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RESEARCH ARTICLE

Optimum tracking of ship routes in 3g-WAM simulated rough weather using IRS-P4 (MSMR) analysed wind fields

J. K. Panigrahi · J. K. Tripathy · P. A. Umesh

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Abstract Rough weather ship routing is studied using model hindcast wave climate. With the launch of IRS-P4 (OCEANSAT-I), it became possible to carry out routine wave forecasting over the Indian Ocean. The MSMR channel of the satellite gives scalar wind, which is analysed at National center for Medium Range Weather Forecasting (NCMRWF), India for converting to vector winds. The same is used as input to third generation wave model for the rough weather month of July 2000. Simulations are carried out using Cycle-4 of third generation spectral wave model WAM for regional grid system. This simulated wave climate formed the basis for computing effective ship velocity in the irregular seaway. This study gives a quantitative estimation of change in ship velocity in the open Indian Ocean for a Liberty type ship. The optimal route is charted using Dijkstra's algorithm for minimal time path between Calcutta and Sumatra. The optimum track information has broad scope for obtaining a safer route, least time route by avoiding delay in schedule with minimum fuel consumption.

J. K. Panigrahi[1] (✉) · J. K. Tripathy[2] · P. A. Umesh[3]
[1]Department of Marine Science, Berhampur University, Orissa
[2]Department of Remote Sensing & GIS, North Orissa University, Orissa
[3]Department of Atmospheric Sciences, Cochin University of Science & Technology, India

e-mail: jeetendra@scientist.com

Introduction

The effects of the state of the sea on the safety and economy of a ship's route are of considerable concern to the shipping industry. For the past several years, there had been no systematic wave observations and regular wave forecast over the Indian Ocean. Hence, it was not possible to operationally forecast minimal time ship routes based on sea-state. In recent times, with the advancement of wave modeling, many operational models give wave parameters in a coarse and fine grid resolution over world oceans. The synoptic model predictions of six-hourly wave fields help in alerting the ship navigators in advance. Waves have maximum impact on ships and alter the ship velocity in an irregular seaway. It is easy for navigators to decide the optimum track to be navigated from departure to destination in a known wave climate. The synoptic model predictions bring out the characteristics of the rough waves that the ship is going to encounter on its route in the seaway. The ship route can be decided before sailing based on the wave forecast. Hence an effort has been made to determine the minimal time route from Calcutta to Sumatra using 3g-WAM simulated wave climate for the typical monsoon month of July, 2000.

Data

In the present study the data used are model hindcast wave data. Wave fields are generated by assimilating IRS-P4 analysed wind fields to wave model WAM. IRS-P4 (Oceansat-I) was launched by India in 1999, with two payloads, namely Multi-frequency Scanning Microwave Radiometer (MSMR) and Ocean Color Monitor (OCM). The MSMR sensor is configured as an eight-channel radiometer using four frequencies with dual polarisation. It has three resolutions and the geophysical products are also processed for three standard grid sizes (150×150, 75×75 and 50×50 km) covering the globe. There are totally eight geophysical products, which include wind speed (accuracy ± 2 m/s) without direction (Bhatia, 2001). The exact repeat period of the satellite is two days. However, both wind speed and direction are essential for sea-state prediction. Hence, the MSMR winds over 150×150 km are merged with the medium range global weather forecasts by (NCMRWF) along with the various other available data including the data received through Global Telemetric System (GTS) for the preparation of analysed fields suitable for sea-state nowcasting. Since the IRS-P4 gives scalar winds, which is not

