Estimation and Use of Wave Information for Ship Monitoring

Wataru FUJIMOTO*, Rei MIRATSU*, Kinya ISHIBASHI*, Tingyao ZHU*

1. INTRODUCTION

In recent years, active development of ship monitoring and digital twin technologies has been underway in the ship field. For example, in the field of propulsion performance, the Japan Maritime Cluster Collaborative Research on Evaluation of Ship Performance in Actual Seas (OCTARVIA) Project has been carried out as joint research by 25 organizations in the Japanese maritime industry [1)], and as part of this, an understanding of the meteorological and oceanographic conditions that ships encounter is necessary and indispensable [2)]. In the structural field, research on digital twin for ship structures has been carried out, and estimation of the encountered sea states by ships has also attracted strong interest in this field [3)]. In the joint symposium "Frontline of Ship Monitoring" of the Kansai Branch of the Japan Society of Naval Architects and Ocean Engineers (JASNAOE) and KFR/KSSG held in March 2022, estimation and use of wave information was a common topic in these two fields, and the fact that there are diverse types of wave information was recognized [4)]. Furthermore, in order to use information related to ocean waves safely and at an advanced level, use must be based on its respective strengths and limitations of this information.

Nippon Kaiji Kyokai (ClassNK) participates in various types of monitoring and digital twin projects and has also conducted analyses of wave data to promote research and development in the industry. Through these initiatives, the organization has gained certain knowledge of the requirements for wave data in various applications.

This paper examines the use of wave data in ship monitoring, defined as a general term in a sense that also includes digital twins for ship structures (DTSSs). First, a brief explanation of the observation devices and analysis techniques that are generally in wide use is presented, followed by a discussion of their applicability to ship monitoring, while also presenting a review of the features of the main types of wave information.

2. SHIPBOARD OBSERVATION DATA: CENTERING ON RADAR

Radar is a powerful device for observing a wide wavefield in the vicinity of a ship and has attracted considerable interest in recent years. However, since there are many areas that cannot be observed directly because they are hidden by the crests of waves, interpolation of those areas by some technique is necessary. The following presents an overview of the principle of radar observation, the types of radar and their features and limitations.

2.1 Principle of Radar

Because the wavelength of microwaves is near that of capillary waves, they are strongly scattered in the direction opposite the microwave irradiation direction by the mechanism called Bragg resonance scattering (Fig. 1). For this reason, observation of waves by radar is limited to conditions where the wind velocity is sufficient to generate capillary waves (Fig. 1). Here, capillary waves are sometimes called "surface tension wave" and refers to ripples that are formed by surface tension as the restoring force.

* Research Institute, ClassNK

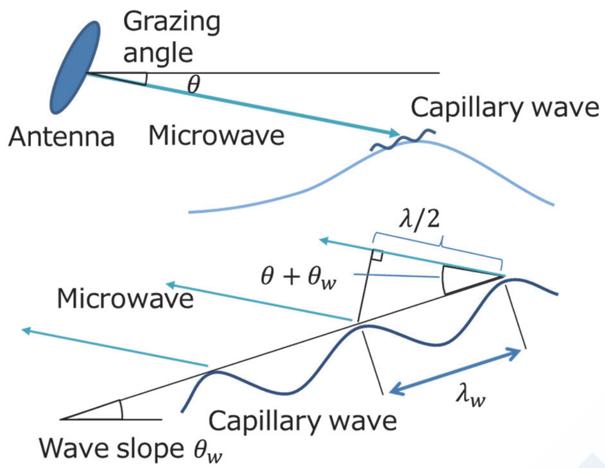

Fig. 1　Schematic diagram of wave observation by microwave radar

(Top) Arrangement of antenna and ocean wave, (bottom) enlarged diagram at scale of capillary wave

When $\lambda/2 = \lambda_w \cos(\theta + \theta_w)$, microwaves are strongly reflected to the antenna by Bragg resonance scattering.

The intensity of the wave scattering, as known as radar cross section (RCS), changes by the following mechanism [5].

① Shadowing modulation

Effect in which the opposite side of the wave crest as seen from the radar is hidden (shadowed) (Fig. 2). The installation height of ship radar is around several 10 m, while the observation radius of X-band radar is roughly several km, and shadowing becomes dominant as the area becomes more distant from the radar. Since it is necessary to use observation values from as far away as possible in wave forecasting, shadowing modulation is very important.

② Tilt modulation

Effect in which radar reflection changes depending on the angle of the wave surface (Fig. 2). As the distance from the radar increases, only the crest of the wave is observed. Therefore, the slope of the wave surface decreases and tilt modulation becomes weak. Although tilt modulation is strong in the range near the radar, this area is excluded from the observation range in many cases because the reflection is too strong.

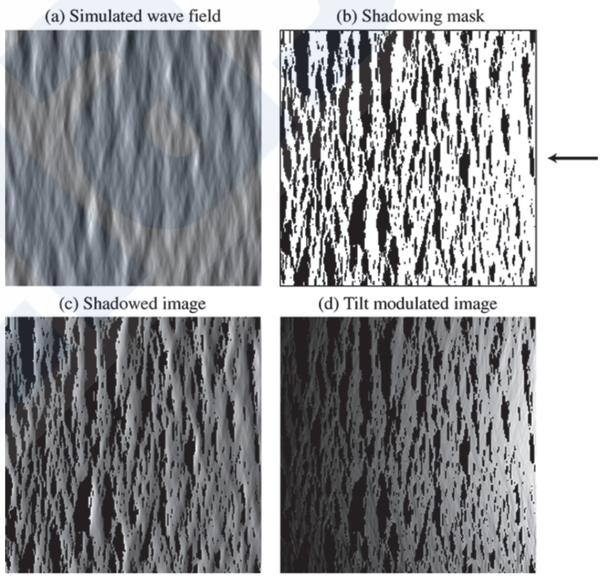

Fig. 2　Images of shadowing modulation and tilt modulation [5]

©American Meteorological Society. Used with Permission.

It is necessary to note that radar does not measure the wave profile directly, but only measures the RCS. The standard techniques for estimating the wave spectrum from the radar reflection [5] are as follows.

① The spatiotemporal data $\rho(\boldsymbol{x}, t)$ of the radar reflection are acquired, and their rectangular region is extracted (Fig. 3 (a), (b)). 3D FFT (**F**ast **F**ourier **T**ransformation) is performed, and the image spectrum of $(\boldsymbol{k}, \omega)$ is obtained (Fig. 3 (c)). Here, $\boldsymbol{x} = (x, y)$ is the horizontal spatial coordinate, t is time, $\boldsymbol{k} = (k_x, k_y)$ is the wavenumber in the horizontal direction and ω is the angular frequency.

