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A Basic Study on Estimating the Effects of Wind Propulsion Systems

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ABSTRACT

In recent years, the implementation of EEDI and EEXI has led to a greater focus on energy conservation in shipping. Recently, marine equipment manufacturers have started developing and implementing innovative energy-saving devices, such as air lubrication systems and wind-assist propulsion systems (WAPS), to further reduce energy consumption. Examples of wind-assist devices include the wind-assisted ship propulsion systems developed by Mitsui O.S.K. Lines[1] and the automated kite system developed by Kawasaki Kisen Kaisha, Ltd.[2], both of which are expected to have a certain energy-saving effect. However, a study by Sogihara et al.[3] has shown that weather lading significantly impacts the energy-saving effect of wind-assist devices. Against this background, the authors estimated the energy-saving effect of wind-assist devices using a high-quality, practical meteorological and oceanographic database. In addition, the difference in energy saving effect depending on the resolution of the database used was confirmed.

Keywords: wind-assist propulsion systems; WAPS; wind; waves; hindcast data; energy saving

1 INTRODUCTION

As mentioned above, auxiliary propulsion systems that actively utilise wind, a natural energy source, have attracted attention as a technology for reducing greenhouse gas (GHG) emissions and achieving carbon neutrality. Among these systems, rotor sails are expected to be deployed on ships in service due to their relatively low initial costs and ease of installation. In this study, the authors focus on rotor sails, estimating the thrust obtained by installing them and their associated GHG reduction effect.

The ship type used for the calculations is a VLCC. Hyundai has developed an optimisation scheme for wind assist devices for VLCCs and there is expected to be future demand for this innovative energy-saving device for slow-moving, fully loaded ships. The energy-saving effect of wind-assist devices on the route from Japan to the Middle East known as the 'oil shipping route' were verified in this paper. High-precision, high-resolution meteorological and oceanographic data is desirable for simulations, etc. In this study, the authors used two models with different resolutions: a global model (spatial resolution of 1/2 degree) and a coastal model (spatial resolution of 1/30 degree). The differences in energy-saving effect verification results due to differences in resolution are also described.

2 THE CHARACTERISTICS OF THE SEA STATE ALONG THE PLANNED ROUTE

First, oceanographic data of the subject routes was extracted to understand its characteristics and trends. As the subject route is over 12,000 miles long, it was also confirmed whether it was necessary to divide it into sections for the simulation. The wind conditions that the ship would encounter during the voyage were also examined, i.e. the relative wind direction and speed.

2.1 Particulars of Planned Route and Subject Ship

Fig.1 shows the subject route, which is an oil shipping route from Japan to the Middle East. The subject ship type was a VLCC and the assumed navigation speed was 12 knots. The extraction points for oceanographic data along the route are shown in Fig.1.

1) Data extraction points were set at intervals of approximately 60 NM. However, areas where oceanographic data is unavailable, such as coasts and shallow waters, were excluded.
2) The target period for the extracted oceanographic data was three years: from 1 December 2021 to 30 November 2024.
3) Oceanographic data was extracted every six hours at each meteorological extraction point set out in 1).
4) The ship's speed over ground, which was used to calculate the relative wind direction and speed, was set to 12 knots. The ship's heading course on each route was assumed to be as shown in the Tab.1.
5) Considering the difference in oceanographic conditions, the oil shipping route was divided into three routes: Route 1, 2 and 3. The period was divided into four seasons: March to May, June to August, September to November and December to February. Statistics were calculated for each area and season.
6) The area between Japan and Taiwan on Route 1 (shown in blue in Fig.1) has both global grid (spatial resolution of 1/2 degree) and coastal grid (spatial resolution of 1/30 degree) data available. The simulation results for all the points in this coastal area (points 1-02 to 1-19) were compared to determine the impact of input data resolution on the simulation results.

