

**RELATION BETWEEN LONG-TERM VARIATION OF SUMMER-TIME WAVES AND REANALYZED METEOROLOGICAL CHARACTERISTICS AT THE NORTHERN-PACIFIC COASTLINE OF JAPAN****Nguyen Trinh Chung<sup>1</sup>**

**Abstract:** *In this analysis, long-term trends of significant waves in summer-time in duration 1973-2013 at two northern-Pacific coastline wave stations (Tomakomai and Hachinohe) in Japan are investigated. Then, some related reanalysed meteorological factors which have been retrieved from ERA-20C are analysed to reveal possible relations with the observed waves. The Mann-Kendall tests for monthly mean of wave period indicate long-term increasing trends at 1% significant level in June at both sites. The Lepage tests for monthly mean wave period with sample size of 10 years also detect abrupt jumps at 1% significant level in June around 1988 and 1989 at Tomakomai and Hachinohe, respectively. Averaged values of several related reanalysed meteorological factors in June of study duration around area express light impacts on the increasing trends of wave period at these sites. The average mean of 10 m above sea level wind speed and sea-surface temperature noticeably increase, while the values of sea level pressure slightly decrease at these both sites in this duration.*

**Keywords:** Long-term trend; Mann-Kendall, Lepage tests; significant wave; reanalysed; meteorological.

**1. INTRODUCTION**

Ocean waves are essentially important natural features for related marine engineering activities such as port construction, the design of coastal structures, prevention of coastal disasters and others. Recently, ongoing climate change phenomenon has also been placing various significant impacts on ocean wave characteristics. Measured data in different areas have presented various changing trends of wave height, period and incoming wave direction, which are the key features for coastal-protection projects. As basic engineering information, deep understanding of regional wave characteristics is expected to provide useful insight to cope with these issues.

The wave observation around the coast of Japan was started since the early 1970s by the NOWPHAS (Nationwide Ocean Wave information network for Ports and HarborS)

project by the Ministry of Land, Infrastructure, Transport and Tourism, Japan (Nagai et al., 1994), in which there have been more than 15 sites along Pacific coastline. Previously, Nagai (1997) summarized the observed wave characteristics obtained from the NOWPHAS system over 25 years (1970 – 1994). After that, Shimizu et al. (2006) extended the analysis over 35 years, (1970 - 2004). The results indicated that there were 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 was 0.6 cm/year. Seki et al. (2011 and 2012) examined

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the long-term trend of wave characteristics on Japanese coast over the last 40 years (1970-2009). 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 significant wave period concentrated on the northern sites of the coastline (Tomakomai, Hachinohe, Onahama, and Hitachinaka).

On the northern Pacific coastline of Japan the complex atmospheric pattern has significant impacts on the wave characteristics. The regional coastal topography has placed noticeable effects on the development of strong local winds, which are known as the low-level cool air flow induced by the developed Okhotsk high (Shimada and Kawamura, 2007), while strong local winds underlie the regional wave climate. Moreover, Shimada (2014) investigated summer wave variability at this area and showed that significant decreasing trends in significant wave height had been found in the south area of northern Japan in August. In order to obtain a deep physical understanding of the wave characteristic's variation at this area, this study investigates long-term trends of summer waves (June to August) observed at two NOWPHAS's sites in the northern Pacific coastline of Japan, namely Tomakomai and Hachinohe. Several related meteorological characteristics are also analyzed to examine possible relation with the investigated waves.

## 2. DATASETS AND METHODS

### 2.1 Field site and datasets

Around the Japanese coastline, the number of observation sites of NOWPHAS has reached up to 61 until 2012 (Seki et al, 2012). In this analysis, two observed sites have been selected to represent the northern Pacific coastline of Japan. The locations of the observed sites are shown in Figure 1. The site numbers, names, types and water depth of setting instruments, the periods of data analysis, the statistical data over observed duration at the two sites are summarized in Table

1. The observation data includes wave direction, mean, significant, and 1/10 wave height and period. The statistical data processing had been performed in time intervals of 2 hours from the start of observations until the end of the 20<sup>th</sup> century. After that, the data processing has been conducted every 20 minutes. In this study, the time intervals of 2 hours are used. In the analysis, to suppress the errors of long-term data, the monthly as well as the annual mean of wave characteristics are not calculated if the data are not available for more than 70 percent of the time in each month or year.



