A Newly Developed Wave Monitoring System on Ocean Platform

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***Abstract* - A new wave monitoring system was developed to meet a need for measuring waves accurately and continuously for long period in ocean.**

This paper describes the newly developed wave monitoring system which is able to monitor not only frequency spectra but also directional spectra. The results of the model experiments are shown ,which was carried out in order to confirm the validity of the system. It is demonstrated that the accuracy of the wave measurement is fairy good. One of the measured wave data, which were obtained when a big typhoon hit Okinawa in September of 2002 is presented.

I. INTRODUCTION

We have developed a new wave monitoring system to meet a need for measuring waves with good accuracy for long period in ocean. The first system was installed on the CRL (Communications Research Laboratory) platform “COMPASS”, which has been operating 40 km off Iriomote Island of Okinawa and observing waves, current, wind and temperature to obtain the sea-truth-data for development of the long-range ocean radar by Okinawa Subtropical Environment Remote-Sensing Center of CRL [1]. Photo 1 shows the COMPASS operating in the sea.

This paper presents firstly the outline of the COMPASS. Secondly we describe the newly developed wave monitoring system with emphasis on how to measure waves with good accuracy in any sea condition such as calm, moderate and severe sea. Thirdly the results of the model experiments are shown, which were conducted to confirm the validity of the system and obtain the response functions of the platform motions. Lastly one of the monitored wave data of a big typhoon is shown, which are compared with the results of hindcast.

Photo 1.CRL Platform “ COMPASS “

II. CRL PLATFORM “COMPASS”

The COMPASS is a big platform with diameter of the floating body of 9 m and displacement of about 100 ton-force as shown in Fig. 1. The platform has sensors for wind, current and water temperature. Solar panels are installed on the decks to supply electricity through the lead battery to these sensors and the computer for the observation system, watching system and the data communication system inside the body.

The installed location of the platform is 24°37' north latitude and 123°27' east longitude at water depth of about 1,500m shown in Fig. 2. The shaded fan-shaped area is