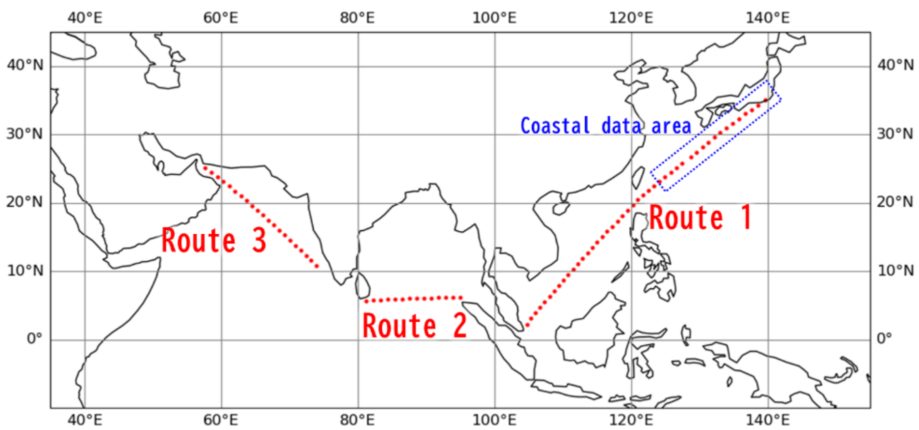

Figure 1: The subject route: an oil shipping route from Japan to the Middle East.

Table 1: Data extraction points on each route.

Route 1			
Point	Latitude	Longitude	Heading course
1-01	35.022	139.572	225 / 45
1-02	34.306	138.588	
1-03	33.669	137.650	
1-04	33.024	136.727	
1-05	32.339	135.770	
1-06	31.661	134.846	
1-07	30.965	133.920	
1-08	30.288	133.041	
1-09	29.609	132.180	
1-10	28.895	131.293	
1-11	28.175	130.418	
1-12	27.450	129.555	
1-13	26.719	128.703	
1-14	25.754	127.471	
1-15	25.118	126.632	

Route 1			
Point	Latitude	Longitude	Heading course
1-16	24.477	125.801	225 / 45
1-17	23.832	124.979	
1-18	23.182	124.165	
1-19	22.528	123.359	
1-20	21.871	122.561	
1-21	21.209	121.770	
1-22	20.446	120.995	
1-23	19.680	120.228	
1-24	18.911	119.468	
1-25	18.139	118.715	
1-26	17.364	117.969	
1-27	16.586	117.229	
1-28	15.805	116.495	
1-29	15.022	115.767	
1-30	14.237	115.044	

Route 1			
Point	Latitude	Longitude	Heading course
1-31	13.450	114.326	225 / 45
1-32	12.660	113.613	
1-33	11.869	112.904	
1-34	11.076	112.200	
1-35	10.281	111.499	
1-36	9.485	110.801	
1-37	8.688	110.107	
1-38	7.889	109.416	
1-39	7.089	108.727	
1-40	6.288	108.041	
1-41	5.486	107.357	
1-42	4.683	106.675	
1-43	3.880	105.994	
1-44	3.113	105.346	
1-45	2.274	104.826	

Route 2			
Point	Latitude	Longitude	Heading course
2-01	6.218	95.046	270 / 90
2-02	6.193	93.979	
2-03	6.166	92.912	
2-04	6.136	91.846	
2-05	6.105	90.779	
2-06	6.072	89.713	
2-07	6.036	88.647	
2-08	5.998	87.581	
2-09	5.959	86.515	
2-10	5.917	85.449	
2-11	5.873	84.383	
2-12	5.827	83.318	
2-13	5.779	82.253	
2-14	5.729	81.174	

Route 3			
Point	Latitude	Longitude	Heading course
3-01	10.884	73.942	315 / 135
3-02	11.605	73.188	
3-03	12.334	72.427	
3-04	13.062	71.666	
3-05	13.801	70.895	
3-06	14.538	70.120	
3-07	15.273	69.340	
3-08	16.004	68.554	
3-09	16.733	67.762	
3-10	17.459	66.964	
3-11	18.182	66.160	
3-12	18.901	65.349	
3-13	19.617	64.531	
3-14	20.329	63.706	
3-15	21.037	62.874	

Route 3			
Point	Latitude	Longitude	Heading course
3-16	21.741	62.033	315 / 135
3-17	22.440	61.184	
3-18	23.135	60.327	
3-19	23.826	59.460	
3-20	24.512	58.585	
3-21	25.192	57.699	

2.2 Ocean Wind and Wave Hindcast Database

Hindcast data[3][4] are the most probable meteorological and oceanographic data, reanalysed using fixed conditions and assimilating all periods through observation. These data are most suitable for analyses such as the basic survey of sea state characteristics carried out in this paper, due to their prediction accuracy and resolution.

