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Accurate Evaluation for Low-Carbon Shipping Using Wave Hindcast Database

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ABSTRACT

Voyage evaluation analysis requires actual data on voyage and external forces (i.e., meteorological and oceanographic). Although voyage data, often referred to as noon data, were previously collected once a day, monitoring systems have gradually become popular in recent years, and data is collected at small sampling intervals. In contrast, winds are generally observed as meteorological and oceanographic data by onboard anemometers; however, it may include observation errors. Although waves are also crucial while considering the impact on ships, onboard wave observations are currently difficult. Therefore, the use of hindcast data, re-analysed oceanographic estimation, is gradually increasing due to its high accuracy. A comparative verification was performed in this study based on different sampling intervals of voyage data and different types and elements of oceanographic data to confirm the possible sea conditions that a ship would encounter on an actual voyage and obtain estimated performance curves using wind and waves. The results confirmed the importance of the sampling interval of voyage data, the possibility that hindcast data can accurately reproduce sea conditions encountered by ships, and the effectiveness of wave hindcast data in aerating speed–power chart and estimating performance curves.

Keywords: waves; hindcast data; voyage evaluation; ocean conditions; calm water performances

NOMENCLATURE

GHG	Greenhouse gas
SOG	Speed over ground
STW	Speed through water
BHP	Brake horsepower
BF	Beaufort wind force
MCR	Maximum Continuous Output Rating
IMO	International Maritime Organization
ISO	International Organization for Standardization
NOAA	National Oceanographic and Atmospheric Administration
JWA	Japan Weather Association
JMA	Japan Meteorological Agency

1. INTRODUCTION

As part of the IMO’s GHG reduction from international shipping measures, two new indicators, namely the Energy Efficiency Convention for Existing Ships (EEXI) and the Carbon Intensity Indicator (CII) rating system for fuel consumption performance, have been launched in 2023 that encourage additional efforts in assessing actual voyage. Voyage evaluation is based on the actual voyage results.

Due to advances in the ship-to-shore communication environment and sensor technology, the collection of detailed voyage data has begun in recent years, and the environment analysis using dense voyage data is currently underway; however, uncontrolled external factors, such as sea conditions, have a significant impact on the analysis; most of the analyses are currently performed using only onboard wind observation from onboard anemometers due to their availability. The three types of meteorological and oceanographic estimations based on time series, including estimations of wind and wave data, are as follows: forecast, nowcast, and hindcast. Hindcasts are the most reliable re-analysed data and are therefore suitable for evaluating actual voyage results. With regard to the above estimations of wind and waves, considering their wave effects is necessary for voyage analysis; however, numerous problems with wave observations onboard are currently observed.

Thus, the use of wave estimations is appropriate. Therefore, the authors demonstrated the statistics of wind and wave hindcast data on the actual voyage, the creation of speed–power chart with wind and filtering and the estimated ship performance curves. The performance curves were compared with the results of sea trials.

2. ACQUISITION OF ENCOUNTERED HISTORICAL OCEAN CONDITION DATA DURING THE ACTUAL VOYAGE

The actual oceanographic data were extracted on the actual voyage of the Japanese coastal tramper. Two types of oceanographic data are used: observations, which were observed by onboard anemometers, and hindcast, which is the most probable value re-analysed after such observations.

2.1 Actual Voyage Monitoring Data

The subject ship was equipped with an onboard voyage data monitoring system. A wide range of data, including positions, navigation instruments, and engine instruments, was collected every 10 min. Among these data, the position, relative wind direction and relative wind speed observations from the onboard anemometer, SOG, STW, and BHP were used in the current study. Data are shown in Table 2-1, and the target period is one year just after entering service, onboard wind observations were used for comparative verification. The observed values are relative winds; thus, these values were corrected to absolute winds and further modified for altitude.

Table 2-1. Actual voyage monitoring data used for the analysis

Data Items	Source Device	Remarks
Ship’s position	Input value from DGPS/AIS	10 minute average
BHP	Calculated values from shaft horsepower meter	10 minute average
Wind speed and wind direction	Input value from onboard anemometer	10 minute average
SOG	Input value from DGPS/AIS	10 minute average
STW	Input values from data loggers	10 minute average
Heading	Input value from AIS	10 minute average

The ship data monitoring environment is considerably better developed than in the past. Nevertheless, developing new advanced monitoring systems, especially for ships in service, is difficult in several cases. As the monitoring intervals for voyage data are rough in most cases, the current study will also examine the effect of these intervals on the re-creation of sea conditions on the actual voyage and the assessment of ship performance. Traditionally, the most common methods of ship data collection have been once a day (i.e., noon report) and every four hours (i.e., voyage log abstract). Therefore, each dataset was pseudo-created based on data collected every 10 min, and the following three comparisons were made:

A) 10-minute monitoring data: Original voyage monitoring data.