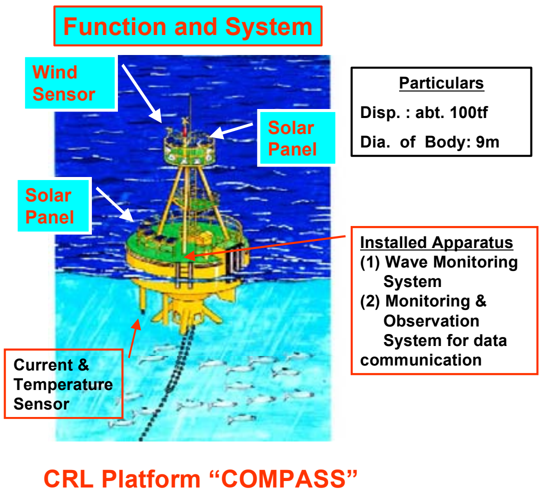

Fig. 1.Sensor and instrument

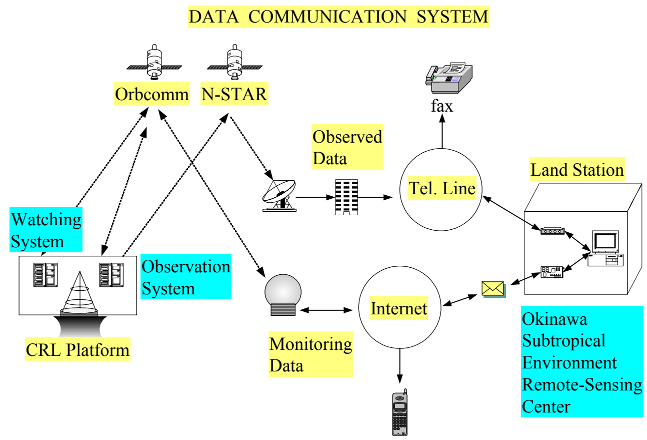

Fig. 3. Schematic diagram of whole system

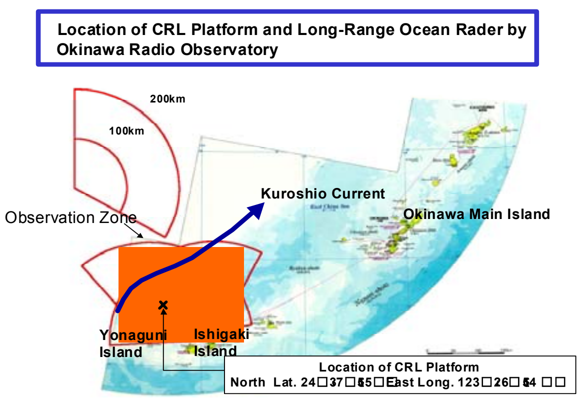

Fig. 2.Location of COMPASS and long range ocean radar

observation zone where the long-range ocean radar can observe waves and current.

Fig.3 shows the schematic diagram of the whole system, which is composed of above mentioned three systems. The observation system is for measuring waves, current, wind and temperature. The watching system monitors the platform position, the power level and flooding of the equipment room. If emergency condition occurs, the voice alarm operates at the land station of Okinawa Subtropical Environment Remote-Sensing Center. The data communication system utilizes two satellites " Orbcomm" and "N-STAR". Orbcomm is an orbital satellite and used to send watching data such as power level and position of the platform and receive the command signals from the land station. On the other hand, N-STAR is a still satellite and send a lot of raw data such as time history data of the platform motions responding to the order from the land station.

III. WAVE MONITORING SYSTEM

A. Principle of Wave Measurement

A wave monitoring buoy operating in ocean for long period needs to measure not only waves themselves but also wind ,current and temperature, which are important as monitoring environment. To fulfill this requirement, the buoy necessarily becomes large. The large buoy cannot follow shorter waves and as a result, the measuring accuracy deteriorates.

To solve this problem, the influence of the motions on wave measurement must be eliminated. The present wave monitoring system is designed to minimize the effect by converting the measured motion time-history data to those of wave elevation and slope using motion response functions.

Since the shape of the platform is vertical body of revolution as shown in Fig.1, the motion responses are independent on directions of incident waves. Therefore if the motion response function of the platform to incident waves from one direction is given, the motions can be transformed into the wave elevation and wave slopes with FFT based on principle of superposition.

Fig.4 shows the analyzing procedure of the wave monitoring system. High precision and reliability of the motion sensor are essential to accurate and long period monitoring. One of the motion sensors on the market was selected, which has abundant deployment in north sea where sea is very severe in winter. The time-history data of the motions are measured by the sensor and are transformed into Fourier integrals by FFT.

The Fourier integral of the motions are transformed into the time-histories of the wave elevations and wave slopes with the motion response functions of the platform, which were obtained from model tests and theoretical calculations. Spectrum analysis gives frequency spectrum and directional spectra from which significant wave height, average wave period and dominant wave direction are estimated. The calculation method of directional spectra will be described below.

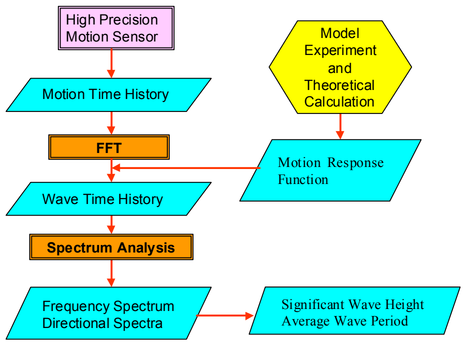

Fig. 4.Analyzing procedure

B. Calculation Method of Directional Spectra

Various calculation methods of the directional spectra of ocean waves have been proposed so far. This system employs a method based on the maximum entropy analysis proposed by Hashimoto [2]. The feature of this method is to be able to analyze ocean waves composed of sea and swell. This is suitable for oceans around Japan where many typhoons pass every year

1) Transform of Motions into Waves

Time-history data of the motions $x(t)$ are measured automatically at the arranged time. These data are stored temporarily in the hard disk of the computer on board. According to the command from the land station, ordered data are sent to the land station via the satellite "N-STAR", and are analyzed with the computer there.

