# Summary

# Long-term variation of wave characteristics at the Kaestu Coast, Japan and regional comparison of wave climate along Japan coastline

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**Abstract**

First, wave properties and related morphological indices at the Kaetsu Coast, Japan are investigated based on wave observation at Kanazawa Port in duration 1971-2012. An increasing trend in annual significant wave period has been detected. The wave height and period in July have significantly increased. Wave energy is concentrated in winter from NWW, NW, NNW direction. The shoreline is advanced during summer, while the recessions occur in other seasons. Second, the comparison of wave climate along the coastline facing to the Sea of Japan are conducted based on observed waves at Wajima, Rumoi and Hamada Port. The wave climates indicate similar and significant seasonal changes. The wave periods in July also have significantly increased at Wajima. Third, wave data at six sites facing to the Pacific Ocean coastline of Japan; Tomakomai, Hachinohe, Onahama, Kashima, Shionomisaki, and Shibushi are investigated. The long-term trends and abrupt jumps concentrate in wave period at the northern sites (Tomakomai, Hachinohe). Finally, wave period in July in duration 1971-2012 at Kanazawa Port are compared with climate indices, observed, and reanalysis meteorological factors. Observed and reanalysis wind speed express similar patterns to the wave periods in long-term variation.

## I. OBJECTIVES

The first objective of this study is to quantify the long-term variation in wave characteristics and related morphological indices at the Kaetsu Coast, Japan based on NOWPHAS's observed data at Kanazawa Port in duration 1971-2012. The second objective of this study is to investigate the relation between wave characteristics at the Kaetsu Coast with other nine observed sites, which are located around Japan coastline. The third objective of this study is to quantify the relationship between climate change phenomena and the variation of the long-term wave characteristics at the Kaetsu Coast as well as around Japan coastline.

## II. METHOD OF ANALYSIS

This study investigates the long-term variation in wave characteristics for the last four decades measured at ten NOWPHAS's sites around Japanese coastline in Figure1. The datasets of analysis include: NOWPHAS dataset, climate indices dataset, and ERA-20C dataset. The analyses includes: analysis of wind wave characteristics; analysis of wave forcing and related morphological indices, which are estimation of potential deep-water wave energy, breaker heights and depths, closure depths, Sunamura index, and analysis of infragravity waves; the statistical tests(the Mann-Kendall and the Lepage tests); comparison with climate indices and some meteorological factors.

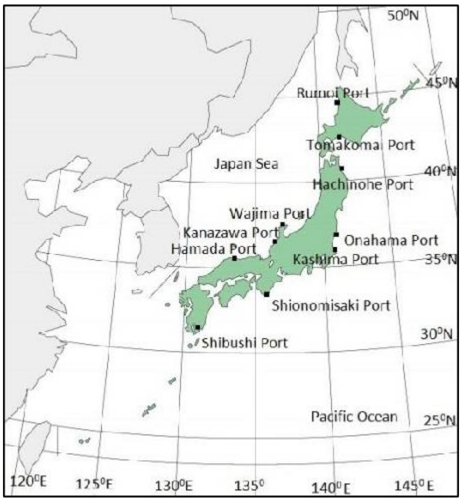


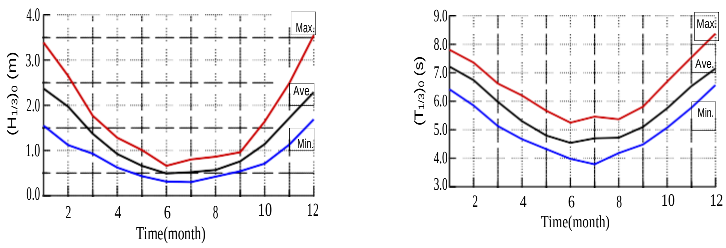

**Figure 1** Location of research area

## III. LONG-TERM VARIATION OF WAVE CHARACTERISTICS ON THE KAETSU COAST, JAPAN

This part of the study examined 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. The main results are shown as follows:

### 1. Seasonal variation in wave height, period and direction

On the overall, the seasonal variation in wave characteristics at the Kaetsu Coast is significant. Generally, wave conditions are really calm during summer. On the contrary, the wave climate becomes violent in the winter season (Figure 2)




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

**Figures 2** Seasonal variation in Monthly-mean wave properties

The mean values of wave height and period are strongly interdependent. They can be correlated very well with a second order polynomial (Figure 3).

