

# Safe-Economical Route Model of a Ship to Avoid Tropical

## Cyclones Using Dynamic Forecast Environment

Lichuan Wu<sup>1,2</sup>, Yuanqiao Wen<sup>1,3</sup>, Dingyong Wu<sup>1,3</sup>, Jinfeng Zhang<sup>1,3</sup>, Changshi Xiao<sup>1,3</sup>

<sup>1</sup>Hubei Inland Shipping Technology Key Laboratory, Wuhan, China

<sup>2</sup>Department of Earth Science, Uppsala University, Uppsala, Sweden

<sup>3</sup> School of Navigation, Wuhan University of Technology, Wuhan, China

Correspondence to: Lichuan Wu (wulichuan0704@gmail.com)

### Abstract

In heavy sea conditions related to tropical cyclones (TCs), losses to shipping caused by capsizing are greater than other kinds of accidents. Therefore, it is important to consider capsizing risk in the algorithms used to generate safe-economic routes that avoid tropical cyclones (RATC). A safe-economic routing and assessment model for RATC, based on a dynamic forecasting environment, is presented in this paper. In the proposed model, a ship's risk is quantified using its capsizing probability caused by heavy wave conditions. Forecasting errors in the numerical models are considered according to their distribution characteristics. A case study shows that: the economic cost of RATCs is associated not only to the ship's speed, but also to the acceptable capsizing probability which is related with the ship's characteristic and the loading condition. Case study results demonstrate that the optimal routes obtained from the model proposed in this paper are superior to those produced by traditional methods.

### 1 Introduction

Weather hazards are the main threat to shipping. The goal of weather routing is to plan routes that avoid weather hazards safely and economically. Tropical Cyclones (TCs), as a kind of hazardous weather, cause extensive damage to the ship and crew. The total loss caused by ship capsizing is very serious to the ship company and cargo owner. Compared to the capsizing, the loss of cargo and ship damage caused by other accidents is much less in TCs. Ships can avoid TCs safely with routes based on the methods applied in navigation practice –Sector diagram typhoon avoidance method (Chen,2004); 34KT rule (Holweg,2000); and the Diagram of the 1-2-3 rule (Wisniewski et al., 2009) – but routes generated by these methods

1 ignore costs and increase shipping expenses. Furthermore, in these models the ship's  
2 performance in resisting wind and waves is not considered.

3 As a major transportation mode, maritime transportation play an important role in the  
4 international trade. The daily operating costs of a ship can be tens of thousands of dollars.  
5 Ship routing draws more and more attention from scientists and engineers. Last decade, there  
6 are lots of research about ship routing and scheduling. Linear programming model (LP),  
7 mixed integer programming (MIP) model and set partitioning (SP) formulation are used to  
8 solve the routing problem. Christiansen et al. (2004) gave a detail review of the past decade  
9 research about the ship routing and scheduling. In the research about optimization, lots of  
10 methods are used to solve the problem, i.e. dijkstra's algorithm, semi-Markov decision  
11 process (Azaron and Kianfar, 2003) and so on. Weather routing is a ship routing problem with  
12 multiple restrictions and changing environment condition. The relevant literature includes  
13 research on weather routing, numerical forecast errors, RATC, and vessel risk analysis.

14 There are several widely used methods for weather routing. These methods are based on the  
15 isochrone method and have been refined since its introduction. James (1957) proposed an  
16 isochrone method, which was widely used for decades. Based on the work of James,  
17 improvements have been made to update the method (Hagiwara,1989). Chen (1978)  
18 developed a dynamic programming algorithm to solve the minimum voyage cost problem  
19 under uncertainty constraints. In the algorithm, the sea-keeping features of the ship are a  
20 function of weather. McCord et al. (1999) investigated the potential for strategic ship routing  
21 through dynamic currents to determine 3-day routes. The results showed that this kind of  
22 strategic ship routing can reduce fuel consumption by 25% on average. Delitala et al. (2010)  
23 showed that weather routing improves ship performance by 37% thus supporting ship captains  
24 throughout an entire voyage. Panigrahi et al. (2008) and Padhy et al. (2008) optimized the  
25 ship's route based on the output of the WAM (WAVE Modelling). Maki et al. (2011) designed  
26 a real-coded genetic algorithm weather routing method to calculate the safety ratio and fuel  
27 efficiency based on the probability of accidents caused by parametric rolling. Soda et al.  
28 (2011) gathered and used high-resolution wind and wave data forecasted using SWAN  
29 (Simulating Waves Nearshore model) and WRF (Weather Research and Forecasting Model)  
30 to study wave and wind effects on ship's manoeuvring. From the aspect of minimum pollute  
31 probability to the coast, fairways in the Gulf of Finland are designed based on the current  
32 condition from the ocean model (Andrejev et al., 2011).

