A Long Term Wave Hindcast System Using ECMWF Winds

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Abstract

A long-term shallow water hindcast system for the evaluation of wave climate is applied to consecutive computation of nearshore waves over a period of 9 years from 1986 to 1994 at 6 wave measurement stations of the Pacific coast of Japan. The data of the wind fields was acquired from the ECMWF wind data sets. Comparison between hindcasts and measurements is made for wave climate represented by not only significant waves and mean wave direction but also frequency-integrated directional wave energy and directional spectrum in addition to time variation of significant waves and mean wave direction. The conclusion is that the newly-revised system is fairly useful for a reasonable and computationally efficient evaluation of the wave climate at the level of spectral representation.

Introduction

Evaluation of long term wave conditions over several years, the so called wave climate, is of great importance for the mitigation of wave-induced disasters such as beach erosion and so on. The authors (1990, 1991, 1992, 1993, 1995, 1997) developed a long term shallow water wave hindcast system which makes it possible to consecutively follow wave conditions over several years with reasonable accuracy. Applicability of the system was verified by close agreement between computations and measurements for time series and climatic characteristics of significant waves and mean wave direction over 2 to 8 years at several locations around the coasts of Japan.

The system consists of a wind estimation model and a wave estimation model. Wind estimation is due to the application of the Bijvoet model (1957), in which input data are atmospheric pressure data obtained every 3 hours at irregularly-distributed points on the weather charts. Accordingly, tremendous efforts are required to acquire atmospheric pressure data sets, which make it

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practically impossible to extend data sets over several years, and the accuracy of the estimates at the Pacific coast of Japan in the cases of complicated wind fields associated with movement of intense typhoons and low systems is not high owing to the use of a simple wind model.

This paper presents a revised system for the estimation of wave climate around the coasts of Japan by using wind data sets provided by ECMWF (European Centre for Medium-range Weather Forecasts) for atmospheric pressure data sets in the former system as input conditions. Wave hindcasting is conducted over 9 years (1986-1994) at 6 wave measurement stations in the Pacific coast of northern Japan. In order to investigate the validity of the system, wave climates represented by not only significant waves and mean wave direction but also frequency-integrated directional wave energy and directional spectrum in addition to time variations of significant waves are compared with those obtained from measured wave data.

Description of the System

(1) Wind Estimation

Wind data at a height of 10 m (U_{10}, θ_w) is gathered from uninitialized analysis surface wind data sets in ECMWF/TOGA Advanced Operational Analysis Surface and Diagnostic Fields Data Sets. This is hereafter called the ECMWF wind data. The ECMWF wind data is provided every 6 hours on a spherical grid system with a space resolution of 1.125 degree for a period of Jan. 1, 1986 to Sept. 16, 1991 and with a space resolution of 0.5625 degree for a period of Sept. 17, 1991 to Dec. 31, 1994. The wind data with a time resolution of 6 hours is bilinearly interpolated onto a Cartesian grid system with a grid size of 80km set on the Northwestern Pacific Ocean area over a period of 9 years from Jan. 1, 1986 to Dec. 31, 1994.

(2) Wave Estimation

A shallow water wave prediction model (Yamaguchi et al., 1987), which traces the change of directional spectrum along a refracted ray of each component focusing on a hindcast point is applied for long-year wave hindcasting in order to save computer processing time. The model belongs to a decoupled propagation model classified into the first generation. The source function consists of linear growth term by the Phillips mechanism, exponential growth term by the Miles mechanism and energy dissipation term by opposing winds, bottom friction and pseudo-viscosity. Energy dissipation due to wave breaking is evaluated by imposing the limitation of a saturated spectrum.

Wave ray is traced on the nesting grid system composed of the Northwestern Pacific Ocean with a medium grid size of 5 km and a small sea area surrounding the hindcast point with a fine grid size of 1 km. At the land boundary, the directional spectrum is set at zero. At the open boundary, the directional spectrum is given, which is obtained from the product of a modified Pierson-Moskowitz spectrum using local wind speed and the $\cos^1\theta$ type angular spreading function using local wind direction. In the wave hindcast, 25 frequency components ranging from 0.04 to 0.5 Hz and 19 to 37 directional components, determined by taking into account angular width of a wave window at each hindcast point, are employed.

