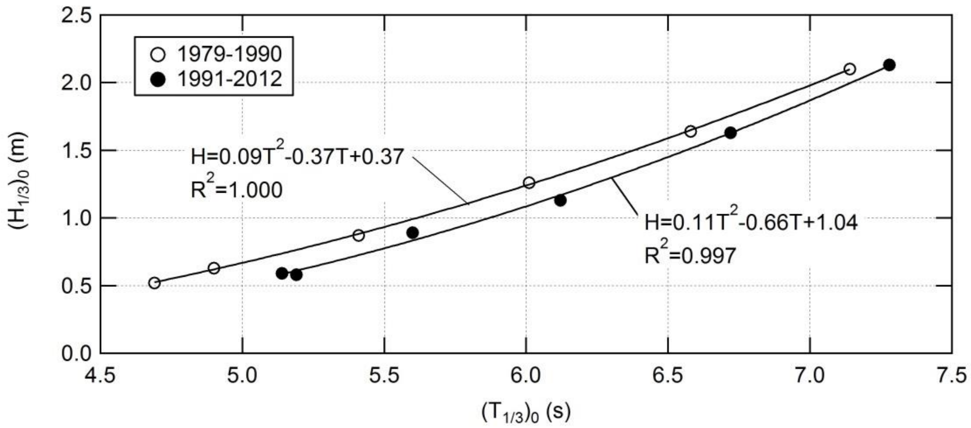
(c) Period of maximum significant waves

Figures 5.6 Long-term variation in episodic wave characteristics at Wajima and Kanazawa

Next, the long-term variation in monthly-mean wave height and period were examined. Figures 5.7 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 in Chapter 3 for Kanazawa.



(a) From January to June



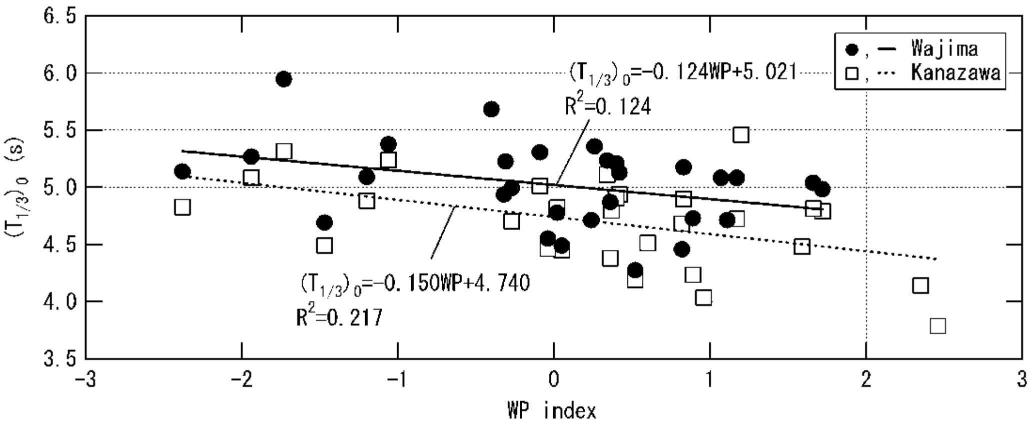
(b) From July to December

Figures 5.7 Comparison of relationship between monthly-mean wave characteristics before and after 1990 at Wajima

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 5 % level, and in July at 1 % level. At Kanazawa, increasing trends with 5% significance level in April and July have been detected for wave height. For wave period at Kanazawa, increasing trends have been significant at 1% level in March, April and July, and an increasing trend at 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), and North Pacific Index (NPI). 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 Figure 5.8.

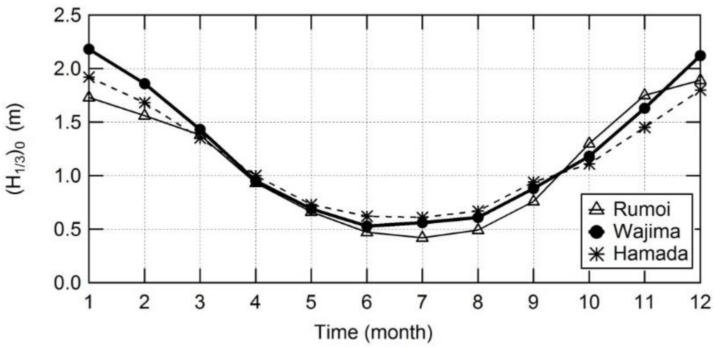


Figures 5.8 Relationship between monthly-mean wave period and Western Pacific index in July at Wajima and Kanazawa

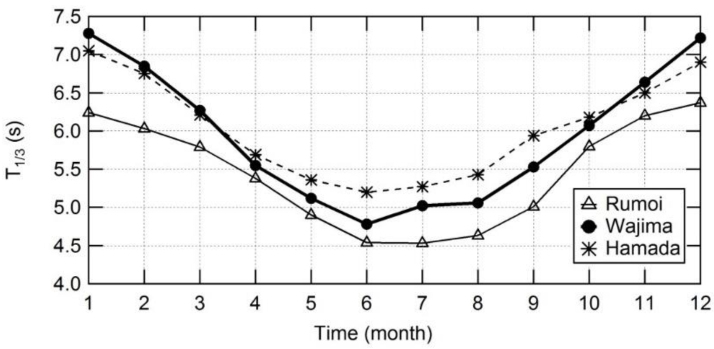
3. Overall comparison along the Sea of Japan coastline

3.1. Seasonal variation of wave characteristics

Wave climates at Rumoi and Hamada also have significant seasonal changes like at Wajima and Kanazawa (Figure . 5.9). 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 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.



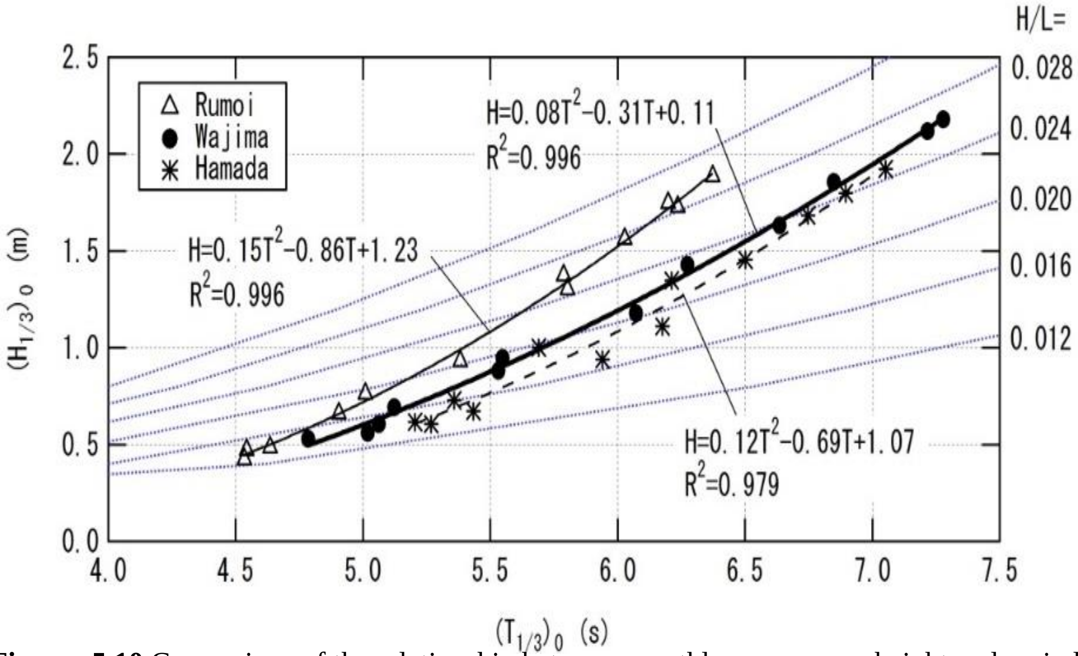
(a) Wave height



(b) Wave period

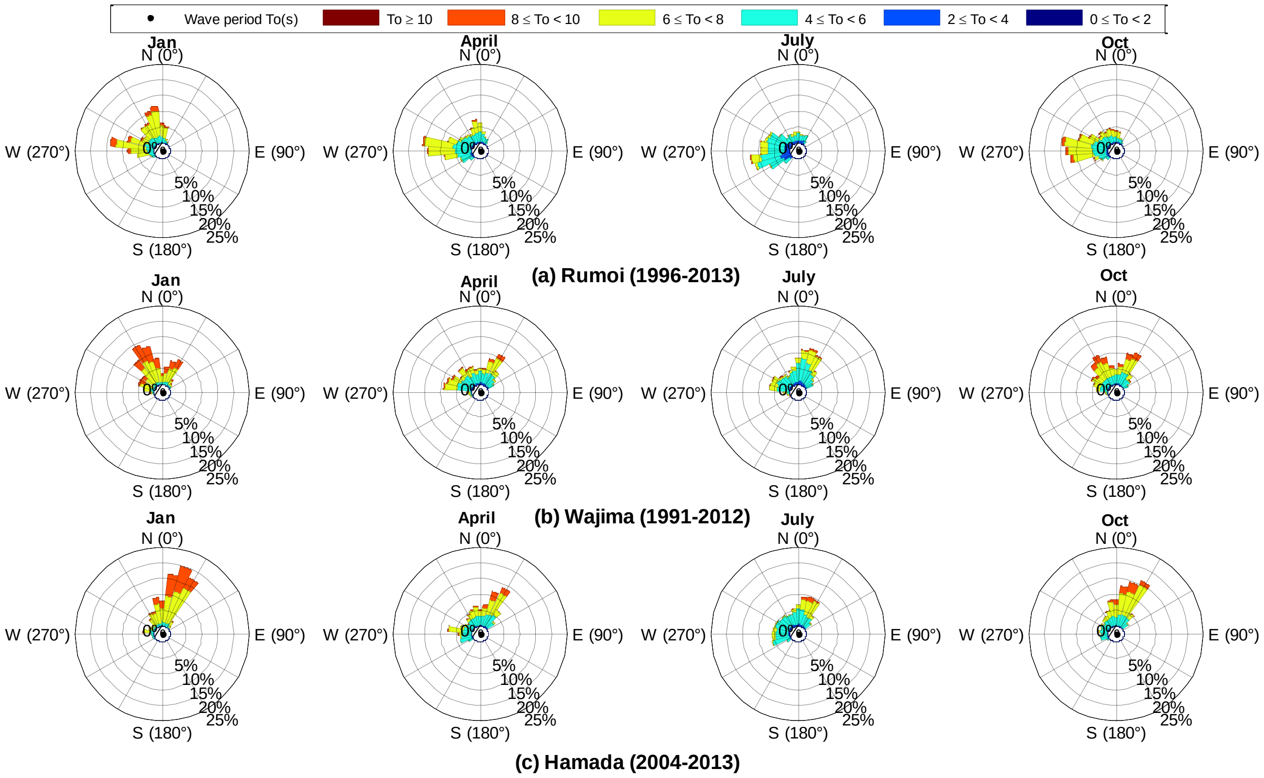
Figures 5.9 Comparison of seasonal variation in monthly-mean wave properties at Rumoi, Wajima and Hamada

The relationship of monthly-mean wave height and period at the above 3 sites is then investigated. Figure 5.10 compares the relationship between the monthly-mean 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 monthly-mean 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 flatter 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 value of 0.013.



Figures 5.10 Comparison of the relationship between monthly-mean wave height and period at Rumoi, Wajima, and Hamada

Wave direction along the coastline indicated significant differences. Figures 5.11 compare 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 WNW direction. In spring, summer, and autumn dominant wave directions are the WSW and WNW. 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 Sea of Japan, 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.

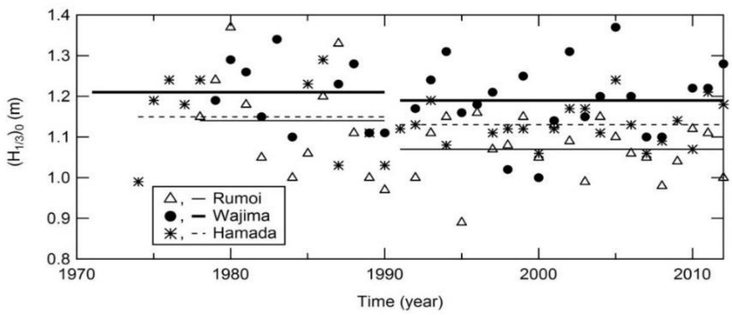


Figures 5.11 Incoming wave direction and wave periods in the four seasons at Rumoi, Wajima, and Hamada

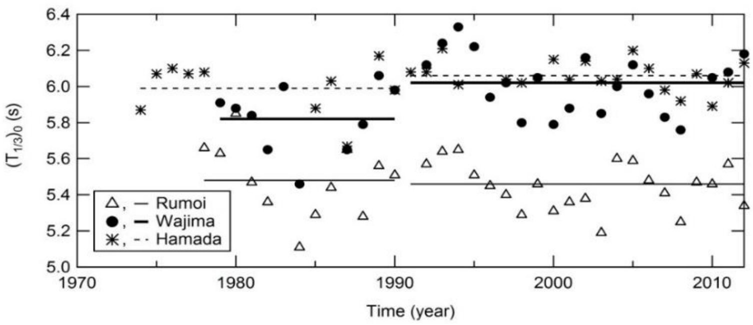
3.2. Long-term variation of wave characteristics

The long-term variation in annual significant wave properties along the Sea of Japan showed some different features. Figures 5.12 compares the long-term variation in annual-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 annual-mean 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 0.89m, 1.37m at Rumoi and 0.99m, 1.29m 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 there. 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 Figure .5.12 (b), the annual-mean significant wave period at Hamada is 6.04s, which is larger than that of Wajima and Rumoi, 5.95s and 5.47s, respectively. Similar to Wajima, at both Rumoi and Hamada, the statistical tests indicated no significant trends or jumps in long-term wave period.



(a) Wave height



(b) Wave period

Figures 5.12 Long-term variation in annual-mean significant wave characteristics at Rumoi, Wajima and Hamada

In order to clarify the long-term differences in the regional variation, wave characteristics of the four sites averaged over the obserbation period are compared together in Tables 5.1 and 5.2. The tables show that, except for the long-term average of significant wave height in autumn, the long-term average 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.

Table 5.1 Comparison of annual-mean significant wave properties averaged over the study period 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 5.2 Comparison of seasonal significant wave properties averaged over the study period at the four sites

(a) Wave period (s)

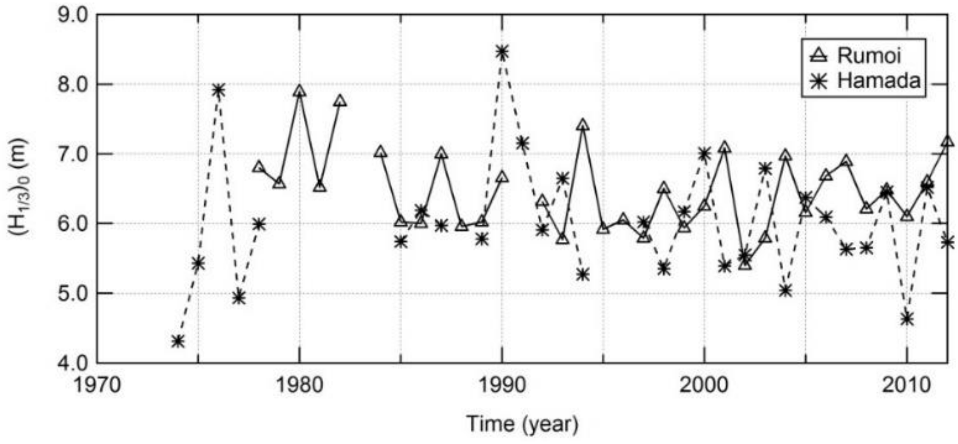
No	Site Name	Mean in Winter	Mean in spring	Mean in summer	Mean in autumn
1	Rumoi	6.21	5.36	4.57	5.67
2	Wajima	7.11	5.65	4.96	6.08
3	Kanazawa	7.04	5.36	4.66	5.80
4	Hamada	7.65	6.58	5.30	6.21

(b) Wave height (m)

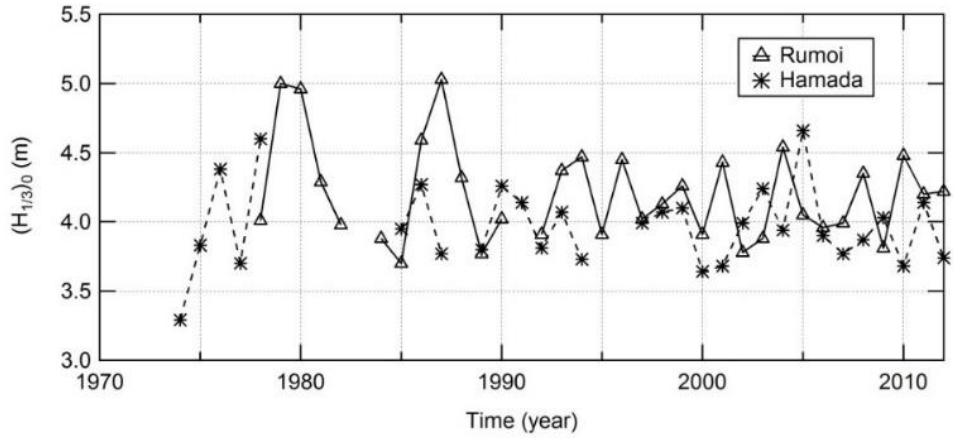
Site	Site Name	Mean in Winter	Mean in spring	Mean in summer	Mean in autumn
1	Rumoi	1.73	0.99	0.46	1.27
2	Wajima	2.05	1.02	0.57	1.23
3	Kanazawa	2.21	0.98	0.53	1.21
4	Hamada	1.80	1.02	0.63	1.17

The episodic events also vary from the north to the south parts of the study area. Figures 5.13 compare the maximum and top 1% of significant wave at Rumoi and Hamada. Figures 5.13(a) and 5.13(b) demonstrate that, at Rumoi, the maximum wave height 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 8.47m at 1990. In 2005, top 1% of significant wave height recorded the highest value of 4.66 m. Figure . 5.13(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 variation in annual maximum values, the Mann-Kendall and Lepage tests revealed no significant trends or jumps at Rumoi and Hamada.