For example, if we express Fourier integral of the heaving motion $x(t)$ by $X(f)$, wave elevation $\eta(t)$ is calculated by the following equation.

$$\left.\begin{aligned} &\eta(t) = 2\int_0^\infty \frac{|X(f)|}{|H(f)|}\cos(2\pi ft + \theta_f - \varepsilon\ )df \\ &\text{where} \\ &\qquad X(f) = |X(f)|e^{i\theta_f} \\ &\qquad H(f) = |H(f)|e^{i\varepsilon} : \quad \textit{response function} \end{aligned}\right\} \quad (3.1)$$

2) Directional Spectra and Cross Spectrum

Directional spectra $S(f,\theta)$ can be expressed in the following form :

$$S(f,\theta) = S(f)G(\theta\,|\,f) \qquad (3.2)$$

where $S(f)$:Frequency Spectrum(f : frequency)

$G(\theta\,|\,f)$: Directional Distribution Function

Then the relation between directional spectra and cross spectrum $\Phi_{mn}(f)$ takes the form :

$$\Phi_{mn}(f) = h_m(f)h_n^*(f)S(f) \times \int_0^{2\pi} G(\theta,f)(\cos\,\theta)^{\alpha_m+\alpha_n}(\sin\,\theta)^{\beta_m+\beta_n}\,d\theta \qquad (3.3)$$

where h_m is a function associated with wave variables such as wave elevation, wave slopes and wave particle velocity. Since wave elevation η, wave slopes η_x and η_y are used ,which are transformed from motions of the platform, the h_m is expressed as follows:

$$\begin{aligned} &h_1(k) = 1\ , && \alpha = \beta = 0 && \text{for } \eta \\ &h_2(k) = ik\ , && \alpha = 1, \beta = 0 && \text{for } \eta_x \\ &h_3(k) = ik\ , && \alpha = 0,\ \beta = 1 && \text{for } \eta_y \end{aligned} \qquad (3.4)$$

where k is wave number.

3) Estimation of Directional Distribution Function

Directional distribution function $G(\theta\,|\,f)$ is supposed to be positive and satisfy the following equation:

$$\int_0^{2\pi} G(\theta\,|\,f)d\theta = 1 \qquad (3.5)$$

This means that $G(\theta\,|\,f)$ can be considered as a probability density function defined in the section [0,2π]. Then maximum entropy method can be applied and the following expression for $G(\theta\,|\,f)$ is derived.

$$G(\theta\,|\,f) = \exp\{-\lambda_0 - (\lambda_1\cos\theta + \lambda_2\sin\theta + \lambda_3\cos 2\theta + \lambda_4 4\sin 2\theta)\} \qquad (3.6)$$

The unknown constant $\lambda_i (i = 1,2,3,4)$ can be obtained by solving the following simultaneous equations which are derived from (3.3) and (3.4) :

$$\left.\begin{aligned}
&\int_0^{2\pi}(\beta_i-\alpha_i(\theta))\exp\left\{-\sum_{j=1}^{4}\lambda_i\alpha_i(\theta)\right\}d\theta=0 \\
&\qquad\qquad\qquad (i=1,2,3,4) \\
&\text{where} \\
&\alpha_0(\theta)=1,\ \alpha_1(\theta)=\cos\theta,\ \alpha_2(\theta)=\sin\theta, \\
&\alpha_3(\theta)=\cos 2\theta,\ \alpha_4(\theta)=\sin 2\theta \\
&\beta_1=\frac{Q_{12}(f)}{kC_{11}(f)},\quad \beta_2=\frac{Q_{13}(f)}{kC_{11}(f)}, \\
&\beta_3=\frac{C_{22}(f)-C_{33}(f)}{k^2C_{11}(f)},\quad \beta_4=\frac{2C_{23}(f)}{k^2C_{11}(f)} \\
&\Phi_{ij}=C_{ij}-iQ_{ij} \\
&\quad C_{ij}:\text{cospectrum} \\
&\quad Q_{ij}:\text{quadrature spectrum}
\end{aligned}\right\}\qquad(3.7)$$