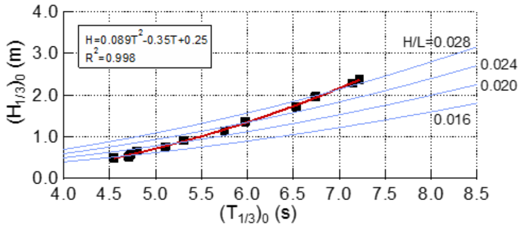
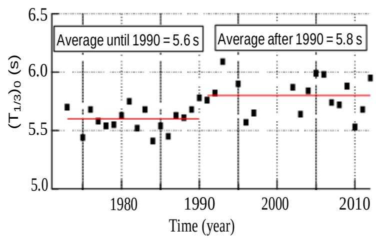



**Figure 3.** Relationship between monthly-mean wave characteristics (1971-2012)

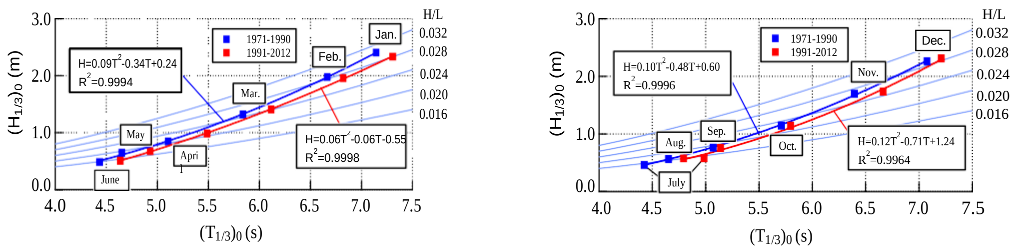
## 2. Long-term variation in wave height and period

The annually-mean significant wave height expressed no clear tendencies, while wave period in the last two decades has noticeably increased (Figure4). 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 annually-mean significant wave period around 1990 at the 1% significant level.

The wave periods in July have significantly increased from 4.43s in the first two decades to 4.98s in the last two decades (Figure5). The Mann-Kendall statistics demonstrated that the wave period in March, April and July have increasing trends significant at the 1% level.




**Figures 4.** Long-term variation of annually-mean significant wave period




**(a)** From January to June

**(b)** From July to December

**Figures 5.** Comparison of the relationship between monthly-mean wave characteristics over two periods

## IV. CHARACTERISTICS OF WAVE FORCING AND RELATED MORPHOLOGICAL INDICES AT THE KAETSU COAST, JAPAN

This part 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 in the nearshore, and infragravity waves. In addition, the related morphological parameters are estimated to deduce the possible influence of wave forcing on the morphological change at the coast. The main results are as follows:

**1. Energy flux of offshore wind waves**

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 is approximately $1.6\times10^8$ kN in winter, $8.0\times10^6$ kN in summer, and $5.0\times10^7$ kN in spring and autumn. The accumulative incoming wave energy flux in winter reaches 60 percent of the total. 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 $2.6\times10^8$ kN. Among them, the NWW, NW, and NNW are the dominant directions of wave incidence. The annual-mean wave power from these dominant directions is 6.6 kW/m and corresponding accumulative wave energy ($2.1\times10^8$ kN) reaches 80 % of the total.