Details of the hindcast data are shown in Tab.2. This hindcast database has been validated using a variety of observation data and is accurate. Fig.2 shows the results of comparing observed wave data from NOAA buoys, actual condition estimates and additional data, as an example of the accuracy verification. The scatter plots indicate that the hindcast data show minimal variation and superior agreement with the observed values. The correlation coefficient for wave height is 0.94, while the coefficients for wave period and direction are above 0.8. All the regression coefficients are greater than 1.0. These findings demonstrate that the hindcast value is equivalent to the buoy observation value, providing a highly accurate estimation.

Table 2: Overview of Ocean Hindcast Database.

	Global Database[4]	Coastal Database[5]
Operative area	All longitude 70° N to 70° S latitude	120° E to 150° E latitude 20° N to 50° N latitude
Spatial resolution	1/2 degree (≒50 km) *Interpolated to 20 m	1/30 degree (≒3.7 km) *Interpolated to 20 m
Temporal resolution	1 hour *Interpolated to 10 min	1 hour *Interpolated to 10 min
Registered data period	From 1951 to the present	From 2001 to the present
Items	Wind Speed and Wind Direction at 10m height Significant Wave Height, Significant Wave Period and mean Wave Direction, Ocean and Tidal Current, Sea Surface Temperature, Wave Spectrum	
Model	Wind: MSM, GSM Wave: WAM cycle4 *JWA improved model	

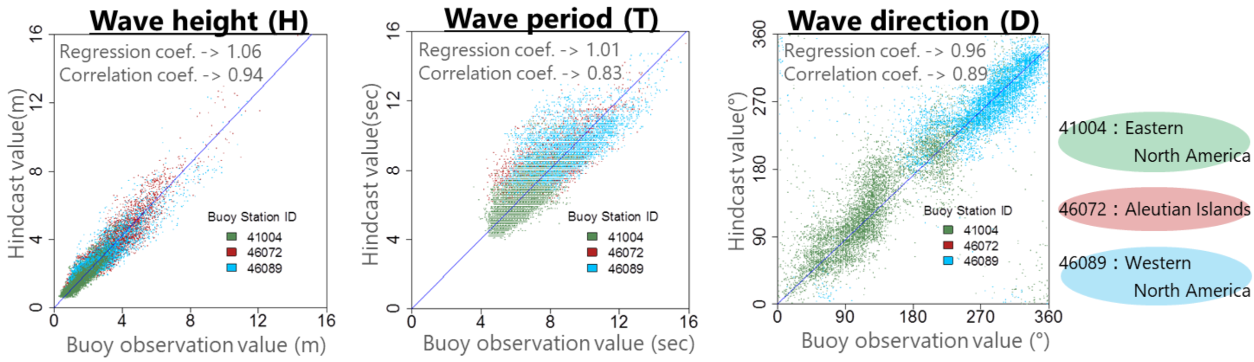

Figure 2: Example of the accuracy verification of hindcast data.

2.3 The characteristics of the sea state

Ocean wind and wave hindcast data were extracted in accordance with Section 2.1. This data was divided into three routes and quarters, and the following statistical values were calculated: mean, median and mode. These statistics are shown in Tab.3, and the histogram and wind rose of true wind direction and speed for the southbound track of Route 1 are shown in Fig.3. Examining the histogram in Fig.3, it is difficult to conclude that the mean and median values are representative of the sea state for each route and quarter, particularly given that the data indicates direction, such as wind direction. Therefore, the mode was determined as the representative value and used as the input value for the BHP calculation with rotor sails.