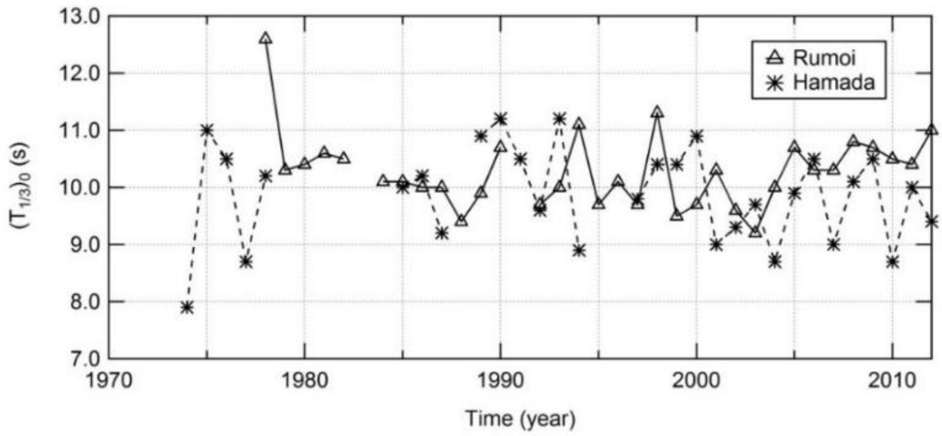
Isozaki. (2006) proposed a hypothesis on the existence of negative correlation between the episodic wave characteristics at the middle and north side of the Sea of Japan coast. In order to examine this hypothesis, the year to year variation between the annual maximum significant wave height at Rumoi is compared with those at Wajima and Hamada as shown in Figures 5.14. 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).



(a) Height of maximum significant waves

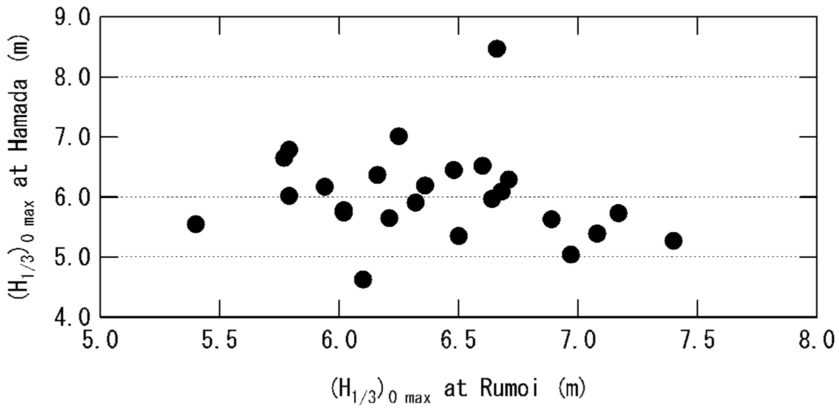


(b) Height of top 1% of significant waves

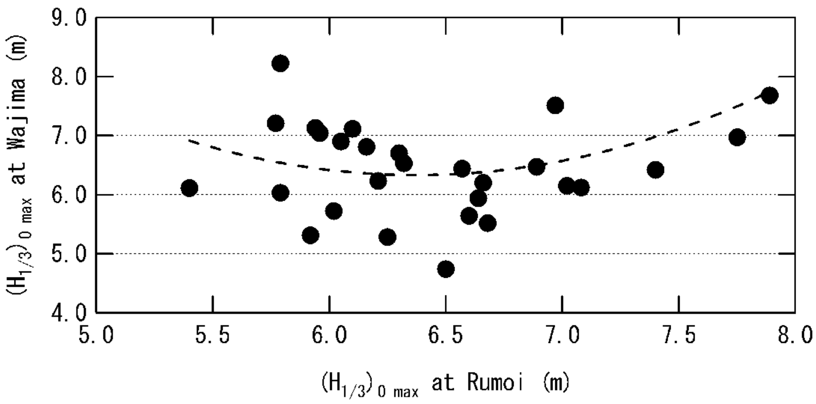


(c) Period of maximum significant waves

Figures 5.13 Long-term variation in episodic wave characteristics at Rumoi and Hamada



(a) Rumoi and Hamada



(b) Rumoi and Wajima

Figures 5.14 Year to year variation of maximum significant wave height at Rumoi, Hamada, and Wajima

In terms of long-term variation in monthly-mean 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, which are averaged over 2 different durations: before 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 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 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 5.3 summarizes the long-term trends for monthly-mean significant wave characteristics at the four sites. The two sites at the middle of the coastlines 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.

Table 5.3 Summary of the long-term trends for monthly-mean significant wave characteristics at the four sites

Month	Rumoi		Wajima		Kanazawa		Hamada	
	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
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.*

A wide variety of abrupt jumps have been detected by the Lepage tests. Tables 5.4 summarize the years of abrupt jumps for monthly-mean significant wave characteristics at the four 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. On the contrary, data at Hamada Port are quite stable during the study period. The jumps were just found in five 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 four sites, we have conducted further analysis on the long-term typhoon records, wind speed records and others in order to deduce the possible reasons responsible for the differences. However, the factors contributed to the differences of wave characteristics at these four sites are quite complicated. At this moment, principal factors contributed to the differences of wave characteristics at these four sites are not clear. More detailed analyses are needed in the future research.

Table 5.4 Years of abrupt jumps detected by the Lepage test for monthly-mean significant wave characteristics at the four sites with sample size of 10 years

Month	Rumoi		Wajima		Kanazawa		Hamada	
	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
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	1998			
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*)

4. Summary

This part of the 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 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., 2010). In order to clarify the characteristics of such impact, more detailed efforts using wave model prediction is needed.

CHAPTER 6. COMPARISONS OF WAVE CLIMATE ALONG THE PACIFIC COASTLINE OF JAPAN

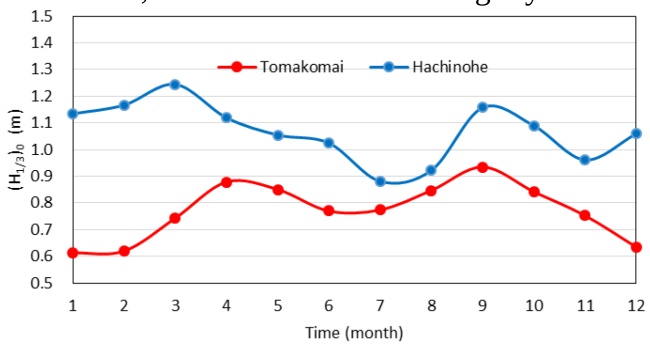
1. Introduction

In recent years, many scientists and engineers have placed great interests on the influence of the climate change to long-term wave characteristics (wave height, period, and incoming direction) along the coast of North Pacific Ocean. The NOWPHAS's observation of wave climates around the coast of Japan has started since the early 1970s, in which there have been more than 15 sites along North Pacific coast of Japan. Recently, several remarkable features of the present wave climates have been detected in previous studies conducted along this coastline as mentioned in Chapter 1. For the time scale of several decades, the influence of climate change is also expected, that may cause further impacts on the regional variation of wave characteristics. The spatio-temperal variation of wave climate along this coastline deserves further study. Accordingly, this part of the study investigates the long-term wave variation observed at the six sites along Pacific Ocean coast of Japan, in which Tomakomai and Hachinohe sites are located at the north part, Onahama and Kashima represent the middle part, and the representative sites for the south part are Shionomisaki and Shibushi as shown in Figure 2.1. First, the regional characteristics of waves are investigated as follows: the seasonal variation of wave properties averaged over the observation period; the long-term variations in annual- and monthly-mean wave properties. Second, an overall comparison of wave characteristics among the sites are conducted in order to reveal the distinguishing aspects along the coastline. In the analysis, the Mann-Kendall and Lepage tests are also conducted in order to detect the significant trends or jumps in the long-term variation.

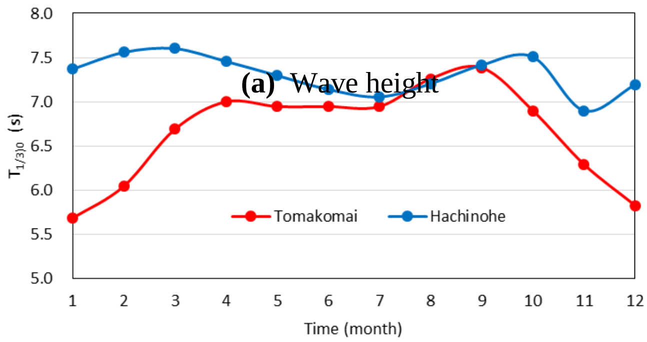
2. Variation of wave characteristics at the northern area

2.1. Seasonal variation of wave characteristics

In general, the seasonal variation of wave climates along the Pacific coastline of Japan are not significant; the differences among four seasons are small, and the significant wave periods in winter are always the smallest. Figures 6.1 show the monthly mean of significant wave height and period at Tomakomai and Hachinohe. Monthly mean of significant wave height and period at Tomakomai is respectively 30% and 10% smaller than that at Hachinohe. The significant wave height at Tomakomai varies from 0.61 to 0.93 m, while it varies from 0.88 to 1.24 m at Hachinohe. The range of wave period at Tomakomai and Hachinohe are 5.68 to 7.68 s and 6.9 to 7.6 s, respectively. In addition, the pattern of seasonal variation at each site is different. At Tomakomai, waves in spring and autumn are slightly higher than that in summer and winter, while at Hachinohe, waves in summer are slightly smaller than those in other seasons.



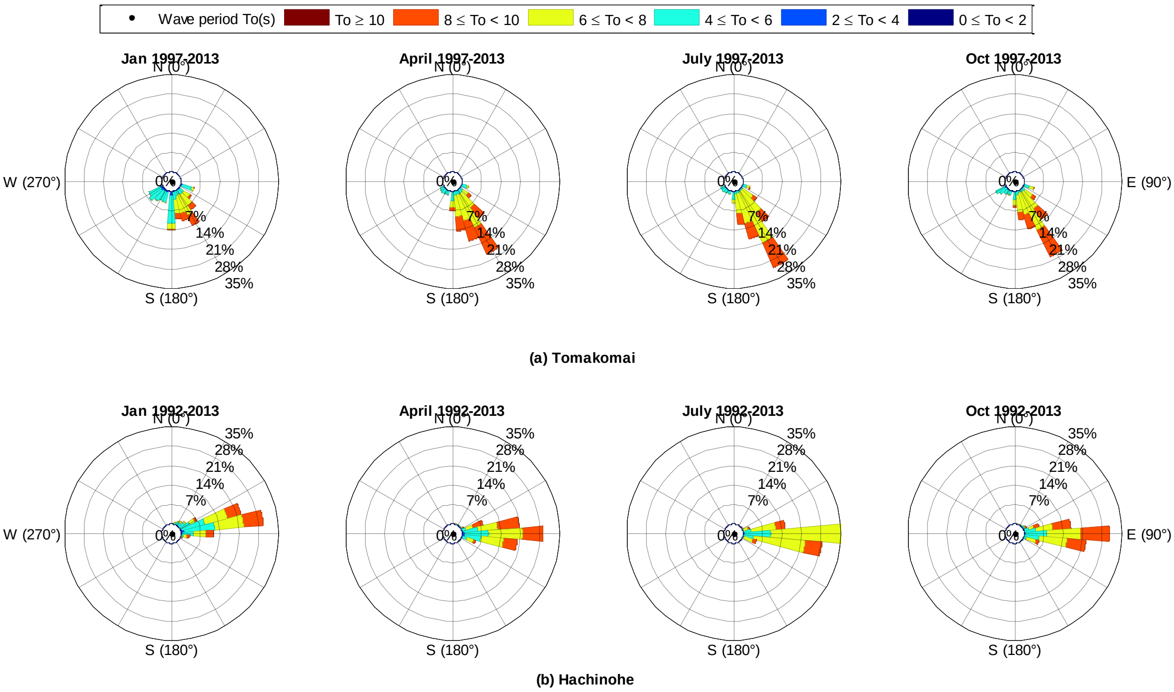
(a) Wave height



(b) Wave period

Figures 6.1 Seasonal variation in wave properties at Tomakomai and Hachinohe

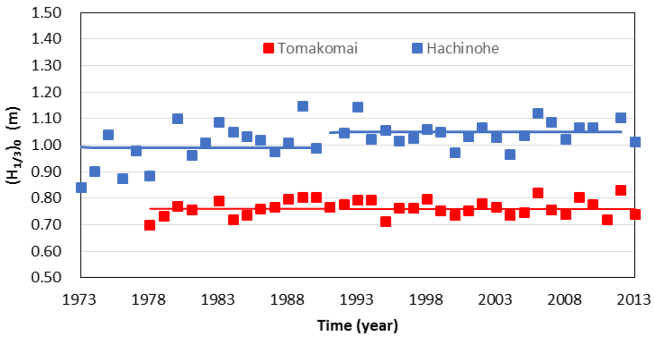
Next, the seasonal variation of wave direction at Tomakomai and Hachinohe are examined. Figures 6.2 show the incoming wave direction relating to wave period at these sites in January, April, July, and October that are representative for winter, spring, summer, and autumn, respectively. At Tomakomai, wave direction in spring, summer and autumn are SSE. In winter, waves approach shoreline from both the SSE and SSW direction. In addition, most of the waves incoming from the SSW direction have short period. At Hachinohe, in spring, summer and autumn, waves mostly approach shoreline from the East direction, while the main direction of incoming waves in winter is the ENE.



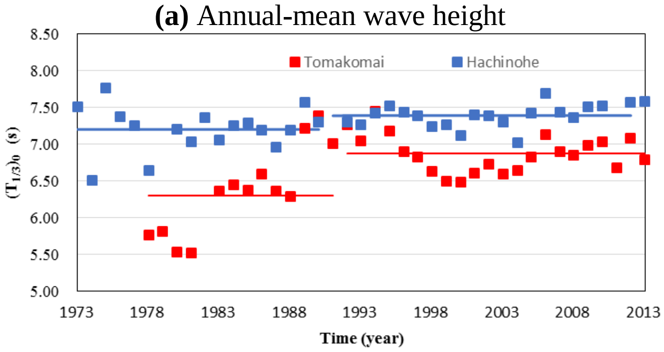
Figures 6.2 Incoming wave direction and wave periods in the four seasons at Tomakomai and Hachinohe

2.2. Long-term variation of wave characteristics

The long-term variations of annual-mean wave properties indicate some interesting features at these sites. Figures 6.3 show the variation in annual-mean significant wave properties at Tomakomai and Hachinohe. Figure 6.3(a) describes that the annual-mean wave height at Tomakomai is about 30% lower than that at Hachinohe. The values at Tomakomai vary from 0.70 to 0.83 m, while they are from 0.84 to 1.15 m at Hachinohe. When the data are examined separately by 1990, at Tomakomai in both duration the averaged values as well as the standard deviation are similar (0.76 m, and 0.03 m, respectively). At Hachinohe, the averaged-value in second duration (1991-2013) slightly increases in comparison with that in the former duration (from 0.99 to 1.05 m), while the standard deviation in the second duration is half of the former (0.08 and 0.04 m, respectively). Figure 6.3 (b) illustrates that the significant wave period at Tomakomai is about 10% smaller than that at Hachinohe, in which the range of annual mean wave periods at Tomakomai and Hachinohe varies from 5.52 to 7.45 s, and from 6.51 to 7.76 s, respectively. The averaged value in the second duration at Tomakomai increases significantly (from 6.30 in the first to 6.87 s in the second duration). The data in the first duration are much scattered with the value of standard deviation of 0.57 s. It is 0.25 s in the second duration. At Hachinohe the difference in the values in the two duration is also noticeable (from 7.2 in the first to 7.39s in the second duration). The standard deviation in the first and the second duration is 0.30 and 0.15 s, respectively.