33 The weather routing problem is complicated since weather conditions are uncertain. The  
34 forecast error in numerical models must be considered when designing weather routing  
35 (Magirou and Psaraftis, 1992). Hopkins (1997) examined the offshore forecast statistical  
36 errors derived from the numerical forecasting models. RMS (root mean square) errors in wind  
37 speed and wave height forecasts have a seasonal variation. The RMS errors of the  
38 WaveWatchIII model against altimeter and buoy data are 15% of the mean observed wave  
39 heights for most of the global domain (Tolman,2002). Bedard(2008) evaluated the forecast

1 technology of WaveWatchIII based on the comparison with buoy-measured wave data in deep  
2 water of Washington and Oregon, U.S.A. Chu et al. (2004) compared the model result of  
3 WaveWatchIII with the T/P (Topex/Poseidon) significant wave height (SWH) data over the  
4 satellite crossover points in the South China Sea (SCS). The results showed that the model  
5 errors of SWH had Gaussian-type distribution. The research of Guo and Hou(2010) coincides  
6 with Chu's (Chu et al.,2004) research results in that the WaveWatchIII forecast error of SWH  
7 follows a Gaussian distribution.

8 Although the literature on weather routing is rich, little work focuses on RATC. The sector  
9 diagram typhoon avoidance method (Chen,2004), and the 34KT rule (Holweg, 2000) are  
10 widely used in navigation. Wisniewski (2009) discussed the application of the 1-2-3 rule for  
11 calculations for routing vessels using evolutionary algorithms. Liu et al. (2006) built a  
12 safety-economic decision-making model of RATC using risk theory and fuzzy information  
13 optimization. Zhang et al. (2010) proposed a multilevel decision method for RATC using  
14 multi-source track forecasting. Wu et al. (2010) built a model to evaluate the benefit for  
15 RATC. Wisniewski and Kaczmarek (2012) analysed reactions, such as reducing speed and  
16 changing course, when a ship is avoiding a TC. At present, these RATC methods are mainly  
17 based on TC forecast tracking, experience, and fuzzy analysis. All these methods, in the final  
18 instance rely on qualitative judgement. These methods also do not consider the performance  
19 or reactions of different vessels under the same wave or wind conditions. Therefore, different  
20 vessels might require different routing strategies to safely and economically avoid TC.

21 Quantification of ship's risk under heavy weather conditions is an important aspect for  
22 weather routing. Most researchers assess a ship's risk using fuzzy analysis, the risk cannot be  
23 quantified (Zhang et al., 2010; Liu et al., 2006). In heavy sea conditions related to tropical  
24 cyclones (TCs), losses to shipping caused by capsizing are the total losses of ship and cargo,  
25 which are much greater than other kinds of accidents. So, it is resonable to considered the  
26 capsizing probability as the risk level in RATC. In recent years, capsizing probability has  
27 received attention as an empirical measure to quantify the ship's risk. Shen and Huang (2000)  
28 studied the length of time before capsizing and the capsizing probability of ship based on  
29 Markov chain theory. Huang et al. (2001) studied the capsizing probability of a ship under the  
30 combined action of beam wind and beam sea. In this method, the capsizing probability of  
31 every random heeling in an unstable domain is calculated according to the density of heeling  
32 extreme value. Thompson (Thompson, 1990; Thompson et al., 1992) used the theory of safe  
33 basis erosion to study the ship capsizing probability. Shi et al. (2011) studied the calculation  
34 method of ship's movement and capsizing probability in random waves and winds using  
35 formula of Gauss-Legendre based on the path integration techniques. Gu (2006) calculated  
36 the ship's rolling probability using a new path integration method, which avoided the problem  
37 of solving the equations of Fokker-Planck-kolmogorov(FPK). The method of Melnikov is

also used to calculate the ship's capsizing probability (Falzarano et al., 1992; Bikdashy et al., 1994; Tang et al., 2004).