Figure 1. Location of research area

In addition, 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, 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. In this study, the retrieved dataset in June of duration 1970-2010 have been analyzed in order to obtain a further understanding about relation between wave characteristics and related meteorological features around study area. The

retrieved data include mean speed and direction of 10 m above sea level wind, the sea level pressure, and the sea-surface temperature.

**Table 1. Wave measurement information at the sites**

Site No.	Site Name	Instrument type	Water depth (m)	Observed periods (Year. Month)		Analyzed period (Year. Month)
				Start	End	
1	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	
2	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	

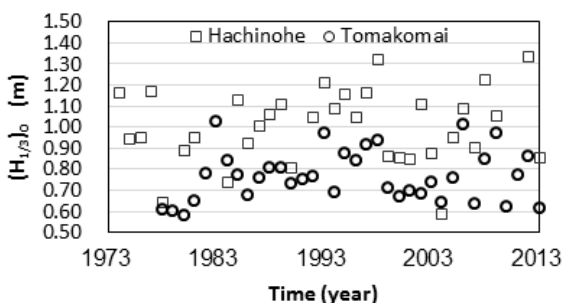
(PW: Pressure-type Wave Gauge; SRW: Step-type Wave Gauge; USW: Ultrasonic-type Wave Gauge; CWD: Ultrasonic-type Current meter; DWDM: Doppler-type Wave Directional Meter)

## 2.2 Method of analysis

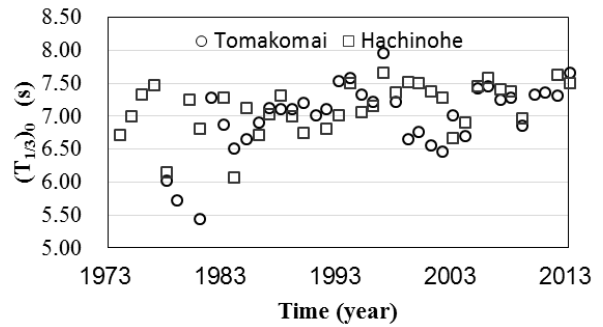
Firstly, wave heights are converted into corresponding deep water values based on the linear wave (shoaling) theory. Next, the long-term variations of wave characteristics are examined. The monthly-mean values of significant wave (quantified as the 99% quantile of wave height records) properties are calculated. Then, Mann-Kendall (Kendall, 1938) and Lepage (Lepage, 1971) tests are conducted in order to detect capable significant trends or jumps in the long-term variation of wave height and period at each site. Finally, retrieved related meteorological features of ERA-20C are analyzed.

## 3. STATISTICAL TESTS OF LONG-TERM SUMMER-TIME WAVE TRENDS

### 3.1. The variation of long-term summer wave characteristics at the sites



(a) Annual-mean wave height



(b) Annual-mean wave period

Figures 2. Long-term variation in annual-mean of summer significant wave height and period at Tomakomai and Hachinohe

The long-term variations of annually-mean wave in June at the sites show some interesting features. Figures 2 show the variation in annually-mean significant wave at Tomakomai and Hachinohe. Figure 2(a) describes that averaged-annual wave height at Tomakomai is about 20% lower than that at Hachinohe. The annual values at Tomakomai vary from 0.58 to 1.03 m, while they are from 0.59 to 1.34m at Hachinohe. Figure 2 (b) illustrates that the averaged values of significant wave period at Tomakomai and Hachinohe seem to be the same. The range of annual values at these sites are from 4.95 to 7.97s, and from 6.08 to 7.66s, respectively. The long-term trends and abrupt jumps in the variation of monthly-mean wave properties in summer-time are examined by non-parameter statistical tests, namely Mann-Kendall and Lepage tests.

The Mann-Kendall (MK) 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 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  $i = 1, 2, 3, \dots, N-1$  and  $j = i+1, i+2, i+3, \dots, N$ . 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:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sgn}(X_j - X_i) \quad (1)$$

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).

