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(Citation)
Journal of Maritime Researches,8:25-41

(Issue Date)
2018-08

(Resource Type)
departmental bulletin paper

(Version)
Version of Record

(JaLCDOI)
https://doi.org/10.24546/81012983

(URL)
https://hdl.handle.net/20.500.14094/81012983

Journal of Maritime Researches Vol. 8, March 2019: 25-41.

A DEVELOPMENT OF WEATHER FORECAST AND OPTIMAL SHIP ROUTING

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ABSTRACT

It is inevitable for vessels to forecast the influences in given weather conditions, such as waves, winds, currents, etc. Seafarers used to estimate the change of sea conditions from their experience with intuition, when the weather forecasting was not practically in use. The optimal weather routing has been studied from 1950s by combining the numerical weather forecasting. Major shipping companies already introduced the optimal routing mainly for container vessels, which are operating in tight schedule. It consists of the weather forecasting and estimation of ship performances in actual seas. The weather forecasting has been developed remarkably in recent decades, because of the engineering innovation of computer technology. Global weather information is released from some meteorological institutions, and can contribute to safe operation of vessels. On the other hand, there are some differences of estimated results in each meteorological institution. This point could affect the accuracy of optimal ship routing, such as the voyage time, voyage route, and fuel consumption, etc. In this study, the optimal shipping routes are numerically simulated for a container vessel in the North Pacific using the latest weather reanalysis database with the isochrotone method. The difference of optimal ship routing is compared from the spatial and time resolutions in different seasons. The effectiveness and future subjects to improve the optimal routing are considered at the end.

Keywords: optimal ship routing, weather hindcast, ship performance, global database, isochrotone method, numerical simulation

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1. INTRODUCTION

More than 95% of global logistics is transported at seas all over the world. The development of global network requires the punctuality of maritime transportation more than before. Vessels are strongly influenced with the variation of weather conditions, because vessel motions are occurred in waters with waves or currents. Waves are usually generated if winds have been blowing in certain durations and speeds. Ocean waves are irregular periodic phenomenon, which makes the theoretical modeling complicate. It also makes difficult the estimation of various influences such as the vessel's motions or the wave resistances, than those on other transportations. Moreover, the weather forecasting has not been so reliable when the performance of computation was vulnerable was poor. In those periods, vessels have been fully operating with the experience with intuitions of ship' masters. In 1950s, a new concept how to operate vessels using the weather forecasting is shown as the first study of optimal ship routing (James, 1957). Although related studies have followed after 1960s, the computing performance was not enough to forecast global weather accurately. Seakeeping theories have developed for decades since 1950s, and many studies are shown how to estimate ship motions or added resistance in waves (Newman, 1978; Faltinsen, 1990; Kashiwagi, 1992). Some studies related on the speed loss of vessels by combining theories between seakeeping and propulsion, are also shown (Naito, et al, 1980; Faltinsen, et al, 1980). It can contribute the accurate evaluation of ship performances in actual seas, and the weather forecasting becomes accurate as the improvement of computation performance from 1990s. Global computation of weather and ocean are available by using high-performance computers in the field of meteorology. The optimal ship routing is on the tipping point because of these backgrounds, and the numerical computation is expected as more accurate. Various meteorological organizations computed weather and oceanographic parameters as the global analysis, and they make public on their web sites. Especially, two major databases are frequently used in many studies. One is the NCEP (National Center for Environment and Prediction), which is the American meteorological organization linked with the numerical models of WRF (Weather and Research Forecasting) and WaveWATCH III. Another is the ECMWF (European Centre for Medium-Range Weather Forecasts), which is based on the Europe. They show the global weather database every 6 hours on their web sites, NCEP-FNL and ERA interim, respectively. They cover the weather information globally. However, there are little measured weather data in the oceans than those in lands, especially in high latitudes or the Southern Hemisphere. Authors showed the validation of weather hindcasting in three sea areas in the Southern Hemisphere using the measured onboard data for 28,000DWT class bulk carrier (Lu, et al, 2017; Sasa, et al., 2017). Winds and waves could be pretty different in rough sea conditions there, and it is shown that the accuracy is not enough yet for some cases. Optimal route or navigation time strongly depends on ship performances in forecasted weather conditions. Thus, it is important to show the difference of simulated results with the latest global weather databases. This study aims to simulate optimum routes of the SR108 container vessel between Japan and

U.S.A. across the North Pacific Ocean in 2016. Numerical simulation of optimal routes is obtained by the isochrone method (Suzuki and Hagiwara, 1995), based on the reanalyzed weather databases of waves, winds, and currents in the global region. The accuracy of optimal ship routing is discussed here using the latest global weather databases, and authors finally summarize the future image of optimal ship routing combining weather forecasting and seakeeping theory.

2. Theory of Optimal Ship Routing

Theories of the optimal ship routing are briefly explained here to evaluate the optimal route considering ship performance in weather conditions. In section 2.1, the isochrone method, which is one of the route analyses in oceans, is summarized. In section 2.2, the evaluation of speed loss is described in waves and currents. The optimal route problem is solved the following governing equations.

$$X_{i+1} = X_i + f\left(X_i, U_i, t_i\right) \tag{1}$$

$$f\left(X_i, U_i, t_i\right) = \begin{cases} \phi_i + \dfrac{V_i \cos\left(\theta_i + \alpha_i\right) + N_i}{R_m\left(\phi_i\right)} \Delta t \\ \lambda_i + \dfrac{\left(mp\left(\phi_{i+1}\right) - mp\left(\phi_i\right)\right)\left(V_i \sin\left(\theta_i + \alpha_i\right) + E_i\right)}{V_i \cos\left(\theta_i + \alpha_i\right) + N_i} \end{cases} \tag{2}$$

$$X_i = \begin{bmatrix} \phi_i \\ \lambda_i \end{bmatrix}, \quad U_i = \begin{bmatrix} \theta_i \\ n_i \end{bmatrix} \tag{3}$$

$$J = \sum_{t_0}^{t_N} A\left(X, U, t\right) \Delta t + B\left(t_f, t_d\right) \tag{4}$$

where, X_i is the position vector, ϕ_i is the latitude, and λ_i is the longitude at time t_i. U_i is the control vector, V_i is the ship speed, n_i is the propeller speed, mp_i is the meridinal parts, α_i is the drift angle, and N_i, E_i is the current speed in north-south direction, east-west direction, respectively. J is the evaluation function, A is the evaluated object, and B is the penalty from depart time, t_d, and finish time, t_f. Eq.(1) is solved to minimize the value of J in Eq.(4).