Based on work related weather routing summarized above, we can conclude that the resolution and precision of ocean and atmospheric models are increasing in tandem with the rapid development of computational power, thus allowing more possibilities for ship routing with precise and less uncertain forecast results (Delitala et al., 2010). Many researchers have done weather routing work using ocean and weather numerical models, the forecast errors of models are not considered in their works (Padhy et al., 2008; Maki et al., 2011). As a major threat, TC has made lots of loss to ships sailing on the sea. Nowadays, it is feasible to find routes to avoid TCs (RATC) using dynamic wind and wave fields forecasted by numerical models. In this paper, based on the idea, a minimum economic cost route was designed to avoid TCs from the following aspects: (1) The forecast errors of models are considered in the route design; (2) The ship's characteristics are considered in assessing the risk in the heavy weather conditions; (3) The ship's risk is quantified; (4) The ship's speed loss is considered.

## 2. Mathematical model

The movement of ships sailing on the ocean can be described as the change of ship's position over time. The ship's position  $(x(lon, lat))$  and time  $(t)$  form the ship's track. The ship's dynamic response to varying environmental conditions can be described by a control vector  $U$  and restraint vector  $M$ . The ship's heading direction and speed are described by  $U$ . The restraint conditions are described by  $M$ . The external environment which varies with time is described by  $E$ . The dynamic process of a ship can be expressed as:

$$(x, t) = f(x', t', E, U, M), \quad (1)$$

in which,  $t' = t - \Delta t$ ,  $E$  is the external environment at location  $x'$  at time  $t'$ . The ship is controlled by  $U$  during time  $\Delta t$ . The ship will arrive at location  $x$  at time  $t$ . The economic cost  $C$  of the whole voyage can be expressed as:

$$C(x_D, t) = \int_{T_0}^T C_{oil}(D, V, Q_a) + C_t, \quad (2)$$

in which,  $C_{oil}$  is the fuel consumption per unit time, and related to ship's speed, displacement and the oil price;  $C_t$  is ship's profitability per unit time, and related to type of ship and the production plan.

How to improve the economic benefit of a ship based on safety criteria is the concept behind of RATC. An economical and safe RATC based on a dynamic forecasting environment increases ship safety and reduces costs using the wave and wind conditions forecasted by numerical models. Costs may be very different given the same risk because of the difference between the ship and cargo's value. To assess the economic benefit of RATC, a benefit-cost ratio for a route is built. A ship's safety can be valued as the safety probability multiplied by the ship's fixed assets including the value of both ship and cargo. Then, the benefit-cost ratio ( $Ra$ ) of RATC can be expressed as:

$$Ra = \frac{C_{cost}}{M_{all} \cdot P_{safe}}, \quad (3)$$

where,  $C_{cost}$  is the economic cost of the whole voyage, including the time cost and fuel consumption.  $P_{safe}$  is the safety probability of ship, considered as the probability that ship will not capsize.  $M_{all}$  is the value of the ship and the cargo.  $Ra$  is the total cost of ensuring a ship's economic safety in economic cost units when avoiding TCs. Therefore, the smaller the  $Ra$  is, the less it takes to ensure a ship's safety when avoiding TCs.

The mathematical model for RATC can be considered as a ship's avoidance of an obstruction that changes shape and position over time. The accident probability of ship must not exceed a acceptable risk level for the operator. Assuming that a ship begins to take an action to avoid TC at time  $t_0$ , and will pass through the TC after time  $T$ . Then, during time  $T$ , the ship's speed and course will change predetermined route. The points at which the ship's speed or course is changed are considered to be waypoints. The avoidance process is regarded as complete when the ship arrives at the next waypoint of the original predetermined route. The whole process of avoiding TCs therefore, can be regarded as an optimal path problem.