Figure 1 shows the grid system used in the wave computation and location of 6 wave hindcasting points. The use of a nested grid system with high topographical resolution yields a reasonable estimate of waves in coastal sea water. Wave hindcast points are 5 coastal stations such as Sendai-shinko (water depth h=20m), Soma (h=16m), Onahama (h=19m), Hitachinaka (h=30m) and Kashima (h=23m), and an offshore station of Iwakioki (h=154m). Wave measurements at 6 stations have been conducted by the Second District Port Construction Bureau of the Ministry of Transport, Japan. These stations constitute some parts of NOWPHAS (Nationwide Ocean Wave information network for Ports and HArbourS) managed by the Port and Harbour Research Institute of the Ministry of Transport. The measured data (Coastal Development Institute of Technology, 1992-1995) and analyzed results for wave climate (Kobune et al., 1988-1991, Nagai et al., 1992, Nagai et al., 1993-1996) have been published as annual reports. Coastal stations where measurement data of significant waves and mean wave direction are acquired are located within a distance of 1 to 2 km from

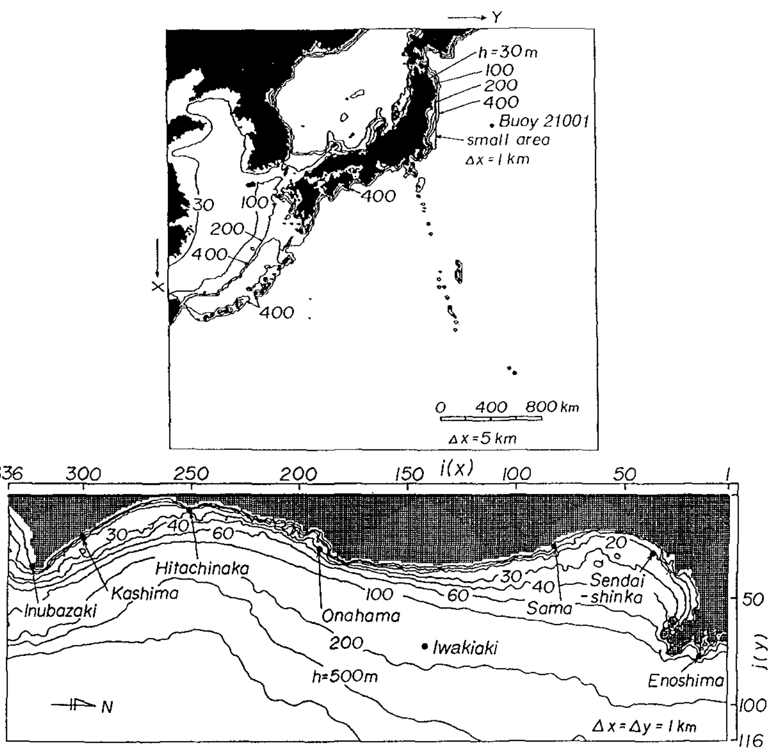

Figure 1. Medium and Fine Grid Systems of the Northwestern Pacific Ocean, Contour Plot of Water Depth and Location of Wave Hindcast Points

the coast. The offshore station Iwakioki, where measurement data of not only significant waves but also directional spectra and frequency-integrated directional energy using a multi-gauge array are acquired, is located 42 km off the Pacific coast in the Tohoku district of northern Japan. In wave hindcasting, the ECMWF wind data over the area with a time resolution of 6 hours is linearly interpolated every 1 hour on time domain and then is bilinearly interpolated onto a wave ray of each component.

Verification of the System

(1) Wind Climate

Figure 2 shows the comparison between ECMWF analysis winds and measured winds for monthly-averaged wind speed and occurrence rate of wind speed over 10 m/s, and directionally-grouped occurrence rate of wind speed over 10 m/s at Buoy 21001 of the Japan Meteorological Agency. A close agreement between analyzed and measured data is obtained, in spite of the discrepancy that analyzed data tends to indicate a slightly stronger concentration to the NW direction than does the measured data. But there is a possibility that the measured data at the buoy may be used in the data assimilation of the ECMWF analysis winds. In this case, a close agreement would be a natural result.