(a) Annual-mean wave height



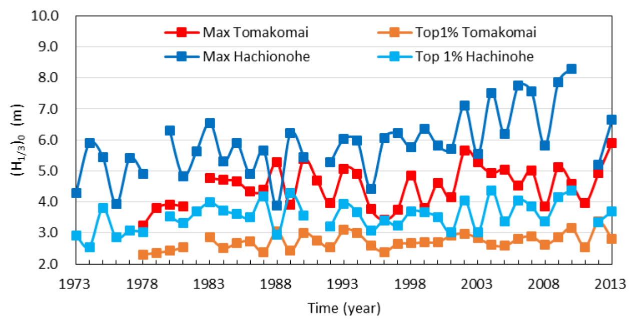
(b) Annual- mean wave period

Figures 6.3 Long-term variation in annual-mean significant wave characteristics at Tomakomai and Hachinohe

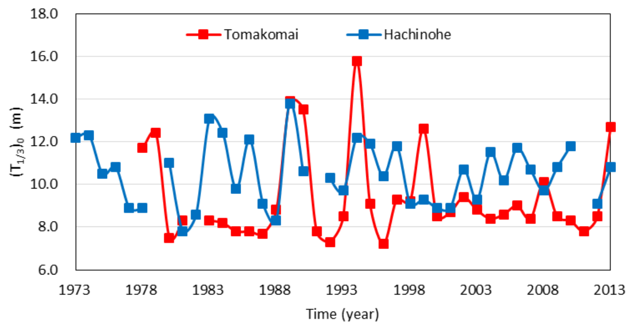
Additional interesting features are then found based on the episodic events. Figures 6.4 show the height of maximum and top 1%, and period of maximum significant waves. The figure 6.4(a) illustrates that the maximum and top1% of wave height at Tomakomai are much lower than those at Hachinohe. At Tomakomai, the peak value of maximum wave height is 5.66 m in 2002, while at Hachinohe it reaches up to 8.29 m in 2010. Top 1% of significant wave height records the highest value of 3.36 m at Tomakomai in 2012 and 4.37 m at Hachinohe in 2004. In contrast, the maximum value of wave period at Tomakomai is about 2 s larger than that at Hachinohe. Figure 6.4(b) shows that the maximum value of wave period in Tomakomai and Hachinohe is 15.8 s at 1994 and

13.8 s at 1989, respectively. However, the annual values of the maximum wave period at Tomakomai are almost lower than those in Hachinohe.

Next, the ratios between the maximum and the mean significant wave height are investigated as shown in Figure 6.5. The maximum values of wave height are always four to eight times larger than the corresponding mean values. In addition, the ratio expresses no abnormal values, though the water depth and the types of the observed equipment changed during the study period and from site to site.

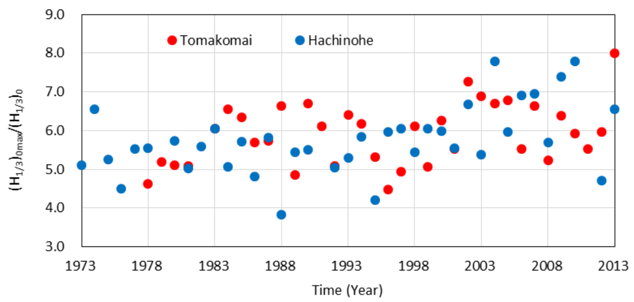


(a) Height of maximum and top 1% of waves



(b) Period of maximum significant waves

Figures 6.4 Long-term variation in episodic wave characteristics at Tomakomai and Hachinohe



Figures 6.5 Ratio between maximum and mean of significant wave height at Hachinohe and Tomakomai

Next, the long-term trends and abrupt jumps in variation of wave characteristics are examined by the Mann-Kendall and the Lepage tests as shown in Tables 6.1 and 6.2.

Table 6.1 shows that at Tomakomai, increasing trends significant at 1% level are detected in long-term variations of annual wave period and top 1% of wave height by the Mann-Kendall statistical tests. Lepage tests with sample size of 10 years detect abrupt jumps at 1% significance level in 1989, 1990, 1996 for annual wave periods, and in 1997 for the top 1% of wave height. In addition, the Mann-Kendall test also detects an increasing trend at 5% significant level in long-term variation of maximum wave height. Moreover, many abrupt jumps at 5% significant level are found by the Lepage tests with sample size of 10 years in long-term variation of annual wave height, annual wave period and the top 1% of wave height. At Hachinohe, the Mann-Kendall tests detect increasing trends at 1% significant level in annual wave period and maximum wave height, and at 5% significant level in annual wave height and the top 1% wave height. The Lepage tests with sample size of 10 years detect an abrupt jump at 1% significant level around 1989 in long-term variation of annual wave period, and many abrupt jumps at 5% significant level in long-term variation of maximum wave height and the top 1% of wave height. According to Table 5.2, the Mann-Kendall tests in long-term variations of monthly-mean wave characteristics illustrate that at Tomakomai increasing trends in wave period are found in all of the four seasons, in which increasing trends occurr in January, June and July at 1% significant level, and April, May, October and December at 5% significant level. In contrast, long-term variations of wave height at this site indicate an increasing trend just at 5% significance level in May. Moreover, a decreasing trend at 5% significance level is detected in August. At Hachinohe, for the variations of wave period, increasing trends are detected in June and November at 1% significant level and in April at 5% significant level, while a decreasing trend at 5% significant level is found in February. For wave height, increasing trends are detected in May at 1% significant level, in April and November at 5% significant level. The Lepage tests also detect abrupt jumps in a variety of years with. Especially, abrupt jumps at 1% significant level are found around 1989, 1990 in January, 2000 in April, 1997 in May, and 1988, 1993 in June in the variation of wave period, around 1992 in the variation of wave height at Tomakomai, and around 1997 in January, 1992, 2003 in November in the variation of wave period at Hachinohe.

Table 6.1 Summary of the statistical test for annual values of significant wave characteristics at the north sites

Kind of trends tests	Long-term trends detected by Mann-Kendall tests		Abrubt jumps detected by Lepage tests with sample size of 10 years	
	Tomakomai	Hachinohe	Tomakomai	Hachinohe
Annual-mean wave height		△	1995, 1996	
Annual-mean wave period	▲	▲	1989*, 1990*, 1991, 1992, 1993, 1994, 1995, 1996*, 1997, 1998, 1999	1988, 1989*
Maximum wave height	△	▲		1996, 1997 2001, 2002, 2003
Maximum wave period				
Top 1% wave height	▲	△	1997*, 1998	2001

▲ *Increasing trend significant at 1% level;*

△ *Increasing trend significant at 5% level;*

▽ *Decreasing trend significant at 5% level.*

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

Table 6.2 Summary of the statistical test for monthly-mean significant wave characteristics at the north sites

Month	Long-term trends detected by Mann-Kendall tests				Abrubt jumps detected by Lepage tests with sample size of 10 years			
	Tomakomai		Hachinohe		Tomakomai		Hachinohe	
	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
Jan	▲				1989*, 1990*, 1991, 1992, 1993		1996, 1997* 1998	1997
Feb			▽		1991, 1997		1986	2001
Mar								
Apr	△		△	△	1988, 1999 2000*, 2001			1984
May	△	△		▲	1990, 1991, 1996 1997* 1998	1992		1985, 1987
Jun	▲		▲		1988* ,1989, 1990, 1993* 1996, 1997, 1998, 1999	1997, 1998 1999	1992, 1993 1994, 1997	1987
Jul	▲				1992, 1993 1994 , 1995	1991, 1992* 1993, 1994, 1995	1993, 1994, 1996, 2000	
Aug		▽				2003 , 2004	1986, 1995, 1996, 1997, 1998 , 1999	
Sep					1989	1999 , 2000		
Oct	△				1989, 1990		1994	
Nov			▲	△	1990 , 1998	1998	1992*, 1993 2002 , 2003*	1992 , 2002, 2003
Dec	△				1989, 1990,	2004		

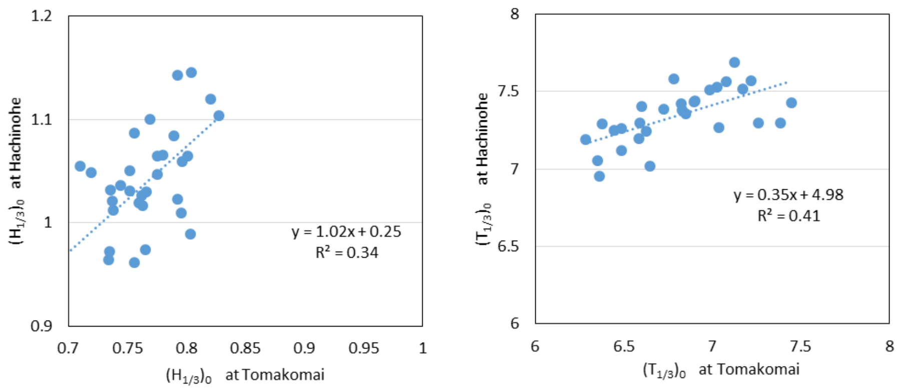
▲ *Increasing trend significant at 1% level;*

△ *Increasing trend significant at 5% level;*

▽ *Decreasing trend significant at 5% level.*

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

Next, the year to year comparison between long-term annual significant wave characteristics at Tomakomai and Hachinohe is conducted as shown in Figures 6.6. The waves at Tomakomai and Hachinohe have a weak positive relation. In addition, wave height and period at Tomakomai is lower than that of Hachinohe about 30% and 10%, respectively.



Figures 6.6 Year to year comparison of wave properties at Tomakomai and Hachinohe

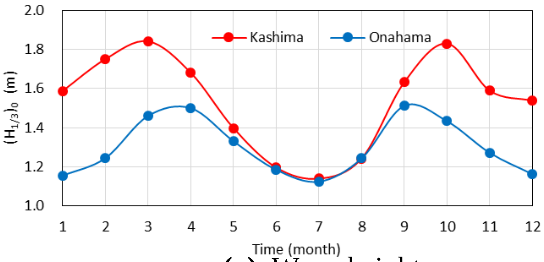
3. Variation of wave characteristics at the middle area

3.1. Seasonal variation of wave characteristics

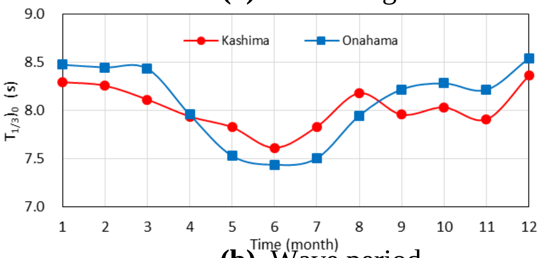
Similar to the north sites, the seasonal variation of wave climates at the midle area are not significant. Figures 6.7 show the monthly-mean of significant wave height and period at Onahama and Kashima. Monthly-mean of significant wave height averaged over the study duration at Onahama is approximately 20% smaller than that at Kashima. The differences are clear in autumn and winter seasons, while they are small in spring and summer. The averaged significant wave height at Onahama varies from 1.12 to 1.51 m, while it varies from 1.14 to 1.84 m at Kashima. For wave period, the differences between Onahama and Kashima as well as the variation from season to season at each site are not clear. The range of wave period variation at these site are almost similar, from 7.44 to 8.36 s. The pattern of seasonal variation in wave height is different from the wave period, but similar at both sites. Wave heights in summer and winter are much lower than that in spring and autumn, while wave periods in summer are slightly smaller than that in autumn, spring and winter.

Seasonal variation of wave direction at these middle sites also indicate substantial discrepancies. Figures 6.8 show the incoming wave direction relating to wave period at the sites in January, April, July, and October that are representative for winter, spring, summer, and autumn, respectively. At Onahama, Wave directions in all of the four seasons have the same pattern, in which ESE direction is dominant. At Kashima wave direction have the same pattern with that of Hachinohe in the north part of the coastline.

In spring, summer and autumn, waves mainly approach shoreline from the East direction, while the main direction in winter is the ENE.

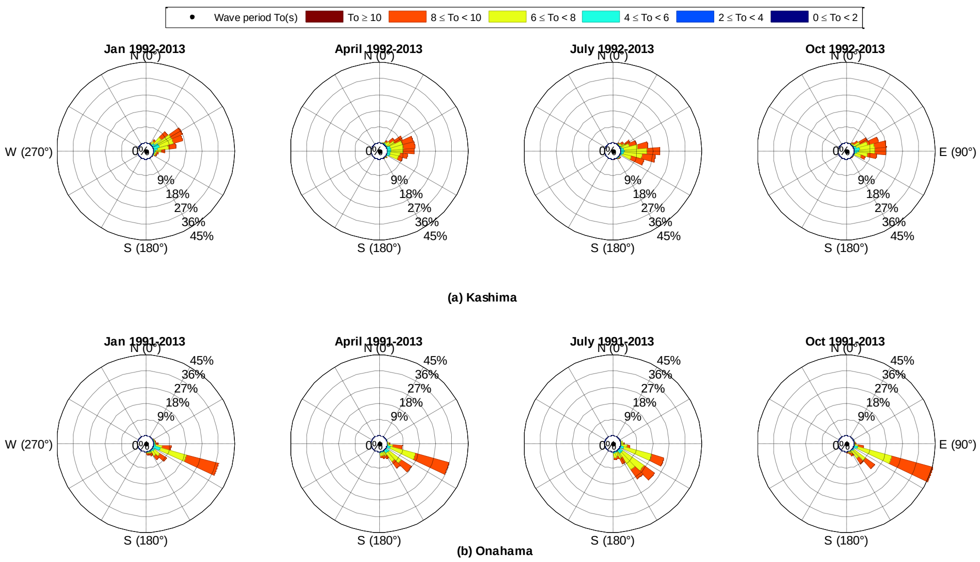


(a) Wave height



(b) Wave period

Figures 6.7 Seasonal variation of wave properties at Onahama and Kashima

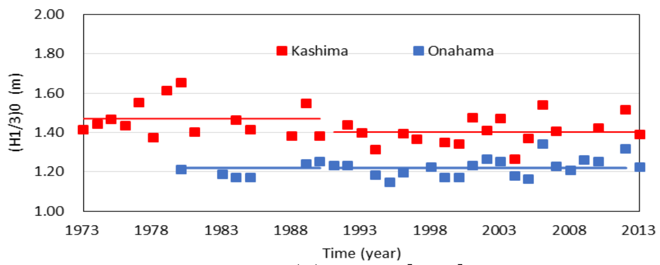


Figures 6.8 Incoming wave direction and wave periods in the four seasons at Kashima and Onahama

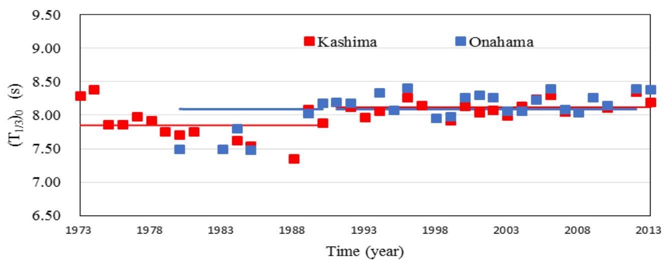
3.2. Long-term variation of wave characteristics

The long-term variations of annual-mean wave characteristics at Onahama and Kashima are investigated in Figures 6.9. According to the Figure 6.9(a), annual-mean wave height at Onahama is about 20% lower than that at Kashima. The values at Onahama vary from 1.15 to 1.34 m, while they vary from 1.27 to 1.65 m at Kashima. At Onahama, although the observed data is available from 1980, they are not examined separately by 1990 because the data in 5 years (1981, 1982, 1986, 1987, 1988) are omitted for the lack of normal data. At Kashima, when the data are examined separately by 1990, the averaged value in the second duration (1991-2013) slightly decreases in comparison with that in former duration (from 1.47 to 1.40 m). The standard deviation in the second duration also slightly decreases in comparison with that in the first duration (from 0.09 to 0.07 m). Figure 6.9 (b) illustrates that the difference in annual significant wave period at both sites is not clear, in which the values fluctuate from 7.35 to 8.41 s. At Kashima, the averaged value in the second duration has a considerable increase (from 7.85 in the first to 8.12 s in the second duration), while the standard deviation decreases significantly (from 0.26 to 0.11 s).