② From the image spectrum of $(\boldsymbol{k}, \omega)$, bandpass filtering is applied only to components which follow the linear dispersion relation (Fig. 3 (d)). Here, the linear dispersion relation adjusted for the Doppler effects of the current velocity and ship's velocity is used. The filtered-out components are regarded as noise.

③ In order to consider shadowing modulation, a **M**odulation **T**ransfer **F**unction (MTF) $M(k)$ is introduced. Since it is known empirically that $M(k)$ follows the power law, tuning is performed by comparing the exponent q, assuming $M(k) = k^{-q}$, with other observational values (e.g., data from buoys, etc.) (Fig. 3 (e); the black line and red dotted line were acquired by radar and buoy observation, respectively). Here, $k = |\boldsymbol{k}| = \sqrt{k_x^2 + k_y^2}$.

④ The effect of shadowing is corrected from the image spectrum by using the MFT, and the wave surface is estimated by inverse 3D FFT (Fig. 3 (f)).

⑤ The significant wave height is estimated by comparison with buoy observation results. That is, a regression formula is created by comparing the **S**ignal **N**oise **R**atio (SNR) of the bandpass-filtered signal in ②, in which other components were treated as noise, with the wave height measured by the buoy, and thereafter, the wave height is estimated based on this regression formula.

For highly accurate observation of ocean wind waves, calibration of the radar by using a buoy or other observation device is extremely important [7]. If a wave radar system fixed on the coast is available, calibration is comparatively easy, since the weather conditions are limited and buoys and other observation devices are also easy to install. However, on ships which navigate in the open sea, the weather conditions change greatly, and in some cases it is difficult to prepare a separate observation device for use as a reference.

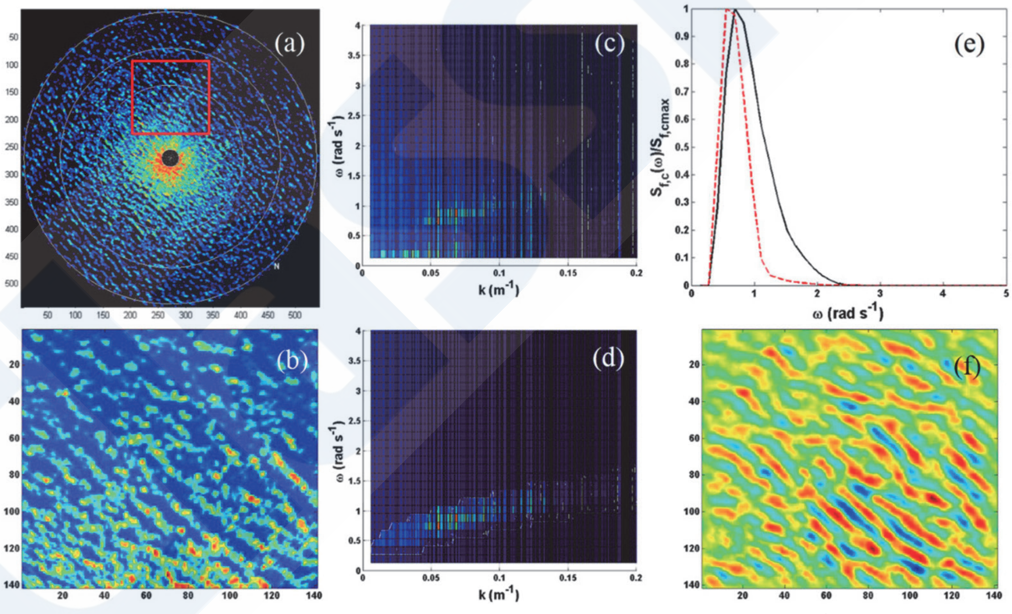

Fig. 3 Images of analysis of radar reflection images [6]

© American Meteorological Society. Used with permission.

2.2 Types of Radar

Radar is classified according to its microwave wavelength. Mainly the X band (8 to 12 GHz) and the S band (2 to 4 GHz) are used in ship radar.

Because the X band is close to the wavelength of capillary waves, and intensity of scattering, that is, the radar cross section (RCS) is large, its spatial resolution is finer than that of the S band. However, as a weak point, during rainy weather, the microwaves are scattered by raindrops and accuracy easily decreases. Although the S band is also used, its resolution is coarse in comparison with the X band due to its longer wavelength. On the other hand, S-band radar has the advantage that observational accuracy is relatively robust to precipitation because of its long wavelength.

Cheng and Chien (2017) [8] compared X-band radar and S-band radar installed in a coastal area in Taiwan and illustrated the differences in spatial resolution and the effects of precipitation visually.

Section 2.1 described a type of radar in which the phases of the transmitted waves irradiated from the radar device are not controlled, that is, noncoherent radar. The type called coherent radar, in which the phases are controlled, measures the particle velocity on the water surface by the Doppler effect [7]. In some cases, this is also called Doppler radar [9]. A commentary on Doppler radar can be found in Kanrin – Bulletin of the Japan Society of Naval Architects and Ocean Engineers [10].

2.3 Other Shipboard Observation Data: Ship Wavemeters

Among the various types of shipboard wave measurement devices, ship wavemeters are also widely used. Ship wavemeters are mainly installed on bow and directly measure the change in distance (relative water level) between the sensor and the sea surface directly under it by a microwave technique, etc. [11]. In obtaining the water level from the still water surface (absolute water level), the vertical movement of the ship measured by an accelerometer or the like installed on the bow is subtracted from the relative water level. While the reliability of the wave height is comparatively high, only the point time-series wave height can be obtained, and it is not possible to measure the wave direction.

3. WAVE MODELS

Wave models make it possible to estimate waves comprehensively worldwide, and public meteorological agencies and private weather companies provide wave model data. Applications include use in weather routing for ships and activities for wave prediction (wave estimation) in designated waters for fixed offshore structures. The following describes what a wave model solves, and the points to note from the viewpoint of their use in ship monitoring.

3.1 Basic Equations

In a wave model which is widely used at present, the wave power spectrum $S(k,\theta)$ is obtained by solving a time-development equation for the amount of conservation (wave action conservation law) called wave action $N \equiv S(k,\theta)/\sigma$ [12) 13)].