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:

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

In the (2) formula,  $W = \sum_{i=1}^{n_1+n_2} u_i$ ;  
 $E(W) = \frac{1}{2}n_1(n_1+n_2+1)$ ;  $V(W) = \frac{1}{12}n_1n_2(n_1+n_2+1)$ ;  
 $A = \sum_{i=1}^{n_1} u_i + \sum_{i=n_1+1}^{n_1+n_2} (n_1 + n_2 - i + 1)u_i$ ;

When  $n_1 + n_2$  is even,  $E(A)$  and  $V(A)$  are estimated as follow:

$$E(A) = n_1(n_1+n_2+2)/4; \quad V(A) = n_1n_2(n_1+n_2-2)(n_1+n_2+2)/48(n_1+n_2-1);$$

When  $n_1 + n_2$  is odd,  $E(A)$  and  $V(A)$  are estimated as follow:

$$E(A) = n_1(n_1+n_2+1)^2/4(n_1+n_2); \quad V(A) = n_1n_2(n_1+n_2+1)[(n_1+n_2)^2+3]/48(n_1+n_2)^2;$$

Here, for  $\{x=x_1, x_2, \dots, x_n\}$  and  $\{y=y_1, y_2, \dots, y_n\}$ , 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 exceeds 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 is also created to apply the Lepage statistical tests on procedure of jump detection.

Only the differences at 5% and 1% significant levels are considered.

The results of Mann-Kendall and Lepage tests for monthly-mean wave properties in summer-time are shown in Table 2. Mann-Kendall test for monthly-mean significant wave period indicate that increasing trends at 1% significant level are detected in June and July at Tomakomai, in June at Hachinohe. For monthly-mean significant wave height, in August, decreasing trends at 5% significant level are detected at Tomakomai. In addition, many abrupt jumps at both 1% and 5% significant level are found by Lepage tests with sample size of 10 years in long-term variation of monthly wave characteristics. The results indicate that increasing trends at 1% significant level are detected in June at both sites for long-term wave period.

**Table 2. Summary of the statistical test for monthly values of significant summer wave characteristics at the sites**

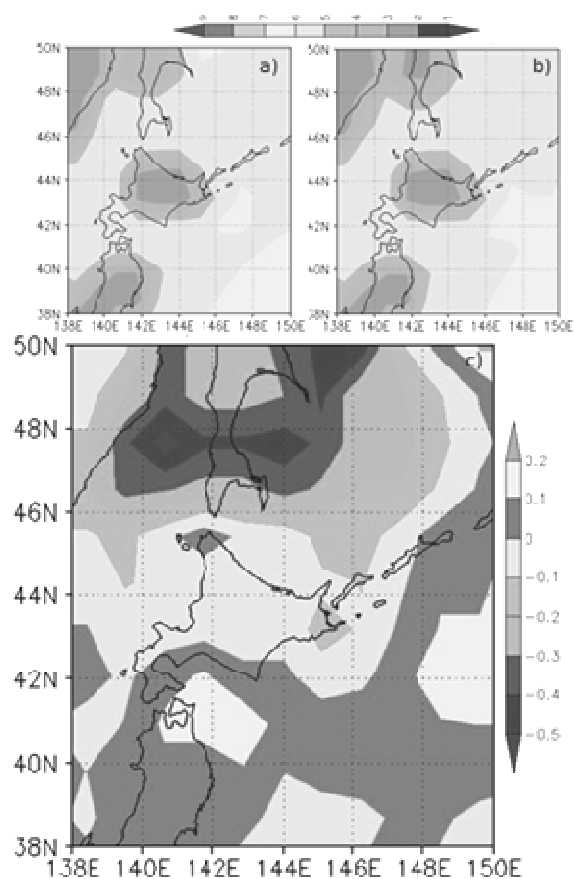
Month	Long-term trends detected by Mann-Kendall tests				Abrupt jumps detected by Lepage tests with sample size of 10 years			
	Tomakomai		Hachinohe		Tomakomai		Hachinohe	
	(T1/3) <sup>o</sup>	(H1/3) <sup>o</sup>	(T1/3) <sup>o</sup>	(H1/3) <sup>o</sup>	(T1/3) <sup>o</sup>	(H1/3) <sup>o</sup>	(T1/3) <sup>o</sup>	(H1/3) <sup>o</sup>
Jun	▲		▲		1988*, 1989, 1990, 1993, 1996, 1997, 1998, 1999	1997, 1998, 1999	1989*, 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	

▲ Increasing trend significant at 1% level;  
 ▼ Decreasing trend significant at 5% level;  
 Years with \*: significant at 1% level; years without \*: significant at 5% level