In order to clarify the characteristics of episodic waves, the annual maximum and top 1% of significant wave characteristics at Onahama and Kashima are examined as shown in Figures 6.10. The figures illustrate that the maximum wave heights and periods fluctuate in a wide range with the similar values at both sites. Figure 6.10(a) demonstrated that, in Onahama, the maximum wave height reaches up to 8.10 m at 2002. In 2006, top 1% of significant wave height records the highest value of 4.68 m. At Kashima, the maximum significant wave height reaches up to 7.51 m at 1975. In 1980, top 1% of significant wave height records the highest value of 5.54 m. Figure . 6.10(b) shows that the maximum of the significant wave period at Onahama and Kashima is 15.4 s in 1994 and 16.6 s in 2013, respectively.

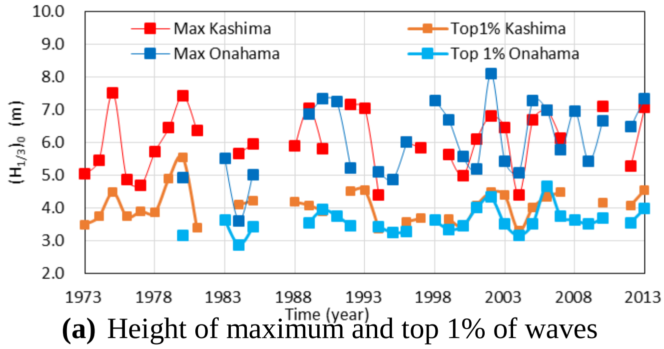


(a) Wave height

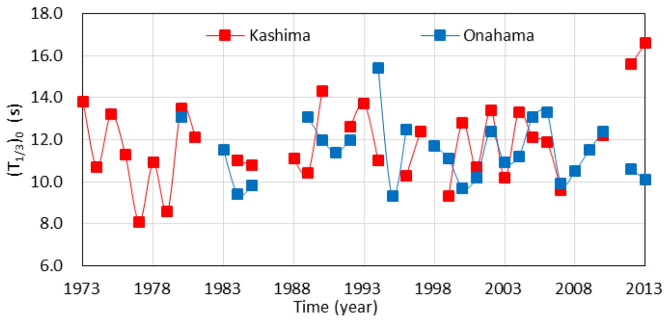


(b) Wave period

Figures 6.9 Long-term variation in annual-mean significant wave characteristics at Onahama and Kashima



(a) Height of maximum and top 1% of waves



(b) Period of maximum significant waves

Figures 6.10 Long-term variation in episodic wave characteristics at Onahama and Kashima

The ratios between the annual values of maximum significant wave height and the annual mean of significant wave height are investigated as shown in Figure 6.11. The results indicated that, the maximum value of wave height is always 3 to 6 times larger than the corresponding mean value. In addition, the ratios also express no abnormal values.

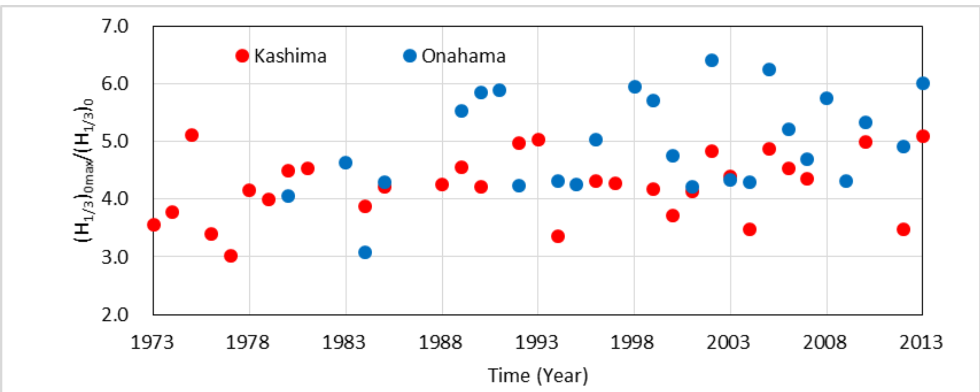


Figure 6.11 Ratio between maximum and mean significant wave height at Onahama and Kashima

Next, the Mann-Kendall and Lepage tests are conducted to examine the long-term trends and abrupt jumps in variation of wave characteristics. Tables 6.3 and 6.4 show the results of statistical tests for annual- and monthly-mean of wave characteristics. Table 6.3 shows that the Mann-Kendall test detect an increasing trend at 1% significant level in annual wave period at Onahama, and an increasing trend at 5% significant level in annual wave period at Kashima. Lepage tests with sample size of 10 years detect no abrupt jumps at Onahama, while many years are detected with abrupt jumps at both 1% and 5% significant levels in annual wave height and period at Kashima. Table 6.4 shows that at Onahama for wave period, the Mann-Kendall tests detect increasing trends at 1% significant level in January, April, May and June, and an increasing trend at 5% significant level in October. The Lepage test with sample sizes of 10 years just detect some abrupt jumps at the 5 % level in June. For wave height, increasing trends at 5% significant level are detected in October and December. In addition, a decreasing trend at 5% level is detected in August. The Lepage tests with sample sizes of 10 years detect abrupt jumps at 5% significant level in February, June, October and December. At Kashima, the Mann-Kendall test detects just one decreasing trend at 5% significant level in wave height in August. In contrast, the Lepage tests with sample size of 10 years detect jumps in many years at 5% significant level in monthly wave height and period in almost every months.

Table 6.3 Summary of the statistical test for annual values of significant wave characteristics at the middle sites

Kind of trends tests	Long-term trends detected by Mann-Kendall tests		Abrubt jumps detected by Lepage tests with sample size of 10 years	
	Onahama	Kashima	Onahama	Kashima
Annual wave height				1985, 1988, 1990, 1994
Annual wave period	▲	∆		1989*, 1990*, 1992*, 1993*, 1994*, 1996
Maximum wave height				
Maximum wave period				
Top 1% wave height				

▲ *Increasing trend significant at 1% level;*

∆ *Increasing trend significant at 5% level;*

∇ *Decreasing trend significant at 5% level.*

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

Table 6.4 Summary of the statistical test for monthly-mean significant wave characteristics at the middle sites

Month	Long-term trends detected by Mann-Kendall tests				Abrubt jumps detected by Lepage tests with sample size of 10 years			
	Onahama		Kashima		Onahama		Kashima	
	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
Jan	▲						1994	1997
Feb						2003		
Mar								
Apr	▲							1986, 1989, 1990, 1993, 1994
May	▲							1990
Jun	▲				1996, 1998, 1999, 2003	1994		
Jul							1992	1990
Aug		▽		▽				1999, 2000
Sep							1985, 1987, 1988, 1990, 1992, 1993	1987
Oct	△	△				2001, 2002	1985, 1990 ,1992	1985, 2001
Nov								1989
Dec		△				2002, 2003		

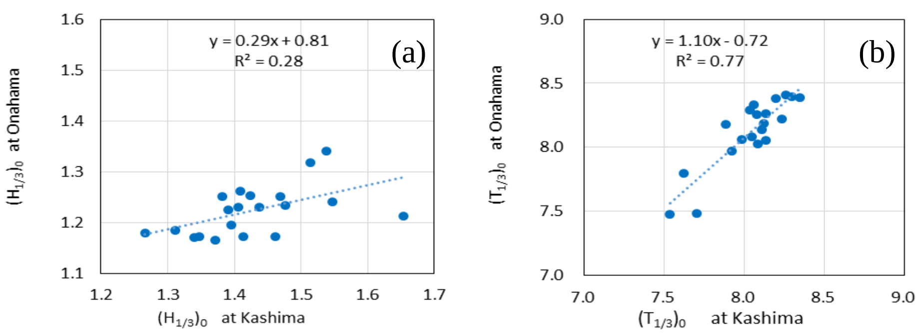
▲ *Increasing trend significant at 1% level;*

△ *Increasing trend significant at 5% level;*

▽ *Decreasing trend significant at 5% level.*

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

The year to year comparison between annual significant wave height at Onahama and Kashima is conducted in Figures 6.12. According to the Figure 6.12(b), wave period at Onahama and Kashima correlate well with first order polynomials with high correlation coefficient. In addition, the wave height at Onahama is about 20% lower than that at Kashima, while the values of wave period are almost the same at both sites.

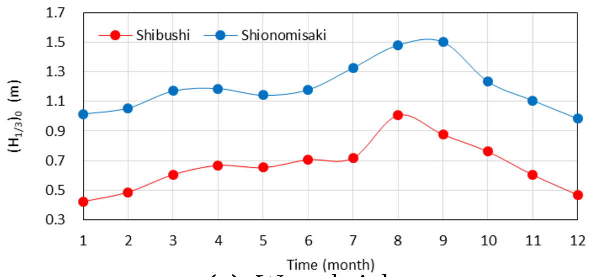


Figures 6.12 Year to year variation of wave properties at Onahama and Kashima

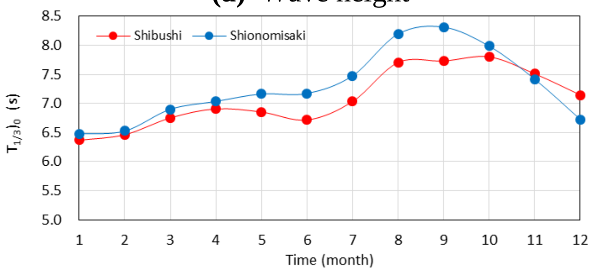
4. Variation of wave characteristics at the southern area

4.1. Seasonal variation of wave characteristics

Similar to the north and the middle sites, seasonal variation of wave height and period at the south sites are not significant. Figures 6.13 show the monthly-mean of significant wave height and period in observed duration at Shionomisaki and Shibushi. On the overall, monthly-mean of significant wave height and period at Shionomisaki is respectively about 40% and 3% larger than that at Shibushi. The averaged significant wave height at Shionomisaki varies from 0.98 to 1.50 m, while it varies in a small range from 0.42 to 1.01 m at Shibushi. The range values of wave period at Shionomisaki and Shibushi are 6.48 to 8.31 s and 6.37 to 7.8 s, respectively. In addition, the pattern of seasonal variation at both sites are quite similar. The variation of waves among winter, spring and summer are not clear, while the values in autumn are slightly higher than those of other seasons.



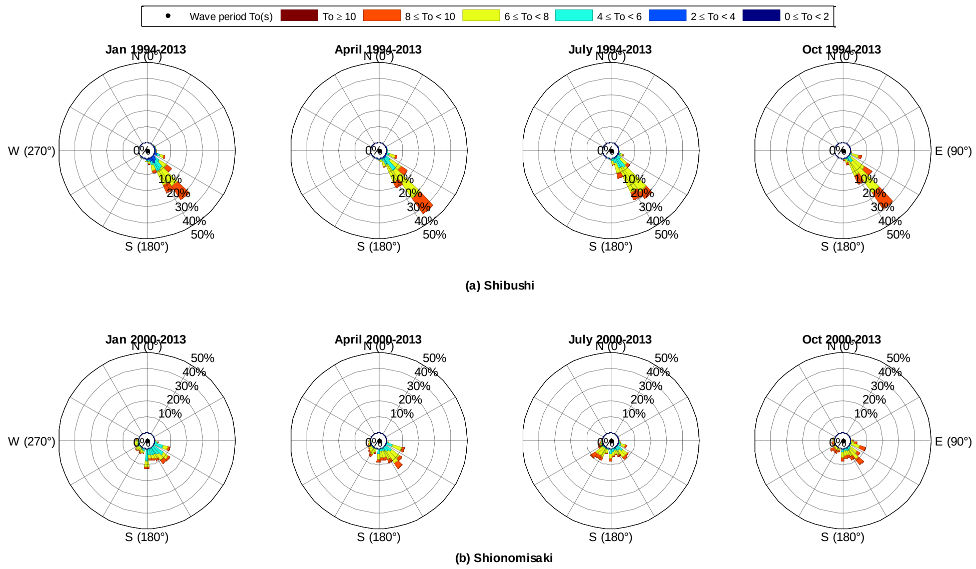
(a) Wave height



(b) Wave period

Figures 6.13 Seasonal variation in wave properties at Shionomisaki and Shibushi

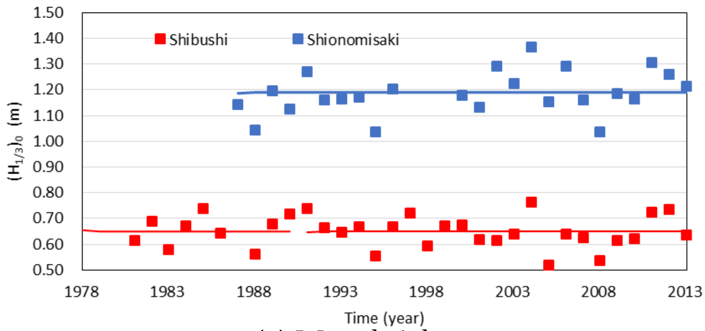
Seasonal variation of wave direction at these sites have noticeable differences. Figures 6.14 show the incoming wave direction relating to wave period at the sites in January, April, July, and October that are representative for winter, spring, summer, and autumn, respectively. At Shionomisaki, dominant wave direction in autumn, winter and spring seasons are the SE, while in summer season the main direction of wave are the SE and the SW. At Shibushi, wave direction in all of the four seasons had the same pattern with dominant direction of the SSE.



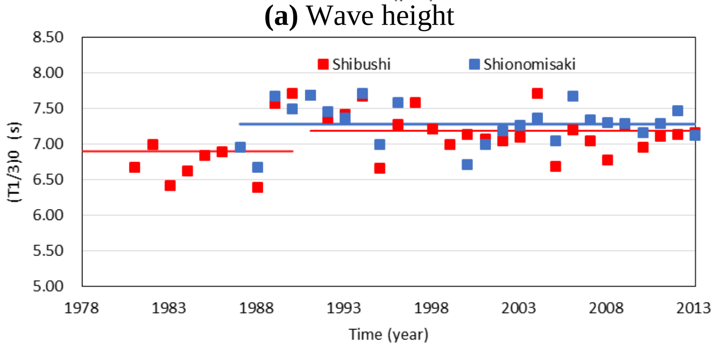
Figures 6.14 Incoming wave direction and wave periods in the four seasons at Shionomisaki and Shibushi

4.2. Long-term variation of wave characteristics

The long-term variations of annual-mean wave characteristics at Shionomisaki and Shibushi are investigated in Figures 6.15. According to Figure 6.15(a), annual-mean wave height at Shionomisaki is about 40% larger than that at Shibushi. The annual values at Shionomisaki vary from 1.03 to 1.37 m, while they vary in a small range from 0.52 to 0.76 m at Shibushi. At Shionomisaki, the observed data are available from 1987 and therefore at this site the data are not examined separately by 1990. At Shibushi, when the data are examined separately by 1990, the averaged values as well as the standard deviations in both duration are similar, in which the averaged value and the standard deviation is 0.65 m and 0.06 m, respectively. Figure 6.15(b) illustrates that the difference in annual significant wave period at these sites is just 3%, in which the values fluctuate from 6.67 to 7.71 s at Shionomisaki and from 6.39 to 7.71 s at Shibushi. The averaged value in the second duration at Shibushi slightly increases (from 6.90 in the first to 7.19 s in the second duration), while the standard deviation decreases significantly (from 0.44 to 0.29 s).