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\dot{x}N+\frac{\partial}{\partial y}\dot{y}N+\frac{\partial}{\partial k}\dot{k}N+\frac{\partial}{\partial \theta}\dot{\theta}N=\frac{S_{force}}{\sigma} \tag{1}$$

$$\dot{x}=c_g\cos\theta+U_x \qquad \dot{y}=c_g\sin\theta+U_y \tag{2}$$

$$\dot{k}=-\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial s}-\boldsymbol{k}\cdot\frac{\partial \boldsymbol{U}}{\partial s} \qquad \dot{\theta}=-\frac{1}{k}\left[\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial m}-\boldsymbol{k}\cdot\frac{\partial \boldsymbol{U}}{\partial m}\right] \tag{3}$$

Where $\sigma^2=gk\tanh kd$ is the angular frequency of a component wave, g is gravitational acceleration, $\boldsymbol{k}=(k_x,k_y)$ is the wavenumber of a component wave and d is water depth. Here, $k=|\boldsymbol{k}|=\sqrt{k_x^2+k_y^2}$. $c_g\equiv\partial\sigma/\partial k$ expresses the wave group velocity, and $\boldsymbol{U}=(U_x,\ U_y)$ is the current velocity due to ocean currents, etc. It should be noted that σ is the angular frequency in a coordinate system which is moved along a current velocity $\boldsymbol{U}$ by ocean currents, tidal currents or the like. Furthermore, θ expresses the wave direction of a component wave, and s and m represent a coordinate system parallel and perpendicular to direction θ, respectively, and S_{force} is an external force term called the source term (described in the following). The coordinate system described above is shown in Fig. 4.

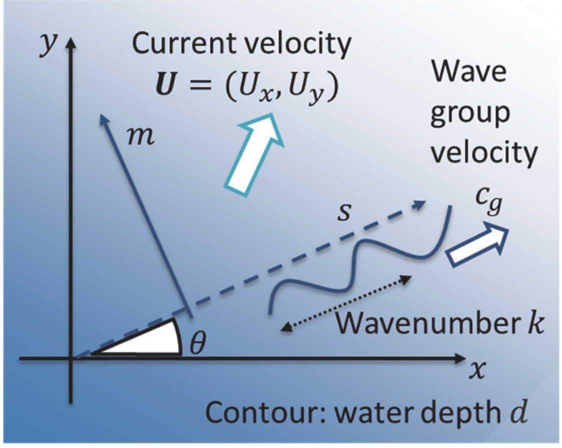

Fig. 4 Coordinate system considered by wave model

First, the meaning of Eq. (1) will be considered. $\frac{\partial}{\partial x}\dot{x}N + \frac{\partial}{\partial y}\dot{y}N$ is an advective term for spatial direction and is similar to the advective term in the Navier-Stokes equation. As can be understood from Eq. (2), the velocity at which a wave action N is conveyed by advection depends on the wave group velocity c_g at which the energy of the waves propagates and the velocity $\boldsymbol{U}$ due to ocean and tidal currents.

In a wave action equation, a derivative term $\frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial \theta}\dot{\theta}N$ with respect to the spectrum space (k, θ), also appears. This includes the differentiation of the coordinate system (s, m) parallel and perpendicular to the wave direction θ for the water depth d, i.e., $\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial s}$ and $\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m}$. This represents diffraction and refraction of the wave by the sea bottom topography. Because the effect of diffraction and refraction by the bottom topography is large in coastal waters, it is necessary to increase the accuracy of the differentiation term for the water depth d. Thus, it is necessary to improve spatial resolution.

Although the terms $\frac{\partial \boldsymbol{U}}{\partial s}$ and $\frac{\partial \boldsymbol{U}}{\partial m}$ appear, these expresses the velocity gradient of the current velocity $\boldsymbol{U}$ as seen from the wave direction θ. The refraction of the wave by the current velocity $\boldsymbol{U}$ is expressed by this term.

Wave parameters such as the significant wave height, the mean wave period and the mean wave direction are obtained by integrating the wave spectrum $S(k, \theta)$. Some meteorological agencies and weather companies also provide wave parameters, such as parameters in which multiple spectral peaks corresponding to wind waves and swells are decomposed. Since the wave spectrum itself involves an extremely large volume of data in comparison with integrated wave parameters, some organizations do not provide wave spectra.

3.2 Source Term

The external force term S_{force}, which is called the "source term," mainly includes the following terms:

$$S_{force} = S_{in} + S_{ds} + S_{nl} + \cdots$$

S_{in} shows the development of an ocean wave by wind. To drive an ocean wave model, wind velocity data published by various meteorological agencies, or estimated values of the wind velocity calculated independently by a downscaled weather model, are used. For example, the Japan Meteorological Agency (JMA), the **N**ational **O**ceanic and **A**tmospheric **A**dministration (NOAA) in the United States and the **E**uropean **C**entre for **M**edium-**R**ange **W**eather **F**orecasts (ECMWF) publish estimated wind velocity values. Since the accuracy of the wind velocity directly affects the accuracy of the ocean wave model, it is necessary to verify the accuracy of the wind velocity before running the ocean wave model.

S_{ds} expresses the dissipation of wave energy by breaking waves (whitecaps, etc.). S_{in} and S_{ds}, which show the input and dissipation of energy in the ocean wave field, are important in estimation of the significant wave height.

S_{nl} shows the nonlinear interaction between component waves [14]. In the case of a linear wave, the energy of the component waves is always constant and the wave spectrum is invariable, but due to nonlinearity, the wave spectrum changes by exchanges of energy between component waves and wave spectrum changes. This term is closely related to the shape of the wave spectrum.

In addition to the above, friction between ocean waves and the sea bottom and the interaction between ocean waves and sea ice are incorporated in S_{force}, etc., making it possible to consider various physical processes in the ocean wave model.

3.3 Ocean Wave Model Programs

The ocean wave models which are mainly used in ocean wave forecasting at present are called third-generation ocean wave models, and provide explicit solutions for detailed physical processes in the spectrum space, as described in Sections 3.1 and 3.2. The main third-generation ocean wave model programs are introduced here.

WAM (**WA**ve **M**odeling) was developed by the **Wa**ve **M**odel **D**evelopment and **I**mplementation Group (WAMDI Group) and was the first of the third-generation ocean wave models [15)] [16)]. The ECMWF meteorological agency has developed an internal model derived from WAM called ECWAM [17)].

WAAVEWATCH III [18)] was developed centering on the NOAA. Since it is an open source program, active improvement by universities and research institutes is continuing.

SWAN (**S**imulating **WA**ves **N**earshore) [19)], which was developed by Delft University of Technology, prioritized analysis of waves in coastal regions from the outset, and at present, use of this program still centers on coastal areas and storm surge. It is also an open source program.

Depending on the meteorological agency or weather company, some have developed independent models. The wave model used by the Japan Meteorological Agency is MRI-III, which was developed by the Meteorological Research Institute [20)].

3.4 Temporal Evolution of Ocean Wave Model

Because atmospheric circulation has the nature of chaos, if there is an error in the initial values, the error in the predicted values will also increase exponentially due to the phenomenon called “butterfly effect.” For example, an error in an atmospheric disturbance such as a mid-latitude low pressure system will double in about 2 to 3 days and will reach its maximum in around 10 days [21)]. This means that the limit for weather forecasting in the middle latitudes is approximately 10 days.