2.1 Isochrone Method

There are some kinds of simulation methods on the optimal ship routing, such as the Dynamic programming method or the Isochrone method. The former method is developed as the optimal model for multi step decision process in 1950s. defines computation grids for sea areas, as shown in Figure 2.1.

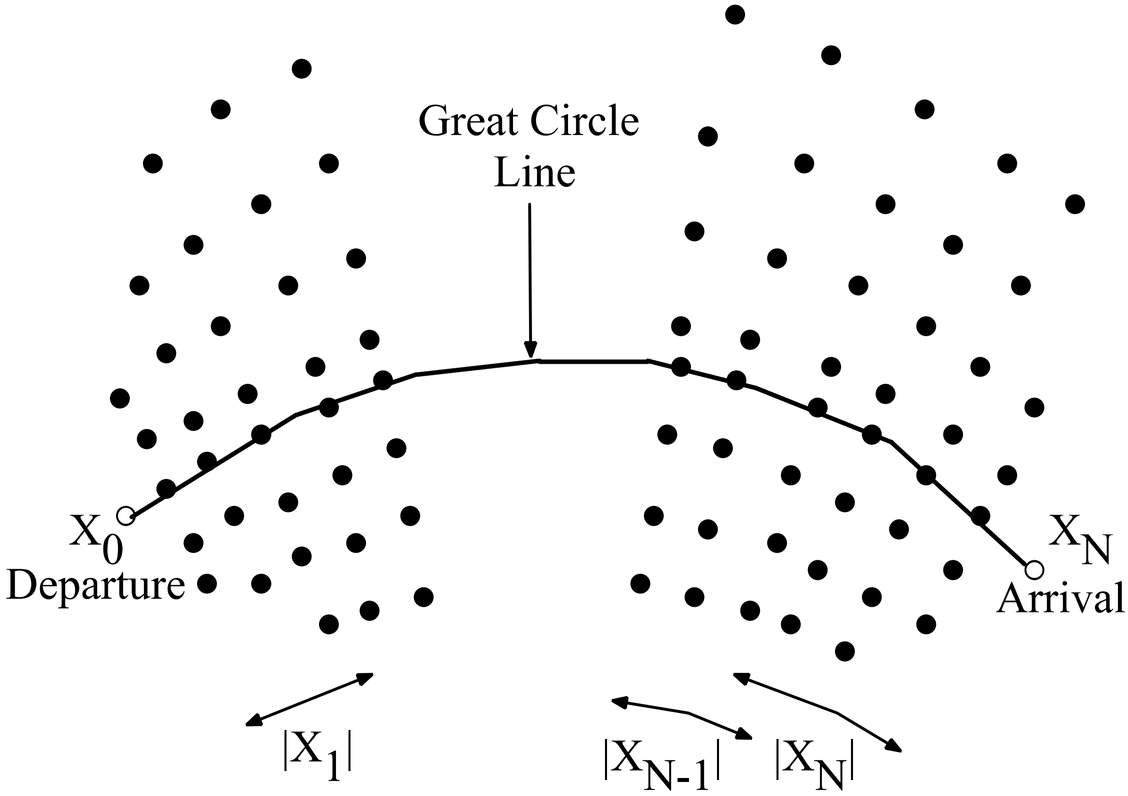


Figure 2.1 Definition of computation grids in Dynamic programming method

Optimal grids are chosen from the previous ones with speed loss on given weather conditions. The latter one is characteristic that a vessel runs in variable courses from the initial great circle course, and optimal points is decided from multiple routes in each sector, which is drawn from the previous point as shown in Figure 2.2.