λ_0 can be calculated by the following equation:

$$\lambda_0=\ln\left[\int_0^{2\pi}\exp\left(-\sum_{j=1}^{4}\lambda_j\alpha_j\right)d\theta\right] \qquad (3.8)$$

IV. MODEL EXPERIMENT

A. Response Function

In order to estimate the motion response functions and validate the accuracy of the wave measurement, model experiments were carried out at the wave tank of Kyushu University. Figure 5 shows the schematic picture of the model experiments. A 1/12-scale model was made and the real motion sensor was fixed on it.

In regular wave tests, heave, surge and pitch motions were measured to get the response functions. Free oscillation tests were conducted to estimate viscous damping coefficients.

Theoretical calculations were also performed based on a linear potential theory [3] to obtain the response functions. The estimated viscous damping coefficients are included in equations of the motions.

Both the experimental and theoretical response functions of the heaving and pitching are shown in Fig. 6 and 7 respectively. The agreement between them is fairy good as expected. The theoretical response functions are employed in the wave monitoring system.

B. Accuracy of Wave Measurement

In long crested irregular waves, we measured the incident waves by a wave probe and motion time histories by the real motion sensor at same time. Heaving motion is only analyzed by the present method to estimate the wave frequency spectrum $S(f)$.

When we have the wave frequency spectrum $S(f)$, we

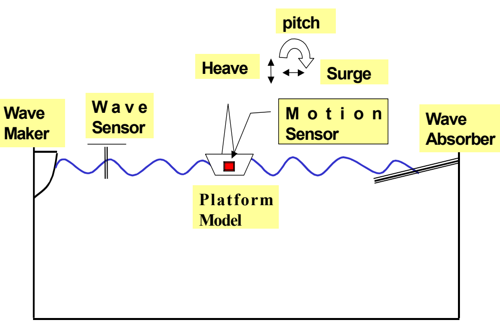

Fig. 5.Schematic picture of experiment

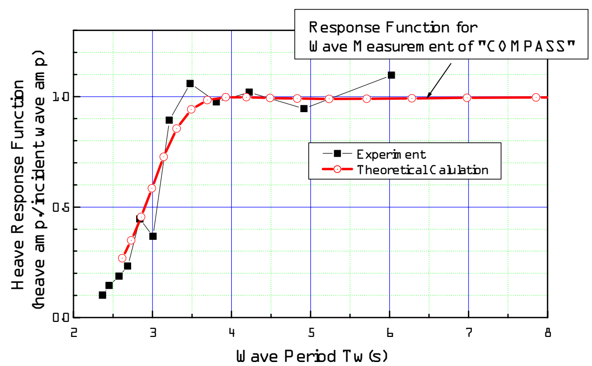

Fig. 6.Heave response function

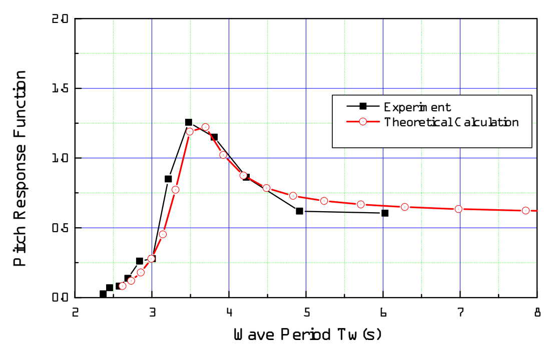

Fig. 7.Pitch response function

can easily calculate spectrum moment m_0 and m_1 from the following equations:

$$m_0 = \int_0^\infty S(f)df, \quad m_1 = \int_0^\infty fS(f)df \qquad (4.1)$$

The significant wave height $H_{1/3}$ and average wave period $T_{0\square}$ are obtained from the following equations [4]:

$$Significant\ Wave\ Height: H_{1/3} = 4.0\sqrt{m_0} \qquad (4.2)$$

$$Average\ Wave\ Period: T_{01} = 2\pi\ m_0 / m_1 \qquad (4.3)$$

Fig. 8 shows the result of the comparison of significant wave height and average wave period between incident waves and estimated waves. Left side of the figure is the result for wave1: wave height is 5cm and period is 1.1 seconds. Right one for wave 2: wave height is 5cm and period is 2.0 seconds longer than that of the case of wave 1. Blue bar is incident waves and red bar is estimated waves. We can easily find good agreement between incident and estimated wave. From these comparisons, it was confirmed that the new wave monitoring system could estimate ocean waves with good accuracy.

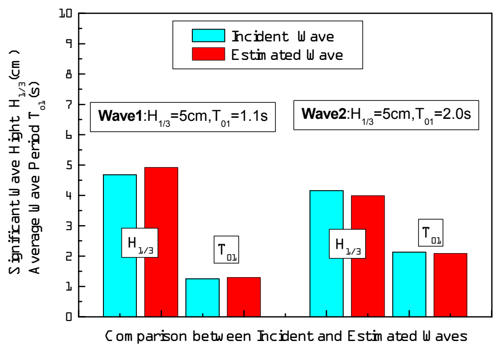

Fig. 8.Comparison between incident and estimated wave

V. MEASUREMENT of TYPOON 16

A strong typhoon 16 with maximum wind speed of 41 m/s hit Okinawa in September 2002. The typhoon 16 came from east, crossed the southern part of Okinawa island and landed on China as shown in Fig. 9 The platform "COMPASS" succeeded in continuous and regular monitoring of sea waves by the typhoon 16.

A. Time Trend of Monitoring Data

Fig.10 shows the time trend of the average and maximum wind speed measured every hour from 1st to 12th in September. The wind speed increased linearly as time passed. The maximum speed 35m/s was recorded at 0:00 on the 7th and afterward it went down rapidly to about 5 m/s around noon on the 8th. The time trend of the significant wave height as shown in Fig. 11 indicates