(a) Wave height

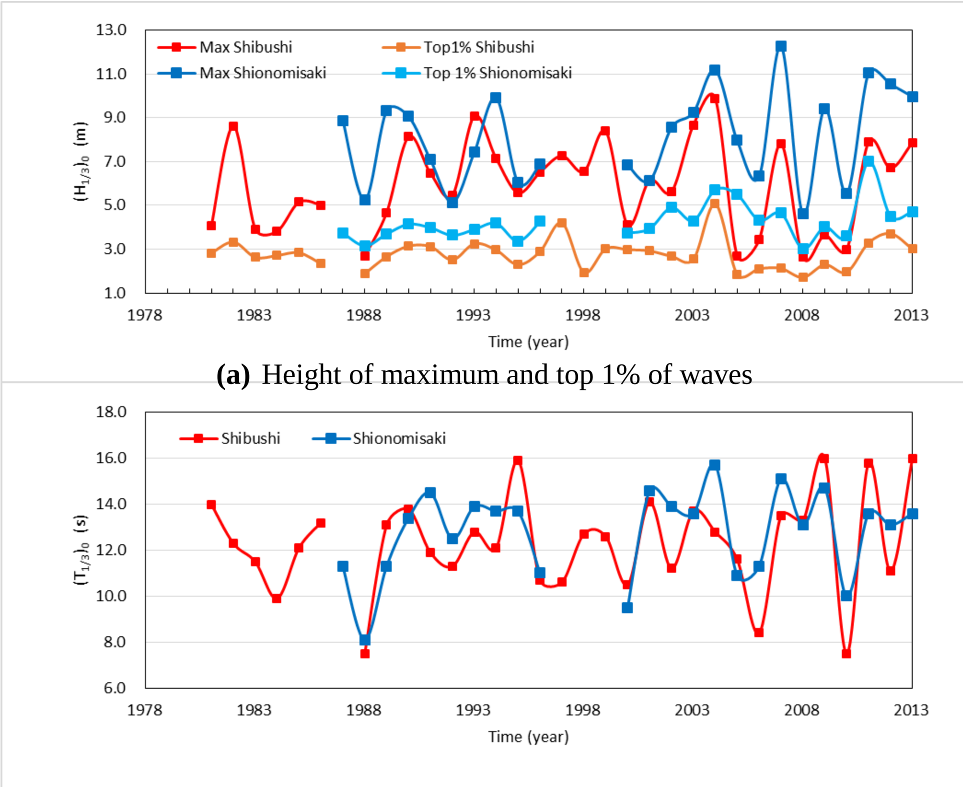


(b) Wave period

Figures 6.15 Long-term variation in annual-mean significant wave characteristics at Shionomisaki and Shibushi

The annual maximum and top 1% of significant wave characteristics at Shionomisaki and Shibushi are examined as shown in Figures 6.16. According to Figure 6.16(a), at Shionomisaki, the maximum wave height reaches up to 12.27 m at 2007. In 2011, top 1% of significant wave height records the highest value of 7.01 m. At Shibushi, the maximum significant wave height reaches up to 9.88 m in 2004. In the same year, top 1% of significant wave height records the highest value of 5.07 m. In Figure 6.16(b), the maximum of the significant wave period at Shionomisaki and Shibushi is respectively 15.7 s in 2004 and 16.0 s in both 2009 and 2013.

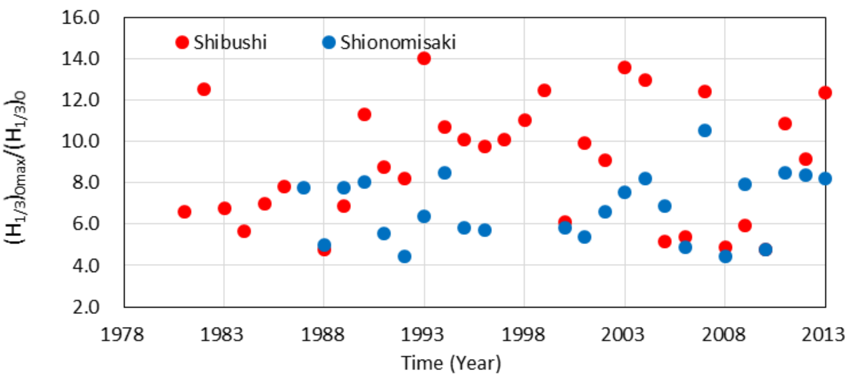
Next, the ratios between the maximum and the mean of significant wave height are investigated in Figure 6.17. While the maximum value of wave height at Shionomisaki was four to eight times larger than the corresponding mean value, the ratio at Shibushi fluctuate in a wide range from four to fourteen.



(a) Height of maximum and top 1% of waves

(b) Period of maximum significant waves

Figures 6.16 Long-term variation in episodic wave characteristics at Shionomisaki and Shibushi



Figures 6.17 Ratio between maximum and mean of significant wave height at Shionomisaki and Shibushi

The Mann-Kendall and Lepage tests detect the following features in the long-term trends and abrupt jumps at the south sites. Table 6.5 shows the results of statistical tests for annual values of significant wave characteristics at these sites. The Mann-Kendall tests detect only one increasing trend at 5 % significant level in the top 1% wave height at Shionomisaki, although the Lepage tests detect abrupt jumps in many years at 5% significant level in both sites. Table 6.6 shows the results of statistical tests for monthly values of significant wave characteristics at these sites. While the Mann-Kendall tests detect no trends at Shionomisaki, an increasing trends at 5% significant level in wave period are detected in February and May at Shibushi. In addition, a decreasing trend at 5% significant level in wave height in March are detected at Shibushi. Several abrupt jumps at 5 % significant level are detected by the Lepage tests with sample size of 10 years at both sites. There is only one abrupt jumps at 1% significant level around 2004 in the variation of wave height in February at Shionomisaki.

Table 6.5 Summary of the statistical tests for annual values of significant wave characteristics at the south sites

Kind of trends tests	Long-term trends detected by Mann-Kendall tests		Abrubt jumps detected by Lepage tests with sample size of 10 years	
	Shionomisaki	Shibushi	Shionomisaki	Shibushi
Annual wave height				1992
Annual wave period			2000, 2001, 2002, 2003	1992, 1993, 1994, 1999
Maximum wave height			2003, 2004	1992, 2000, 2002, 2003, 2004
Maximum wave period				
Top 1% wave height	△		2000, 2001, 2002, 2003, 2004	2003, 2004

△ *Increasing trend significant at 5% level;*

Table 6.6 Summary of the statistical tests for monthly-mean significant wave characteristics at the south sites

Month	Long-term trends detected by Mann-Kendall tests				Abrubt jumps detected by Lepage tests with sample size of 10 years			
	Shionomisaki		Shibushi		Shionomisaki		Shibushi	
	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$	$(T_{1/3})_0$	$(H_{1/3})_0$
Jan							1995	1994, 1995
Feb			△			2002, 2003, 2004*		
Mar				▽	2000		1991, 2000, 2001	
Apr						2002, 2003		1992
May			△			1999	1991, 1993	
Jun					1997, 2000	1997		
Jul								
Aug								
Sep						2003	2000	
Oct						2003	1995, 1996, 1997, 1998	
Nov								
Dec						2001		

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

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

Next, the year to year comparison between annual significant wave height and period at Shionomisaki and Shibushi are conducted as shown in Figures 6.18. According to the figures, waves at Shionomisaki and Shibushi correlate with first order polynomials with medium magnitudes of correlation coefficients. In addition, wave height at Shionomisaki is about 40% larger than that of Shibushi, while the values of wave period at Shionomisaki is just about 3% larger than that of Shibushi.

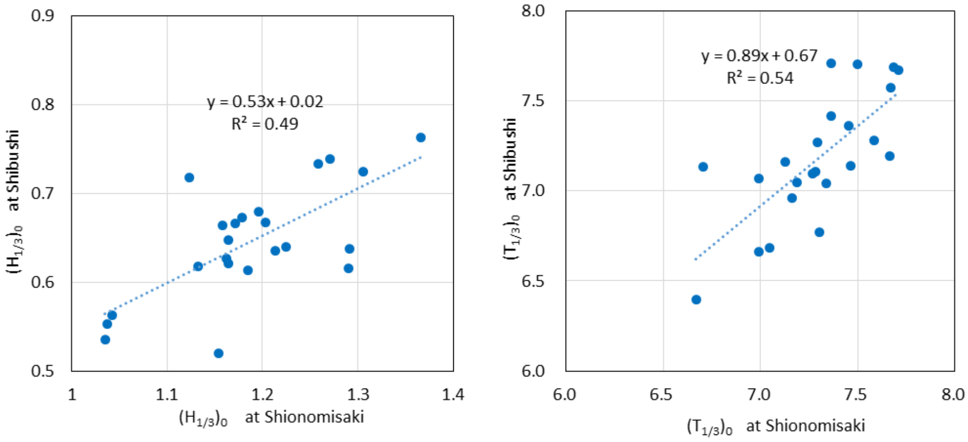


Figure 6.18 Year to year comparison of wave climate at Shionomisaki and Shibushi

5. Overall comparison along the Pacific side coastline of Japan

On the overall, the seasonal variation of wave climates along this coastline are not significant. The discrepancies in the values as well as the seasonal pattern of significant wave height and period among the seasons are not clear. The distinguishing features in seasonal variation of wave height and period along the coastline is that waves in autumn and spring are slightly larger than that in other seasons and generally waves in winter are the smallest. This is contrary to the variation of seasonal wave characteristics along the Sea of Japan coast, in which the difference in values among the seasons is considerable and waves in winter are always the largest (Chapter 3). This result can be explained by the weather factors as follows: Waves in winter are the smallest because of the reduced fetch by the prevailing northwesterly East Asian winter monsoon in this season (Shimada, 2014). On the contrary, the distribution of swells and wind waves developed under the influence of typhoons in autumn makes the waves in this season the highest in comparison with that of other seasons.

The differences in variation of significant wave height from the north to the south sites as well as at the three regional sites are quite clear, while the variations of significant wave periods among these sites are quite small. The regional(local) differences of wave height are 30% at the north sites, 20% at the middle sites, and 40% at the south sites, while the largest difference in regional wave period is less than 10%. Significant wave height at Kashima, the central site of the coastline, is the highest. The wave height decreases northward and southward. The annual means of significant wave heights at Tomakomai (the furthest site at the north) and at Shibushi (the furthest site at the south) are just equal to about 50% that of Kashima). A previous study by Shimada (2014) indicated that in summer time (June to August) as far north and south from the central coastline, the mean of significant wave height decreases as much. This study is not only coincident with the previous finding, but also clarifies that the northward and southward decreasing of significant wave height occur throughout the year. Moreover, Tomakomai and Shibushi ports are effected by the local topographies of the coastline: that is, these ports are located at the iner part of bays and sheltered from waves. This partially contributes to the lower values of significant wave height at these sites in comparison with that of other sites along the coast.

The Mann-Kendall tests for annual mean of long-term wave period indicate increasing trends at 1% significant level at both north sites (Tomakomai, Hachinohe) and one northern middle site (Onahama). The tests also detect an increasing trend at 5% significant level at the other middle site (Kashima). In contrast, no trends are detected at the south sites (Shionomisaki and Shibushi). In addition, the Lepage tests with sample size of 10 years also detect abrupt jumps at 1% significant level around 1989-1990 at Tomakomai, Hachinohe, and Kashima. These results are quite close to the results revealed by Seki et al (2012), in which among six observed sites the increasing trends of annual significant wave period were just found at Tomakomai and Onahama. For annual mean of long-term wave height, the Mann-Kendall test indicate that only one increasing trend at 5% significant level at Hachinohe. Previously, some researchers investigated the increasing trend of annual wave height in the North Pacific Ocean based on 10 years of observation data (1985-1994) and 10 years of hindcasting data (1975-1984). Their result indicated increasing trends at Tomakomai, Hachinohe, Onahama, and Shibushi, in which the largest rate of increasing trends occurred at Hachinohe (Okada et al., 1998). Although the duration of the previous research is different from this one, the result of this study is partially consistent with previous one.

Research conducted by Seki et al (2012) indicated no trends in annual significant wave height among the six sites.

The Mann-Kendall tests for annual maximum wave period indicate no trends at all of the six observed sites. This result is fully coincident with the result of Seki et al (2012). For annual maximum wave height, the statistical tests indicate the increasing trends only at the north sites, in which the increasing trend at Tomakomai is not so clear (at 5% significant level). This is also consistent with the result revealed by Seki et al (2012). Statistical tests for the annual values of top 1% significant wave height also indicate increasing trends at 1 % significant level at Tomakomai (at the north), and at 5% significant level at Hachinohe (at the north) and Shionomisaki (at the south). The Mann-Kendall test for monthly-mean of significant wave period indicate that increasing trends at 1% significant level are detected in winter and summer at Tomakomai, in summer and autumn at Hachinohe, in winter, spring, and summer at Onahama. In contrast, no clear tendencies are found at Kashima, Shionomisaki, and Shibushi. The only difference between this research and the one by Seki et al (2012) is that at Onahama the later research detected an increasing trend in autumn. For monthly-mean of significant wave height, the Mann-Kendall tests detect increasing trend at 1% significant level in spring at Hachinohe. At other sites, the increasing and decreasing trends are not so clear. This result is consistent with that of Seki et al (2012).

The year to year variation of regional wave climates at the north and the south sites indicate little correlations, while wave height and period at Onahama and Kashima correlate well with a first order polynomial, in which the correlation coefficients show intermediate magnitude. This result may be explained by the close distance between Onahama and Kashima (about 110 km).

6. Relations between wave periods and climate indices, meteorological factors

The statistical tests indicate noticeable increasing trends in wave period at Tomakomai, Hachinohe, and Onahama. In order to connect these changes with climate change phenomenon, monthly mean of significant wave periods, which were divided into seasonally- and yearly-mean, at these sites are compared with various climate indices, including the Western Pacific (WP), Arctic Oscillation (AO), East Atlantic

(EA), East Atlantic/Western Russia (EAWR), East Pacific-North Pacific (EP-NP), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Pacific/North American (PNA), Polar/ Eurasia Pattern (POL), Scandinavia (SCAND), El Nino-Southern Oscillation (ENSO), and North Pacific Index (NPI). Table 6.7 shows the correlation coefficients between the mean of significant wave period and the climate indices at Tomakomai, Hachinohe, and Onahama. The results indicate that PNA, SO and NPI express a light impact on the change at Tomakomai in winter, autumn and yearly values. WP, SO, NAO and NPI, PNA, respectively, have a weak relation to the change in spring, summer, autumn, winter in Hachinohe. At Oahama while EAWR, PDO, PNA, and NPI have a little correlation with wave period in winter, SO indicates light impact on the change in autumn. In general, some climate indices seem to have correlations with wave period in winter and autumn but the correlation coefficients are small.

Table 6.7 Correlation coefficients between the mean of significant wave period and the climate indices at Tomakomai, Hachinohe, and Onahama

Sites / Index	Tomakomai					Hachinohe					Onahama				
	Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly	Winter	Spring	Summer	Autumn	Yearly
WP	0.00	0.01	0.06	0.02	0.00	0.07	**0.11**	0.04	0.09	0.05	0.07	0.08	0.02	0.07	0.02
AO	0.06	0.06	0.01	0.00	0.02	0.03	0.04	0.00	0.01	0.01	0.04	0.00	0.01	0.06	0.01
EA	0.00	0.02	0.03	0.00	0.00	0.00	0.01	0.01	0.02	0.01	0.02	0.00	0.01	0.00	0.01
EAWR	0.03	0.01	0.01	0.02	0.00	0.06	0.03	0.03	0.03	0.01	**0.11**	0.01	0.01	0.02	0.01
EPNP	0.04	0.02	0.01	0.00	0.01	0.00	0.04	0.02	0.00	0.01	0.03	0.02	0.01	0.01	0.00
NAO	0.01	0.01	0.02	0.04	0.01	0.01	0.02	0.00	**0.12**	0.00	0.02	0.01	0.01	0.07	0.00
PDO	0.07	0.07	0.01	0.02	0.01	0.06	0.05	0.00	0.04	0.03	**0.21**	0.01	0.02	0.01	0.04
PNA	**0.16**	0.00	0.02	0.03	0.01	**0.12**	0.02	0.03	0.08	0.05	**0.12**	0.00	0.02	0.05	0.01
POL	0.02	0.01	0.01	0.01	0.06	0.02	0.02	0.00	0.00	0.01	0.01	0.01	0.03	0.06	0.00
SCAND	0.04	0.03	0.03	0.01	0.00	0.03	0.01	0.03	0.01	0.00	0.00	0.00	0.05	0.02	0.00
SO	0.00	0.00	0.06	**0.12**	0.02	0.06	0.05	**0.11**	0.02	0.00	0.07	0.04	0.08	**0.13**	0.00
NPI	**0.13**	0.07	0.03	**0.19**	**0.33**	0.09	0.01	0.00	**0.13**	0.04	**0.12**	0.08	0.02	0.03	0.08

The statistical tests for significant wave periods at Tomakomai and Hachinohe indicated increasing trends at 1% significant level not only in annual values but also the values in June. In order to obtain a further understanding on this distinguishing feature as well as to deduce the possible cause of the change, several related meteorological factors in June in duration 1970-2010 around study area are investigated. The reanalysis datasets include mean speed and direction of 10m above sea level wind, wind wave direction, sea level pressure, and sea surface temperature. Figures 6.19 show the mean of 10 m above sea level wind speed in June in two durations (1970-1990 and 1991-2010) as well as the discrepancy between these separate durations. Accordingly, around the study area wind speed in the second duration increases noticeably. On average, the increasing values at the whole area are in the range 0 to 0.2 m/s. Moreover, around

Hachinohe area the increasing values are always the highest. In addition, the figures also illustrate that in second duration while the wind speed around Okhotsk Sea decrease significantly, the values nearby Pacific Ocean increase.