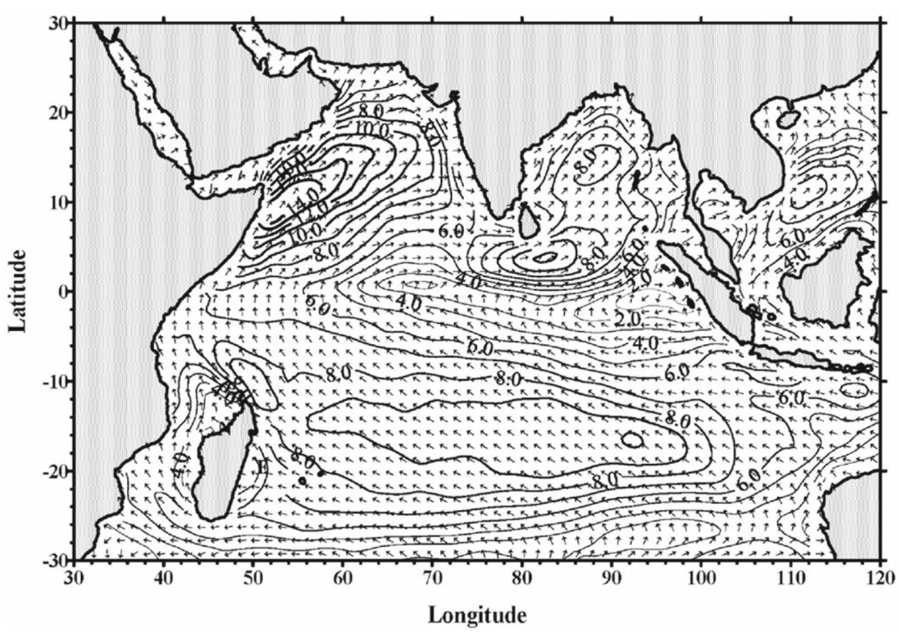

Fig. 1 Mean monthly IRS-P4 analysed wind field for July 2000.

directly useful for wave model prediction, these are converted to vector winds by an appropriate operator from observation space to analysis space. This wind is known as IRS-P4 (MSMR) analysed wind field, which is used in this study for wave model hindcast. The same is averaged over the month and presented in Fig. 1 as a contoured map. The contours show the wind speed in m/s and the arrows represent direction. The six-hourly analysed wind fields are obtained from NCMRWF. These winds are processed at NCMRWF by merging the IRS-P4 (MSMR) scalar winds with model predicted winds, measured buoy winds etc. to obtain vector winds (Rupa *et al*., 2002). The u- & v- components of winds covering the south to north Indian Ocean are supplied for sea state forecasting. The same has been assimilated with third generation wave model WAM for simulating six-hourly wave parameters. The wind speed and direction for the peak monsoon month of July are used here for wave model hindcasting. The model interpolates the temporal wind from 6 hourly to 3 hourly time step to initialise the energy field over the model area. As the present wave model is a spectral wave model, it not only takes care of wind-input term and associated spectral change but also the total change in spectral energy due to non-linear wave-wave interaction and dissipation due to white capping.

Methodology

The wave model used in this study is the third generation wave model 3g-WAM (Cycle-4) originally developed by WAMDI group (1988), Germany. It is based on the physics understood till recently by the wave research community. It integrates the basic transport equation without any prior assumption on the shape of the wave spectrum. It is presently used for global and regional wave forecasting purposes by several countries and research institutions in the world. 3g-WAM requires wind input at the prescribed model grids and computes the evolution of two-dimensional wave spectrums for the full set of degrees of freedom (Komen *et al.,* 1996). It provides 25 frequencies and 12 directional discretisations for evolution of wave spectrum by solving 1.2 million equations at each grid. The source terms and the propagation are computed with different numerical methods and time steps. The model outputs are significant wave height, peak and mean wave periods, mean wind-wave directions, the swell wave height, swell frequency and direction, frictional wind velocity, wave-induced stress, and the two-dimensional wave spectrum. The model is being updated with new advances and continually validated with long-term measurements of moored buoys and satellite data (Swain, 2003).

The physics of the wave model is described in this section. With the advancement of wave research, the WAMDI group came up with the state-of-art third generation wave model. In contrast to first and second-generation wave models, 3g-WAM computes the 2d-wave variance spectrum through integration of the basic transport equation:

$$\frac{\partial F}{\partial T} + \frac{\partial}{\partial \phi}(\dot{\phi} F) + \frac{\partial}{\partial \lambda}(\dot{\lambda} F) + \frac{\partial}{\partial \theta}(\dot{\theta} F) = S,$$

where: F - represents the spectral density with respect to (f, θ, φ, λ), f- denotes frequencies, θ- directions, φ- latitudes and λ- longitudes.