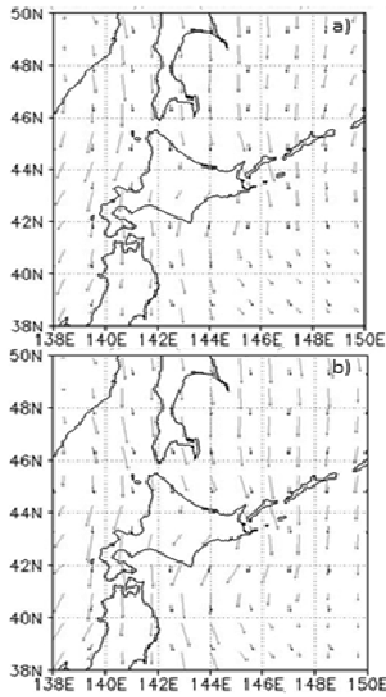
#### 4. LONG-TERM TRENDS OF RELATED REANALYZED METEOROLOGICAL FACTORS

The statistical tests for significant wave periods at Tomakomai and Hachinohe indicated increasing trends at 1% significant level 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 reanalyzed meteorological factors in June in duration 1970-2010 around study area are investigated. The reanalysis datasets include mean speed and direction of 10 m above sea level wind, wind wave direction, sea level pressure, and sea surface temperature. Figures 3 show the average 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 study area wind speed in the second duration increases noticeably. On average, the increasing values at the whole area are in 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 decreases significantly, the values nearby Pacific Ocean increase. Figures 4 describe the 10 m above sea level wind direction and the wind wave direction in June in the two separate durations. However, the discrepancy between the values of these two durations is not clarified. Almost no changes are revealed around the study area. Next, the average values of sea level pressure in June in the two durations are investigated as shown in Figures 5. According to the figures, around 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 temperatures in June of the two durations are examined as shown in Figures 6. The average values in second durations increase from 0.2 to 0.4 degree in comparison with that of the first

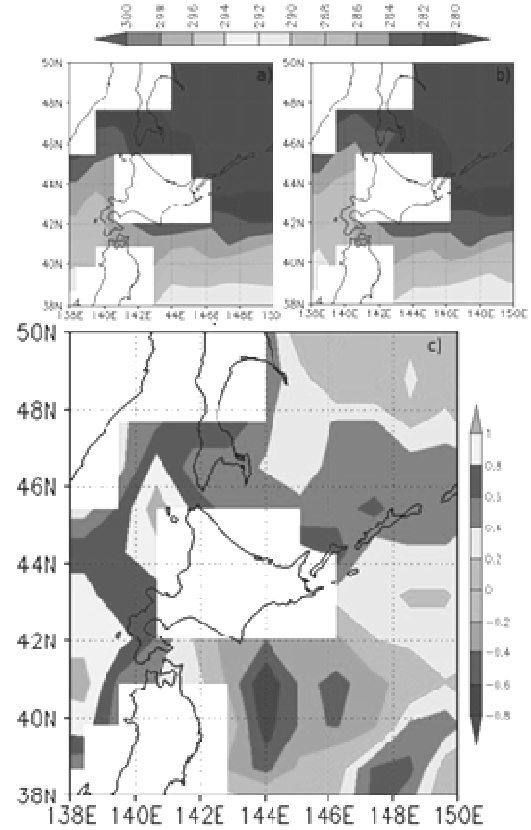
duration. The Mann-Kendall and Lepage statistical tests are conducted in order to reveal possible increasing/decreasing trends of these meteorological factors. However, no clear tendencies are indicated. In addition, the connections between significant wave height and period of the two NOWPHAS wave gages and the reanalyzed meteorological factors of ERA20C in study duration have been investigated. The results showed that the relationships between data of the two wave gauges and the ERA20C data are very close. The correlation coefficients between significant wave height and period and the mean speed and direction of 10 m above sea level wind, wind wave direction, sea level pressure, and sea surface temperature are higher than 0.9.