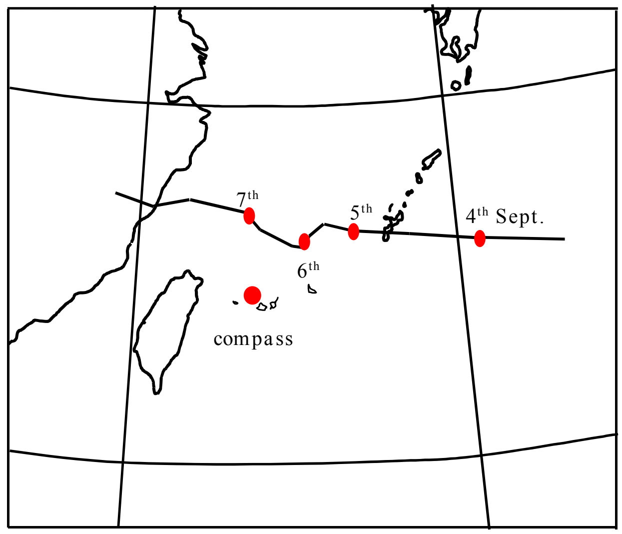

Fig. 9.Path of Typhoon 16

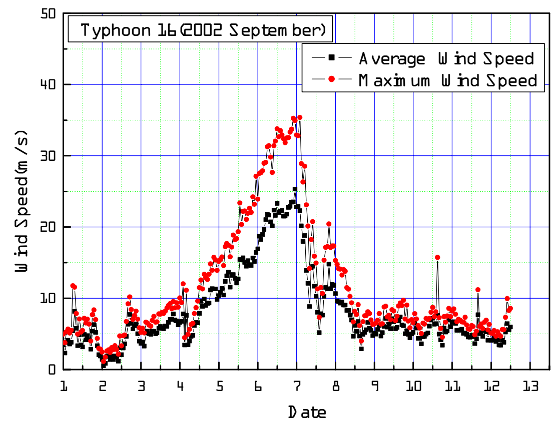

Fig. 10.Time trend of wind speed

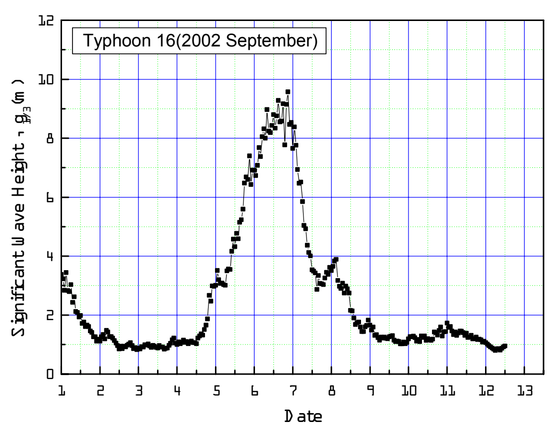

Fig. 11.Time trend of significant wave height

same tendency as that of the wind speed. Rapid increase of the significant wave height began at noon on the 4th half a day behind wind speed, and maximum significant wave height was up to 9.5m.

B. Directional Wave Spectra

As mentioned above, according as the typhoon approaches the platform, wave height increases rapidly. At the early stage of approaching, it is supposed that the ocean waves are composed of sea and swell. As an example of such waves, the data measured at 2:00 on the 5th September are analyzed. Also are analyzed the data at 20:00 on 6th September when the typhoon 16 approached the platform closely.

1) Ocean Waves with Sea and Swell

The motions of the platform are recorded for about 20 minutes with sampling interval 0.07 seconds. The total digital data of 16384(=2^{14}) for each motion are analyzed by the present method. Fig. 12,13 and 14 show the time-history, frequency spectrum and directional spectra of the waves, respectively. The frequency spectrum has a feature of broad band. The contour map of the directional spectra indicates that the swell from the typhoon comes from northeast and the sea induced directly by the wind of the typhoon enters from north. This agrees with the inference from the path of the typhoon.

2) Ocean Waves closely near Typhoon 16

The wave elevation, frequency spectrum and directional spectra at 20:00 on 6th September are shown in Fig. 15,

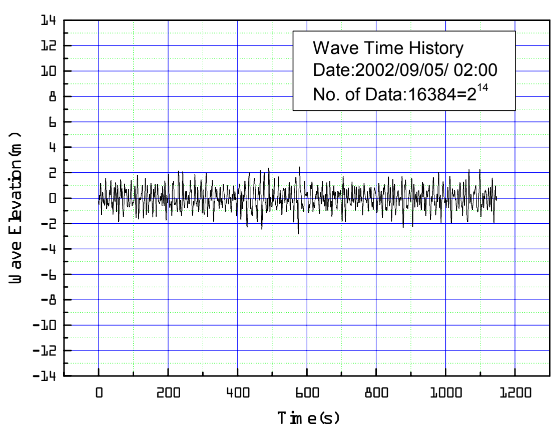

Fig. 12.Wave time history of 5th September

16 and 17, respectively. It is found that the directional spectra have a sharp single peak and the wave power concentrates around 0.7 Hz. And the dominant wave direction is clearly indicated to be east-northeast.