Make  $x_0$  as the starting point for ships to avoid TC.  $x_n (n=1,2,\dots)$  are the alternative waypoints of the route;  $l_{i,i+1}$  is a segment of the route between two adjacent alternative waypoints;  $d_{i,i+1}$  is the distance between any two adjacent alternative waypoints;  $p_{i,i+1}$  is the accidental probability of a ship in a unit time between any two adjacent alternative waypoints;  $v_{i,i+1}$  is the average speed-to-ground when ship is sailing on segment  $l_{i,i+1}$ . Then, the ship's safety probability  $P_{safe}$  in the whole process is:

$$P_{safe} = \prod_{i=1}^n (1 - p_{i-1,i}). \quad (4)$$

1 The economic cost in the whole process is:

$$C_{cost} = \sum_{i=1}^n \frac{d_{i-1,i}}{v_{i-1,i}} \cdot (C_t + C_{oil}). \quad (5)$$

2 The benefit-cost ratio ( $Ra$ ) of the route is :

$$Ra = \frac{\sum_{i=1}^n \frac{d_{i-1,i}}{v_{i-1,i}} \cdot (C_t + C_{oil})}{M_{all} \cdot \prod_{i=1}^n [(1 - p_{i-1,i})]}. \quad (6)$$

3 The acceptable risk level restriction is:  $p_{i-1,i} < p_a$ .

4 In which,  $p_a$  is the acceptable accident probability of ship capsizing;

5  $i$  is an alternative waypoint of the route;

6  $n$  is the amount of the alternative waypoints;

7  $Q_{oil} \propto D^{2/3} \cdot V \cdot Q_a$  is oil cost in per unit time;

8  $D$  is displacement of the ship, and  $Q_a$  is the oil price.

9 The most economical route (the minimum economical cost route) based on the safety is

10  $\min\{C_{cost}\}$ .

11

## 12 **3. The RATC algorithm**

### 13 **3.1. Relevant parameters**

#### 14 **3.1.1. Ship capsizing probability**

15 Waves are stimulated by the wind during TCs. Wind and waves are strongly correlated. In  
 16 this paper, the risk factor is simplified using the risk of capsizing in random waves. Some  
 17 methods are used to calculate the ship's capsizing in waves, i.e. Safe basis erosion (Thompson,

1990; Thompson et al. 1992), Gauss-Legendre (Shi et al., 2011), Melnikov (Bikdash et al., 1994; Tang et al., 2004).

The differential equation of ship's nonlinear rolling motion in random wave conditions is (Gu, 2006b):

$$(I + I_1(\omega))\ddot{\phi} + B_1(\omega)\dot{\phi} + B_2(\omega)\phi^3 + \Delta GZ = F_{sea}(\tau), \quad (7)$$

where,  $I$  is the rotational moment of inertia around an assumed rolling centre;  $I_1(\omega)$  is the added moment of inertia due to the ambient fluid;  $B_1$  and  $B_2$  are linear and cubic damping coefficients respectively;  $\Delta$  is the ship displacement;  $GZ$  is the righting arm of a rolling ship;  $F_{sea}(\tau)$  is the external excitation resulting from random beam seas, the over-dots denote differentiation with respect to time  $\tau$ ;  $\omega$  is the wave angular frequency in radians;  $\phi$  stands for ship's roll angle.

The righting arm is approximated by the following odd cubic polynomial of  $\phi$ ,

$$GZ(\phi) = C_1\phi - C_3\phi^3. \quad (8)$$

The excitation moment resulting from the random seas is expressed as:

$$F_{sea} = I_0\alpha_0\omega_0^2 \frac{\sqrt{2\varpi}}{g} \sum_{n=1}^N (n\varpi)^2 \sqrt{S} \cos(\omega_n t + \xi_n), \quad (9)$$

in which,  $I_0 = I + I_1(\omega)$ ;  $\alpha_0$  effective wave slope;  $\omega_0$  is the natural frequency of ship's roll;  $\varpi$  is the interval of wave frequency;  $S$  is the excitation intensity of white noise;  $\xi_n$  is the random phase angle in  $(0, 2\pi)$ ;  $g$  is gravitational acceleration.