The limit for weather forecasting in the middle latitudes is also important for wave forecasting because there are cases where the wave height increases due to strong extratropical cyclone. The courses of typhoons and other tropical cyclones also depend on the atmospheric pressure pattern in the mid-latitudes and the position of the prevailing westerlies. Thus, the forecasting limit for ocean waves, which are driven by wind, is limited by the forecasting limit for weather, and as a guideline, that limit is considered to be no more than about 10 days.

When using wave forecasting values in ship monitoring, it is necessary to hold the forecasting period to approximately 10 days. Within the forecasting limit, ensemble forecasts are used as data for considering the uncertainty of forecast values for weather and ocean waves. An ensemble forecast is a set (ensemble) of forecasts which is obtained by generating several dozen initial values with perturbations, and then calculating an atmospheric/wave model based on those values. Ensemble forecasting is already used in forecasting of typhoons and seasonal forecasting for flood control and agriculture [22)], and is also thought that ensemble forecasting might also be used in ship monitoring in the future. The JMA, NOAA, ECMWF and other meteorological agencies provide ensemble forecasts for ocean wind waves. Fig. 5 shows the visualization of the data of the ECMWF’s wave ensemble forecast ENS-WAM [23)] for a certain coastal navigation route in Europe. The initial value is for November 22, 2021, and the forecast covers a four-day period. Each forecast in the ensemble (N = 50) is color coded. As can be seen from the figure, when the forecast period becomes longer, the variation of the significant wave height and other wave parameters becomes larger. As a point to note in ensemble forecasting, ensemble calculations frequently have coarser spatial resolution than deterministic forecasts that present only one initial value, corresponding to the large number of forecasts in the ensemble.

To maintain the forecasting accuracy of a weather model, it is necessary to continue to reflect the state of the atmosphere, which is chaotic, in the weather model. Therefore, measured values are reflected periodically in the model by data assimilation [21)]. Three types of estimated values are used in weather and wave models, depending on the data assimilation and time axis [24)]. The first is the estimated value of the actual situation (nowcast), in which a value is obtained by data assimilation using measured values, which is performed for the initial time of the estimated value given by a numerical model. The second value (forecast) is a value in which the future with respect to that time is estimated based on the nowcast, and the third (hindcast) is an additional value, in which the meteorological and oceanographic conditions in the past are estimated by using fixed observation values covering the entire analysis period. Because the volume of data that can be applied in data assimilation increases in the order of hindcast > nowcast > forecast, the accuracy generally tends to higher in the same order.

Use of hindcast is recommended when a real-time analysis is not needed, for example, when the aim is to determine the condition of a ship in the past. For cases that exceed the limit of the above-mentioned forecast period, for example, when evaluating the ship safety, it is desirable to acquire wave hindcast for a long period (on the order of several decades) and carry out a statistical analysis of that data.

Wave hindcast mainly consist of two types: ① Type using only hindcast for the wind field without data assimilation for waves, and ② Type in which data assimilation is also performed for waves using data from marine satellite altimeters, buoys, etc. The wave hindcast dataset called IOWAGA [25] and ERA5 [26] are used in the 2022 Comprehensive Revision of Part C of the ClassNK Rules for the Survey and Construction of Steel Ships [27]. IOWAGA corresponds to Pattern ①. WAVEWATCH III is driven by the NOAA wind product CFSR and the calibration using marine altimeter data and buoy data is performed by the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER). ERA5 corresponds to Pattern ②, where ECWAM is driven by ECMWF and the analysis values are obtained by data assimilation with satellite altimeter data [28].

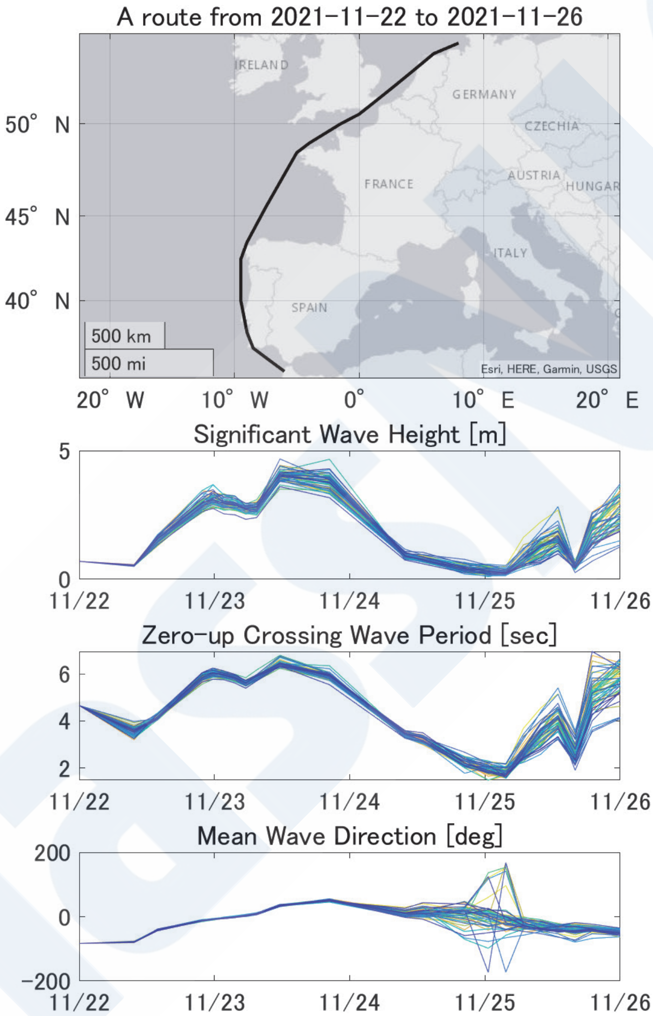

Fig. 5 Example of visualization of data for ECMWF wave ensemble forecast ENS-WAM [23] for the example of a certain European coastal route

3.5 Issues of Wave Models

There are still issues in accurately considering the dispersion relationship, dissipation, etc. of swells that arrive from distances of several 1,000 km or more [29]. For example, when the results obtained by buoy observation and wave model calculations were compared, cases in which there was a difference of several tens of hours in the swell arrival time have been reported [30]. While data assimilation of swells is possible by using marine satellite altimeter data, it is difficult to capture all swells [29].

As mentioned above in Section 3.1, the effects of the current velocity $\boldsymbol{U}$ include advection and refraction of waves. A number of strong ocean currents exist in various ocean areas of the world, including the Mexican Gulf Stream (Gulf Stream), the *Kuroshio* (Black Current) near Japan and the Agulhas Current in the Indian Ocean as representative examples. It has also been pointed out that wave heights are affected by vortexes in these currents, which reach a scale of 10 km to 100 km [31]. To determine whether the effect of these currents is incorporated in a wave model or not, a comparative study with measured data, etc. is recommended. (Note: In the above-mentioned IOWAGA and ERA5, good agreement with buoy measurements was confirmed in the North Atlantic Ocean [32)-34)].) The JMA's Meteorological Research Institute devised an equation for correction of the forecast values of ocean currents [35)], and the waters that are affected by ocean currents are shown in JMA wave forecast charts [36)].