B) 4-hour monitoring data: Data extracted from the voyage data in (A) at 0:00, 4:00, 8:00, 12:00, 16:00 and 20:00 on each day were pseudo-created assuming that they were voyage log abstract data.

C) Daily monitoring data: Data corresponding to 12:00 of each day were extracted from the operational data in (A) and were assumed to be noon data and pseudo-created.

2.2 Hindcast Data of Ocean Wind and Waves

Hindcast data are the most probable meteorological and oceanographic data re-analysed using fixed conditions, which assimilated all periods by observation. It is the most suitable data for ex-post analysis considering prediction accuracy and resolution. The hindcast of the JWA on the Japanese coastal area was used as the hindcast data[1][2]. Details of the hindcast data are shown in Table 2-2. This hindcast is an accuracy-assured database that has been validated using a variety of observation data. As an example of the accuracy verification, Figure 2-1 shows the comparison results of observed wave data from NOAA buoys, actual condition estimates, and additional data. The scatter plots indicate that the hindcast has minimal variation and superior agreement with the observation values. The correlation coefficient of wave height is 0.94, and wave period and direction are above 0.8. All the regression coefficients are above 1.0. These findings show that the hindcast value is equivalent to the buoy observation value and is a highly accurate estimation value.

Not only hindcast is superior to nowcast in accuracy but also resolution. For example, Figure 2-2 shows the comparison results of nowcast and hindcast for the world's largest wave height; hindcast can accurately represent the observed wave height peaks because it has a resolution of 1 h whereas nowcast has a resolution of 6 h; thus, the observed wave height peak cannot be reproduced.

Table 2-2. Overview of Japan coastal hindcast database

Items	Ocean Wind Wind speed and Wind direction at 10m height	Significant Wave Wave height, Wave direction and Wave period
Model	MSM, GSM	WAM cycle4 *JWA improved version
Spatial resolution	1/30 degree (About 3.7 km) *Interpolated to a time interval of 10 min	1/30 degree (About 3.7 km) *Interpolated to a time interval of 10 min
Temporal resolution	1 hour *Interpolated to a distance interval of 20 m	1 hour *Interpolated to a distance interval of 20 m
Registerd data period	From 2001 to the present	From 2001 to the present