$\dot{\varphi}$, $\dot{\lambda}$ and $\dot{\theta}$ are the rates of changes of position and propagation direction of wave packets travelling along the great circle path.

$$\dot{\phi} = \frac{d\phi}{dt} = v \ R^{-1} cos\,\theta,$$
$$\dot{\lambda} = \frac{d\lambda}{dt} = v \ sin\theta \ (R \ cos\,\phi)^{-1},$$
$$\dot{\theta} = \frac{d\theta}{dt} = v \ sin\theta \ tan\,\phi \ R^{-1},$$

where $v = g/4\pi f$ denotes the group velocity, g is acceleration due to gravity and R is the radius of the earth.

The time and space evolution of ocean surface wave field or the source function S may be represented by

$$\frac{\partial F}{\partial t} + v \bullet \nabla F = S = S_{in} + S_{nl} + S_{ds},$$

where $v = v\,(f, \theta)$ is the deep water group velocity and the net source function S is represented as the sum of the input S_{in} by the wind, the non-linear transfer S_{nl} by resonant wave-wave interactions and dissipation S_{ds}. The advantage of this model is that, it exactly computes the evolution of two-dimensional directional wave spectrum including the spectral variance of non-linear wave-wave interaction. Also it takes care of the extreme wind-wave conditions.

The sea state parameters are simulated using six-hourly IRS-P4 analysed wind fields. The mean monthly wave climate for the peak monsoon month of July 2000 is established using this model. The outputs are plotted in Fig. 2 show the spatial distribution of wave height and direction over the Indian Ocean. The average 2d-directional wave spectrum simulated at a grid of central Bay of Bengal for the month of July, 2000 is presented in Fig. 3. It is an absolute representation of waves in an irregular seaway. The multiple peaks of the spectrum show the occurrence of various wave groups having different wave periods. The spectral peaks show the maximum energy levels associated with predominant wave directions.

In this study, a Liberty type ship ranging overall length (LOA) 100–150 m, weighing 10,000–15,000 dead weight tonnage (DWT), 10–12 m draught band moving at a speed of 16–20 knots is chosen. In view of a longer trajectory, a navigation track from Calcutta to Sumatra is assumed for demonstrating the optimal route. A schematic of the seaway and ship headings for a ship moving at 18 knots encountering the simulated wave climate is shown in Fig. 4. In general practice, the route is charted by the navigator before setting up the voyage from departure to destination. The ma-