Table 3: True wind speed and direction statistics on oil shipping route [Global Database].

Route	Period	True Wind Speed (m/s)			True Wind Direction (deg)		
		Mean	Median	Mode	Mean	Median	Mode
Route 1	1st Quarter	6.1	6.0	5.0	21.9	48.0	44.0
	2nd Quarter	6.1	6.0	5.0	-47.1	-117.0	-141.0
	3rd Quarter	6.9	6.0	6.0	10.4	40.0	53.0
	4th Quarter	8.7	9.0	9.0	27.1	38.0	38.0
Route 2	1st Quarter	5.1	5.0	3.0	-20.5	7.0	-125.0
	2nd Quarter	8.3	8.0	9.0	-128.4	-132.0	-132.0
	3rd Quarter	6.0	6.0	7.0	-80.5	-118.0	-127.0
	4th Quarter	6.1	6.0	7.0	39.2	48.0	49.0
Route 3	1st Quarter	4.5	4.0	4.0	-39.4	-43.0	-31.0
	2nd Quarter	8.2	8.0	8.0	-75.9	-15.0	-115.0
	3rd Quarter	4.5	4.0	4.0	-10.2	-2.0	43.0
	4th Quarter	4.8	5.0	5.0	14.5	19.0	26.0

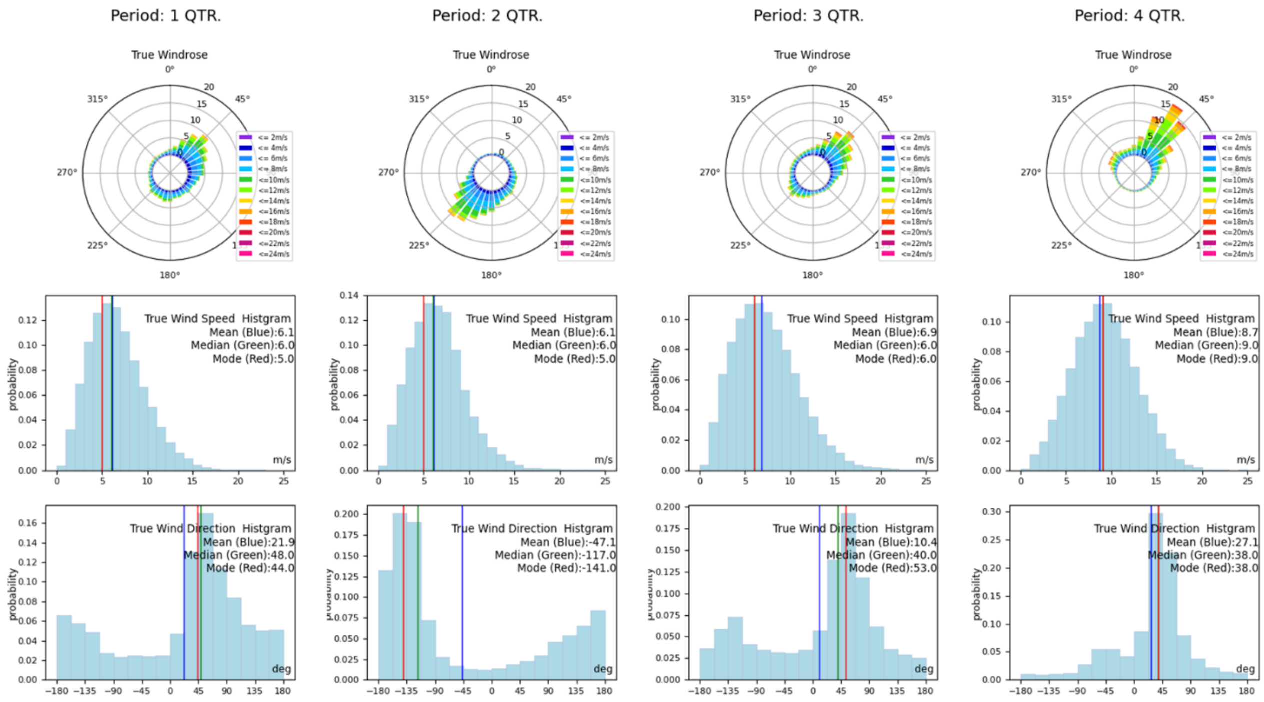

Figure 3: Histograms and wind roses of true wind speed and direction for Route 1[Global Database].