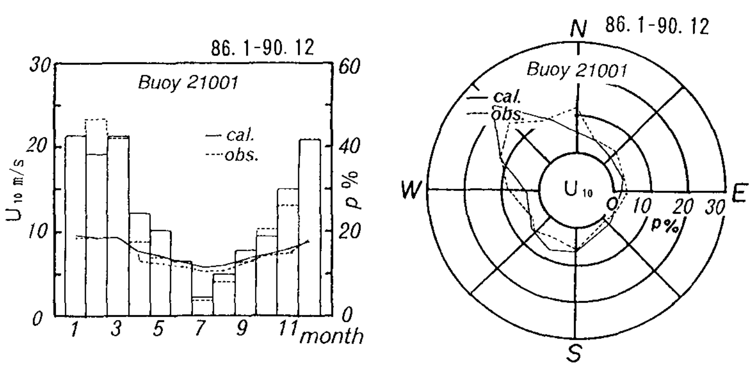

Figure 2. Comparison of Analysis Data and Measurement Data for Monthly-Variations of Mean Wind Speed and Occurrence Rate of Strong Winds, and Yearly-Average of Directionally-Grouped Occurrence Rate of Strong Winds

(2) Time Variations of Significant Waves and Mean Wave Direction

Comparison between computed and measured results was conducted for the time variations of significant wave height $H_{1/3}$, significant wave period $T_{1/3}$ and mean wave direction $\overline{\theta}$ over a period of 9 years from 1986 to 1994 at 6 measurement stations. Two examples of the comparison over 3 months in summer at the offshore station (Iwakioki) and at the coastal station (Onahama) are given in Figure 3. Calm sea states associated with low swell continue in summer except for some less frequent periods of passage of typhoons. The system generally reproduces the measured time variations of waves with reasonable accuracy,

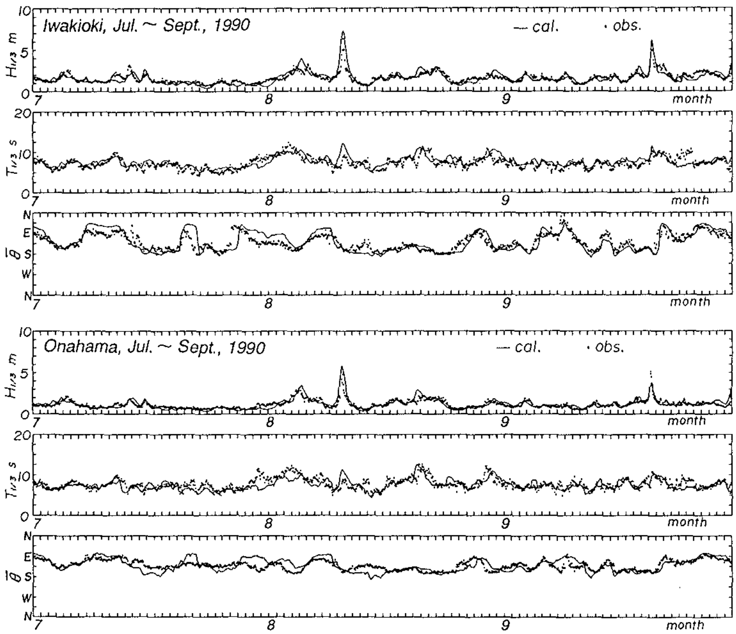

Figure 3. Comparison between Hindcast and Measurement for Time Variations of Significant Waves and Mean Wave Direction over 3 Months.

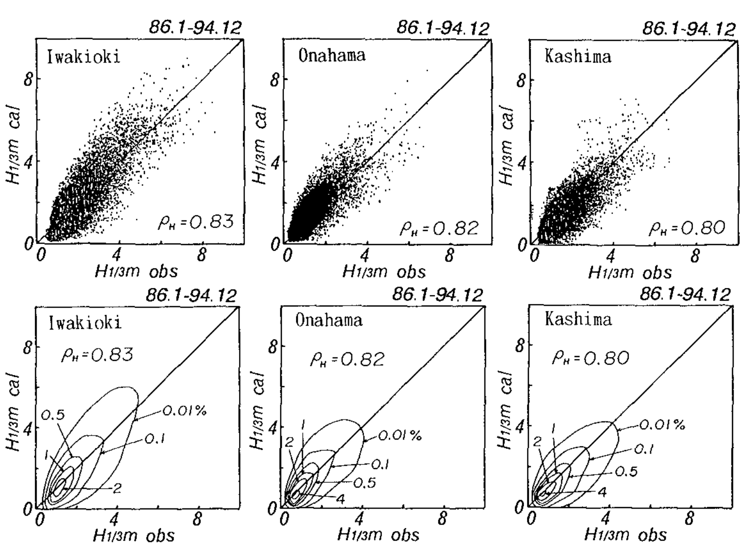

Figure 4. Scatter Diagram between Hindcast and Measurement for Significant Waves and Contour Plot of Relative Occurrence Frequency in a Segment of Wave Height at 3 Stations

although a slight overestimation is observed for the typhoon period.