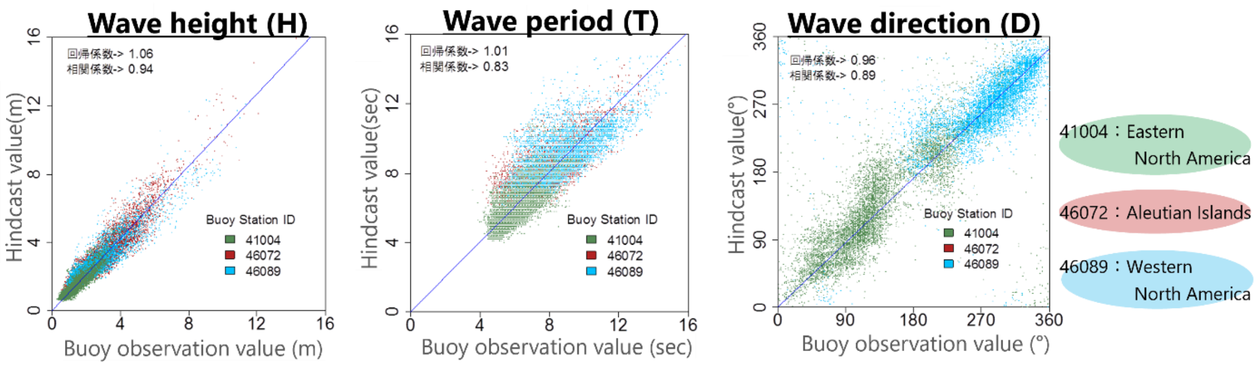


Figure 2-1. Example of the accuracy verification of hindcast data

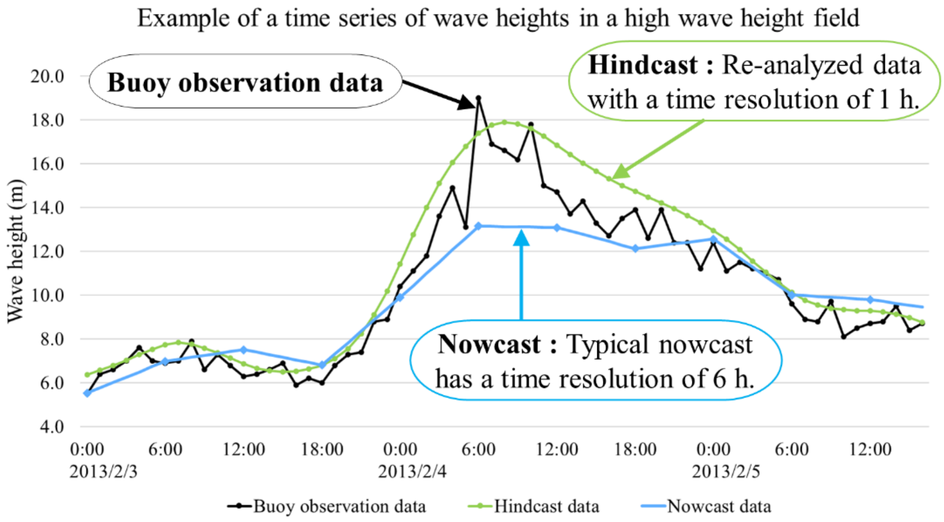


Figure 2-2. Example of comparison results of nowcast and hindcast

3. ACTUAL SEA CONDITIONS DURING THE VOYAGE

3.1 Sea conditions by data type and monitoring interval

The onboard wind observations and wind and wave hindcast data on the actual voyage were extracted and organized. Histograms of wind direction and wind speed are shown in Figure 3-1 and wind roses are presented in Figure 3-2 for onboard observations and hindcast data by different monitoring intervals.

In a finding that indicates the difficulty of observing onboard wind direction, as shown in histograms in 3-1, the wind speeds demonstrate the same trend for observations and hindcast; however, a variation is observed in the wind direction. Observations from onboard anemometers are sometimes inaccurate due to the influence of structures around the installation site and the boundary layer[3]. This situation can be inferred from the wind roses in Fig 3-2, that south-westerly and north-easterly winds are observed more frequently, while south-easterly cold seems to be less easily observed in this case. In a trend weakened by the increasingly frequent observation of 10-minute monitoring data, which indicates the importance of fine data sampling intervals. While daily monitoring showed that representative wind may not be extracted based on this voyage data, but for data with dense sampling intervals, the hindcast wind data, which does not contain observation errors, can be used as a reference.

Histograms and wave roses of hindcast wave height and direction are shown in Figures 3-3 and 3-4, respectively, by different monitoring intervals. Onboard observations for waves are unavailable; thus, the only comparison is the difference due to the monitoring interval. As shown in Table 3-3, the 10-minute and 4-hour monitoring data show the same trend but the daily monitoring data demonstrate a different trend. In the 10-minute data and 4-hour data, there are two peaks of wave height, around 0.2 m and 1.0 m, but in the daily data, the occurrence frequency of 1.5m wave height is extremely high. Although, compared to the wind data, it shows a similar distribution overall, especially in terms of direction, and does not show a completely different distribution depending on the difference in sampling interval, as is the case with wind direction. From the above, it is considered that the wave hindcast data can be used as a reference value even if the sampling interval is rough. This can be seen from the wave roses in Fig. 3-4, which shows almost the same wave trend regardless of the sampling interval, and there is no indication that strange values appear.