When a ship is at sea, the wave encounter angle ( $\chi$ ) is the angle of wave encounter between the heading direction and wave direction as illustrated in Fig. 1. Also shown in Fig. 1 are the ship's breadth,  $B$ ; the ship's speed,  $\mu$ ; the wave's length,  $\lambda$ . The encounter frequency between wave and ship  $\omega_e$  is (Tang et al., 2006):

$$\omega_e = \omega - \frac{\omega^2}{g} \mu \cos \chi. \quad (10)$$

1 The encounter spectrum's relationship with the wave spectrum:

$$S_e(\omega) = \frac{S(\omega)}{1 - \left( \frac{2\omega}{g} \right) \mu \cos \chi}. \quad (11)$$

2 The wave spectrum, with single parameter, as specified by the ITTC (International Towing  
3 Tank Conference) (Kaplan, 1966) was used:

$$S(\omega) = \frac{A}{\omega^5} \exp \left\{ -\frac{B}{\omega^4} \right\}, \quad (12)$$

4 where  $A = 8.10 \cdot 10^{-3} g^2$ ;  $B = 3.11 / H_{1/3}^2$ ;  $H_{1/3}$  is the SWH.

5 Therefore, the wave excitation torque for random waves is calculated using the following  
6 formula:

$$F_{sea} = I_0 \alpha_0 \omega_0^2 \pi \sin \chi \sum_{n=1}^N \frac{h_n}{\lambda_n} \cos(\omega_{en} t + \xi_n), \quad (13)$$

7 in which wave height  $h_n = 2\sqrt{2\pi S(n\omega)}$  and wave length  $\lambda_n = \frac{2\pi g}{(n\omega)^2}$ .

8 After dimensionless treatment, the differential equation for a ship's rolling motion in random  
9 seas, in which the white noise is considered, is as following (Gu,2006b),

$$\ddot{x}(t) + \varepsilon \delta_1 \dot{x}(t) + \varepsilon \delta_2 \dot{x}^3(t) + x(t) - \alpha x^3(t) = \varepsilon f(t), \quad (14)$$

10 in which,  $x = \phi$ ;  $t = \omega_0 \tau$ ;  $\varepsilon \delta_1 = \frac{B_1(\omega)}{\Delta C_1} \omega_0$ ;  $\varepsilon \delta_2 = \frac{B_2(\omega)}{I + I_1(\omega)} \omega_0$ ;  $\alpha = \frac{C_3}{C_1}$ ;  $\Omega = \frac{\omega}{\omega_0}$ ;

11  $\omega_0 = \sqrt{\frac{\Delta C_1}{I + I_1(\omega)}}$ ;  $f(t) = \frac{F_{sea}}{\Delta C_1}$ ;  $\varepsilon$  is a very small parameter; the time  $t$  is controlled by the

12 natural frequency;  $\varepsilon \delta_1$  and  $\varepsilon \delta_2$  are linear and nonlinear dimensionless dampers, respectively.



1 The joint probability density of  $\phi$  and  $\dot{\phi}$  can be solved by solving the corresponding  
 2 Fokker-Planck-kolmogorov (FPK) equation for Equation (14). In this paper the method  
 3 proposed by Gu (Gu, 2006a) is used to solve the FPK equation. The joint probability is:

$$P_F(x_1, x_2 | \phi) = a \exp \left\{ -\frac{\phi}{D} \left( \frac{x_1^2}{2} - \alpha \frac{x_1^4}{4} \right) \right\} \exp \left\{ -\frac{1}{D} \left( \delta_1 \frac{x_2^2}{2} + \delta_2 \frac{x_2^4}{4} \right) \right\}, \quad (15)$$

4 in which,

$$\phi = \frac{\int_0^\infty x_2 (\delta_1 x_2 + \delta_2 x_2^3) \exp \left\{ -\frac{1}{D} \left( \delta_1 \frac{x_2^2}{2} + \delta_2 \frac{x_2^4}{4} \right) \right\} dx_2}{\int_0^\infty x_2^2 \exp \left\{ -\frac{1}{D} \left( \delta_1 \frac{x_2^2}{2} + \delta_2 \frac{x_2^4}{4} \right) \right\} dx_2}, \quad (16)$$

5  $a$  is normalized parameter which can be calculated using the following formula:

$$\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} P_F(x_1, x_2 | \phi) dx_1 dx_2 = 1, \quad (17)$$

6  $D$  is the amplitude of excitation.

7 Then, marginal probability density of  $\phi$  can be calculated based on the joint probability  
 8 density. Thus, the ship capsizing probability  $P$  can be calculated using the following  
 9 formula:

$$P = \max \left\{ \int_{\phi_{v1}}^{+\infty} P(x_1, t) dx_1, \int_{-\infty}^{\phi_{v2}} P(x_1, t) dx_1 \right\}, \quad (18)$$

10 in which,  $\phi_{v1}$  is the angle of disappearing positive stability,;  $\phi_{v2}$  is the angle of disappearing  
 11 negative stability;  $P(x_1, t)$  marginal probability density.