Figure 4 illustrates some examples of the scatter diagrams between hindcast and measurement for individual significant wave height obtained every 2 hours over 9 years and the contour plot for relative frequency of data contained in a small segment of wave height. Individual data gathers and distributes almost symmetrically around the line indicating a perfect correlation, but the tendency of somewhat excess evaluation to higher waves is found at both Iwakioki and Onahama. It may be said that the hindcasted wave height follows the measured wave height fairly well, taking into account complicated wind and wave fields in an open ocean area, in which case the correlation coefficient ρ_H ranges from 0.80 to 0.83.

(3) Wave Climate for Significant Waves and Mean Wave Direction

Various kinds of mean wave statistics for representing wave climate are obtained from the time series of computed and measured wave data. Figure 5 shows the comparison for monthly averages of significant waves and occurrence rate of high waves greater than 2 m at 6 wave measurement stations. The system evaluates well a general pattern of the seasonal change of the wave climate in the Pacific coastal area of northern Japan, in which high wave conditions associated with frequent passage of intense low pressures occur in spring and autumn, and comparably calm sea states continue in summer. In detail, the system tends to overestimate the occurrence rate of higher waves and to underestimate the wave period in winter particularly at coastal stations. The former results may be caused by the still insufficient grid resolution of 1 km used for the coastal sea area. The latter may be explained as a result of wave computation in a restricted area with artificial open boundary. In winter and in the latter half of autumn, strong landward northwesterly monsoon winds prevail frequently and regularly over the area. Consequently, waves hardly grow by landward winds at coastal sea areas because of the short fetch condition, but low swell-like waves with a longer period propagate from the Pacific Ocean. This means that waves with lower height and longer period reach the coastal area in these seasons. The system may not give a proper estimate for the arrival of low swell-like waves probably due to the above-mentioned reason.

Histograms of wave height grouped every 0.5 m at 6 stations are compared in Figure 6. The system produces well the overall distribution of the histograms for measurement data. But the system tends to underestimate the occurrence rate in the highest rank and the second highest rank, and to overestimate the occurrence rate in the other ranks. Figure 7 indicates the comparison of hindcast and measurement for correlation between wave height and wave period. A higher correlation between wave height and wave period is observed at the offshore station (Iwakioki) where wind waves reach from all directions. This results in the contourlines extending in the right-upward direction. At 5 coastal stations where onshore winds do not give rise to the growth of wind waves and low swell-like waves reach in monsoon seasons, the contourlines show a flatter distribution compared to those at the offshore station. The system yields general features in the correlation diagrams, although each contourline in the hindcast is situated on the shorter period side to the one in the measurement because of underestimation for low swell-like waves.