There are cases where ships sail along ocean currents to improve ship fuel economy. To grasp the fuel consumption performance of ships in such cases, it is desirable to confirm the position accuracy of ocean currents and the effect of the current on waves.

4. OBSERVATION DATA FOR VERIFICATION

In many cases, wave models and radar are verified or calibrated by using observational data acquired by buoys, marine satellite altimeters, etc. which are not located on shipboard. Therefore, although the topic of this paper is application of wave data to ships, non-shipboard observation data for use in verifications will also be introduced here as background knowledge.

4.1 Buoys

Buoy data are considered to be the most basic and reliable form of wave observation data. With a buoy, it is possible to estimate the wave height and frequency spectrum by measuring the displacement of the buoy in the z direction. If data such as the displacement in the x, y and z directions and wave slope can be measured, it is also possible to estimate the 2-dimensional frequency and directional wave spectrum by the Maximum Entropy Principle (MEP) [37)].

In Japan, the data from GPS wavemeters is also aggregated in the NOWPHAS wave information observation network [38)], which is operated by the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT). These GPS wavemeters measure the position of buoys with accuracy of several cm by GPS, and are installed with single point mooring in waters with a depth of 100 to 400 m about 10 to 20 km from the coastline [39)]. These are large-scale buoys with a diameter of 5 to 7 m and a total height of 10 to 19 m. A total of 18 buoys have been installed along the Tohoku coast in northeastern Japan and from the Tokai area south of Tokyo to the western island of Kyushu.

In addition to the above, NOAA has deployed buoys in the Atlantic and Pacific Oceans and publishes the information obtained [40)], while in Europe, the **C**opernicus **M**arine **E**nvironment **M**onitoring **S**ervice (CMEMS) makes data available to the public on the internet [41)].

Smaller buoys have also appeared in recent years. For example, the company Sofar Ocean developed a compact, lightweight buoy called Spotter, which has a diameter of 42 cm and weight of approximately 7.5 kg [42)], and has deployed this buoy since 2019, creating an observation network that now provides global coverage (Fig. 6). Using these buoys, the company performs data assimilation not only for wave height, but also for wave period and wave direction, thereby improving forecasting accuracy for swells [43)]. In addition, there are also many other types of compact buoys, and an article providing a detailed commentary is available [44)].

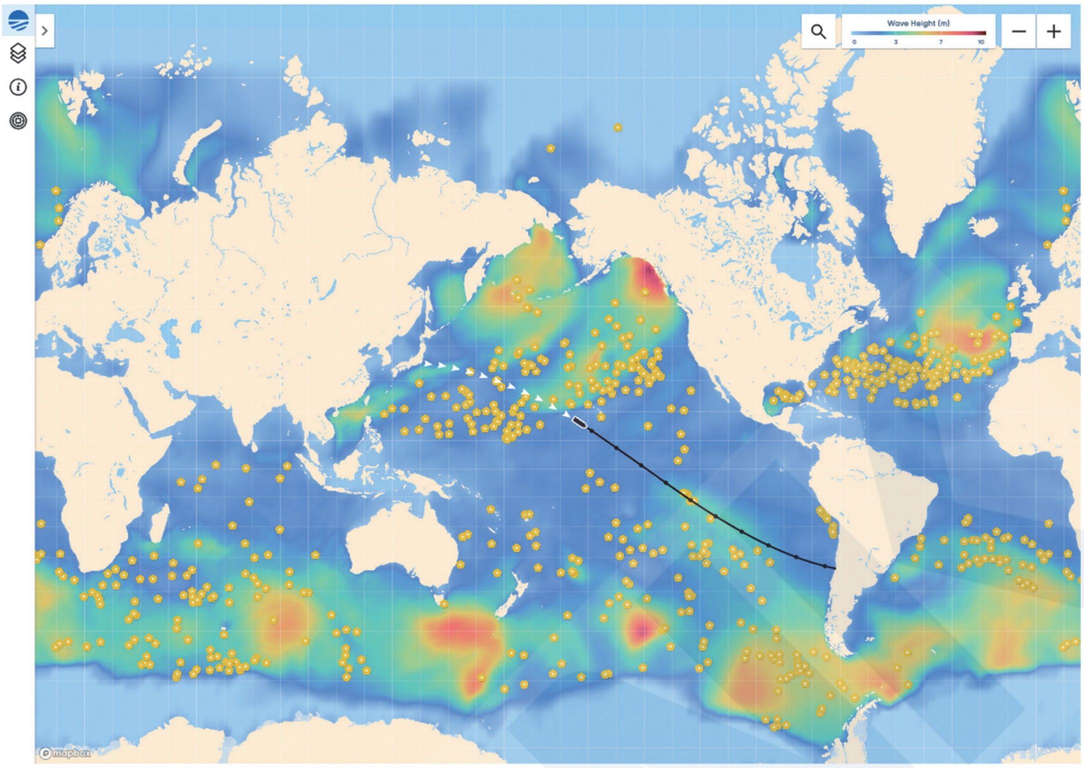

Fig. 6 Map of buoys deployed by Sofar Ocean as a July 2022 [45)]
(yellow dots: buoys, contour lines: wave height)

4.2 Marine Satellite Altimeters

Marine satellite altimeters are capable of measuring the significant wave height by irradiating microwaves on the sea surface, receiving the reflected signals and measuring the transmission time (reference paper [46)], Section 3.3.1). They are used in accuracy verification, calibration and data assimilation of wave models.

Marine satellite altimeters orbit the entire planet with a trajectory similar to a ball of wool (e.g., Fig. 7) and return to their original position in about 10 to 35 days. Multiple satellite altimeters are currently in operation, enabling simultaneous coverage of a wide range. However, since the data are only obtained in the form of moving points, this does not mean that data can be obtained densely and comprehensively for the entire planet. A wave model is necessary in order to obtain a comprehensive grasp of wave worldwide.

The data acquired by marine satellite altimeters are calibrated with buoy data, and datasets combining observational data from multiple satellites for a period of more than 30 years are now available [47) 48)].

Recently, a few satellites estimate wave spectra by using **S**ynthetic **A**perture **R**adar (SAR). Detailed descriptions of this type of satellite are available in the literature [46) 49)].