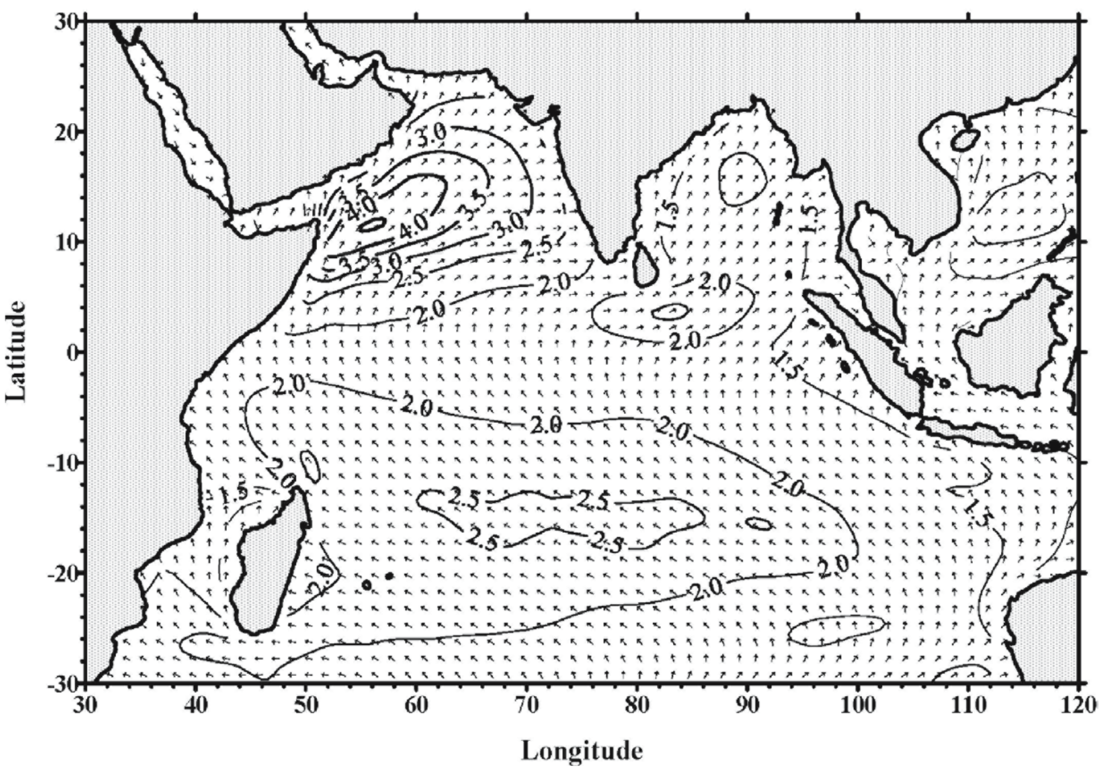

Fig. 2 Mean monthly WAM simulated wave field for July, 2000.

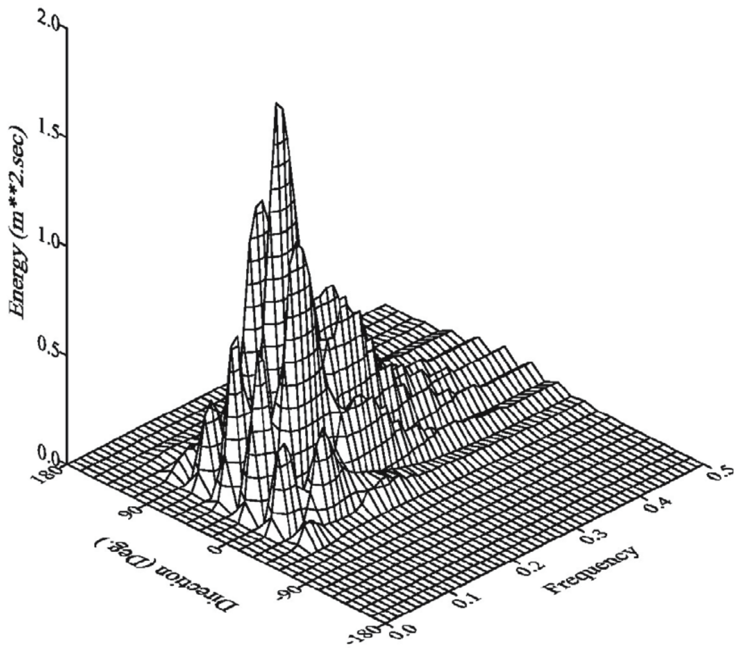

Fig. 3 2d-directional wave spectrum at central Bay of Bengal (July, 2000).

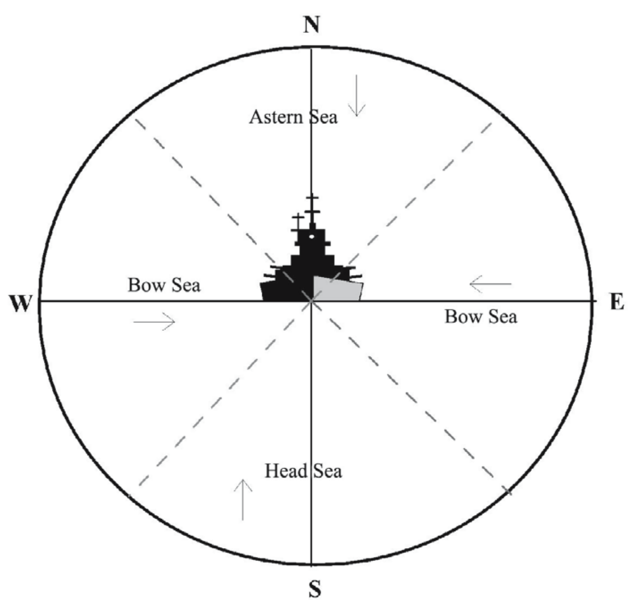

Fig. 4 Schematic diagram of an irregular seaway.