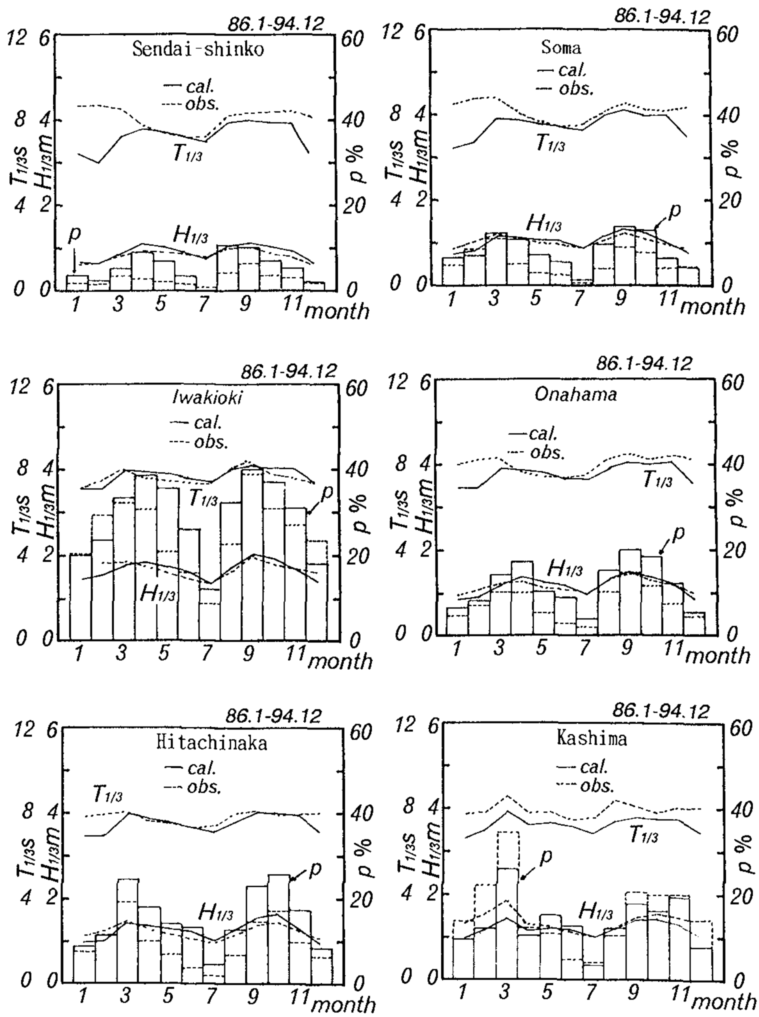

Figure 5. Comparison of Hindcast and Measurement for Monthly Variations of Mean Significant Waves and Occurrence Rate of High Waves

The directionally-grouped occurrence rates of high waves over 2 m at 6 stations are given in Figure 8. Close agreement between hindcast and measurement is found at the offshore station and 3 coastal stations. At 2 coastal stations (Hitachinaka and Kashima), the distribution in the hindcast indicates counterclockwise deviation from the one in the measurement by a directional

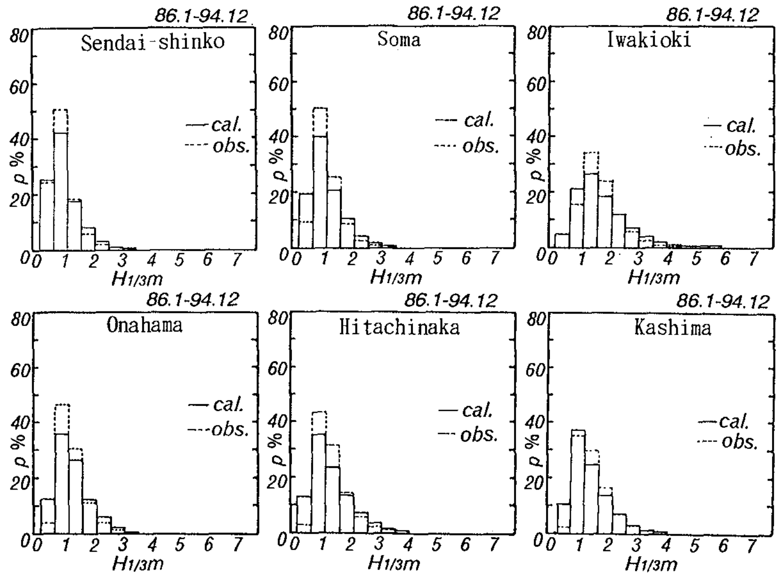

Figure 6. Comparison of Hindcast and Measurement for Histograms of Wave Height

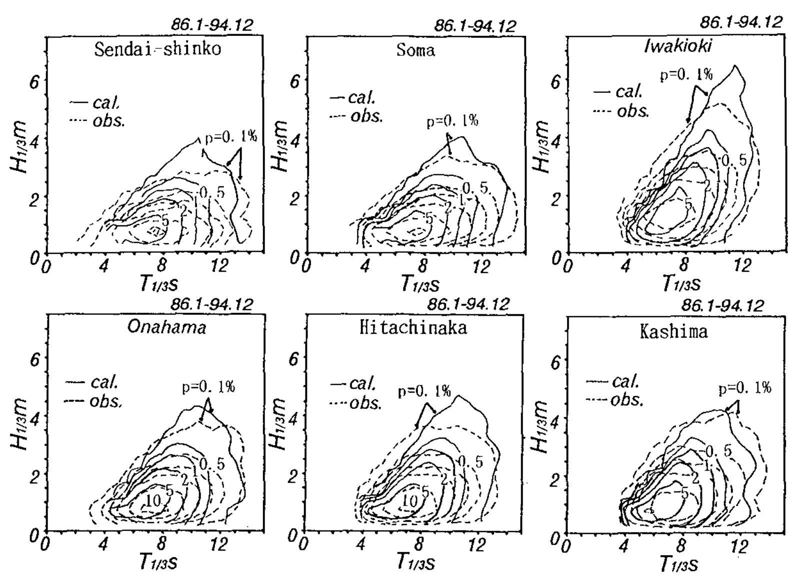

Figure 7. Comparison of Hindcast and Measurement for Correlation between Wave Height and Wave Period