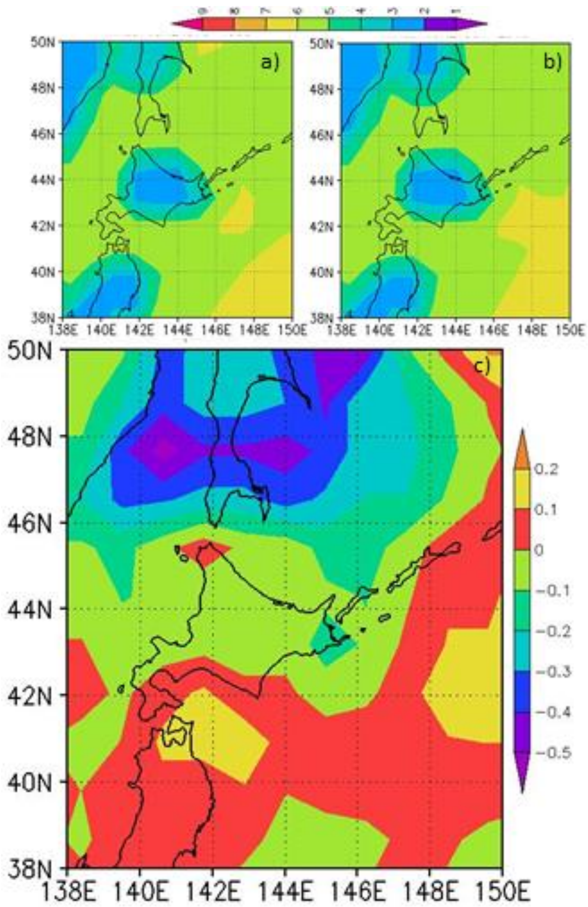


Figure 6.19 Retrieved wind speed in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations

Figures 6.20 describe the 10 m above sea level wind direction and the wind wave direction in June in the two separate duration. However, the discrepancy between the values of these two duration is not clarified. Almost no changes are revealed around the study area.

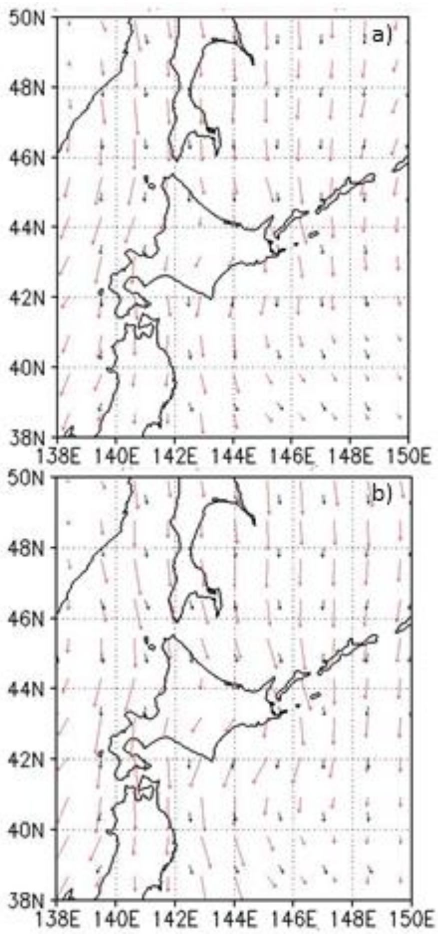


Figure 6.20. Retrieved wind (red vector) and wave (black vector) direction in June around study area; (a) duration 1970-1990, (b) duration 1991-2010

Next, the average values of sea level pressure in June in the two durations are investigated as shown in Figures 6.21. According to the figures, around the study area the sea level pressure slightly decrease in second duration, in which the differences between the durations are about 20 to 40 hPa. Finally, the sea surface temperature in June of the two duration are examined as shown in Figures 6.22. The average values in the second durations increase from 0.2 to 0.4 degree in comparison with that of the first duration. The Mann-kendall and Lepage statistical tests are conducted in order to reveal possible increasing/decreasing trends of these meteorological factors. However, no clear tendencies are indicated.

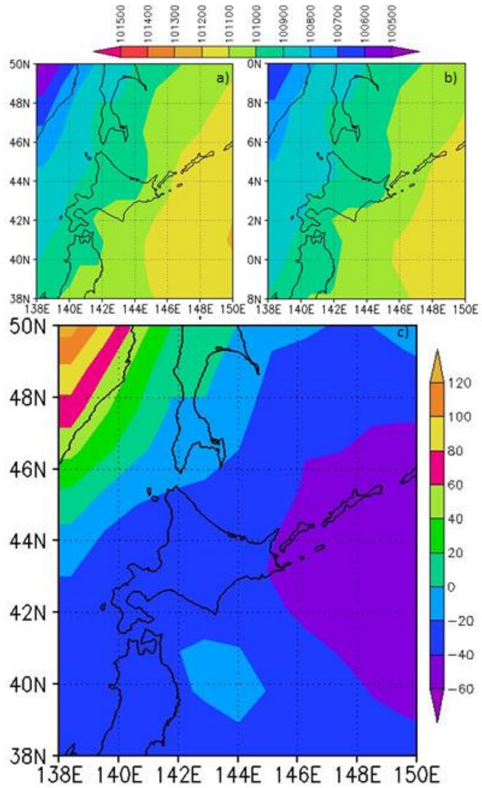


Figure 6.21 Retrieved mean sea level pressure in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations

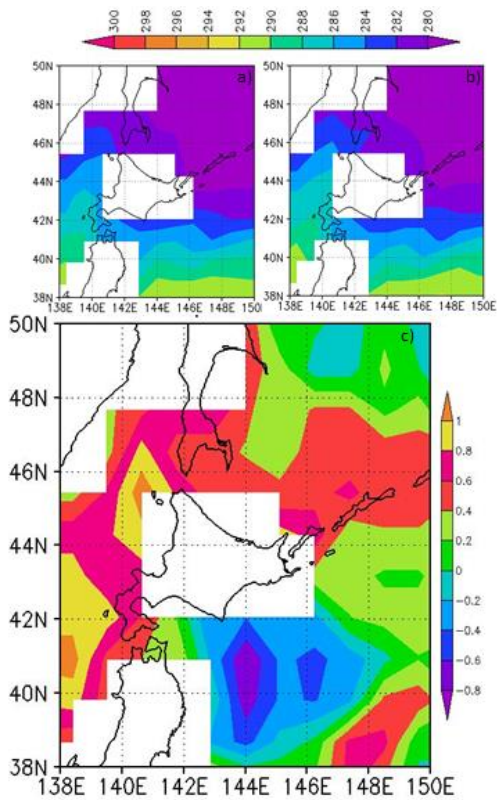


Figure 6.22 Retrieved mean sea surface temperature in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations

7. Summary

In order to clarify the seasonal as well as the long-term characteristics in significant wave properties along the North Pacific Ocean coast of Japan, this part of the study investigated the long-term wave data observed at the six NOWPHAS's observation sites, including Tomakomai, Hachinohe, Onahama, Kashima, Shionomisaki, and Shibushi. The seasonal variation of wave climates along this coastline are not significant. The differences in variation of significant wave height from site to site are considerable, while they are small in variation of significant wave period. The significant wave heights at the central sites of the coastline are the highest. Long-term trends and abrupt jumps concentrate in annual wave period at the north sites of the coastline. The long-term increasing trends and abrupt jumps of wave period in winter, summer, and autumn are also intrinsic to the north sites. Significant wave period at the north sites are compared with various climate indices to clarify the correlation between them. Although some climate indices indicate correlations with wave period in winter and autumn, the correlation are weak. The increasing trends of significant wave period at the northern part of the coastline could be related to the global climate change phenomenon. However, a more detailed study based on numerical wave model is needed to clarify them. Several related meteorological factors around northern area in summer also express changing trends in study duration. The 10 m above sea level wind speed and the sea surface temperature noticeably increase, while the sea level pressure slightly decreases. The increasing trends of significant wave period at this coastline could be related to the changes of the related meteorological factors. However, a more detailed study based on numerical wave model is needed to clarify them.

CHAPTER 7. RELATION BETWEEN CLIMATE CHANGE AND WAVE CHARACTERISTICS IN SUMMERTIME AROUND THE KAETSU COAST, JAPAN

1. Introduction

An essential factor to understand as well as to predict future changes in variation of ocean wave characteristics is the relationship between weather factors and the wave itself. Several weather forecasting centers have taken into account wave forecasting as an part of operational weather forecasting (Bidlot and Holt, 1999), and seasonal meteorological factors are considered to be key elements of the world's weather. As a result, the variation of meteorological factors are expected to play a critical role in long-term change of coastal wave characteristics. Along the Sea of Japan coast, summer-time meteorological factors could have placed significant influence on the variation and bring out the change in long-term wave characteristics in this season.

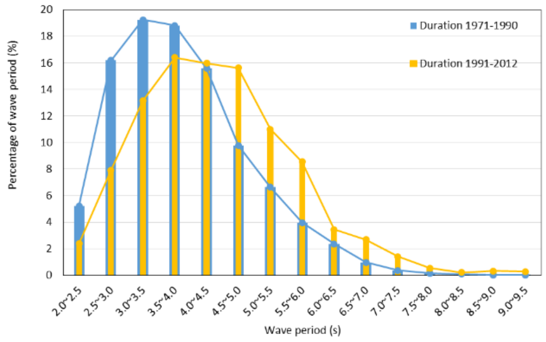
Previously, many researches indicated significant change in wave characteristics in summer along the Sea of Japan coastline. Yamaguchi et al. (2007) indicated increasing jumps for the significant wave height and period in summer. Moreover, an increasing trend in wave period was also observed in summer. The results by Seki et al. (2011, 2012) showed that in spring and summer significant wave height and period expressed increasing trends at several locations along the Sea of Japan coast. The analysis results in Chapter 3 and Chapter 4 showed that the wave periods in July have significantly increased at Wajima and Kanazawa sites which are located on the middle of the coastline. Furthermore, some other scientists investigated and indicated remarkable features about the relation between summer wave and climate in the surrounded areas. Young (1999) analyzed a global climatology data composed of ocean wind and wave conditions based on the combination of satellite remote sensing and model predictions. The results showed that in the western North Pacific and the Okhotsk Sea, summertime wave climate is generally influenced by the prevailing East Asian monsoon. Shimada (2014) investigated in situ measurements and reanalysis data of wave height variability along Pacific and Okkhotsk sea coasts of northern Japan in summer and indicated that the wave variability is enhanced along the coast of northern Tohoku by the strong local winds occurring in the lee of Cape Erimo.

Along the Sea of Japan coast, the distinguishing feature of wave characteristics is that the wave heights and periods are at minimum in summertime. This probably explains the fact that little attention has been placed on the impact of meteorological factors to the change of wave characteristics in summer. In order to deduce possible cause of and future characteristics of coastal accidents in the area such as rip currents, a deep understanding of climate - wave interaction at summertime is necessary. Accordingly, this part further explores the previous study about wave period in July at Kanazawa site and analyzes some observed as well as reanalysis meteorological dataset to examine the relationship between long-term variation of summertime wave and climate characteristics along the coastline.

At Kanazawa port, the monthly-mean significant wave period in July are computed for the study duration in order to examine the long-term variation of wave period in the month. Next, some observed meteorological data (wind speed, sea level pressure and air temperature) retrieved from Wajima site are analyzed to make comparison with the above wave property. Finally, some meteorological reanalysis data in duration 1970-2010, retrieved from ERA-20C of ECMWF, are investigated. The data include mean period and direction of wind wave, mean speed and direction of 10m above sea level wind, sea level pressure, and sea surface temperature. The Mann-Kendall and Lepage tests have been conducted in order to detect the significant trend or jump in the long-term variation of the investigated factors.

2. Detailed analysis of wave periods at Kanazawa in July

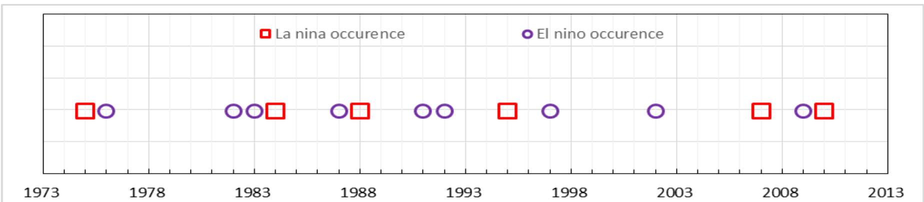
As mentioned in Chapter 3, the significant wave period in July in duration 1971-2012 at Kanazawa indicated a remarkable increasing tendency. Over two different durations, from 1971 to 1990 and from 1991 to 2012, it has significantly increased from 4.43 s in the first two decades to 4.98 s in the last two decades. The Mann-Kendall statistical test illustrated that the increasing trend was significant at 1% level. In order to understand the characteristics of these phenomena and to deduce the possible causes, more detailed analyses are progressed. First, the Lepage statistical test with sample size of 10 years are conducted to clarify significant change in this factor. The result detects an abrupt jump at 1% significant level around 1990. Second, the frequency of wave period in these 2 durations are examined. Figure 7.1 shows the distribution of wave period in July for the time of 1971-1990 and 1991-2012. According to the figure, the range of wave period in this month varies from 2.0 to 9.5 s in both durations. The percentage of short waves (from 2.0 to 4.0 s) in the 1971-1990 duration is much higher than that of the 1991-2012 duration. In particular, the frequency of 2.0-3.0s waves in the first duration is almost double that of the later. In contrast, the distribution of larger waves in the second duration is more than 50% higher than that in the former. The distributions of medium (4.0-4.5s) waves are nearly the same in both durations



Figures 7.1 Distribution of wave period in July at Kanazawa

3. Influences of El nino, La nina and climate indices

The occurrences of El nino and La nina phenomena in duration 1970-2012 are then examined. Figure 7.2 shows the coincidence of El nino and Lanina phenomena in summertime. In the study duration these phenomena occurred 20 years in which 15 times were in the summer. The number of occurrences of these phenomena were nearly the same in both duration (1970-1990 and 1991-2012). Number of typhoons passing 250km around Kanazawa in July in the duration 1971-2012 were also investigated. In duration 1971-1990 there were 5 typhoons passing the area in July while it were 7 in the duration 1991-2012. Namely, the difference of the number of typhoons passing the study area in July was not clear.



Figures 7.2 Occurrence of El nino and La nina phenomena in summer

In Chapter 3, 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), and North Pacific Index (NPI). The result showed that just WP index expresses a light impact on this change. In this part of the study, the wave periods in July of the study duration were compared with other climate indices, including Southern Oscillation Index (SOI), East Atlantic (EA), East Atlantic/Western Russia (EAWR), East Pacific-North Pacific (EP-NP), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Pacific/North American (PNA), Polar/ Eurasia Pattern (POL), and Scandinavia (SCAND). However, while PNA index expressed a considerable impact on the wave period (Figure 7.3), the correlations between the characteristic of waves and the other climate indices were weak. Student's t-test has been performed to judge the relation between the wave period and PNA index. The result indicated that this relation was significant at 1% level.

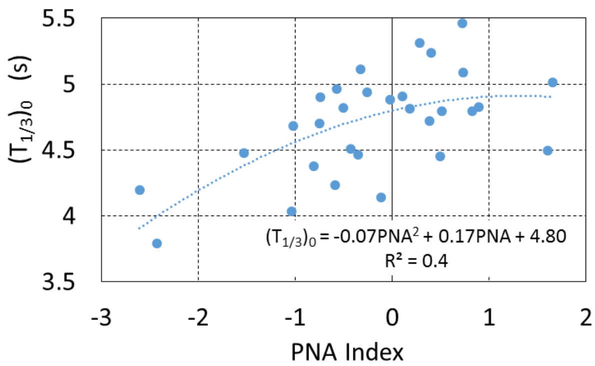
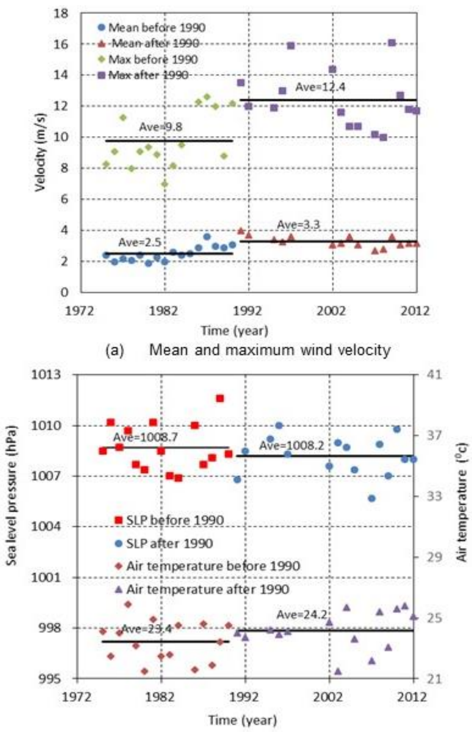


Figure 7.3 The relation between wave period in July at Kanazawa and PNA Index

4. Comparison with observed meteorological factors

Japan Meteorological Agency (JMA), which was officially established in 1956, provides observed meteorological data for many region in Japan. JMA Observation data are updated every hour. The data at Wajima site include information on precipitation, temperature, wind direction/speed, sunshine duration, humidity, atmospheric pressure and daily high/low temperatures. In this research, several observed datasets including wind speed, sea level pressure and air temperature at Wajima site in duration 1972-2012 were examined to estimate the correlation with wave characteristics. Figures 7.4 show the variation of mean and maximum values of wind velocity, mean sea level pressure and mean air temperature in the two durations 1972-1990 and 1991-2012. According to Figure 7.4(a), the averaged values of mean as well as maximum wind velocities in the second duration increased significantly in comparison with that of the former. The averaged values in the durations before and after 1990 were 2.5 m/s and 3.3 m/s, respectively. The maximum value in the first duration was 9.8 m/s, while it was 12.4 m/s in the second duration. The Figure 7.4(b) illustrated that in the two durations while averaged value of sea level pressure is almost the same (with the values of 1008.7 hPa and 1008.2 hPa, respectively), the averaged values of air temperature increased from 23.4 ^{0}C in the first duration to 24.2 ^{0}C in the later.