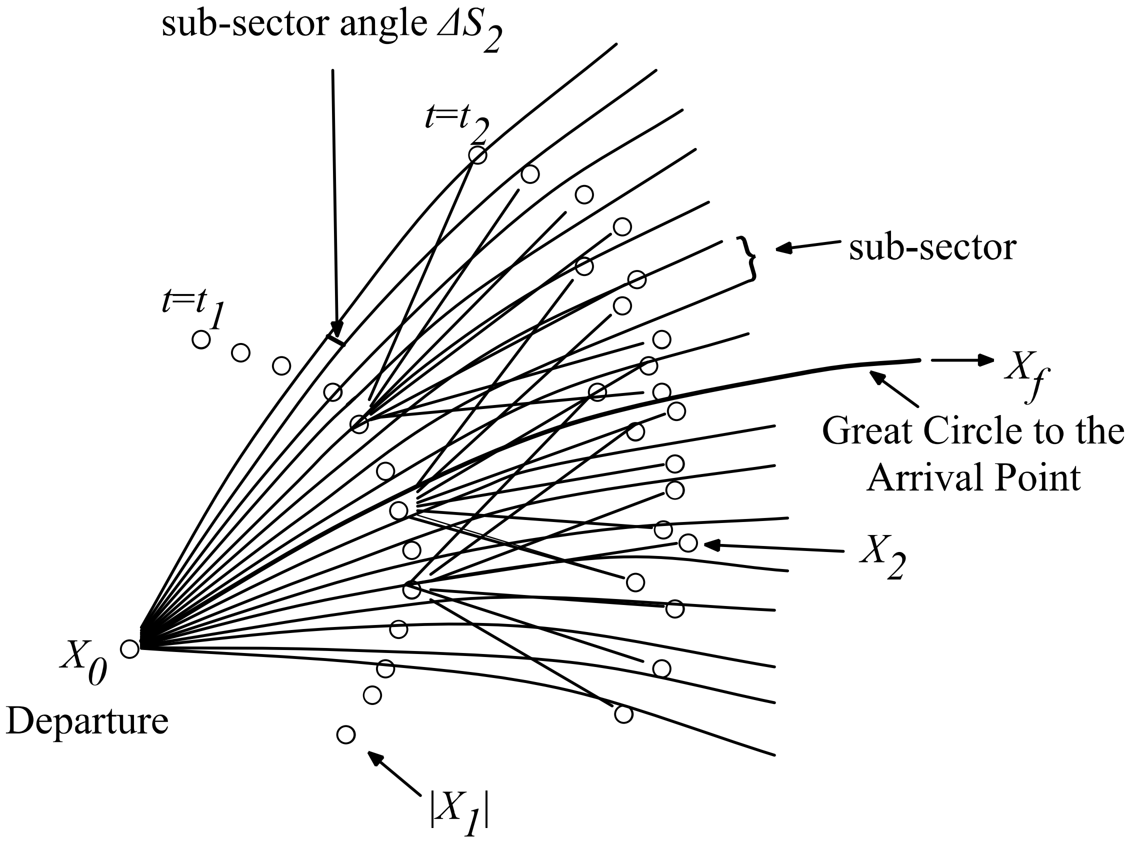


Figure 2.2 Definition of optimal routes in each sector in Isochrone method

As shown here, the isochrone is obtained for the number of sector as the longest distances among multiple routes in each sub-sector. Weather conditions in each point affect to the ship speed, the fuel consumption, etc. If a vessel is in head sea state, the ship speed tends to decrease. On the other hand, the ship speed does not vary very much in following sea state, even if wave conditions are rough. Finally, the optimal route is expressed as the minimum time route between the departure and destination points. The numerical flowchart of isochrone method is shown in Figure 2.3

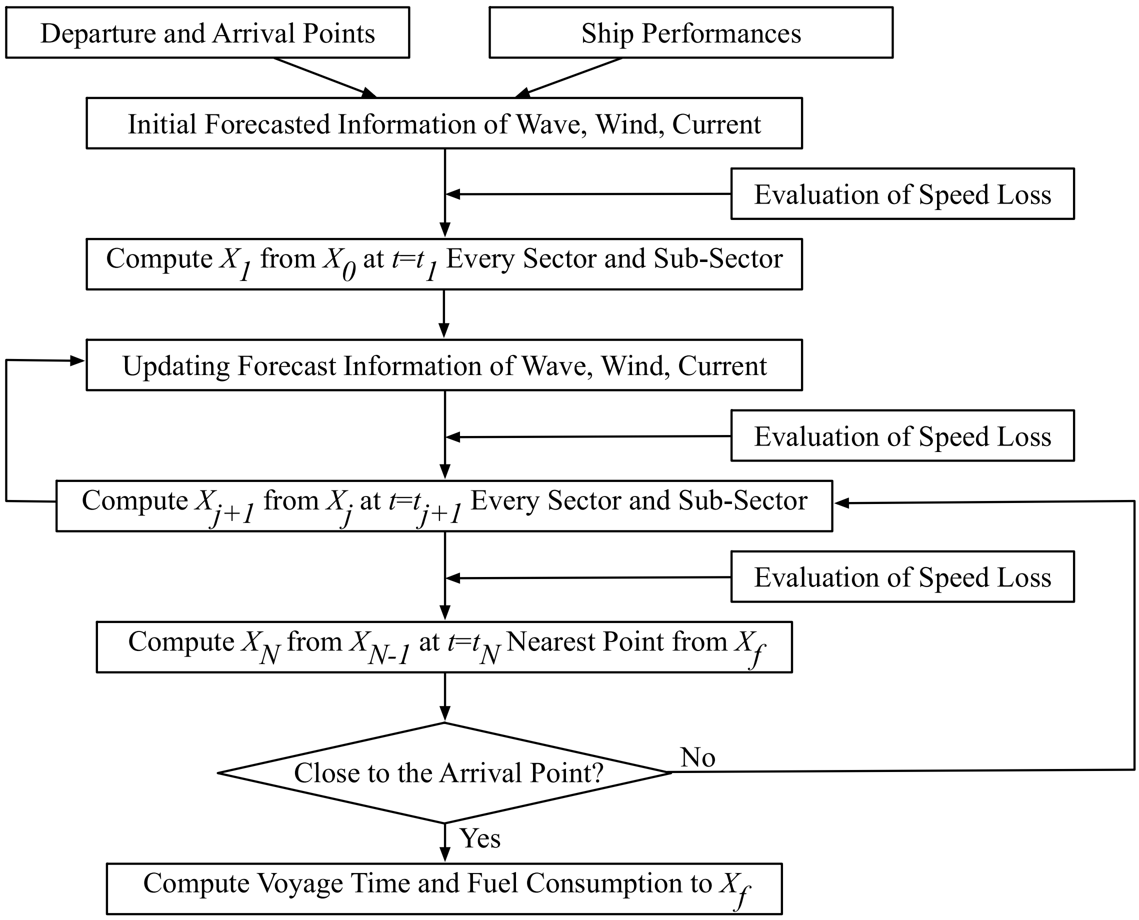


Figure 2.3 Flowchart of isochrone method

As you can see, the evaluation of ship speed is the most important parameter in a given weather conditions, waves, winds, currents, etc. They sometimes make the ship slower than the normal speed, and also increase the fuel oil consumption, the emission of greenhouse gas (Prpic-Orsic, et al., 2012). The ship speed is decided as the relation between the total thrust and resistance, as follows (Sasa et al., 2017):

$$\left(M + m_{11}\left(\omega_i\right)\right)\frac{dV_i}{dt} = T_T\left(V_i, \omega_i, \chi\right) - R_T\left(V_i, \omega_i, \chi\right) \tag{5}$$

where M is the mass of the ship, and $m_{11}(\omega)$ is the added mass in surge mode, U is the ship speed, ω is the angular frequency, and χ is the relative wave direction. The total thrust includes the effect of thrust deductions for the ventilation and machinery factors. The total resistance consists of the resistance in still water and the added resistance in waves and winds. There are various theories of added resistance in the seakeeping theory (Faltinsen, 1990; Kashiwagi, 1995). Damping force is relatively small in the longitudinal direction and is neglected in this study. In an irregular sea state, Eq. (5) must be solved in the time domain. If we estimate the speed loss accurately, these points must be taken into account.