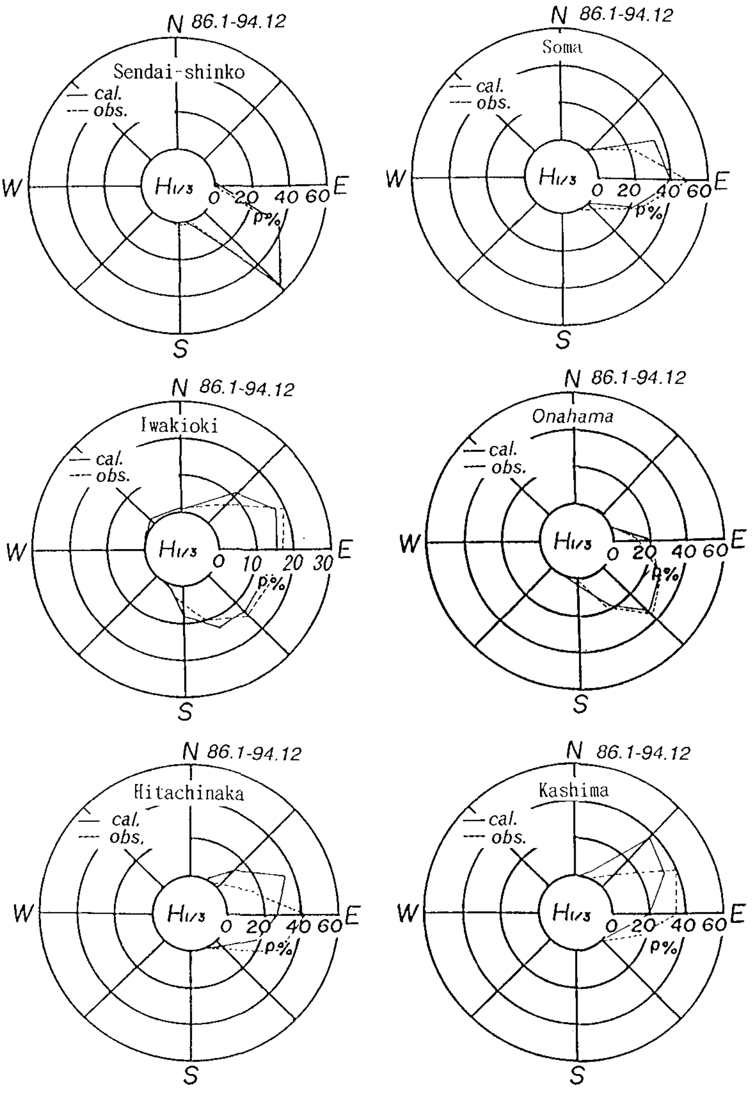

Figure 8. Comparison of Hindcast and Measurement for Directionally-Grouped Occurrence Rate of High Waves Exceeding 2 m

segment (22.5 degree). The reason is not clear, but an insufficient topographical resolution in the nearshore wave computation may contribute to the small discrepancy. While the wave window for high waves at the offshore station has a wider directional range, the wave window at the coastal stations becomes narrower by the presence of the surrounding land topography and the effect of wave refraction during propagation. The system reproduces fairly well the change of the directional distribution of mean wave direction associated with the propagation from the offshore area to the coastal area.

(4) Wave Climate for Directional Energy and Directional Spectrum

As mentioned above, directional spectra have been analyzed using wave data measured over long years with a multi-gauge array at the offshore station (Iwakioki) by a group of the Port and Harbour Research Institute of the Ministry