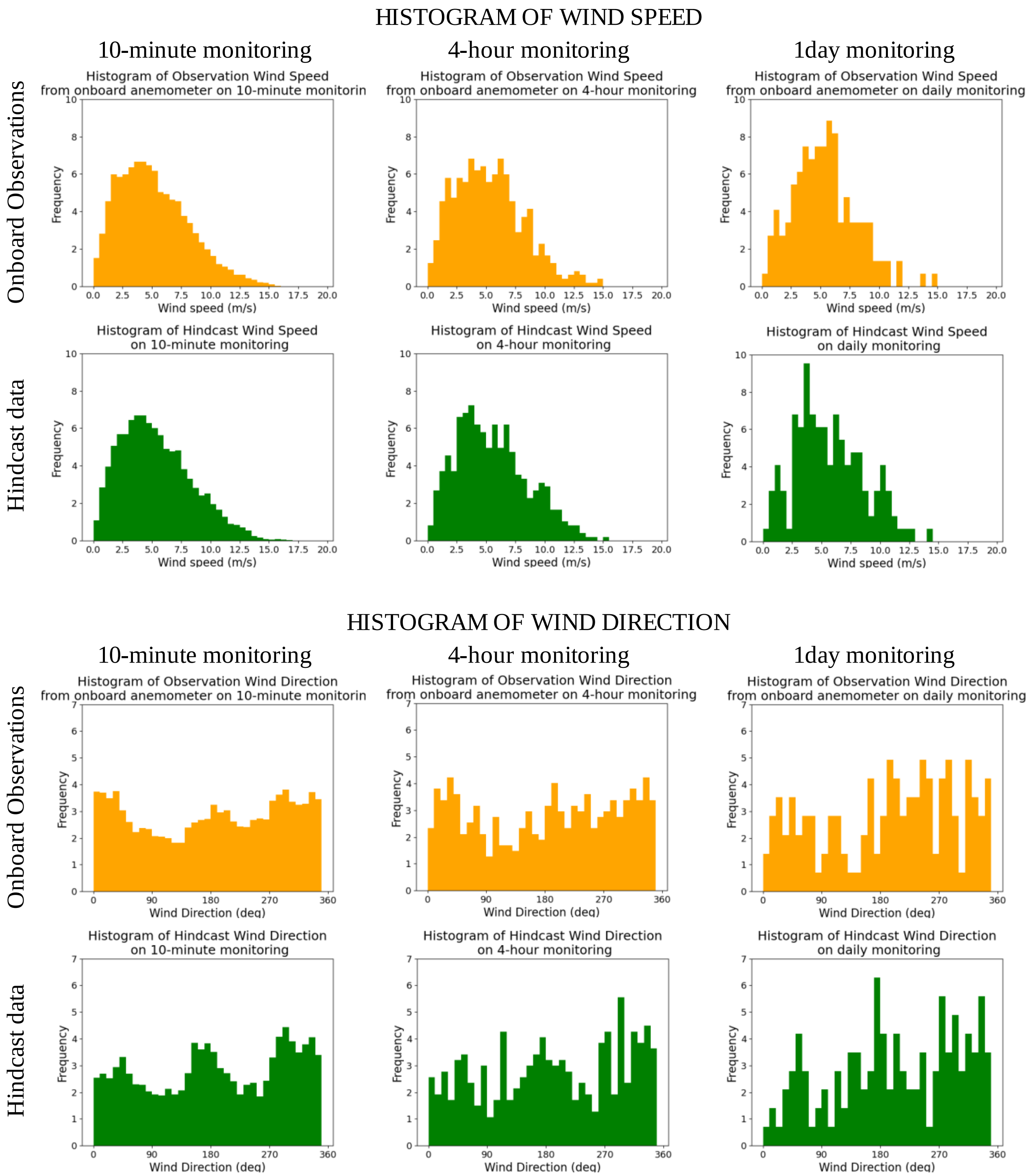


Figure 3-1. Histograms of ocean winds on actual voyage