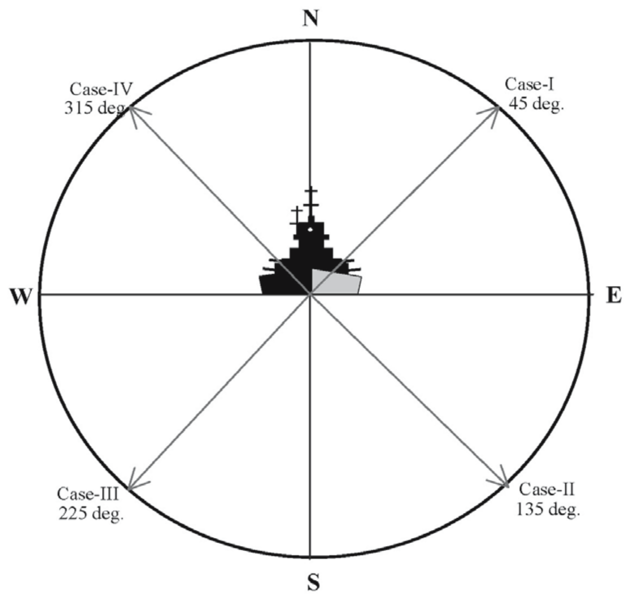

Fig. 5 Ship's heading for four different cases w.r.t true north.

jor headings are pre-planned on the navigation chart, but the rough weather is not considered simultaneously due to lack of real time sea state information. For simple understanding, four heading angles are assumed for a ship moving at a speed of 18 knots as shown in the schematic in Fig. 5. When the ship is heading at 45°, 135°, 225° and 315° with respect to true North in the open Indian Ocean, the seaway changes with respect to different heading angles. The wave height and direction the ship comes across at each grid point decide the ship's kinematics.

In this context, James' investigation (James, 1957) data from the ship's logs were first separated into three categories according to the relative wave direction. For waves coming from directions within 45º of the bow were called 'head waves', waves coming from directions within 45º of the beam were called 'beam waves', waves coming from directions within 45º of the stern were called 'following waves' respectively. In the open Bay of Bengal the seaway changes with respect to difference of angle between the ship's head and wave approach. The wave height and direction the ship comes across at each grid point decide the ship's kinematics.

In the present problem, the time T for a ship travelling at speed V to traverse the path 'c' is given by the line integral:

$$T = \int_c \frac{ds}{V} = \int_c \psi ds,$$

Where $\psi = 1/V$. Since ψ is in general a function of time, position and course, it is natural to express the coordinate x and y in terms of time as a parameter.

$x = x(\mathrm{t}),\ y = y(t)$

Replacing ds in the above equation by $(\dot{x}^2 + \dot{y}^2)^{1/2}$ where the dot means differentiation with respect to t.

The travel time (Haltiner *et al*., 1962):

$$T = \int_0^T \psi(x, y, \dot{x}, \dot{y}, t)\ \ (\dot{x}^2 + \dot{y}^2)^{1/2}\, dt\,,$$

When the ship is travelling through the nodes, she experiences the waves with variable height and direction hindering the ship's speed. The effective speed (V) on the ship is estimated using the relationship between ship's speed (V_0) and wave characteristic (H) by Jame:

$$V = V_0 - [\alpha_1 + \alpha_2 \cos(\beta - \alpha)]\, H,$$

where the angle 'α' gives the ship's course and 'β' is the direction from which the waves are coming. α_1 and α_2 are constants taken from Jame`s (1959), V_0 versus H curve. For the present ship type the values of α_1 and α_2 are 0.30 and 0.15 respectively. The effective speeds on the ship approaching in four different headings (45, 135, 225 and 315 degree) in the Bay of Bengal are estimated with July 2000 wave data to assess the hindrance of wave climate on the ship. The distribution of effective ship speed at various places for the ship's natural speed of 18 knots is presented in Fig. 6. The effective ship speed for a heading is based on the hindcast wave data. It is observed from effective speed distribution for various headings that the ship suffers maximum hindrance from waves when the ship is heading 225 and 135 degrees with respect to true North in the Indian Ocean.