**2. Characteristics of nearshore waves and related morphological indices**

**2.1. Breaker Heights and Depths**

The breaker heights and depths are the highest in winter, medium in spring and autumn and the lowest in summer. The cumulative occurrence probability of breaker depth $P(h_b)$ is shown in Figure 6. In winter 80 percent of waves break at the area with water depths less than 4.0 m, while in summer this value is just approximately 1.0 m. In the spring and autumn the corresponding water depth is around 2.0 to 2.5 m.

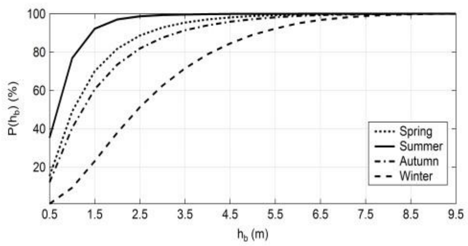



**Figure 6.** Cumulative probability distribution of breaker depth

**2.2. Closure Depths**

The cumulative occurrence probability of inner closure depths $P(D_s)$ are shown for each season in Figure 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.

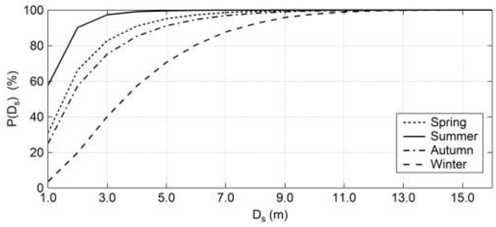



**Figure 7** Cumulative probability of inner closure depths in duration 1971-2012

### 2.3. Sunamura Index

The monthly variation of Sunamura index in duration 1971-2012 were investigated. Referring to the demarcation value of Sunamura index, it is shown 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.

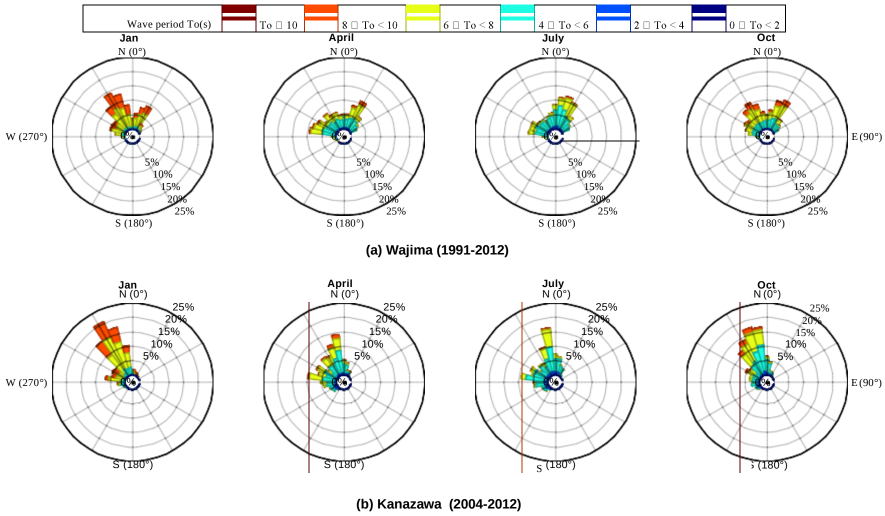
## V. COMPARISONS OF REGIONAL WAVE CLIMATE ALONG THE SEA OF JAPAN COAST

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 main results are as follows:

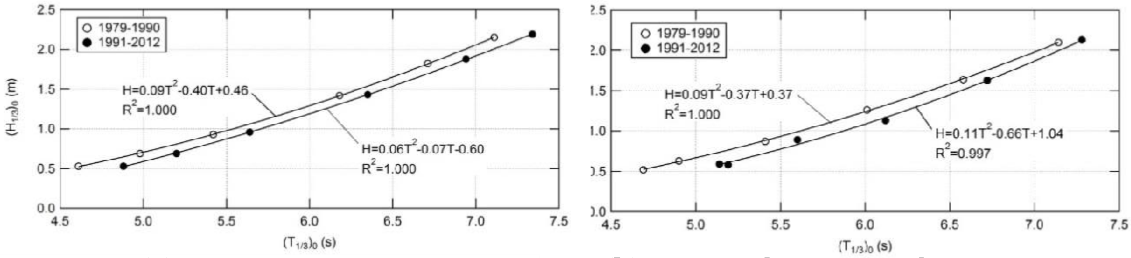
### 1. Wave climate around the coastlines of Ishikawa prefecture, Japan

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 second order polynomials. Since the difference between Wajima and Kanazawa is small, it is deduced that the effects of the Noto Peninsula are small on the wave height and period. On the other hand, 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 (Figure 8).