The Mann-Kendall and Lepage tests were conducted in order to detect significant changes. The Mann-Kendall tests showed an increasing trend in mean and maximum wind velocity significant at 1% level. The Lepage statistics with the sample size of 15 years also detected an abrupt jump in these two factors around 1990 at 1% significant level. There were no significant trends or jumps for sea level pressure and air temperature factors.

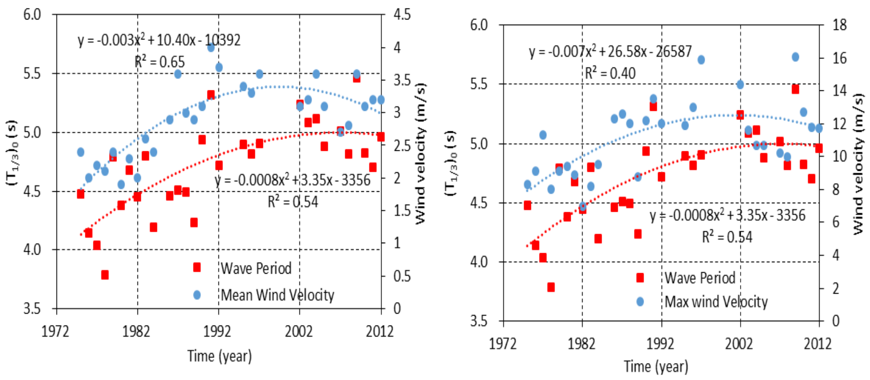


(a) Mean and maximum wind velocity

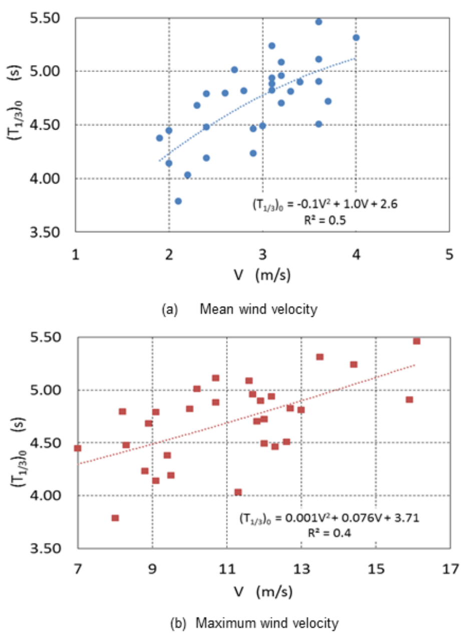
(b) Mean sea level pressure and air temperature

Figures 7.4 Variation of several climate factors in duration 1972-2012 in July

After that, the variation of wave period were compared with mean and maximum wind velocity in duration 1972-2012 as shown in Figure 7.5. It is illustrated that the increasing trends of these two quantities are quite similar and significant



Figures 7.5 Trends of wave period and wind velocity in duration 1971-2012 in July

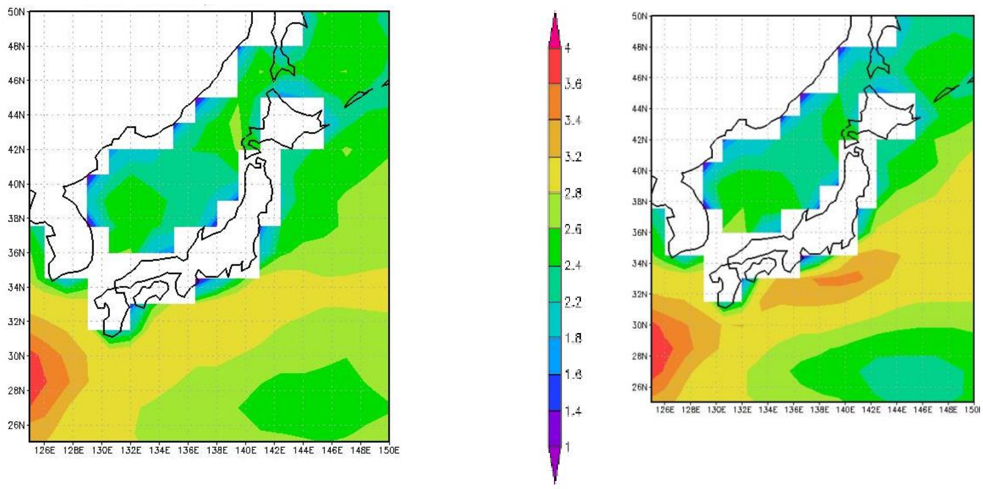


Figures 7.6 The relation between wave period and observed wind velocity in duration 1971-2012 in July at Kanazawa

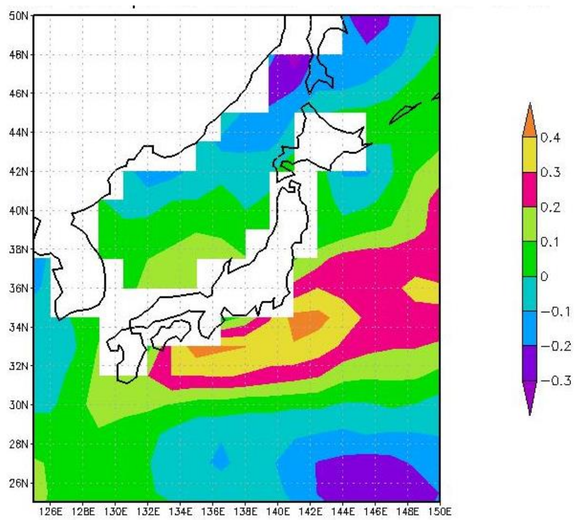
Finally, the relationships between the wave periods and these observed meteorological factors were investigated. The results showed that the wave periods were correlated with mean and maximum wind velocities quite well, in which the correlation coefficient between the wave period and these two factors were 0.5, 0.4, respectively (Figures 7.6), while the correlation between wave period and the others observed climate factors were very weak. Student's t-tests for the relations between the wave period and the two elements of wind velocity were judged to be significant at 1% level.

5. Comparison with reanalysis meteorological factors

The mean properties of wind waves, 10 m above sea level wind, sea level pressure, and sea surface temperature retrieved from ERA-20C were then investigated for the two separate duration 1970-1990 and 1991-2010. First, the averaged wind wave periods in July were compared between these two duration in Figures 7.7. On average the mean wind wave period around the study area in duration 1991-2010 increased in the range of 0.1 to 0.2s (corresponding for 4.5 to 7.7%) in comparison with that of the first duration.



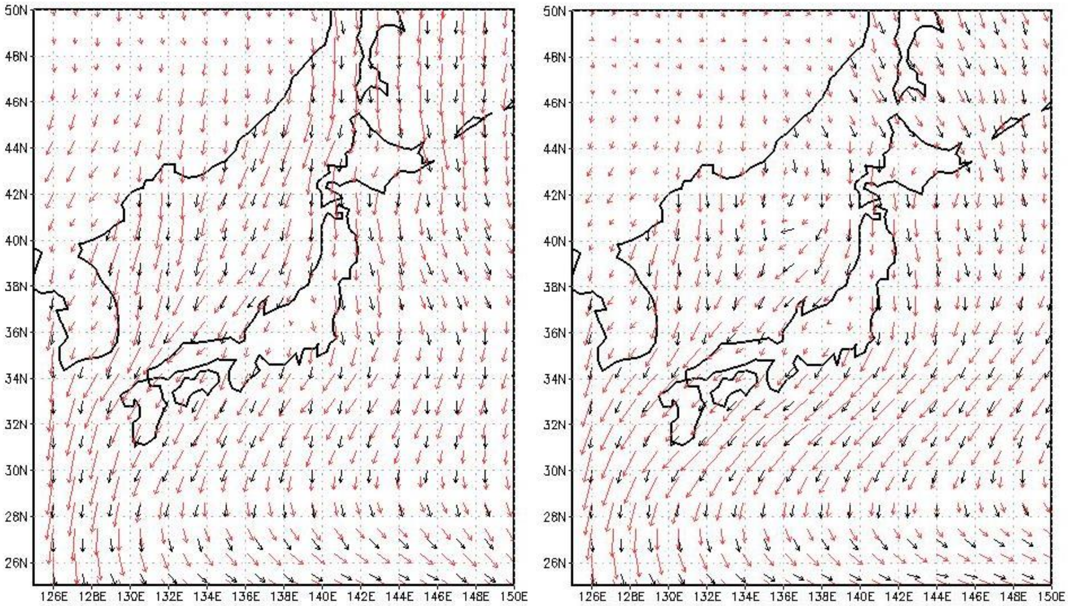
(a) Duration 1970-1990 **(b)** Duration 1991-2010



(c) The difference between two duration

Figures 7.7 Comparison of wind wave period in July for 1970-1990 and 1991-2010

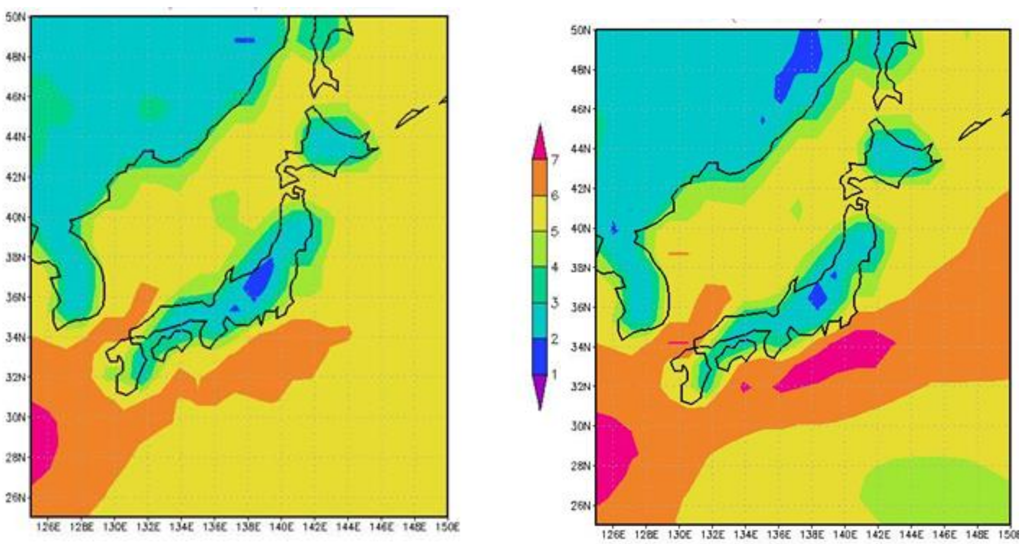
Next, wind wave direction (black vector) and 10m above sea level wind direction (red vector) are compared for the two duration in Figures 7.8. The figures illustrated that both of wind waves and 10m above sea level wind direction slightly move southward in the second duration. The change is more clear in the area of 38^0N to 42^0N latitude and 135^0E to 138^0E longtitude in the center area of the Sea of Japan coast.



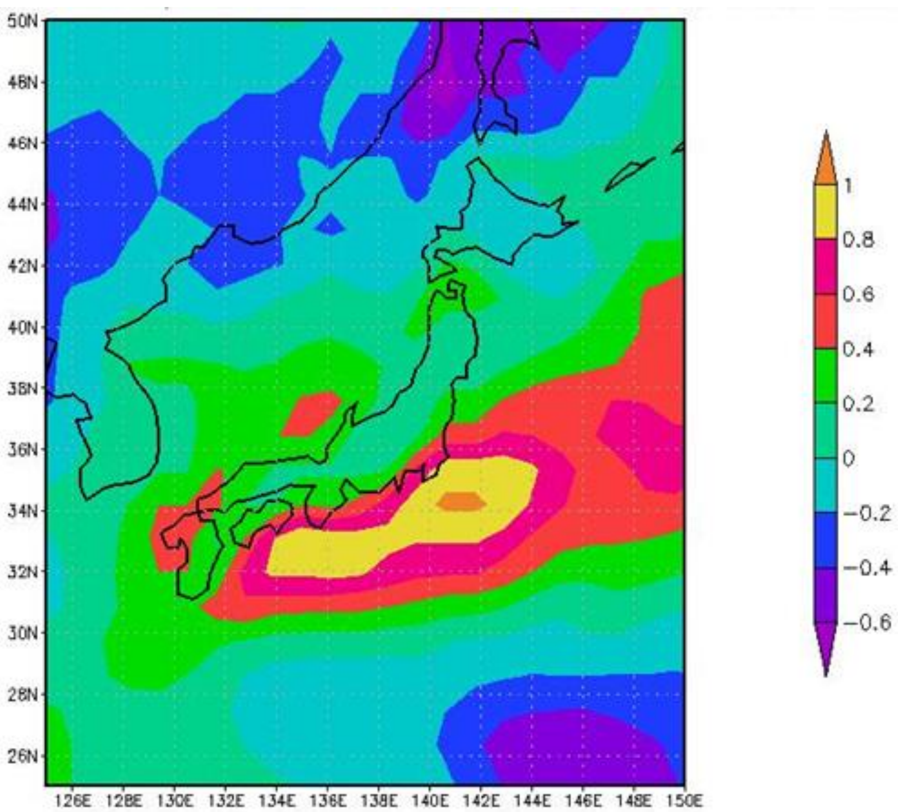
(a) Duration 1970-1990 **(b)** Duration 1991-2010

Figures 7.8 Wind direction and wind wave direction in July 1970-2010

Next, mean value of 10m above sea level wind speed are examined as shown in Figures 7.9. These figures illustrated that around the study area wind speed in the second duration increased by around of 0.2 to 0.6 m/s in comparison with that of 1970-1990 duration. This increase corresponds to 6.5 to 10.0% of the wind speed. Especially, in 135^oE and longtitude 37^oN latitude area the increase in the second duration is considerable. The averaged value of 10m above sea level wind speed in duration 1970-1990 was 4.65m/s while it was 5.07m/s in the second duration. The Mann-Kendall and Lepage tests have been conducted for the data at this area. The results showed that while the Mann-Kendall indicated no significant increasing trend, the Lepage test with sample size of 15 years indicated an abrupt jump significant at 1% level around 1991.



(a) Duration 1970-1990 **(b)** Duration 1991-2010



(c) The difference between 2 duration

Figures 7.9 Comparison of wind speed at 10 m above sea level in July

The values of this wind velocity at point of 136^{0}E longtitude, 37^{0}N latitude, which is the nearest from Kanazawa to the area of noticeable increase of reanalyzed wind speed, correlated quite well with the wave period as shown in Figure 7.10. Student's t-tests indicated the relation to be significant at 1% level. Moreover, Lepage test with sample size of 15 years detected an abrupt jump at 5% significant level for the values of wind velocity at this point.