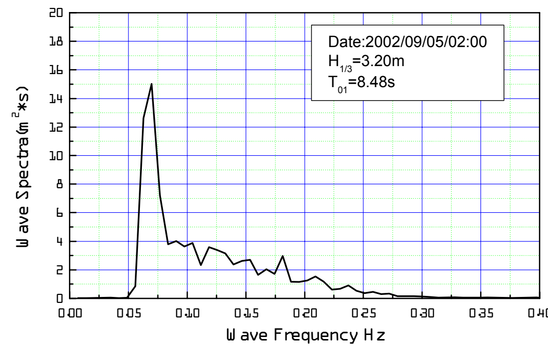

Fig. 13.Frequency spectrum of 5th September

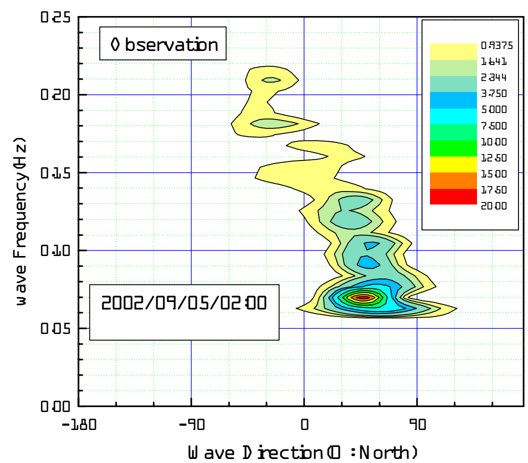

Fig. 14a.Observed directional spectra of 5th

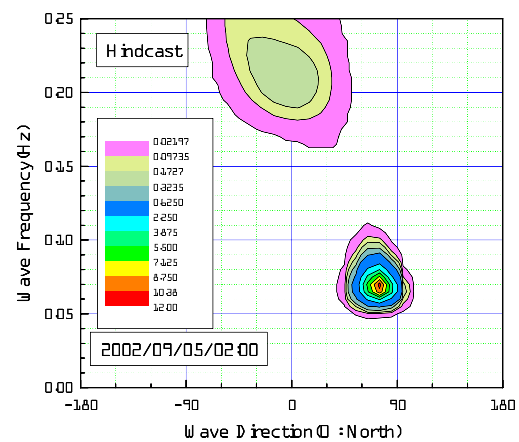

Fig. 14b.Hindcasted directional spectra of 5th Sept.