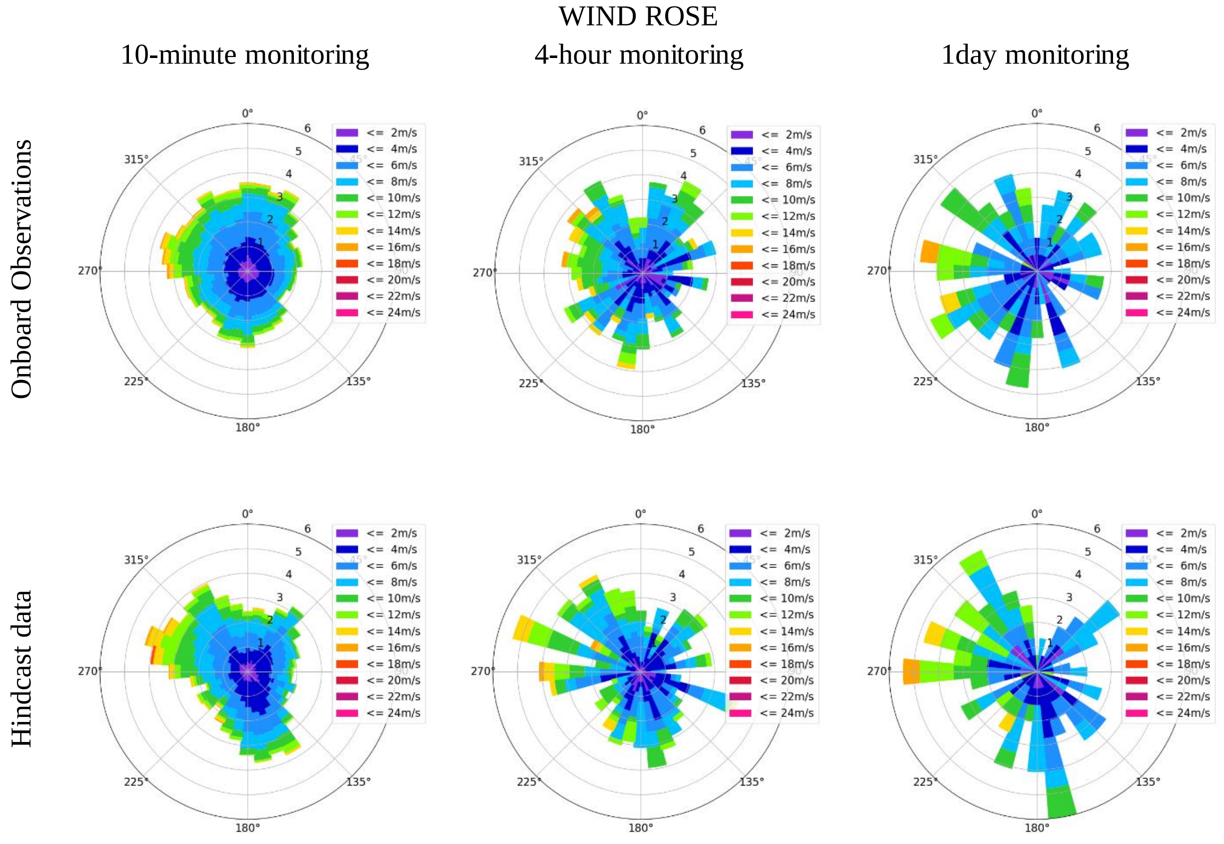
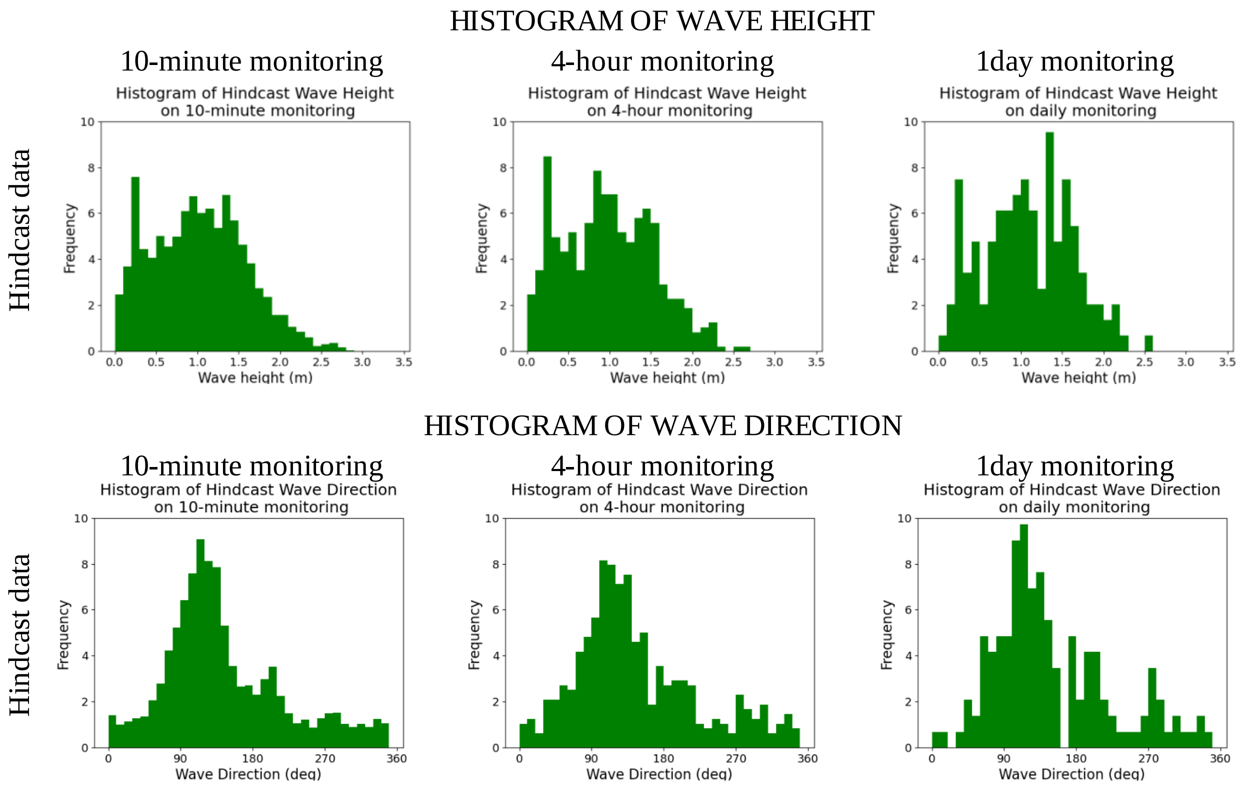