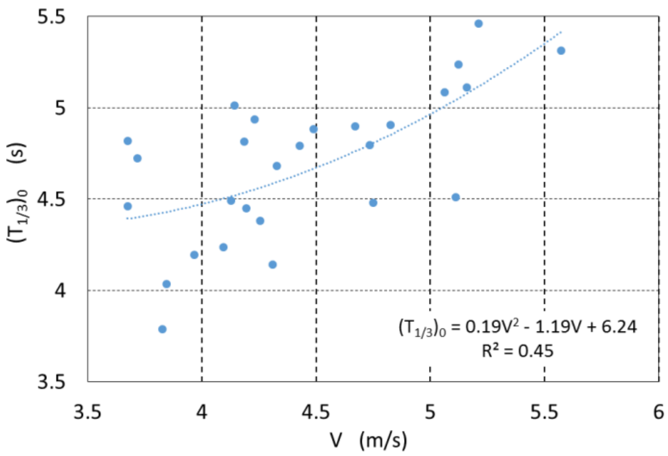
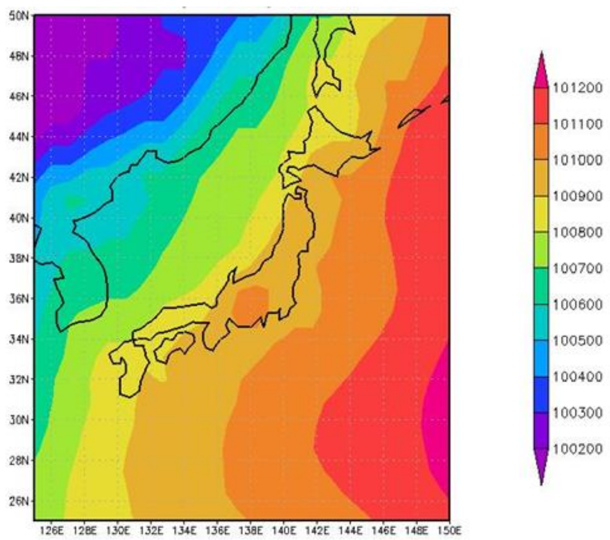
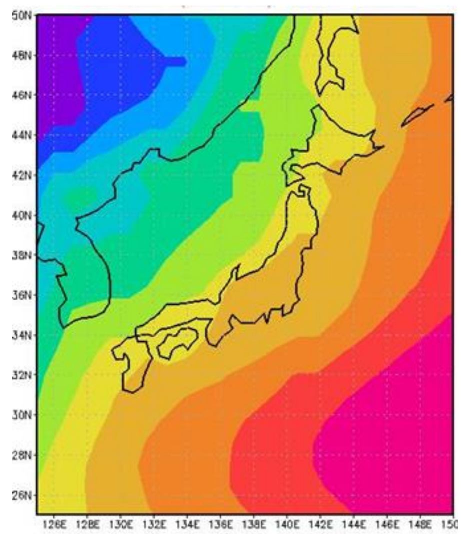


Figure 7.10 The relation between wave period and reanalyzed wind velocity in duration 1971-2012 in July at Kanazawa

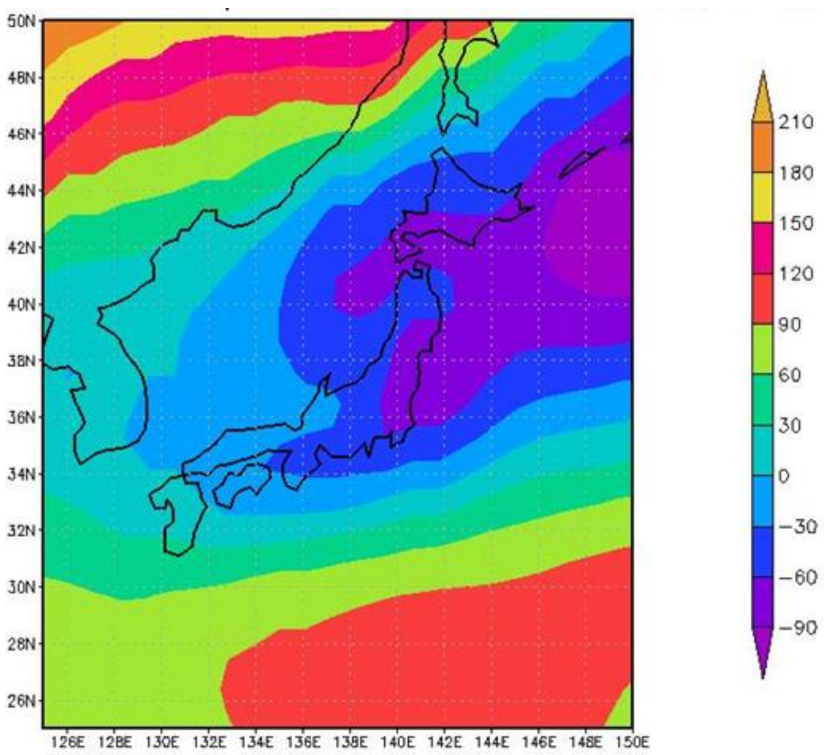
Next, sea level pressure of the two duration around the study area were compared as shown in Figures 7.11. According to the figures sea level pressure in duration 1991-2010 decreased from 30 to 90 Pa in comparison with that of the former duration. This decrease is not considerable.



(a) Duration 1970-1990



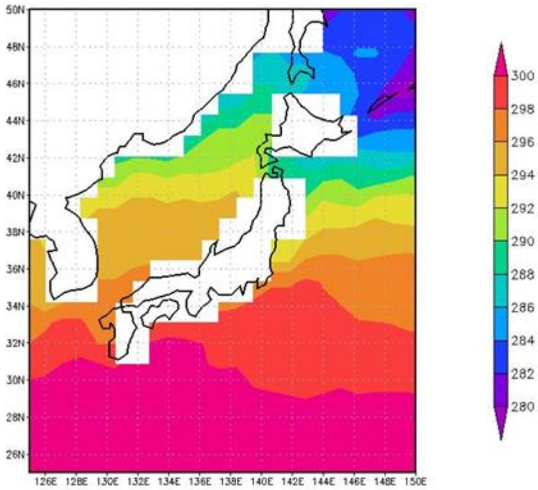
(b) Duration 1991-2010



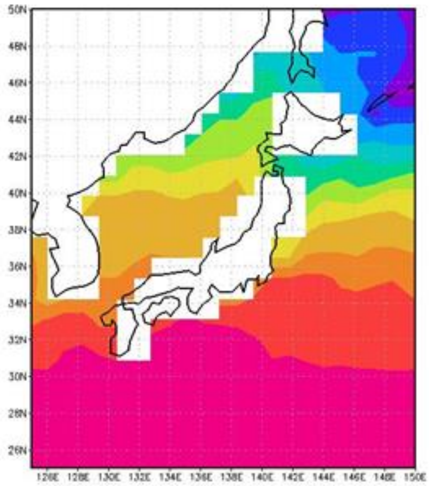
(c) The difference between 2 duration

Figures 7.11 Comparison of sea level pressure in July

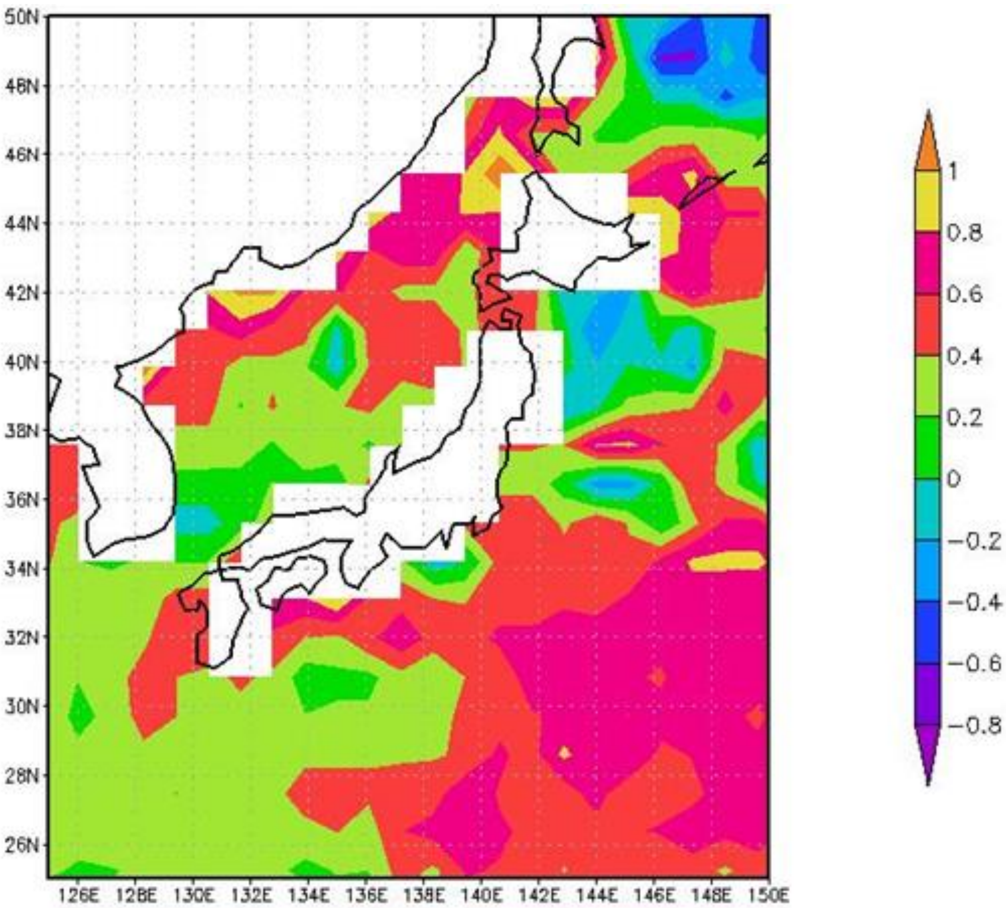
Finally, the sea surface temperature around the study area were investigated to make a comparison between the two duration as shown in Figure 7.12. Comparing with the first duration this meteorological factor of the second duration slightly increased by the amount of 0 to 0.4 degree.



(a) Duration 1970-1990



(b) Duration 1991-2010



(c) The difference between 2 duration

Figures 7.12 Comparison of sea surface temperature in July

6. Summary

In this part, observed significant wave period in July in duration 1971-2012 at Kanazawa port are further analyzed and compared with some observed as well as reanalysis meteorological factors. The results indicated several interesting features. The Lepage test has confirmed the increasing trend of wave period in July recently at Kanazawa which were figured out in the previous study. The frequencies of investigated wave period in two duration expressed different distributions. Especially, the distribution of larger waves in the second duration (1991-2012) is more than 50% higher than that in the former duration. Both the observed and reanalysis wind speed expressed close patterns with the investigated wave period. The Mann-Kendall statistical test of the mean and maximum observed wind speed indicated increasing trends in the study duration. The Lepage test with sample size of 15 years also detected abrupt jumps at 1% significant level around 1990 for these factors. For the reanalysis wind speed data, although the Mann-Kendall test indicated no significant trend, the Lepage test with sample size of 15 years indicated an abrupt jump significant at 1% level around 1991. Student's t-tests indicated that the relations between wave periods and observed as well as reanalyzed wind velocities were at 1% significant level. Both observed and reanalysis sea level pressure data indicated noticeable decreasing trends. Both observed air temperature and reanalysis sea surface temperature data expressed slightly increasing trend. The El nino, La nina phenomena, the number of typhoons passing the study area, and the climate indices expressed no clear effects on the variation of wave period in July. In conclusion, the increasing trend of wind speed in the study area may partly explain the increasing trend of wave period in July.

CHAPTER 8. CONCLUSIONS

1. Main results

The first part of this research examined the long-term wave data observed at the Kanazawa Port in the last four decades in order to clarify the long-term as well as the seasonal characteristics in significant wave properties. On the overall, the seasonal variation in wave height, period, and direction were shown to be significant. The wave heights and periods were the highest in winter, the lowest in summer and the medium in spring and autumn. The wave slopes in winter were steeper than those of other seasons. The monthly-mean wave height and period were correlated with second order polynomials very well. The differences in monthly-mean wave heights of duration 1971-1990 and duration 1991-2012 were small. In contrast, the differences in wave periods between these two duration were significant. The annual-mean wave period indicated an abrupt increase around 1990. The increase of wave period was most significant in July.

The second part extended the analysis of wave data obtained at the Kanazawa Port in duration 1971-2012 in order to estimate the characteristics of deep-water wave energy flux, nearshore waves and related morphological parameters (breaker height and depth, closure depth, Sunamura index), and infragravity waves. The investigation of seasonal distribution of wave energy relating to incoming wave direction indicated that the wave energy is mostly transported during winter season from the WNW, NW, and NNW direction. The pattern of seasonal variation of breaker height and depth are quite similar; the values are the highest in winter, medium in spring and autumn and the lowest in summer. The cumulative probability distribution of breaker depth indicated that in winter season 80 percent of waves break at the area with water depths less than 4.0 m, while in summer this water depths is just approximately 1.0 m. In the spring and autumn the water depth of the area at which 80 percent of waves break is less than 2.5 m. The cumulative probability of closure depth in the study duration is as follows: over approximately 80 percent of time closure depths are less than 6.0 m in winter, 2.0 m in summer, 3.0 m in spring and autumn. The inspection of Sunamura indices shows that during summer season the shoreline is advanced and the recessions of shoreline generally occur in other seasons. The transitions from recessions to advances of the shoreline occur in March, from advances to recessions in September. In winter season most of waves induce recession of the shoreline, in which the percentage of Sunamura indices with values of greater than 18 contribute about 90 percent. In summer the role of majority of waves is to advance the shoreline (about 60 percent of Sunamura indices is lower than 18). In spring and autumn, approximately 70 percent of waves make shoreline recession and 30 percent make the shoreline advance. Infragravity waves have the same seasonal pattern with the wind waves. The patterns of the daily as well as monthly variation of infragravity waves are similar to that of wind waves. The heights of infragravity waves and wind waves can be linearly correlated very well with a high correlation coefficient.

The third part examined the long-term wave data observed at the four ports; 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. 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 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 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.

In order to clarify the seasonal as well as the long-term characteristics in significant wave properties along the north Pacific Ocean coast of Japan, the fourth part of the study investigated the long-term wave data observed at the six NOWPHAS's observation sites, including Tomakomai, Hachinohe, Onahama, Kashima, Shionomisaki, and Shibushi. The seasonal variation of wave climates along this coastline are not significant. The differences in variation of significant wave height from site to site are considerable, while the variations of significant wave periods are small. The significant wave heights at the central sites of the coastline are the highest. Long-term trends and abrupt jumps concentrate in annual wave period at the north sites of the coastline. The long-term increasing trends and abrupt jumps of wave period in winter, summer, and autumn are also intrinsic to the north sites. Significant wave period at the north sites are compared with some climate indices to clarify the correlation between them. The results indicate that PNA, SO and NPI express a light impact on the change at Tomakomai in winter, autumn and yearly values. WP, SO, NAO and NPI, PNA, respectively, have a weak relation to the change in spring, summer, autumn, winter in Hachinohe.

Finally, the fifth part of this research further analyzed the significant wave period in July in duration 1971-2012 at Kanazawa port and compared it with some observed as well as reanalysis meteorological factors. The results indicated several interesting features. The Lepage test has confirmed the increasing trend of wave period in July recently at Kanazawa which were figured out in Chapter 3 by the Mann-Kendall test. The frequencies of investigated wave period in two duration expressed different distributions. Especially, the distribution of larger waves in the second duration (1991-2012) is more than 50% higher than that in the former duration. Both the observed and reanalysis wind speed expressed close patterns with the wave period. The Mann-Kendall statistical test of the mean and maximum observed wind speed indicated increasing trends in the study duration. The Lepage test with sample size of 15 years also detected abrupt jumps at 1% significant level around 1990 for these factors. For the reanalysis wind speed data, although the Mann-Kendall test indicated no significant increasing trend, the Lepage test with sample size of 15 years indicated an abrupt jump significant at 1% level around 1991. Both the observed and reanalysis sea level pressure data indicated noticeable decreasing trends. Both observed air temperature and reanalysis sea surface temperature data expressed slightly increasing trend. The El nino, La nina phenomena, the number of typhoons passing study area, and the climate index expressed no clear effect on the variation of wave period in July. In conclusion, the increasing trend of wind speed in the study area may partly explain the increasing trend of wave period in July.

2. Future tasks

The significant increasing trends in wave periods are intrinsic to summertime at the Kaetsu coast facing to the Sea of Japan, especially in July. This may be influenced by the recent changes in East Asian monsoons, southern winds . Moreover, the result of investigated wave direction at the coastline in July shows that when the incoming waves from the NNW are quite dominant, the wave period becomes longer. On the contrary, when the waves from the WNW are equally important the wave period becomes short. The wave characteristics in July could have an impact on the occurrence of rip current accidents. It is important to understand the characteristics of these phenomena and to deduce possible causes. Future projection is desirable. For these purposes, more detailed analysis is needed based on the numerical simulation for the wind, wave and current field over the study area.

Although the wave analyses in this study revealed indication of climate change impact on wave characteristics along the Sea of Japan and northern Pacific Ocean coastline during the last 30 to 40 years, it is difficult to provide clear evidence for that. In the future, climate change phenomenon is expected to place stronger impacts on the variation of wave characteristic along Japanese coast. In order to clarify the characteristics of such impact, more detailed efforts using wave model prediction is needed.

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