3 CALCULATION OF BHP REDUCTION BY ROTOR SAIL

The BHP reduction effect of VLCC equipped with rotor sails was simulated using representative sea state values for each route and quarter, as determined in Chapter 2, as input.

3.1 Calculation condition

The KVLCC hull model[6] used is publicly available, and calculated draft was 20.8 m. Four rotor sails were chosen for the vessel, each measuring 5 m in diameter and 35 m in height. The following were taken into consideration regarding hull resistance: wave-making resistance, resistance due to counter rudder, resistance due to cross currents and wind resistance[7] [8]. Regarding rotor sails, the total power required to rotate them, the wind resistance and the generated thrust were calculated. The final increase or decrease in resistance was evaluated by adding up the hull-related resistance and the effect of the rotor sail. Additionally, the thrust of the rotor sail was calculated using CFD results[9]. To estimate the effect of rotor sails on BHP reduction, the BHP required to maintain the design ship speed when sailing with the rotor sail constantly rotating at 180 rpm was calculated and compared with the BHP without rotor sails.

3.2 Comparison of the BHP reduction effects of rotor sails by area and season

Tab.4 shows the calculation results for the total oil shipping route, both inbound and outbound. Tab.4 shows the ratio of estimated BHP for voyages with and without rotor sails on Route 1, i.e., the BHP reduction effect of rotor sails. Where, the electric power for rotation of the rotor sails is included the BHP. As shown in Tab.4, no significant results were observed for many route and seasons. Only the eastbound track of Route 2 and Route 3 in the 2nd quarter showed significant results, with figures exceeding 9%. For this calculation, it was assumed that the rotor sail would not be used if operating it caused more resistance than it prevented. As shown in Tab.4, no energy-saving effects were achieved for Route 1 at any time. As shown in the wind rose of relative wind in Fig.4, the wind is overwhelmingly received from within 30 degrees of the bow on the ineffective route. Therefore, the results can be considered reasonable. This is presumably because representative weather values were set for each route and season. Therefore, the calculations were recalculated for each location and month along Route 1, and the results were averaged. Tab.5 shows the results of these calculations for each location points and month for the section from Japan to Luzon str. in the fourth quarter. In some cases, no benefits were obtained, accounting for around 30%. The average energy saving effect in the fourth quarter was 12.6%. December had the highest effect at 14.9%, while November had the lowest effect at 9.9%. Additionally, it seems difficult to see the effect in locations close to Taiwan.

Table 4: BHP reduction for Route 1 [Quarterly].

		BHP reduction (%)				
		Annual average	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter
Route 1	Southbound	0.0	0.0	0.0	0.0	0.0
	Northbound	0.0	0.0	0.0	0.0	0.0
Route 2	Westbound	0.4	0.0	0.0	0.0	1.7
	Eastbound	2.6	0.0	9.7	0.6	0.0
Route 3	Northbound	2.5	0.0	10.1	0.0	0.0
	Southbound	3.8	0.0	14.3	0.0	0.9
All	Outbound	1.5	0.0	3.4	0.0	0.6
	Inbound	2.1	0.0	8.0	0.2	0.3

Table 5: BHP reduction for the section from Japan to Luzon str. [Global Database].