### 12 3.1.2. Ship speed loss in waves

13 Ship speed loss in waves has an important effect on the estimate of the ship's location in the  
 14 design of RATC. If the ship's speed loss is not considered, it will cause error when  
 15 calculating the ship's position over time. At present, there are many empirical formulas to  
 16 estimate the ship speed loss due to waves (Aertssen, 1969; James, 1957; Li et al., 2011). In  
 17 this paper, however, the formula proposed by He and Dong (2009) is used to estimate the ship  
 18 speed loss in the heavy conditions. The formulas described as follow:

$$\frac{\Delta V}{V} = \frac{12 \cdot \frac{B}{T} \cdot C_w}{\left[ 0.45 \cdot \left( \frac{L}{100} \right)^2 + 0.35 \cdot \frac{L}{100} \right] \cdot L} \cdot \% , \quad (19)$$

1 in which,  $\Delta V$  is ship's speed loss in waves, unit: kn;

2  $V$  is ship's design speed, unit: kn;

3  $L$  is length of two makefasts, unit: m;

4  $B$  is the ship's breadth, unit: m;

5  $T$  is the ship's draft, unit: m;

6  $C_w$  is the index of wave grade, which can be calculated using  $C_w = K \cdot T_1 \cdot H_{1/3}^2$ ;

7  $K$  is the correction factor, which can be calculated using the following formula:

$$8 \quad K = \begin{cases} -0.05 \cdot H_{1/3} + 0.9 & L \leq 150 \\ 1.3 & 150 < L < 200 ; \\ 0.0125 \cdot H_{1/3}^2 + 0.05 \cdot H_{1/3} + 0.7375 & L \geq 200 \end{cases}$$

9  $H_{1/3}$  is the SWH, unit: m;

10  $T_1$  is the wave period, unit: s.

### 11 **3.1.3. Forecast error of numerical model**

12 Although model forecasting accuracy is increasing, the forecast results from numerical  
 13 models still have errors caused by inaccurate initial and boundary conditions. If forecasting  
 14 errors are not considered in designing RATC, the calculation of ship's risk will have  
 15 significant errors. Dealing appropriately with the forecasting errors in numerical models is  
 16 important for weather routing. The SWH and wave frequency (wave period) errors are  
 17 important when calculating a ship capsizing probability.

18 With the increasing accuracy of measurements from satellite, the errors of the SWH from the  
 19 wave model have been assessment by many researchers (e.g. Chu et al., 2004; Guo and Hou,  
 20 2010). But now, measurements of the wave period are little, and most of them are from the  
 21 buoy data near the shore. So it is hard to conclude the distribution of the wave period forecast  
 22 errors of wave models using the limited data. Comparing with three buoys (which are near the  
 23 shore, the location of the three buoys can be found in the Fig. 1 of Zhou et al., 2012)  
 24 measurements of wave period, Zhou et al. (2012) found that WaveWatchIII underestimates

the wave period in the SCS (see their Fig. 5). According to the research of Gu and Miao (2005), under the same SWH, the smaller the period of waves, the higher the capsizing probability. It will overestimate the ship capsizing probability using the wave period from WaveWatchIII results. For the safety of the ship, it is acceptable because it avoid the high risk area far away. Considering the above conditions, we don't take the forecast errors of wave period in the model. The errors of wave period can be considered in the model as the SWH when the distribution are got with the increasing measurements.

In the research of Chu et al. (2004), the SWH errors from WaveWatchIII have a Gaussian-type distribution with a small mean ( $\mu$ ) value of 0.02m, as compared with the T/P altimeter data in the SCS. The RMS error ( $\sigma$ ) and correlation coefficient between the modelled ( $H_m$ ) and observed ( $H_o$ ) SWH are 0.48 m and 0.90 respectively. In this research, 1330 samples were used for statistical analysis.