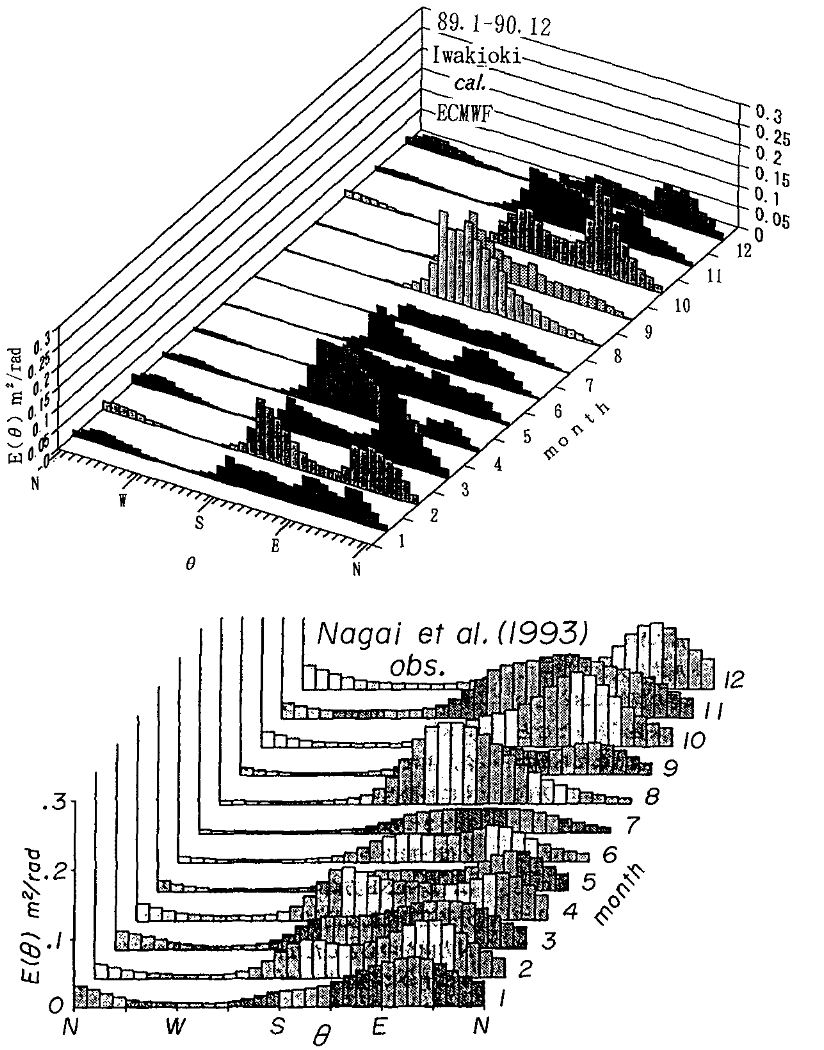

Figure 9. Comparison of Hindcast and Measurement for Monthly-Averaged Directional Energy

of Transport (Nagai et al, 1993, Shimizu et al. 1996). Figure 9 illustrates the comparison of hindcast and measurement for monthly mean of frequency-integrated directional wave energy E (θ) of every 2 hours for the period of 1989 to 1990, in which the measurement data is analyzed by Nagai et al. (1993) using the BDM (Bayesian Directional spectrum estimation Method) proposed by Hashimoto (1987). In winter, directional energy is concentrated in directional ranges of E to NE, and in spring, it has two peaks at the S and NE directions. In summer, directional energy for the S direction is greatly augmented with the passage of intense typhoons, and in autumn, predominant directional energy ranges from E to SE directions. The seasonal change of directional energy is highly correlated with the weather conditions in the concerned sea area. It may be said from the comparison that a gross feature of the seasonal change is reasonably evaluated with use of the present system except for the insignificant difference in directional distribution of each month.

Figure 10 shows the evaluation and measurement (Shimizu et al., 1996) for directional spectrum E (f, θ), normalized frequency-integrated directional energy E (θ) and frequency spectrum E (f) averaged over 7 years, in which the value of the contour line for analyzed directional spectrum was not given in their report. Directional spectrum is analyzed with use of EMEP (Extended Maximum Entropy Principle method) proposed by Hashimoto et al. (1993). General patterns of directional spectrum distribution, directional energy distribution with two peaks and frequency spectrum distribution are rather similar in both results based on the hindcast and measurement.

In order to have a closer look at the applicability of the system, comparison of the spectral informations mentioned above is made at each month. Figure 11 shows examples of monthly-averaged spectral characteristics representing each season. In February, a peak of directional energy is seen in the NE direction, but another peak of directional energy in the S direction is slightly overestimated. In May, the hindcast seems to indicate a clockwise shift of peak direction by a directional segment compared to the analysis. In August, the mutual correspondence seems to be acceptable, but in November, directional range with high energy is

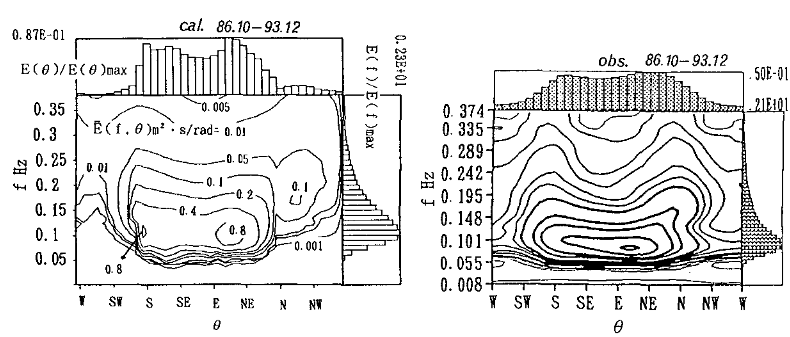

Figure 10. Comparison of Hindcast and Measurement for Directional Spectrum, Directional Energy and Frequency Spectrum Averaged over 7 Years