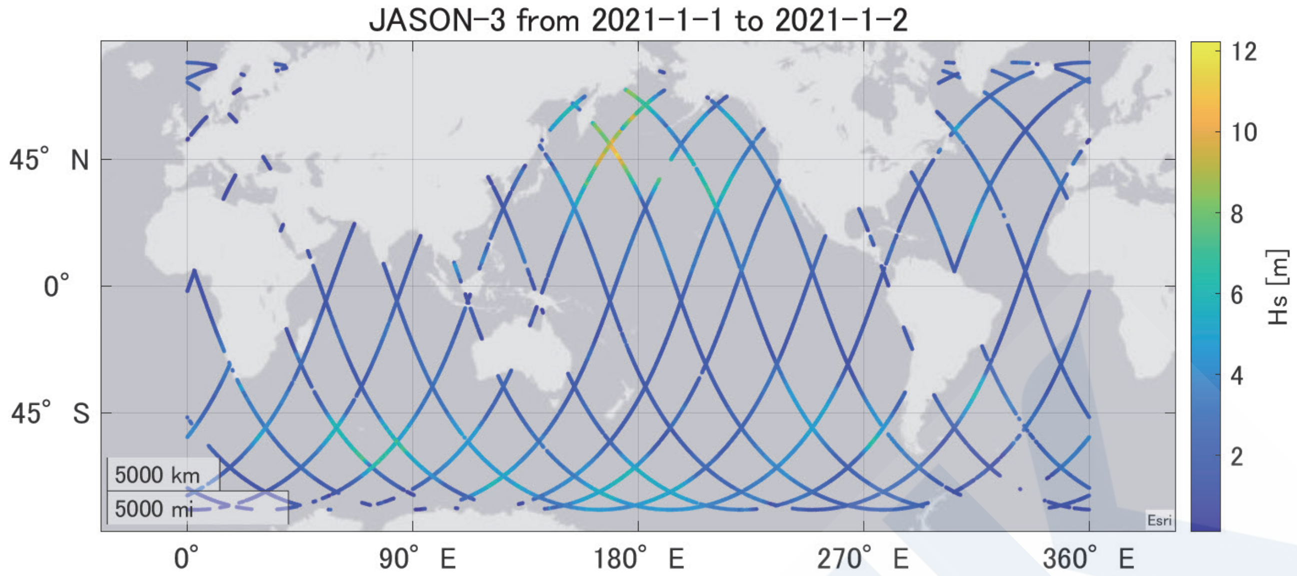

Fig. 7 Example of observed significant wave height and trajectory of satellite JASON-3 on a certain day
Calibrated data of Ribal & Young (2019) [47] were used.

5. DISCUSSIONS: APPLICATION TO VARIOUS TYPES OF SHIP MONITORING

Various types of vessel responses, such as ship motion, stress and added resistance in waves, are required in digital twins for ship structures, monitoring of ship performance in actual seas and related applications. The basic technique for this purpose is a forward analysis method in which the wave spectrum is multiplied by the square of RAO (**R**esponse **A**mplitude **O**perator) obtained in frequency domain. This is so-called short-term prediction of ship response. Techniques utilizing data assimilation and calibration reflecting the measured values of stress and other responses are also available. However, in the sense that the forward analysis does not require measured response values, this technique has the advantages of simplicity and low analysis cost. The following considers the required conditions for wave data to realize various types of ship monitoring, assuming the use of a forward analysis technique.

First, the wave parameters to be obtained are important. In particular, the wave height, wave period and wave direction are essential data for every possible ship response (motion, stress, added resistance in waves, etc.). The usefulness of the wave spectra obtained from wave models and radar will be considered. If the RAO has a gently-varying shape, the dependence of the response on the wave spectral shape will be small. Conversely, if the RAO peak has a sharp shape, the dependence of response on the wave spectral shape is considered to be large. For example, in many cases the RAO peak for roll is sharp, and the peak varies sensitively with GM and ship speed. Although this suggests the possibility that use of wave spectral data may be effective for the short-term prediction of responses with sharp RAO peak, future study is necessary.

The next point is the time range. In fatigue assessment of ship structures, fuel consumption performance and the like, a real-time analysis is not required, and an *ex-post facto* analysis is sufficient. In such cases, hindcast , which are generally considered to be more accurate than nowcast, might be suitable for those applications. Naturally, shipboard observational data such as wave radar data can only be acquired from the past up to the present. When predictions of future responses are desired, forecast obtained by a wave model are necessary. If the uncertainty of predictions within the forecast limit (approximately 10 days) is evaluated by ensemble forecasting, it is also considered possible to assess the uncertainty of responses originating from the uncertainty of forecast values.

Finally, the spatial range must be considered. Wave models can cover almost all ocean areas, and it is possible to extract wave data at a ship's position. However, assuming data are not shared between ships, shipboard observational data are the results of observation of only waves at the ship's position.

Based on these requirements, the types of wave data that are suitable for various types of ship monitoring were roughly arranged, as shown in Table 1.

Table 1 Applicability of wave data for various types of ship monitoring
(○: Applicable, △ : Applicable depending on the case, × : Not applicable)

		Property of data				
		Estimable parameters			Range covered	
Category	Type of data	Wave height	Wave period / wave direction	Wave spectrum	Time	Space
Wave model	Hindcast	○ Data assimilated with observational data.	○	○	Past	○ Can be acquired for almost all ocean areas and ship positions. However, a high resolution wave model is necessary in near-coastal waters.
	Nowcast	○	○	○	Present	
	Deterministic prediction	○	○	○	Future	
	Ensemble forecast	○ In many cases spatial resolution is coarser than that of deterministic prediction.			Future (considers uncertainty of forecast)	
Shipboard observation data	Wave radar	○ Care is required regarding precipitation and calibration.	○	○	Present	○ Shipboard observation
	Ship wavemeter	○	× Cannot measure wave direction.	×		
Observational data for verification	Satellite altimeter	○	△ Recently, a few satellites also estimate wave spectra [46]		Past / present	Full global coverage. Low spatial density of data.
	Buoy	○	○ Requires measured data with at least 3 degrees of freedom.			

		Application			
		Past		Present	Future
Category	Type of data	Fatigue assessment (stress)	Fuel consumption performance evaluation (added resistance in waves)	Ship motion, stress and added resistance in waves	
Wave model	Hindcast	○ If real time is not required, hindcast data are suitable, as accuracy is generally high.			
	Nowcast	○	○	○	
	Deterministic prediction				○
	Ensemble forecast				○
Shipboard observational data	Wave radar	○	○	○	
	Ship wavemeter	△ Because only wave height is measured, it is necessary to use shipboard wavemeter data in combination with other data.			

6. CONCLUSIONS

This paper introduced and compared the outline and other features of various types of wave data for application to ship monitoring, which is currently a subject of active research and development. Technologies for wave estimation are diverse and are advancing rapidly. Due to space limitations, the commentary in this paper was limited to observational devices and analytical techniques that are generally in wide use. Although the outlines of the various technologies were introduced in simple terms here, the reader may refer to the reference literature for details.

For readers who wish to make a deeper investigation of the field of ocean wave, several textbooks are also introduced below.