Nevertheless, this part is simply modeled from the measured data of various container ships (Shoji,).

$$V = (an + b) - \left(cH_{1/3} + dH_{1/3}^2\right) f(\theta) \tag{6}$$

where, n is the propeller speed (rpm), $H_{1/3}$ is the significant wave height, a, b, c, d are the coefficients (a=0.13133739, b=1.78677785, c=0.223417724, d=-0.00081424), and $f(\theta)$ is the function defined as

$$f(\theta) = 0.75\exp\left(-0.65\theta^2\right) + 0.25 \tag{7}$$

where, θ is the relative wave direction (unit is radian) with 0 degree as the head sea state. Eqs. (5)(6) implicate that the speed loss is approximately expressed as the function of significant wave height and relative wave direction. The ship speed, V, is computed in each position by interpolating wave heights and direction in surrounding grids.

3. Computation of Optimal Routing

As mentioned here, the meteorology has been improved in recent decades as the enhancement of numerical computation. This makes the global weather forecasting possible with higher spatial and time resolutions. The development can contribute to the optimal ship routing be more accurate. There are many parameters controls the accuracy, and the difference of computed results are compared in various conditions.

3.1 Meteorological Database

There are many kinds of meteorological database distributed from meteorological agencies. Japan Meteorology Agency (JMA) distributes the high-resolution database near Japan, and it is suitable for the weather analysis in Asian region. On the other hand, the global weather information is required for vessels across the oceans such as the Pacific Ocean, the Atlantic Ocean, the Indian Ocean, etc. Two major organizations are recognized for the global weather forecasting and reanalysis in the field of meteorology. One is the NCEP (National Centers for Environmental and Prediction) which is based on the U.S.A., and another is the ECMWF (European Centre for Medium-Ranged Weather and Forecasts). The NCEP distributes the objective analyzed data in the global region every 1° and 6 hours, NCEP-FNL, which includes basic weather parameters such as the air temperature, the air pressure, the humidity, the sea water temperature, etc. The ECMWF distributes the same kinds of objective analyzed database in the global region every 0.75° and 6 hours, ERA interim, which includes weather parameters, wave parameters, etc. There are sparse observation points in oceans with high latitudes, and dense points in lower latitudes. The objective analyzed database is numerically adjusted for uneven distribution of observed points using air and ocean models. Lu et al. (2017) showed the validation of estimated wave conditions for rough sea voyages in the Southern Hemisphere, and the range of errors is shown there. NOAA (National Oceanic and Atmospheric Administration) also distributes the estimated wave height, wave period, and wave direction, besides of wind speed and wind direction in the global region every 0.5° and 6 hours. Wave conditions are computed using the third generation wave model, Wave WATCH III (Tolman, 2002). They can available from the homepage of NOAA, and are used as the input weather conditions here. Figure 3.1 shows the one of the distributions of significant wave height in the whole earth at 0:00 January 1, 2016.

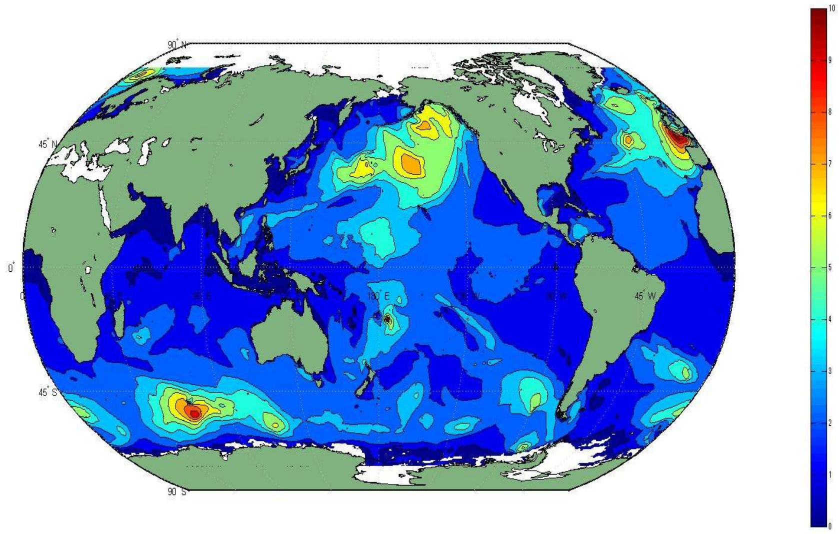


Figure 3.1 Global distribution of wave height (0:00 January 1, 2016)

Figure 3.2 shows the vector distribution of averaged wind speed in the whole earth at 0:00 January 1, 2016.