Figures 9 shows the relationship between the monthly mean significant wave height and period at Wajima, which were averaged over two 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. The Mann-Kendall tests demonstrated that there has been an increasing trend in July at 1 % level.

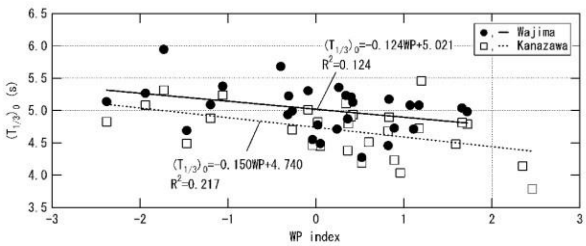



**Figures 8.** Incoming wave direction and wave periods in the four seasons at Wajima and Kanazawa




**(a)** From January to June **(b)** From July to December

**Figures 9.** Comparison of relationship between monthly-mean wave characteristics before and after 1990 at Wajima




**Figures 10.** Relationship between monthly-mean wave period and Western Pacific index in July at Wajima and Kanazawa

In order to deduce the possible cause of change in July, year-to-year variation of wave period in July was compared with several climate indices. The WP index seems to have weak negative correlations with the values at Wajima and Kanazawa (Figure 10).

### 2. Overall comparison along the Sea of Japan coastline

On the overall comparison, wave climates at Rumoi and Hamada have significant seasonal changes, qualitatively similar to Wajima and Kanazawa. The difference in the values of significant waves around these sites is about 10%. 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. 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.

## VI. COMPARISONS OF WAVE CLIMATE ALONG THE PACIFIC COASTLINE 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, 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.

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

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.

### 1. Detailed analysis of wave periods at Kanazawa in July

The frequencies of investigated wave period in two duration (1971-1990 and 1991-2012) expressed different distributions (Figure 11). Especially, the distribution of larger waves in the second duration is more than 50% higher than that in the former. The range of wave period in July 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 first 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.