Points on the section from Japan to Luzon str.	BHP reduction (%)		
	December	January	February
Point 1-02	16.0	-	11.0
Point 1-03	28.0	10.2	43.8

Point 1-04	10.4	9.0	10.8
Point 1-05	8.5	5.4	4.5
Point 1-06	10.0	-	9.7
Point 1-07	15.7	22.3	15.8
Point 1-08	10.3	5.3	7.4
Point 1-09	15.6	16.0	10.3
Point 1-10	13.9	9.1	20.8
Point 1-12	-	10.2	-
Point 1-15	-	2.0	-
Point 1-18	0.5	-	-
Point 1-19	-	-	-
Monthly Average	**12.9**	**9.9**	**14.9**
Quarterly Average	**12.6**		

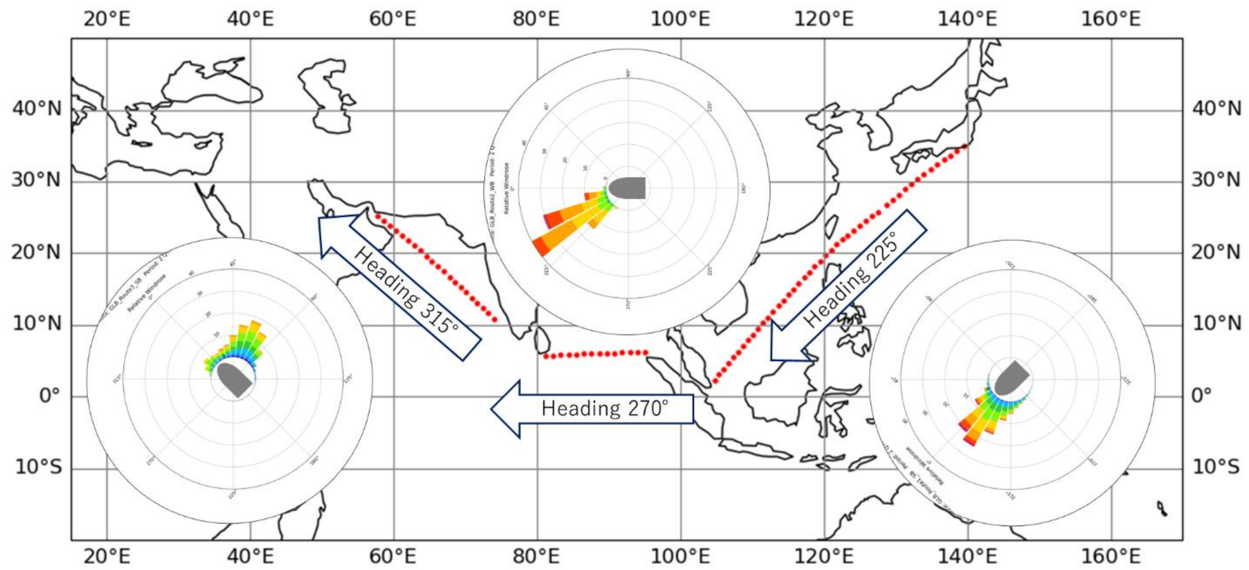

Figure 4: An example of a relative wind rose for the second quarter.

3.3 Comparison of the BHP reduction effects due to differences in the input data resolution

As confirmed in Section 3.2, the energy-saving effect can be estimated by performing detailed calculations for each location and month. The same calculations were performed here using higher-resolution oceanographic data shown in Tab.6 as input, and the results were compared with those in 3.2. The results are shown in Tab.7. Point 18 and Point 19, which are closest to Taiwan, appear to be the least likely to achieve energy conservation benefits. At other points, however, the range of benefits was from 0.5% to 47.1%. The average for the fourth quarter was 4.5%. December saw the highest effect, at 18.6%, while February saw the lowest, at 10.3%. Point 2 and Point 3, which are closest to Japan, saw significant effects of over 40%.

The proportion of ineffective rotor sails was found to be 30% when global database was used, compared to 19% when coastal database was used. Therefore, it can be concluded that using coastal database increases the number of samples for effect verification by more than 10%. On average, the energy saving effect in the 4th quarter was 12.6% at all location points when using global database, compared to 14.5% when using coastal database — an increase of 2%. In December, the average energy saving effect was 12.9% for global database and 18.6% for coastal database, an increase of 5.7%. In January, the figures were 9.9% for global database and

14.2% for coastal database, an increase of 4.3%. However, in February, the figures were 14.9% and 10.3% respectively, a decrease of 4.6%. It was found that using coastal database does not necessarily increase the effect; rather, it allows the actual situation to be reproduced more accurately. Therefore, in some cases, using global data may decrease the effect.