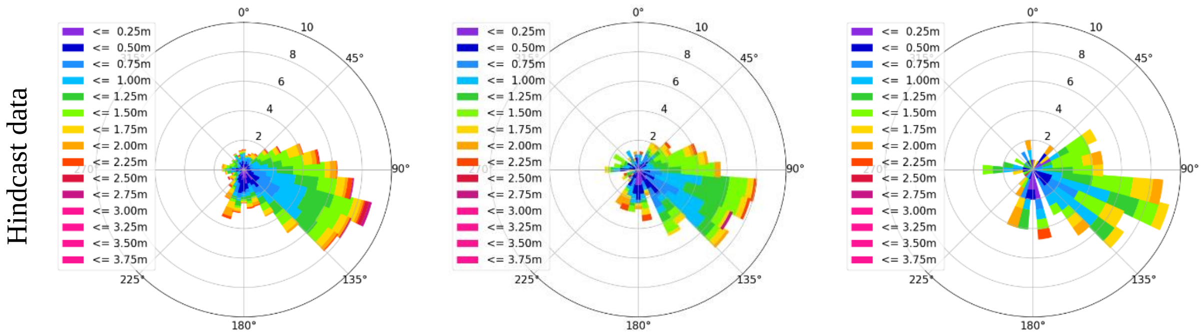
Figure 3-2. Wind roses on an actual voyage



Figures 3-3. Histograms of ocean waves on actual voyage

WAVE ROSE

10-minute monitoring | 4-hour monitoring | 1day monitoring



Figures 3-4. Wave roses on the actual voyage

3.2 Relationship between wind and waves

The ocean wind force is generally expressed in the BF scale, and the indications for the approximate wave heights for each BF number [4] are shown in Table 3-1; however, indicative wave heights may differ from the guideline wave heights under closed target area, wind blowing, or in the presence of a swell. The relationship between wind and waves on the actual voyage in this study is shown in Table 3-2, which reveals that the mode frequencies of wave heights within each BF class strictly deviate from the aforementioned reference wave height indexes for the BF numbers. Estimating wave heights according to a BF scale index from wind data may miss the possibility of the ship encountering high waves. Although the results suggest that wind and wave data filtering may be highly effective, wind filtering is conventionally used in several cases such as the evaluation of ship performance in calm water using ship monitoring data.

Table 3-1. Beaufort wind force scale

Wind Force	Wind Description	Wind Speed (m/s)	Wind Speed (knots)	Wave Height	Wave Period
0	Calm	0.0–0.2	0.0	0.0	
1	Light Air	0.3–1.5	1.0–3.0	0.1	
2	Light breeze	1.6–3.3	4.0–6.0	0.2	
3	Gentle Breeze	3.4–5.4	7.0–10.0	0.6	3.0
4	Moderate Breeze	5.5–7.9	11.0–16.0	1.0	3.9
5	Fresh Breeze	8.0–10.7	17.0–21.0	2.0	5.5
6	Strong Breeze	10.8–13.8	22.0–27.0	3.0	6.7
7	Near Gale	13.9–17.1	28.0–33.0	4.0	7.7
8	Gale	17.2–20.7	34.0–40.0	5.5	

Table 3-2. Relationship between wind and wave frequency of hindcast on actual voyage

Frequency table		BF0 0m/s~	BF1 0.3m/s~	BF2 1.6m/s~	BF3 3.4m/s~	BF4 5.5m/s~	BF5 8.0m/s~	BF6 10.8m/s~	BF7 13.9m/s~	BF8 17.2m/s~	Total
Sea0	0.0m	0.0	0.1	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.9
Sea1	~0.1m	0.1	1.0	0.6	0.1	0.0	0.0	0.0	0.0	0.0	1.8
Sea2	~0.2m	0.1	0.8	1.9	0.9	0.4	0.0	0.0	0.0	0.0	3.9
Sea3	~0.6m	0.1	**2.5**	5.0	**7.1**	5.1	0.7	0.1	0.0	0.0	20.6
Sea4	~1.0m	0.1	1.7	4.7	7.3	6.2	2.4	0.5	0.0	0.0	23.0
Sea5	~2.0m	0.1	**2.5**	**8.0**	**10.6**	**11.0**	**9.1**	**3.4**	0.0	0.0	44.8
Sea6	~3.0m	0.0	0.1	0.2	0.6	0.9	1.7	1.1	**0.4**	0.0	5.0
Total		0.4	8.6	20.6	26.9	23.9	14.1	5.0	0.5	0.0	100.0

*Yellow boxed: Value generally considered to be the reference sea scale for BF scale.
*Bold: Sea scale with the highest frequency of wave occurrence for each BF scale.