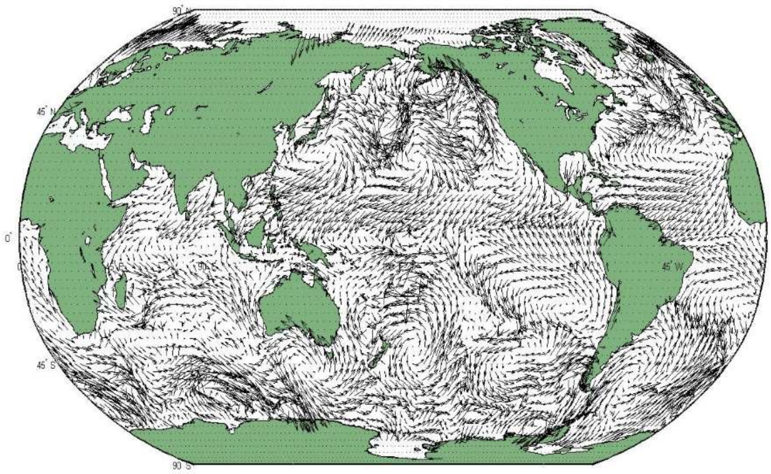


Figure 3.2 Global distribution of wind speed (0:00 January 1, 2016)

It is obvious that wave height and wind speed are remarkable in the North Pacific Ocean, etc. The spatial and time resolutions are important factors to discuss the accuracy of optimal ship routing. The difference of the voyage time or the averaged ship speed is compared in each setting of resolutions as shown in Table 3.1.

Table 3.1 Settings of resolutions in space and time

	0.5°	1.0°
6 hours	Setting-6-05	Setting-6-10
12 hours	Setting-12-05	

3.2 Ship and Voyage Conditions

The optimal ship routing is numerically simulated for a container ship between Tokyo and Los Angles across the Pacific Ocean. The voyage speed is 22 knots, and the engine revolution is set as 150 rpm. The engine power is modeled as

$$P = \alpha n^3 + \beta \Delta V + \gamma \Delta V^2 \tag{8}$$

where, α, β, γ are coefficients of polynomials defined as 0.0690152, 671.5488892, and 129.2651672, respectively. The second and third terms are the variation of power due to waves. If the engine power varies, the fuel consumption, *FOC*, reacts simultaneously. It is simply modeled as

$$FOC = 0.21P \tag{9}$$

Weather conditions are interpolated using four values on surrounding grids, and the ship speed and the fuel consumption are approximately estimated here.

3.3 Simulated Results

3.3.1 Results in Voyages from Tokyo to Los Angles

Computed results of optimal voyage route are shown in Figures 3.3-3.4 in January and August, 2016 from Tokyo to Los Angles.

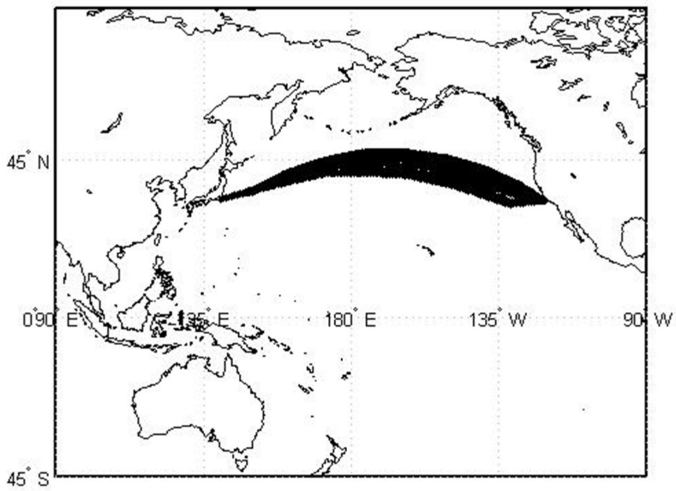


Figure 3.3 Computed results of optimal voyage route (January, 2016, Setting-6-05)

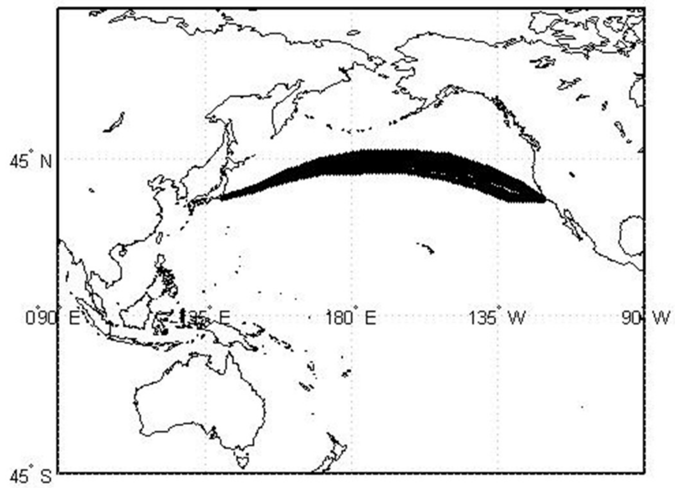


Figure 3.4 Computed results of optimal voyage route (August, 2016, Setting-6-05)

It is obvious that optimum voyages routes look similar in winter (January) and summer (August) here. Dispersions are larger in 135W-180 than those in 135E-180.

Monthly averaged values of voyage time and distance are compared in each month are shown in Figure 3.5.

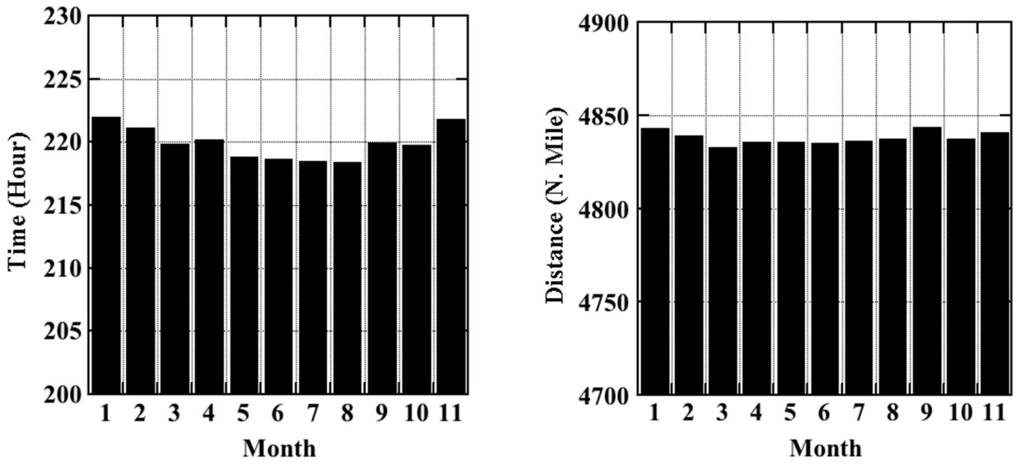


Figure 3.5 Monthly averaged values of voyage time and distance (January to November, 2016, from Tokyo to Los Angles, Setting-6-05)

Differences of 4-5 hours between winter and summer seasons as the monthly averaged voyage time. It implicates that weather conditions affect to the computed results.