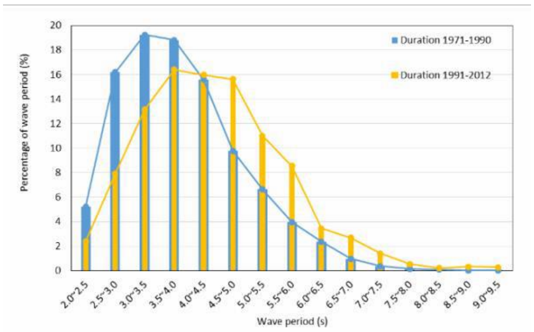


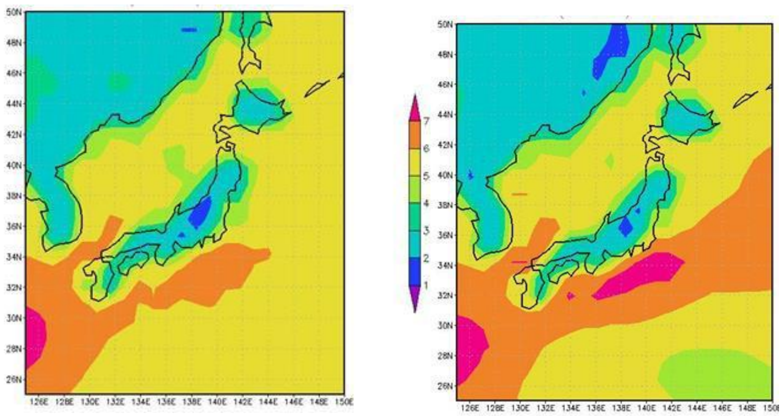

**Figure 11.** Distribution of wave period in July at Kanazawa

### 2. Comparison with observed meteorological factors

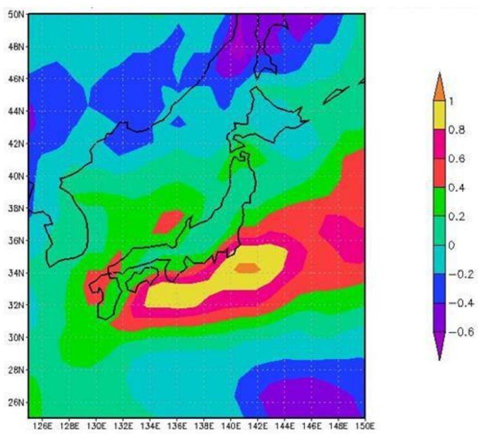
Several observed datasets including wind speed, sea level pressure and air temperature at Wajima site in duration 1972-2012 were examined to estimate the correlation with wave characteristics. The observed wind speed expressed close patterns with the investigated wave period. The averaged values in the 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 Mann-Kendall statistical test of the mean and maximum observed wind speed indicated increasing trends. The Lepage test also detected abrupt jumps at 1% significant level around 1990 for these factors.

### 3. 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 datasets were then investigated for the two separate duration 1970-1990 and 1991-2010. For the reanalysis wind speed data, the Lepage test with sample size of 15 years indicated an abrupt jump significant at 1% level around 1991. Figures 12 illustrated that around the study area wind speed in the second duration increased by around 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$^{o}$E longtitude 37$^{o}$N 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. While 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.



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



(c) The difference between 2 duration

**Figures 12.** Comparison of wind speed at 10 m above sea level in July

平成 29 年　2 月　1 日

# 学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

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

（邦題：加越海岸における波浪特性の長期変動および日本沿岸における波候特性の地域比較に関する研究）

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３．審査結果の要旨（600～650 字）

本学位申請論文に対して審査員全員で面接および試問を行うとともに、論文の内容を検討し、第 1 回審査委員会にて審査方針を決定した。さらに、平成 29 年 2 月 1 日に行われた口頭発表後に第 2 回審査委員会を開催し、協議の結果、以下のように判定した。本研究は、沿岸域における災害軽減や環境保全を考える上で主要な外力となる、波浪特性の変化に着目し、日本海沿岸中央に位置する石川県加越海岸を中心に、多角的かつ詳細な解析を行って、長期・季節変動の特徴を明らかにするとともに、浅海波浪変形の特徴や漂砂・海浜変形に関わる海岸工学的知見を提示したものである。併せて、本研究では、日本海沿岸および太平洋沿岸を対象とした広域比較、さらには、既往の気象観測結果および再解析結果との相関解析を通じて、入射波浪の地域特性や気象要因との関係を明らかにすることを試みている。本研究により、入射波浪諸元の相互関係等が定式化され，過去 40 年間に渡る変動特性が明らかにされるとともに、1990 年前後を境に波浪周期に有意な変動が見られることが示された。波浪周期の長期変化が最も顕著に表れるのは 7 月であり、その変化は、日本海沿岸中部域に特有であること、また、その変動傾向は局所的な風速場の変動と良く相関づけられるなどの新しい知見が提示された。以上の研究成果は、加越海岸における波浪災害や沿岸域保全対策の立案に資する基礎的な学術的知見を与えるものであり、その工学的価値も高い。以上のことから、本審査委員会は本論文が博士（工学）に値すると判断した。

４．審査結果　(1) 判　定（いずれかに○印）　（合　格）・　不合格

(2) 授与学位　博　士（　工　学　）