3.3 Ship performance evaluation in calm water

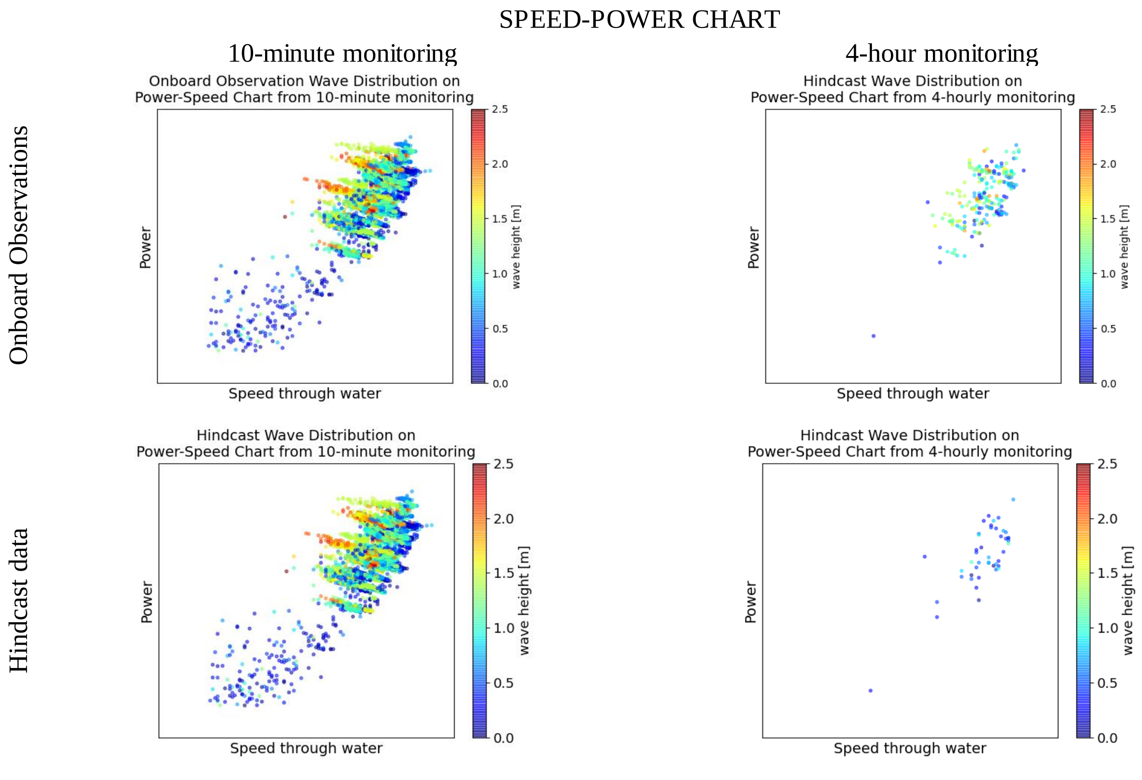
Conventionally, the wind filtering method[5] has been widely used to evaluate calm water performance from data in actual seas. Wind and wave filtering methods are compared in this study because these methods could be performed using readily available meteorological estimations, where the use of wind and wave filtering methods, such as the resistance criteria method method[6], has also begun in recent years. Table 3-2 shows the comparison cases and their results. The sea conditions used for filtering include the following three cases:

a) Filtering for BF4 using shipboard observations (i.e., excluding wind speeds above 8 m).

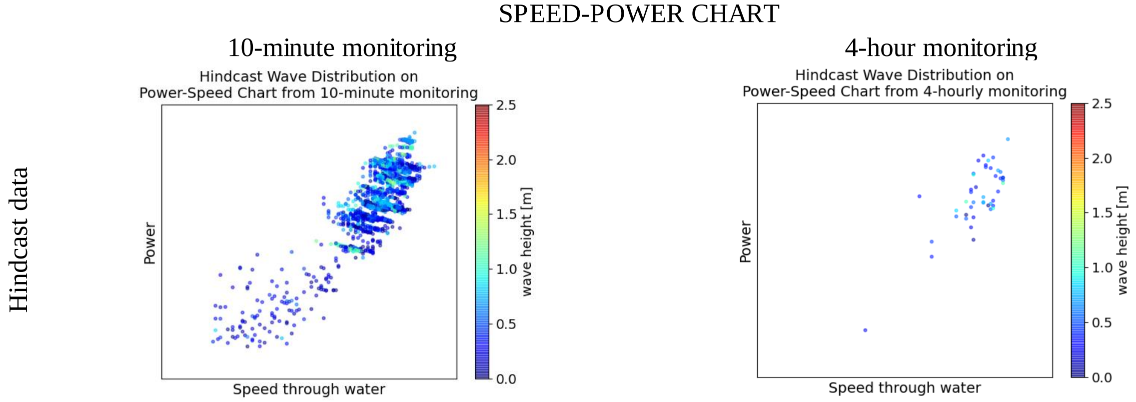
b) BF4 filtering using hindcast wind data (i.e., excluding wind speeds above 8 m).

c) BF4 filtering using hindcast wind and wave data (i.e., excluding wind speeds over 8, wave heights over 2 m, and wave periods over 5.5 s).