Taking the error range into consideration, a ship capsizing probability for the forecast wave height is calculated based on the distribution of the wave model forecast errors. In this paper, the error range was processed using the truncation method. Because the probability of errors bigger than 2 m or less than -2 m is only 0.019, this paper only considers the error range in [-2,2]. The division of the error range  $\Delta E_i$  is shown in Table 1, and the probability for each error range is  $\Delta p_i$ . According to the forecast value of the wave height and the error range, the ship capsizing probability  $\Delta p_i$  in each error range can be calculated. If the value that the forecast value adds to the error range is less than 0, then the probability in this error range will be 0, because the wave height is greater than or equal to 0. Then, the ship capsizing probability  $p$  of ship in the forecast condition can be calculated using the following formula:

$$p = \frac{\sum_{i=1}^8 \Delta r_i \cdot \Delta p_i}{\sum_{i=1}^8 \Delta r_i} . \quad (20)$$

#### 3.1.4. Alternative waypoints

The positioning of the alternative waypoints is important to RATC design. Finding analytic solutions for the minimum economic cost of RATC, however, is intractable since the alternative waypoints can be at any point in the sea. To reduce the computational budget, the alternative waypoints must be artificially restricted by the area of heavy seas and rough weather caused by the TCs. In turn, if the distance between adjacent alternative waypoints is smaller, the route will be more economical but the amount of calculations will increase

dramatically. Alternative waypoints can be based on the range of the practical need and therefore, this extent is a second restrictive condition in the proposed model for minimum economical cost for RATC. A sketch of alternative waypoints is shown in Figure 2.

Practically, in the northern (southern) hemisphere, it is much safer to avoid a TC from the left (right) semicircular side. Therefore in the proposed RATC algorithm, only waypoints on the safer, left (right) semicircular side of a TC are considered.

### 3.2. Algorithm design

The algorithm of the minimum cost route for RATC is as follows (figure 3):

(1) Assume that the start time of a ship's RATC is  $t_0$ ; the ship's position is  $x_0$  at  $t_0$ , the next waypoint of ship's original planned route is  $x_{end}$ . Dividing the segment  $x_0x_{end}$  of the route into  $n$  parts of equal length, each point is  $x_i (i = 1, 2, \dots, n)$ , and drawing lines perpendicular to the segment  $x_0x_{end}$  through points  $x_i (i = 1, 2, \dots, n)$ . According to the range of the heavy weather area of a TC,  $m$  points are chosen on the left semicircular side of the TC for  $x_i (i = 1, 2, \dots, n)$ . These points  $x_{i,j}, (i = 1, 2, \dots, n; j = 1, 2, \dots, m)$  are the alternative waypoints for a ship's RATC (as shown in Figure 2).

(2) Beginning from point  $x_{i-1,j}$  (when  $i = 1, x_{i-1,j} = x_0$ ), separately calculate the time and the cost to sail from  $x_{i-1,j}$  to  $x_{i,k}, (k = 1, 2, \dots, m)$ . The time  $t_{i,j,k}$  and cost  $C_{i,j,k}$  sailing from  $x_{i-1,j}$  to alternative waypoints can be calculated using the following formula:

$$t_{i,j,k} = \int_{x_{i-1,j}}^{x_{i,k}} \frac{1}{v_{ship}(t, x)} dx \quad (i = 1, 2, \dots, n; j, k = 1, 2, \dots, m); \quad (21)$$

$$C_{i,j,k} = \int_{t_{i-1,j}}^{t_{i,k}} C_{oil}(D, V, Q_a) + C_t. \quad (22)$$

Taking the ship speed-loss from waves into account,  $v_{ship}(t, x)$  changes over time, external environment, and ship course. The real-time change data for wind, waves, and current can be obtained from the numerical model forecasting results.

(3) Ascertaining if there is an un-navigable area in a segment of the route  $x_{i-1,j}x_{i,k}$ . According to the environmental conditions of the ship's current position, the capsizing probability can be assessed in relation to the acceptable capsizing probability level. If the capsizing probability is acceptable, go to (4); if it is unacceptable, then  $C_{i,j,k} = +\infty$ .

(4) Calculating the minimum cost  $CC_{i,k} = \min_j(C_{i,j,k})$  and time  $tt_{i,k}$  to reach the point  $x_{i,k}$ . If  $CC_{i,k} = +\infty$ ,  $x_{i,k}$  is a unnavigable point that all segments cannot reach, it will not be used to select the next segment.