3.3.2 Results in Voyages from Los Angles to Tokyo

Computed results of optimal voyage route are shown in Figures 3.6-3.7 in January and August, 2016 from Los Angles to Tokyo.

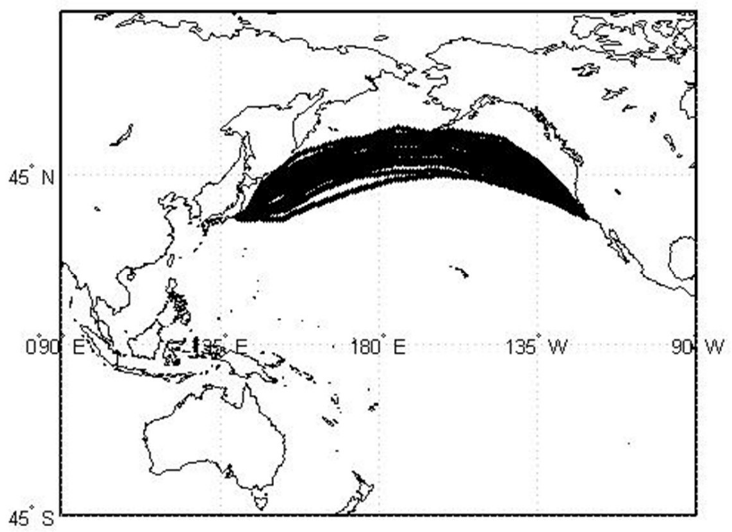


Figure 3.6 Computed results of optimal voyage route (January, 2016, Setting-6-05)

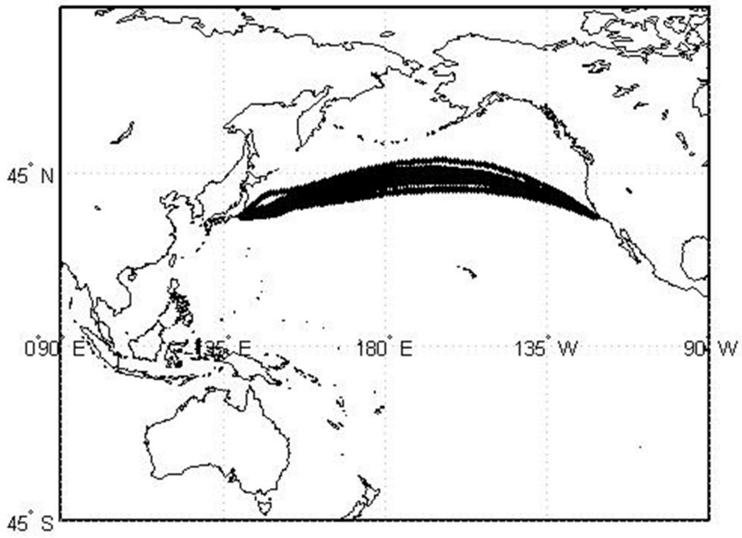
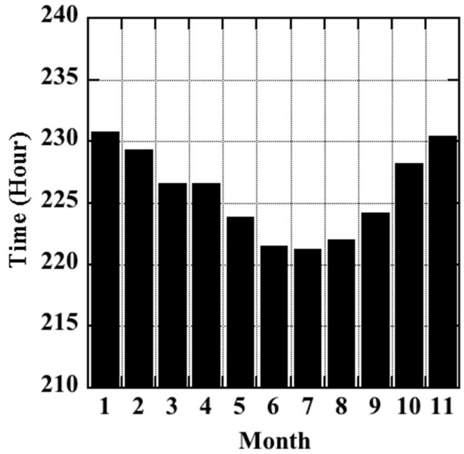


Figure 3.7 Computed results of optimal voyage route (August, 2016, Setting-6-05)

Computed optimal routes have larger dispersions from Los Angles to Tokyo both in January and August. Especially, optimal routes in January are quite different those in Figure 3.3. Monthly averaged values of voyage time and distance are compared in each month are shown in Figure 3.8.



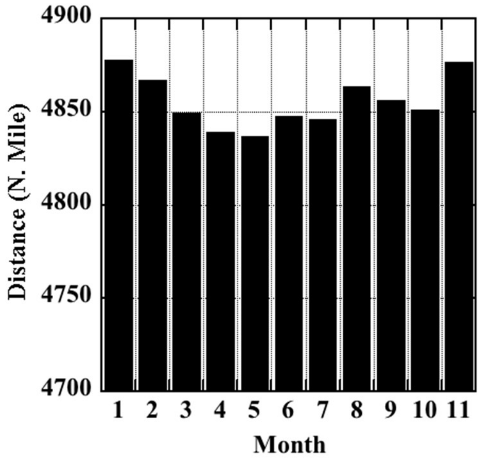


Figure 3.8 Monthly averaged values of voyage time and distance (January to November, 2016, from Los Angles to Tokyo, Setting-6-05)

The averaged voyage time is around 230 hours in winter season, and 10 hours longer than that in summer season. It is also longer for 7-8 hours than that in voyage from Tokyo to Los Angles. It implies that the ship is strongly influenced by weather conditions, especially in wave directions.