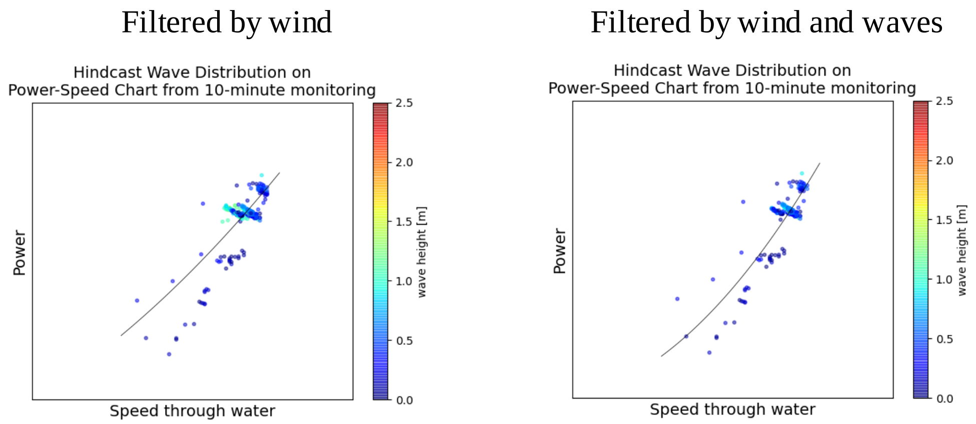
The relationship of speed and power is shown in Figures 3-5 and 3-6 with wave height in different colours. Comparative results of wind and wave filtering revealed that wind filtering has a high degree of variability. In contrast, adding waves to the filtering conditions resulted in small variations. The figure also clearly shows that on higher wave heights, the ship's speed is lower, i.e. performance and fuel consumption are worse, when compared with the same power. The results of creatin a performance curve based on these charts are shown in Figure 3-7, and the comparison results of ship speeds of the same power in these performance curves are shown in Table 3-3 provided that the period covered was the first month of service and the 10-minute monitoring data with the largest number of data was used. The table presents dimensionless values considering the sea trials values. In 10-minute monitoring with a fine data sampling interval, the conventional filtering using wind only resulted in a ship speed difference 2.31% from the sea trial. In contrast, filtering using both wind and waves resulted in a ship speed difference from sea trial of 1.28%, adding wave filtering providing a 1.03% more accurate ship performance evaluation. Assuming that the subject ship had just entered service and therefore would not change significantly from the values at the time of sea trials, 10-minute data monitoring and wind and wave filtering of hindcast data reproduced the correct performance.



Figures 3-5. Speed–power chart filtered by wind of BF scale 4



Figures 3-6. Speed–power chart based on wind and wave filtering of BF scale 4



Figures 3-7. Speed–power curve with different filtering conditions

Table 3-3. Power at the same speed on the performance curve for each filtering condition

Weather conditions for data filtering			Difference from
Wind speed	Wave height	Wave period	sea trial value
Beaufort Scale 4 (Wind speed < 8 m)	-	-	2.31%
Beaufort Scale 4 (Wind speed < 8 m)	Beaufort Scale 4 (Wave height < 2 m)	Beaufort Scale 4 (Wave period < 5.5 sec)	1.28%

*Percentage based on sea trial values
*Power corresponding to the same speed in each speed-power curve.

4. CONCLUSIONS

In this study, voyage data and two types of oceanographic data (onboard observation and hindcast) were used to compare the sea conditions on actual voyage and the speed–power chats in each case. The following conclusions were obtained from the results:

1) While this condition is not the case for the oceanographic data in relation to voyage data with rough sampling intervals, such as noon data, onboard wind observations may contain observation errors due to

the influence of onboard structures, and the use of hindcast wind data can potentially provide highly accurate sea conditions.

2) The use of wave hindcast data on actual voyage enables an understanding of the trends and distribution of the sea conditions that the ship would actually have encountered, regardless of the monitoring interval of the voyage data.

3) Results confirmed that, as the use of wind data alone may only partially consider disturbances when performing actual voyage evaluations, the relationship between winds and waves encountered by the ship does not necessarily match the reference wave height of the BF scale index for each BF scale class.

4) The reduction in ship performance and fuel consumption due to wave effects was clearly visualised by the speed–power charts in calm water filtered by the hindcast data.

5) Assessment of ship performance in calm waters from monitoring data with fine sampling intervals revealed that wave and wind filtering could potentially approach the speed–power baseline approximately 1.03% close to reality in this study.

The current study was conducted on the case of a Japanese coastal tramper; additionally, the extent to which the use of sea conditions can reduce GHG emissions should be verified, and similar verifications should be conducted on other ship types and ocean-going vessels to confirm the trends. Accurate ship assessments and operational improvements could further facilitate GHG measures for existing ships because the use of meteorological and oceanographic data is a software response, which can be easily and inexpensively performed compared to hardware measures. Moreover, retrofitting new ships is easy. The retrofitting measure is highly effective for overcoming the obstacle of GHG countermeasures for existing vessels being particularly high in the maritime industry.

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