Results & Discussion

The paper aims at demonstrating the feasibility of tracking the optimal ship route using remotely sensed wind and model simulated wave climate. The satellite observed wind shows an average wind velocity of 8 m/s prevailing over the Bay of Bengal for SW monsoon month of July. Corresponding to wind the mean monthly wave height ranges from 1.5–2.0 m over Bay of Bengal. The 2d-directional

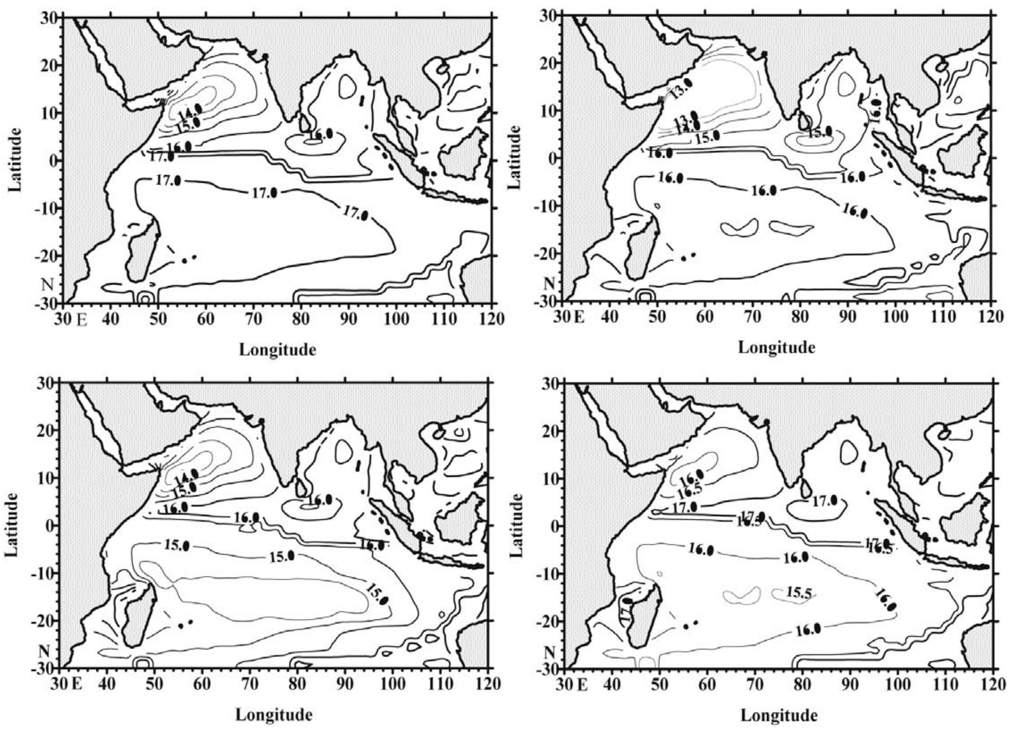

Fig. 6 Distribution of effective ship speed for four different ship headings. (Top): (case 1 & 2, (Bottom): case 3 & 4).

wave spectrum exhibits groups of waves ranging from 4–11s period having an energy level of the order of 0.5–1.5 m^2/hertz prevailing over central Bay of Bengal. The predominant wave approach direction at each model grid decides the irregular seaway like head sea, astern sea and bow sea. The matrix of effective ship speed the ship would experience in the Bay of Bengal, while heading 135° course from Calcutta to Sumatra is estimated and presented in Fig. 7.