① "Physics of Ocean Waves" by Hisashi Mitsuyasu [50]
This book is suitable for beginners, and provides a simple explanation of essential topics such as wave statistics and signal processing, the wave generation and development process, observation by buoys, etc. However, it is difficult to obtain, as it is out of print.

② "Analysis and Forecast of Ocean Waves" by Ichiro Isozaki and Yasushi Suzuki [51]
A comprehensive treatment covering topics from the fundamentals of ocean waves to observation, ocean surface waves

and wave models. In particular, this text provides a detailed description of the operation of wave models in the seas near Japan.

③ "The Interaction of Ocean Waves and Wind" by Peter Janssen [52)]
A textbook that gives a detailed explanation of wave models, written by an expert of the ECMWF.

④ "Ocean Wave Dynamics" by Ian Young and Alexander Babanin [53)]
A text for graduate school students and researchers, which was published in 2019 and covers recent research results. It is an omnibus-type work written by experts in various fields including wave models, satellite observation, nonlinear waves, etc.

In addition, the KANRIN published by the Japan Society of Naval Architects and Ocean Engineers included Special Issues entitled "Frontier of Ocean Wave Research" in Vol. 98 [54)] and "Use of Weather Information in the Ship and Offshore Fields" in Vol. 77 [55)]. Also, the Working Group of the Forum for Operational Oceanography Surface Waves in Australia has arranged the issues for future wave research under the title "15 Priorities for Wind-Waves Research"[29)]. Here, a questionnaire survey of stakeholders in wave-related fields, including persons at research institutes and government-affiliated organizations, private companies was conducted, the issues were arranged by the Steering Committee and the results of a revote by the stakeholders are summarized. Interested readers may also refer to the articles included in "15 Priorities" for the current limits of wave data and wave models and the issues for future wave research. It may be noted that "15 Priorities" mentioned *Better Engagement of maritime industries with research* as one issue.

As noted in the Introduction to the present paper, it is necessary to utilize the wave data which is currently provided in ship monitoring based on an understanding of its usefulness and limitations. The authors will be happy if this paper contributes to the use of wave data in ship monitoring. We also hope that *Better Engagement of maritime industries with research* will be realized through the development of ship monitoring to maritime industries.

REFERENCES

1) National Maritime Research Institute (NMRI), "Joint Research of Maritime Cluster – Start of Evaluation of Ship Performance in Actual Seas Project (OCTARVIA) Phase 2," 2022. https://www.nmri.go.jp/news/press/press20220315.html
2) N. Sogihara and T. Yonezawa, "Establishment of Ship Performance Monitoring Method in Actual Seas," *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.* Vol. 82, pp. 6-11, 2019.
3) M. Fujikubo, "R&D of Digital Twin for Ship Structures," J. Jap. Weld. Soc., Vol. 90, No. 1, pp. 36-43, 2021, doi: 10.2207/jjwa.90.36.
4) A. Maki, "Kansai Branch News," *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, Vol. 102, p. 48, 2022.
5) J. Nieto Borge, G. R. RodrÍguez, K. Hessner, and P. I. González, "Inversion of Marine Radar Images for Surface Wave Analysis," *J. Atmos. Ocean. Technol.*, vol. 21, no. 8, pp. 1291-1300, Aug. 2004, doi: 10.1175/1520-0426(2004)021<1291:IOMRIF>2.0.CO;2.
6) Y. Qi, W. Xiao, and D. K. P. Yue, "Phase-resolved wave field simulation calibration of sea surface reconstruction using noncoherent marine radar," *J. Atmos. Ocean. Technol.*, vol. 33, no. 6, pp. 1135-1149, 2016, doi: 10.1175/JTECH-D-15-0130.1.
7) W. Huang, X. Liu, and E. W. Gill, *Ocean wind and wave measurements using X-band marine radar: A comprehensive review*, vol. 9, no. 12. 2017. doi: 10.3390/rs9121261.
8) H.-Y. Y. Cheng and H. Chien, "Implementation of S-band marine radar for surface wave measurement under precipitation," *Remote Sens. Environ.*, vol. 188, pp. 85-94, 2017, doi: 10.1016/j.rse.2016.10.042.
9) N. Braun, F. Ziemer, A. Bezuglov, M. Cysewski, and G. Schymura, "Sea-Surface Current Features Observed by Doppler Radar," *IEEE Trans. Geosci. Remote Sens.*, vol. 46, no. 4, pp. 1125-1133, 2008, doi: 10.1109/TGRS.2007.910221.
10) C.-K. Rheem, "Stationary Observation of Coastal Ocean Waves by Doppler Radar," *Kanrin Bull. Japan Soc. Nav. Archit. Ocean Eng*., No. 98, pp. 8-11, 2021.
11) S. Takeda, "Wave Measurement by Actual Ship," Techno Marine (Bull. of Soc. Nav. Archit. Jpn.), Vol. 831, pp. 36-41, 2002.

12) K. Hasselmann *et al.*, “Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP),” Deutches Hydrographisches Institut, 1973.

13) H. L. Tolman and N. Booij, “Modeling wind waves using wavenumber-direction spectra and a variable wavenumber grid,” *Glob. Atmos. Ocean Syst.*, vol. 6, pp. 295-309, 1998.

14) K. Hasselmann, “On the non-linear energy transfer in a gravity-wave spectrum Part 1. General theory,” *J. Fluid Mech.*, vol. 12, no. 04, p. 481, 1962, doi: 10.1017/S0022112062000373.

15) T. WAMDI Group, “The WAM model - A third generation ocean wave prediction model,” *Journal of Physical Oceanography*, vol. 18, no. 12. pp. 1775-1810, 1988. doi: 10.1175/1520-0485(1988)018<1775:TWMTGO>2.0.CO;2.

16) G. J. Komen, L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann, and P. A. E. M. Janssen, *Dynamics and Modelling of Ocean Waves.* Cambridge: Cambridge University Press, 1994. doi: DOI: 10.1017/CBO9780511628955.

17) S. Park, “Part VII : ECMWF Wave Model IFS DOCUMENTATION - Cy38r1 Operational implementation 19 June 2012 PART VII : ECMWF WAVE MODEL Table of contents Numerical scheme,” no. June, pp. 1-79, 2012.

18) H. L. Tolman, “User manual and system documentation of WAVEWATCH III,” 2016.

19) R. C. Ris, L. H. Holthuijsen, and N. Booij, “A third-generation wave model for coastal regions: 2. Verification,” *J. Geophys. Res. Ocean.*, vol. 104, no. C4, pp. 7667-7681, Apr. 1999, doi: https://doi.org/10.1029/1998JC900123.

20) H. Minematsu, “Wave Model Operated by Government Agency at the Japan Meteorological Agency,” TENKI (Journal of the Meteorological Society of Japan (JMSJ)), Vol. 56, pp. 669-674, 2009.