Table 6: Comparison of global and coastal data: True wind direction and speed.

Point	Global Database Wind Speed (m/s) / Wind Direction (deg)						Coastal Database Wind Speed (m/s) / Wind Direction (deg)					
	December		January		February		December		January		February	
Point 2	9	-64	4	-64	8	-63	14	-65	12	-64	9	-67
Point 3	10	-47	7	-44	12	-39	12	-41	9	-40	10	-32
Point 4	8	-65	7	-53	8	-11	9	-56	9	-53	8	-42
Point 5	7	-55	6	-35	6	-23	8	-51	6	-41	7	-26
Point 6	7	-47	5	-59	8	-8	6	-43	7	-42	7	-1
Point 7	8	-32	9	-39	8	-34	10	-52	9	-35	8	16
Point 8	7	-43	6	-44	8	-2	6	-51	8	-53	7	-54
Point 9	8	-42	8	-36	7	-35	10	-32	7	-37	7	-45
Point 10	8	-23	7	-24	9	-27	9	-33	7	-7	7	-47
Point 12	8	37	7	-32	6	1	9	-6	7	-15	8	12
Point 15	9	55	7	86	7	22	9	17	7	0	8	18
Point 18	10	31	8	4	6	43	10	57	8	32	7	23
Point 19	9	40	8	61	6	28	9	32	8	56	8	37

Table 7: BHP reduction for locations 2 to 19 [Coastal Database].

Points on the section from Japan to Luzon str.	BHP reduction (%)		
	December	January	February
Point 1-02	47.1	35.8	14.6
Point 1-03	43.7	22.3	28.4
Point 1-04	19.4	20.3	16.2
Point 1-05	15.0	5.4	9.5
Point 1-06	5.3	10.4	3.4
Point 1-07	2.4	22.1	0.5
Point 1-08	4.7	14.4	8.7
Point 1-09	28.2	10.4	10.0
Point 1-10	21.5	5.1	9.8
Point 1-12	13.9	7.3	2.0
Point 1-15	3.1	3.1	-
Point 1-18	-	-	-
Point 1-19	-	-	-
Monthly Average	**18.6**	**14.2**	**10.3**
Quarterly Average	**14.5**		

4 CONCLUSIONS

This study examined the energy-saving effect of using rotor sails on VLCC oil shipping route from Japan to Middle East. Using meteorological data from a global model, calculations showed that the effect of rotor sails was 1.5% on the outbound track and 2.1% on the return track. To obtain more accurate results, it is preferable to calculate the effect of rotor sails at each point along the route and for each month, and then calculate the average for the entire route and season. In this case, the authors confirmed that an effect of 12.6% could be achieved in the section from Japan to Luzon str. in the first quarter. Additionally, the authors found that the characteristics of wind speed and direction could be accurately determined using a high-resolution, high-accuracy coastal database. Using coastal database from Japan to Taiwan, calculations showed that the energy-saving effect was 14.5%, which is 1.9% higher than the result of 12.6% when global database was used. It was confirmed that the energy-saving effect of wind-assist devices can be accurately estimated using highly accurate meteorological and oceanographic data. It was also suggested that sufficient effects could be expected on oil shipping route, despite the fact that the effect is generally considered to be low there.

The energy-saving effect appears to depend greatly on the direction in which the ship catches the wind. In other words, if the wind direction can be controlled using weather routing, even greater effects could be achieved. In subsequent research, the authors intend to use a weather and oceanographic database to investigate the impact of wind direction on operations and related issues. In response to this, the authors intend to continue their research by verifying the energy-saving effects of navigation using wind direction, identifying any associated issues and exploring the possibility of providing optimal course guidance based on statistical data on sea conditions.

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