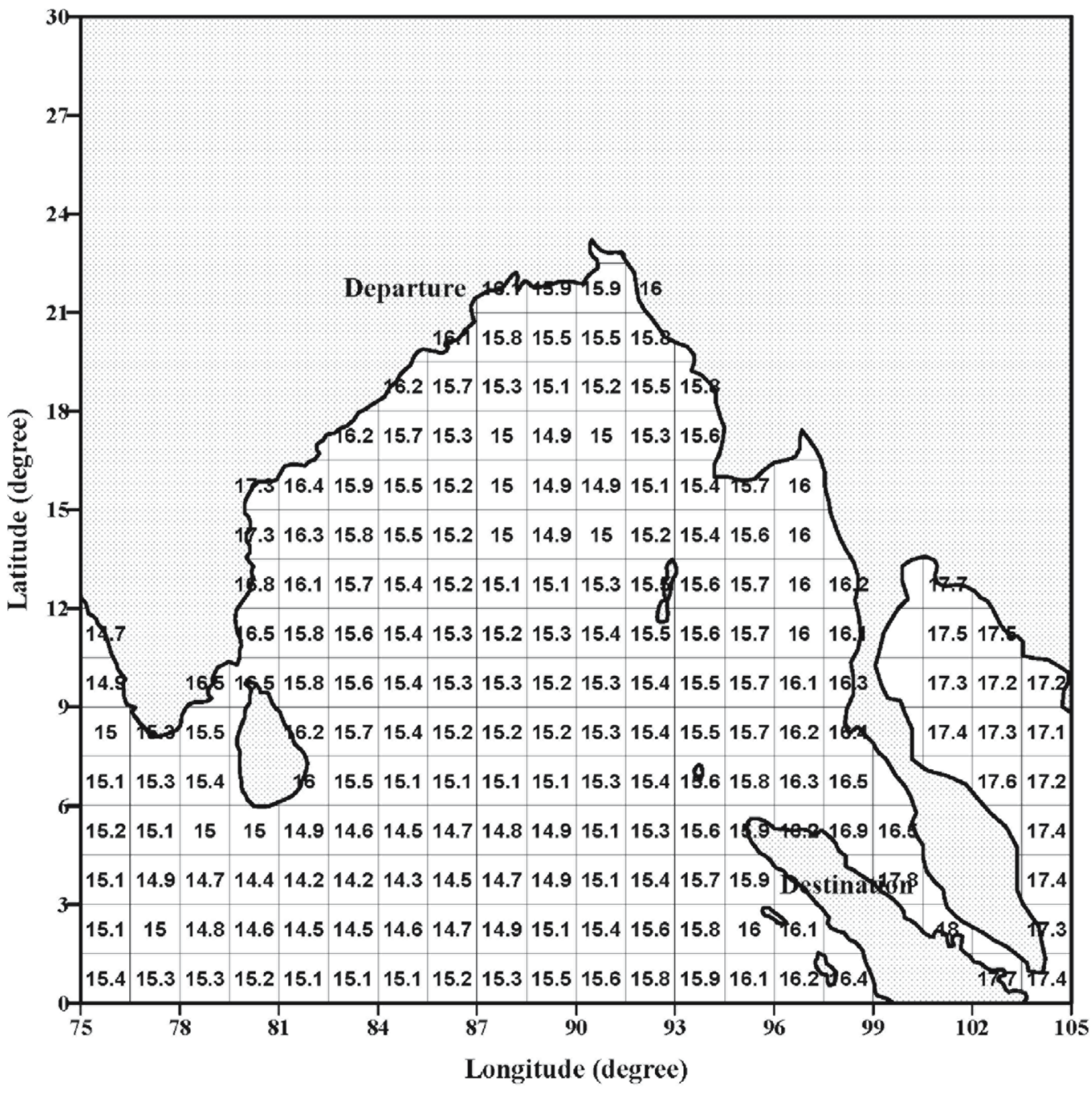

Fig. 7 Effective ship speed at various nodes.

Table 1. Travel time matrix (in hours) at each node using Dijkstra's Algorithm (Thatched area denotes land grids)

Departure	5.18	10.42	15.66	20.87			
5.18	**7.46**	12.78	18.02	23.12			
10.48	12.88	**15.26**	20.53	25.62	30.58		
15.93	18.34	20.79	**23.12**	28.24	33.18		
21.41	23.79	26.25	28.70	**30.93**	35.89	40.68	45.89
26.90	29.27	31.70	34.11	36.41	**38.58**	43.44	48.05
32.38	34.70	37.07	39.40	41.71	43.92	**46.08**	50.81
37.82	40.13	42.40	44.73	47.00	49.26	**51.39**	53.45
43.27	45.53	47.88	50.11	52.38	54.61	**56.70**	58.63
48.75	51.01	53.28	55.55	57.76	59.98	**62.01**	63.77
54.27	56.53	58.80	60.98	63.17	65.31	**67.28**	68.88
59.94	62.16	64.39	66.50	68.62	70.65	**72.52**	74.03
65.69	67.83	69.98	72.02	74.03	75.96	77.76	***Destination***