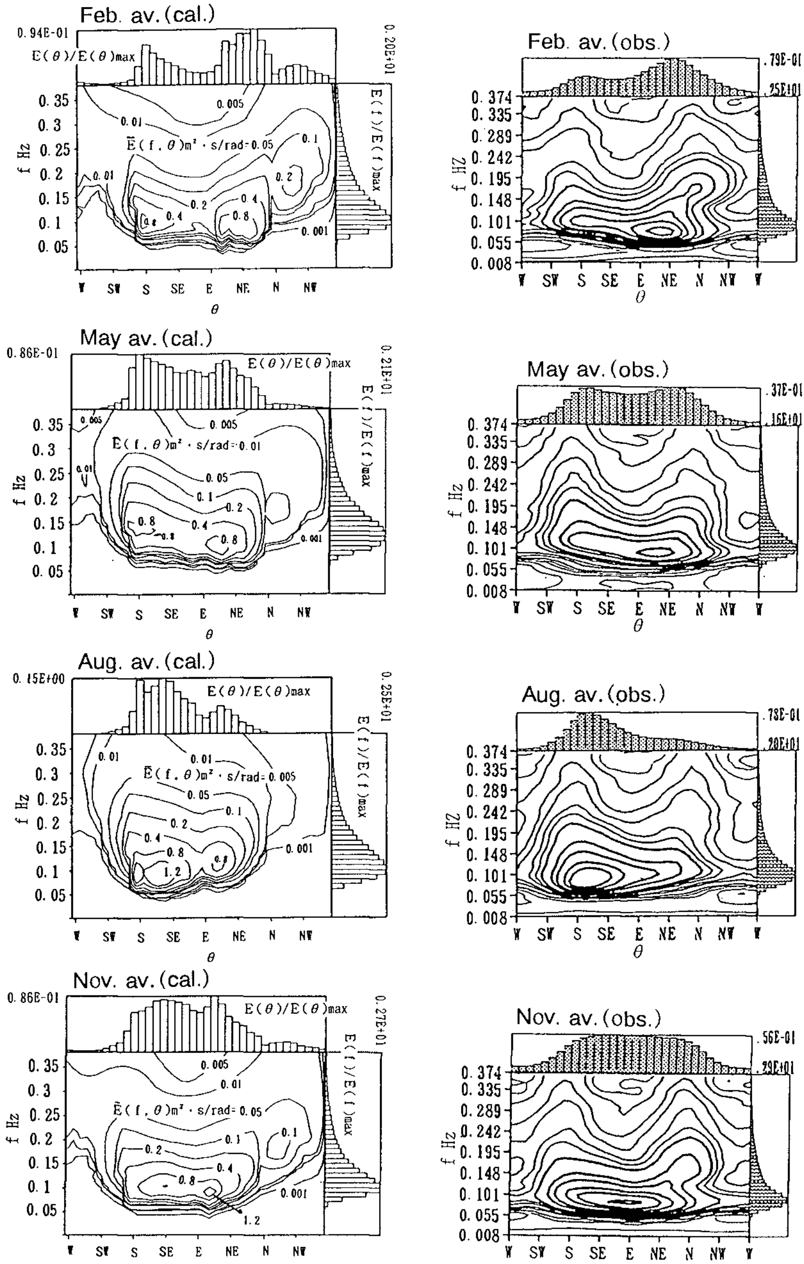

Figure 11. Comparison of Hindcast and Measurement for Monthly-Averaged Directional Spectrum, Directional Energy and Frequency Spectrum

somewhat narrower in the hindcast than in the analysis. In addition, directional energy from W to SW direction is underestimated through all seasons. In spite of such discrepancy observed in detail, the overall pattern of the directional distribution of wave energy in the hindcast is in reasonable agreement with that in the analysis. This may lead to the conclusion that the present system is amply applicable for the estimation of long-term wave climate at the level of spectral representation.

Conclusions

Consecutive wave computations over 9 years were carried out at 6 wave measurement stations near the Pacific coast of northern Japan by using a long term wave hindcasting system. Close correlation between hindcast and measurement emphasizes that a newly-revised system, in which the ECMWF wind data sets are incorporated as input data is fairly useful for reasonable and efficient evaluation of the wave climates represented by not only significant waves and mean wave direction but also directional spectrum and its frequency-integrated directional wave energy.

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