21) T. Miyoshi, “Big Data Assimilation and Weather Prediction,” Jpn. J. Appl. Phys., Vol. 90, No. 8, pp. 470-475, 2021.

22) M. Yamaguchi, “Risk Assessment in the Use of Weather Data – Various Forms of Ensemble Forecasting –,” 2020.

23) ECMWF, “Ocean Wave Model Ensemble 15-day forecast (Set IV - ENS-WAM).” https://www.ecmwf.int/en/forecasts/datasets/set-iv

24) K. Matsuura, M. Maeda, H. Nakano, K. Kuroki, S. Koshida and Y. Sato, “Estimation of Meteorological and Oceanographic Phenomenon and Its Accuracy: For Use Based on the Characteristics of Estimated Values (Special Issue: Use of Weather Information in the Ship and Offshore Fields),” *Kanrin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, No. 77, pp. 6-10, 2018.

25) M. Alday, F. Ardhuin, M. Accensi, and G. Dodet, “A global wave parameter database for geophysical applications. Part 3: improved forcing and spectral resolution,” 2021.

26) H. Hersbach *et al.*, “The ERA5 global reanalysis,” *Q. J. R. Meteorol. Soc.*, vol. 146, no. 730, pp. 1999-2049, 2020, doi: 10.1002/qj.3803.

27) R. Miratsu, T. Fukui and T. Zhu, “Evaluation of the Ship Operational Effect Based on Actually Encountered Sea States by Ships,” ClassNK Technical Journal, Vol. 5, pp. 71-74, 2022.

28) ECMWF, “Forecast User Guide, 2 The ECMWF Integrated Forecasting System, 2.2 Ocean Wave Model - ECWAM,” 2022. https://confluence.ecmwf.int/display/FUG/2.2+Ocean+Wave+Model+-+ECWAM

29) D. Greenslade *et al.*, “15 Priorities for Wind-Waves Research: An Australian Perspective,” *Bull. Am. Meteorol. Soc.*, vol. 101, no. 4, pp. E446-E461, 2020, doi: 10.1175/BAMS-D-18-0262.1.

30) H. Jiang, A. V Babanin, and G. Chen, “Event-Based Validation of Swell Arrival Time,” *J. Phys. Oceanogr.*, vol. 46, no. 12, pp. 3563-3569, 2016, doi: 10.1175/JPO-D-16-0208.1.

31) F. Ardhuin *et al.*, “Small-scale open ocean currents have large effects on wind wave heights,” *J. Geophys. Res. Ocean.*, vol. 122, no. 6, pp. 4500-4517, Jun. 2017, doi: https://doi.org/10.1002/2016JC012413.

32) T. Kodaira, K. Sasmal, R. Miratsu, T. Fukui, T. Zhu, and T. Waseda, “Uncertainty in wave hindcasts in the North Atlantic Ocean,”, submitted to Marine Structures,, 2022.

33) G. de Hauteclocque, T. Zhu, M. Johnson, H. Austefjord, and E. Bitner-Gregersen, “Assessment of global wave datasets for long term response of ships,” *Proc. Int. Conf. Offshore Mech. Arct. Eng. - OMAE*, vol. 2A-2020, no. August, 2020, doi: 10.1115/omae2020-18874.

34) K. Sasmal, T. Kodaira, Y. Kita, R. Miratsu, and T. Zhu, “Modeled and satellite-derived extreme wave height statistics in the North Atlantic Ocean reaching 20 m,” *ESSOAr*, 2021.

35) G. Kubo and N. Kohno, “Study of the Effect of Ocean Currents on Waves,” Weather Service Bulletin, Vol. 77, pp. S141-S157, 2010.

36) N. Kohno and A. Yamane, “Addition of ‘Information on Rough Seas Hazardous to Navigation’ to Wave Forecast Charts,” Weather Service Bulletin, Vol. 85, pp. 1-12, 2018.
37) N. Hashimoto, “Estimation of Directional Spectra from the Maximum Entropy Principle,” Report of the Port and Harbour Research Institute, Vol. 24, No. 3, pp. 123-146, 1985.
38) Ports and Harbours Bureau, Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), “NOWPHAS: Nationwide Ocean Wave information network for Ports and HArbourS.” https://www.mlit.go.jp/kowan/nowphas/index.html
39) Y. Ito, “Basic Knowledge of Port and Harbour Terminology, ‘GPS Wavemeter’,” Kouwan (Ports and Harbours, magazine published by The Japan Port and Harbour Association), Vol. 3, p. 56, 2017.
40) NOAA, “National Data Buoy Center.” https://www.ndbc.noaa.gov/
41) C. M. E. M. Service, “In Situ TAC.” http://www.marineinsitu.eu/dashboard/
42) Sofar Ocean, “Spotter Buoy.” https://www.sofarocean.com/products/spotter
43) P. B. Smit *et al.*, “Assimilation of significant wave height from distributed ocean wave sensors,” *Ocean Model.*, vol. 159, 2021, doi: 10.1016/j.ocemod.2020.101738.
44) Y. Hirakawa, “Measurement of Waves Encountered by Ships and Marine Structures in Oceanic Regions,” *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, Vol. 98, pp. 12-16, 2021.
45) Sofar Ocean, “Sofar Ocean.” https://weather.sofarocean.com/
46) F. Ardhuin *et al.*, “Observing Sea States,” *Frontiers in Marine Science*, vol. 6. 2019.
47) A. Ribal and I. R. Young, “33 years of globally calibrated wave height and wind speed data based on altimeter observations,” *Sci. Data*, vol. 6, no. 1, p. 77, 2019, doi: 10.1038/s41597-019-0083-9.
48) F. Laboratoire d’Océanographie Physique et Spatiale (LOPS), CNRS, IRD, Ifremer, IUEM, Univ. Brest, Brest, “The Sea State Climate Change Initiative dataset is available,” 2019.
49) T. Waseda, “Global Trends and Challenges in Ocean Wave Research,” *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, Vol. 98, pp. 1-7, 2021.
50) H. Mitsuyasu, “Physics of Ocean Waves,” Iwanami Shoten, Publishers, 1995.
51) I. Isozaki and Y. Suzuki, “Analysis and Forecast of Ocean Waves,” Tokai University Press, 1999.
52) P. A. E. M. Janssen, *The interaction of ocean waves and wind*. Cambridge University Press, 2004.
53) I. R. Young and A. V. Babanin, *Ocean Wave Dynamics*. WORLD SCIENTIFIC, 2019. doi: doi:10.1142/11509.
54) Japan Society of Naval Architects and Ocean Engineers, Eds., “Frontline of Ocean Wave Research,” *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, Vol. 98, 2021.
55) Japan Society of Naval Architects and Ocean Engineers, Eds., “Use of Weather Information in the Ship and Offshore Fields,” *Karin Bull. Japan Soc. Nav. Archit. Ocean Eng.*, 2018.