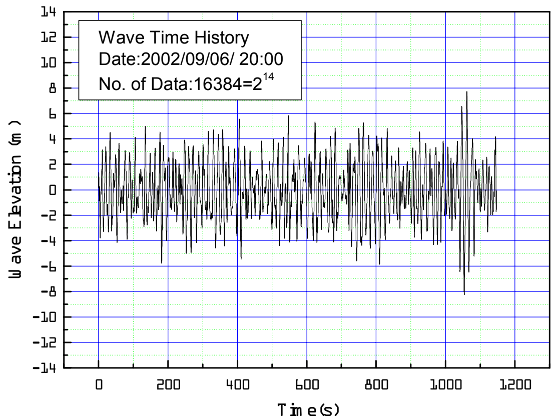

Fig.15.Wave time history of 6th September

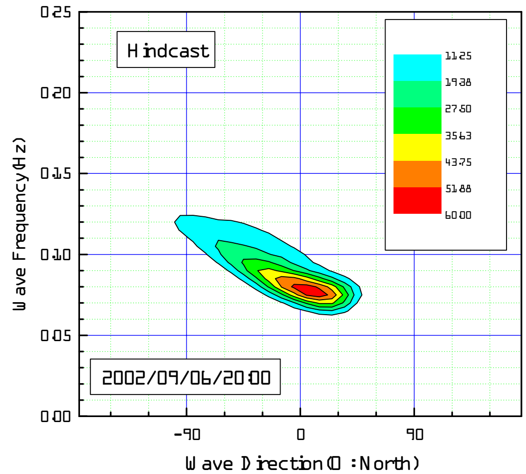

Fig. 17b.Hindcasted directional spectra of 6th

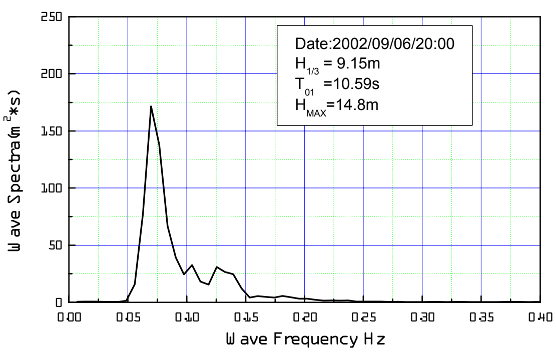

Fig. 16.Frequency spectrum of 6th September

C. Comparison with Hind-casting

A hind-casting of the typhoon was performed. In the hind-casting, firstly information on the path and the strength of the typhoon is collected. And the wind speed distribution above the sea around the path of the typhoon is calculated using a typhoon model. Finally using that distribution as input, the ocean waves are estimated with a third generation wave prediction model JWA3G developed by Japan Weather Association [5]. The results of the hind-casting are shown in Fig.14b, 17b, 18 and 19 which are favorably compared with the measured results.

But the significant wave height by the hind-casting is much smaller than the measured one. This is because only the wind by the typhoon is taken into account and the power of swell outside the calculation area is not included in the hind-casting.

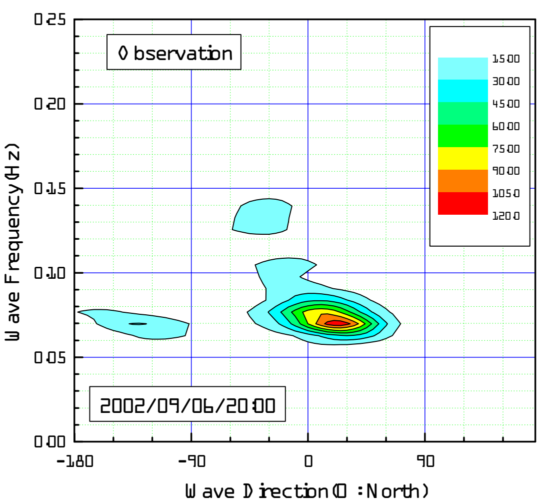

Fig. 17a.Observed directional spectra of 6th Sept.

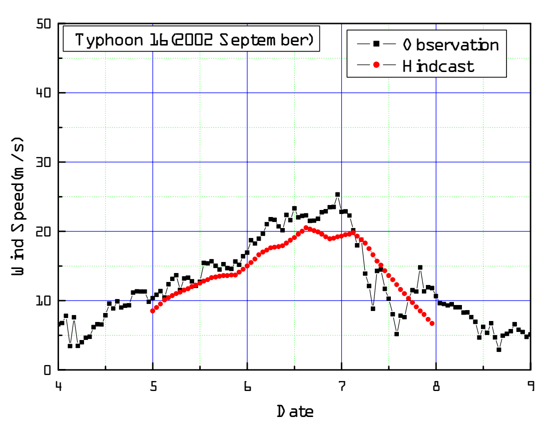

Fig. 18.Hindcasted wind speed

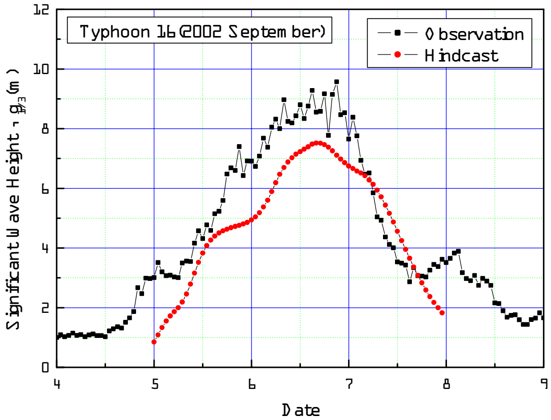

Fig. 19.Hindcasted significant wave height

VI. CONCLUDING REMARKS

The newly developed wave monitoring system on the COMPASS has been measuring ocean wave successfully, and is supposed to operate for five years from 2001. The monitored data will surely be used not only as sea-truth data for the long-range ocean radar but also to increase the knowledge of ocean waves.

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