3.3.3 Influences of Spatial Resolution

As shown in Table 3.1, numerical simulations are compared with the difference of spatial and time resolutions. Figures 3.9-3.10 show computed results of optimal routes with 1.0° and 6 hours from Los Angles to Tokyo in January and August, 2016.

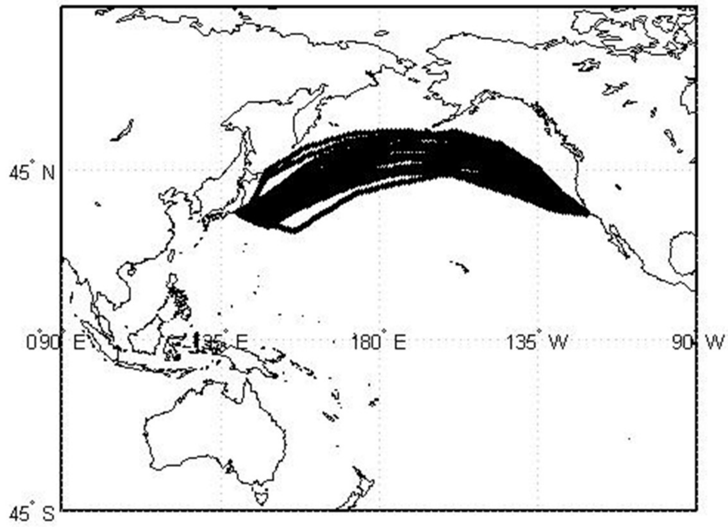


Figure 3.9 Computed results of optimal voyage route (January, 2016, Setting-6-10)

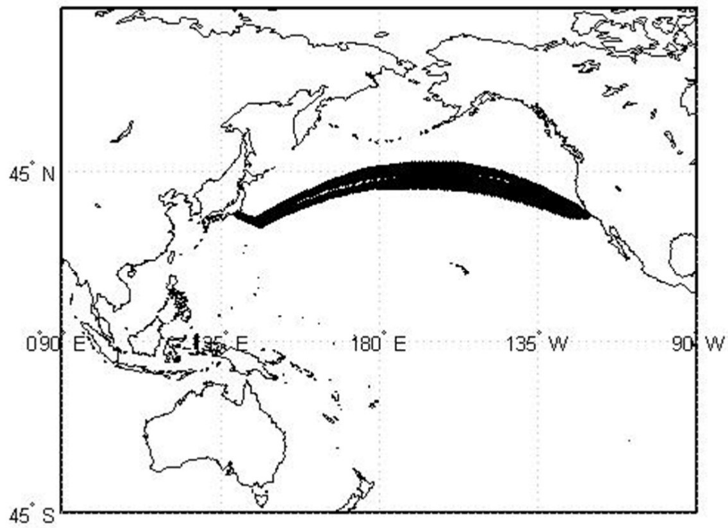


Figure 3.10 Computed results of optimal voyage route (August, 2016, Setting-6-10)

Optimal routes are different from those in Figure 3.6, and the spatial resolution contributes to the result in some cases. Little differences can be seen in August, 2016 between Figure 3.7 and Figure 3.10. Although there are less days of rough sea conditions in August than in January, optimal routes are a bit different each other. Figure 3.11 shows the monthly averaged values of voyage time and distance with the spatial resolution of 1.0° .

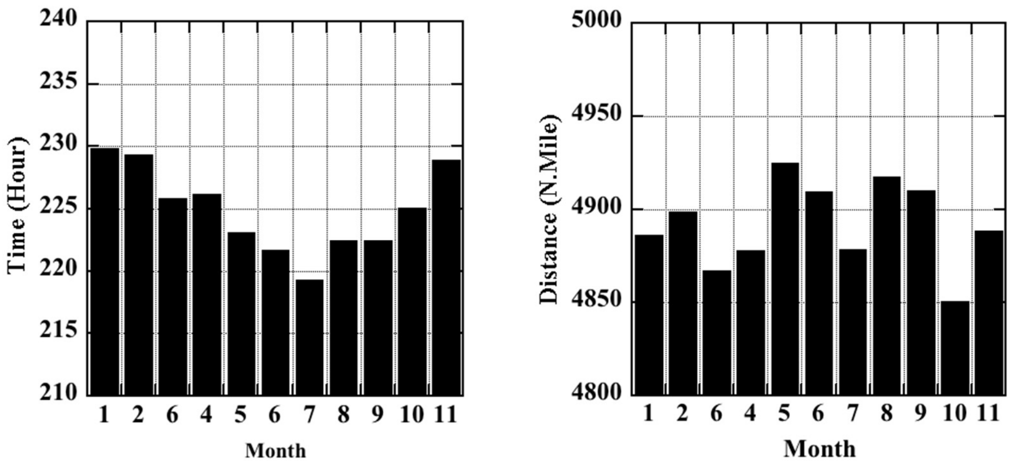


Figure 3.10 Monthly averaged values of voyage time and distance (January to November, 2016, from Los Angles to Tokyo, Setting-6-10)

It is shown that there are relatively similar with those in Figure 3.8. However, the voyage distance is larger in May and August than winter season.

3.3.4 Influences of Time Resolution

The difference of optimal routing is studied here as the influence of time resolution. Figures 3.11-3.12 show computed results of optimal routes with 0.5° and 12 hours from Los Angles to Tokyo in January and August, 2016.