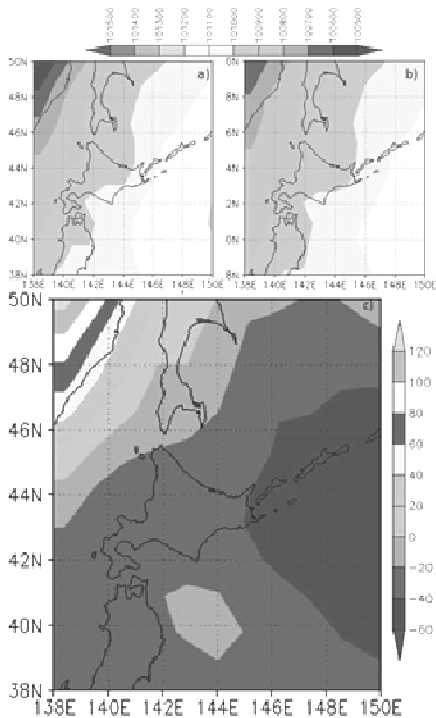
Figures 3. Retrieved wind speed in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations



Figures 4. Retrieved wind (red vector) and wave (black vector) direction in June around study area; (a) duration 1970-1990, (b) duration 1991-2010



Figures 6. Retrieved mean sea-surface temperature in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations



Figures 5. Retrieved mean sea level pressure in June around study area; (a) duration 1970-1990, (b) duration 1991-2010, (c) difference between the two durations

## 5. CONCLUSIONS

In order to clarify the long-term characteristics in summer wave properties at the northern Pacific coastline of Japan, this study investigated the long-term wave data observed at the two NOWPHAS's observation sites: Tomakomai and Hachinohe. The long-term variation of monthly mean of wave characteristics is considerable. At both sites, increasing trends significant at 1% level have been detected in long-term variations of monthly wave period in June by the Mann-Kendall statistical test. Lepage tests with sample size of 10 years detect abrupt jumps at 1% significance level around 1988-1993, for this characteristic of wave at Tomakomai. The statistical tests in long-term variations of monthly mean wave characteristics illustrate that increasing trends at 1% significant level are

detected in June at both sites therefore several related meteorological factors around study area in June have been investigated. The results 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 relationships between data of two NOWPHAS gauges and the ERA20C data are very close with high correlation coefficients. 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 it.

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**Tóm tắt:**  
**MỐI LIÊN HỆ DÀI HẠN GIỮA BIẾN ĐỔI CỦA SÓNG MÙA HÈ  
VỚI MỘT SỐ YẾU TỐ KHÍ TƯỢNG TÁI PHÂN TÍCH TẠI VÙNG BỜ BIỂN  
THÁI BÌNH DƯƠNG MIỀN BẮC NHẬT BẢN**

*Nghiên cứu này phân tích khuynh hướng dài hạn của sóng hữu dụng trong mùa hè giai đoạn 1970-2013 tại hai trạm đo sóng bờ biển bắc Thái Bình Dương (Tomakomai và Hachinohe) của Nhật Bản. Sau đó, một số yếu tố khí tượng tái phân tích liên quan, lấy từ cơ sở dữ liệu ERA-20C, được phân tích để tìm hiểu mối liên hệ có thể có với các đặc trưng sóng quan sát được từ hai trạm trên. Kiểm nghiệm Mann-Kendall trung bình tháng của chu kỳ sóng cho thấy xu hướng tăng dài hạn ở mức ý nghĩa 1% trong tháng 6 tại cả hai địa điểm trên. Kiểm nghiệm Lepage cho chu kỳ sóng trung bình tháng với cỡ mẫu 10 năm cũng phát hiện các bước nhảy đột ngột về giá trị ở mức ý nghĩa 1% vào tháng 6 năm 1988 tại Tomakomai và tháng 6 năm 1989 tại Hachinohe. Giá trị trung bình của một số yếu tố khí tượng tái phân tích liên quan trong tháng 6 giai đoạn nghiên cứu quanh khu vực có sự ảnh hưởng nhất định đến xu hướng tăng của chu kỳ sóng tại các địa điểm này. Trung bình nhiệt độ bề mặt nước biển và tốc độ gió tại độ cao 10 m so với mực nước biển gia tăng đáng kể, trong khi đó giá trị áp lực mực nước biển giảm nhẹ tại cả hai trạm trong giai đoạn này.*

**Từ khóa:** Xu hướng dài hạn; các kiểm nghiệm Mann-Kendall, Lepage; sóng hữu dụng; tái phân tích; khí tượng.

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