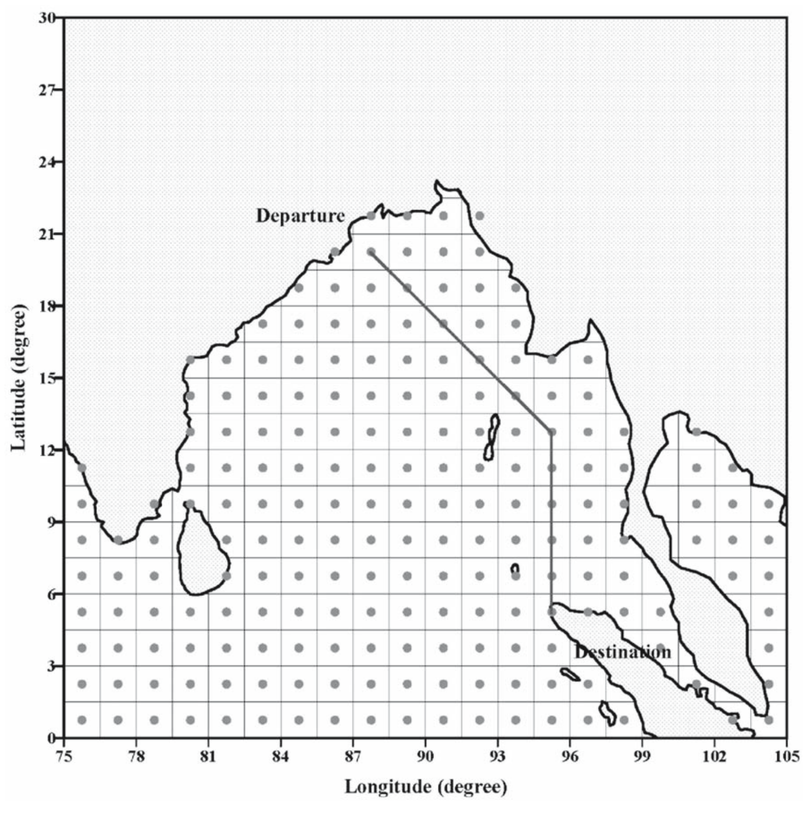

Fig. 8 The minimal time route from departure to destination.

While sailing, the cost of time spent at sea by a ship has always been an important factor in the overall cost of ship operation. In order to minimize the time spent at sea, many efforts have been devoted to save time such as, increasing the power for achieving speed, aerodynamics and the hydrodynamic shape of ships etc. The state of the sea determines the upper bound of attainable speed for each ship. Hence, the numerical model under discussion is based on minimum travel time between specified origin and terminal points. A simple approach adopted here is by taking the centre of grids as nodes and its connectivity to the adjacent grids along the course of the ship as links. The route is defined as a series of connected nodes and the length of the path is the arithmetic sum of corresponding link lengths in the path. The number of possible routes it can navigate through and the time required to travel successive nodes are estimated by accumulating their travel times. From this tree building a minimal time ship route is obtained using Dijkstra's algorithm (1959). This algorithm is extensively used in transportation planning and it operates as skimming tree. In this study, the attribute like travel time is the time to travel the straight and diagonal distance between the nodes. The optimal route for minimum time (hours) is estimated and presented in Table 1. Finally joining the nodes, the minimal time route along the (135 degree course) from departure (Calcutta) to destination (Sumatra) is presented in Fig. 8.

Conclusions

The WAM model simulates the synoptic wave field from IRS-P4 analysed winds with a higher confidence level. The simulated model outputs are very useful for applications like ship routing. The formula suggested by James (1957) and Haltiner (1962) for estimating the effect of waves on ship's speed appears to be realistic. The algorithm (Dijkstra, 1959) used for obtaining minimal time route can be more practically implemented using very high-resolution satellite wind and wave data. The work needs an extensive validation with ship's log data before operationalisation. This study will help navigators to track ships in an optimum route taking into account safety, least time and minimum fuel consumption. It has a broader scope for naval applications like war ship routing.

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