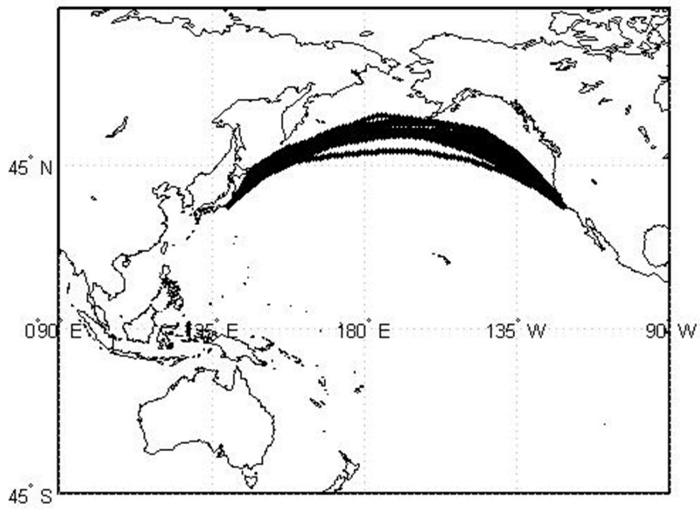


Figure 3.11 Computed results of optimal voyage route (January, 2016, Setting-12-05)

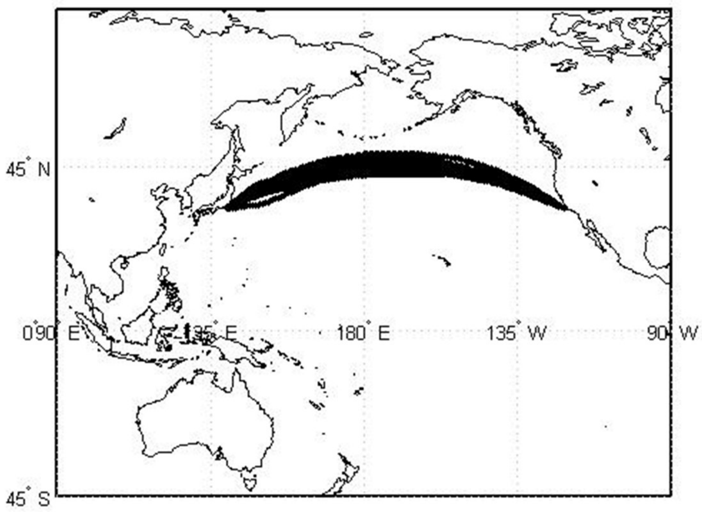


Figure 3.12 Computed results of optimal voyage route (August, 2016, Setting-12-05)

In Figure 3.11, optimal routes are quite different from those in Figure 3.6 and Figure 3.9. Routes are concentrated in northern area of the Pacific Ocean. They are not so different in September, because weather conditions are relatively calm. Figure 3.11 shows the monthly averaged values of voyage time and distance with the time resolution of 12 hours.

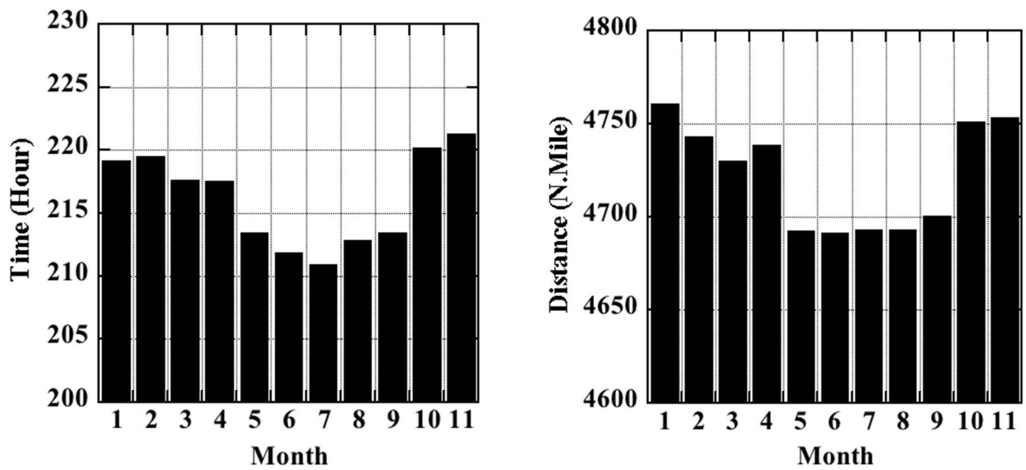


Figure 3.10 Monthly averaged values of voyage time and distance (January to November, 2016, from Los Angles to Tokyo, Setting-12-05)

Computed voyage times are nearly 10 hours shorter than those in Figure 3.8 or Figure 3.10. It implicates that the time resolution affects to the accuracy than the spatial resolution. It is necessary to focus on these points in our next study.

4. Conclusions

Computed results of optimal ship routing are simulated and compared for a container vessel across the Northern Pacific in 2016. Main conclusions and future subjects can be summarized as follows.

(1) Optimal voyage routes vary widely in the route from Los Angeles to Tokyo, westbound than those in the opposite route. Averaged voyage time is around 10 hours longer in winter season than those in summer season. Especially, the tendency is remarkable in winter season. It relates on the wave direction due to low pressures.

(2) Computed optimal routes are not so different between 0.5° and 1.0° of spatial resolutions as the monthly averaged values. However, the difference is occurred if the weather condition is heavy.

(3) The time resolution make more difference to the computed results than the spatial resolutions. The optimal route might not be accurate in sparse time resolutions more than 12 hours.

(4) In this study, the ship speed is simply estimated from encountered wave height and direction. The speed loss is small in the following seas, theoretically. However, ships actually avoid sea areas with low pressures, even if the following wave direction. This point will be additionally modeled in our future studies.

(5) The speed loss should be evaluated on the theory of resistance and propulsion accurately. Authors already show these numerical analyses with measured onboard database. The accurate simulation can be expected by combining those theoretical models.

(6) Patterns of deliberate speed loss is also studied in the measured data on actual seas. This point is also necessary to consider the evaluation of ship speed during the voyage.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Prof. Ruri Shoji, Tokyo University of Marine Science and Technology, for her guidance of optimal ship routing in conducting the study.

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