(5) Making  $i = i + 1$ , and carrying out step two (2) to step five (5) cyclically until  $i = n$ . All the minimum cost segments that connect to the  $x_{end}$  (which is  $x_{n1}$ ) make the shortest time route to avoid TC, which is  $X_0X_1X_2.....X_{end}$ . The times that a ship will arrive at each waypoint are  $T_0, T_1, T_2, ....., T_n$ .

In practice, the fewer the waypoints, the better the route. Fewer waypoints means fewer changes in direction and subsequent speed loss, resulting in more efficient operation. Thus, RATC is optimized to reduce the waypoints with no additional cost. The optimization algorithm is illustrated as follows (figure 4):

(1) The positions of the waypoints, which are the result of the shortest time RATC as discussed in the last section, are assigned to  $xx_i, (i = 0, 1, ..., n)$ . The time that a ship arrives at waypoint  $xx_i$  is assigned to  $tt_i$  and the cost to arrive at this point is  $CC_i$ . Make  $i = 0$ , and continue to the next step;

(2) Starting from  $xx_i$ , calculate the cost  $cc_j$  occurring when the ship is sailing along the segment  $xx_i, xx_j$  from the  $xx_i$  to  $xx_j (j = i + 1, i + 2, ....)$ . At the same time, check for un-navigable areas in segment  $xx_i, xx_j$  in relation to changing wind and wave conditions.

Let  $z = j - 1$  if there is an un-navigable area.

(3) Let  $dc = cc_z - cc_i$ , and  $DC = CC_z - CC_i$ . If  $dc \leq DC$ , then  $i = z$ . Assign  $xx_i$  and  $CC_i$  to set  $x_{ok}$  and  $c_{ok}$  respectively. Continue to the next step. If  $dc \geq DC$ , let  $z = z - 1$  and do step three (3) cyclically.

(4) Let  $i = z$ , do step two (2) to step four (4) cyclically until  $z = n$ .  $x_{ok}$  are the waypoints, and  $c_{ok}$  is the cost for the ship as it arrives at waypoints in the optimized shortest RATC.

#### 4. Case study and results

The TC Nockten was chosen to test the algorithm. Nockten's track for every six hours is shown in Figure 5. Nockten made landfall at Wenchang, Hainan province in China. The centre of the greatest wind speed is up to 25 m/s when landing. The direct economic loss caused by Nockten is estimated at about 0.6 billion dollars and two people were killed. Nockten also exerted serious influence on ships at sea.

Assume that a ship was in 19N, 111.5E at 0000 UTC, 28 July 2011, and that the ship took action to avoid the TC as soon as it received the TC warning. The next waypoint of the original route was at 20.5N, 120E. In this study, this scenario was used to design the RATC. The ship's value was 23.8 million dollars while the value of the cargo was 34.9 million dollars. The price of oil was \$871.00 per ton. The ship's profitability was 11.1 thousand dollars per day. The fuel consumption was 24 tons per day, at a speed of 10 knots (kn). It is assumed that the change of the ship's displacement was ignored in the RATC and that the ship's speed through water was unchanged.

##### 4.1. Numerical TC simulation

The WRF model was used to simulate the TC. In the model, the  $1^\circ \times 1^\circ$  NCEP (National Center for Environmental Prediction) data for 10:00 on 28 July was used as the initial data for the simulation, and six hour time interval daily NCEP data was used as boundary data. The model simulation area was  $99^\circ\text{E}$ - $130^\circ\text{E}$ ,  $0^\circ$ - $30^\circ\text{N}$ . The resolution was  $0.1^\circ \times 0.1^\circ$ , time step was 300s. The wind field as forecasted by WRF was used to drive the WaveWatch-III. The resolution of the wave model was  $0.1^\circ \times 0.1^\circ$ , time step was 900s. The resolution of wave direction was  $15^\circ$ . The results of the two models are shown in Figure 6.

## 4.2. The ship's capsizing probability

To calculate the ship's capsizing probability, the integration time was set to 0-300s; time step was set to 0.0125s; N was set to 180; the upper limit of the wave power spectrum was set to 4.5rad/s; the frequency interval  $\omega$  was set to 0.025rad/s;  $\alpha_0$  was set to 0.729. The change in the ship's capsizing probability with changes in the ship's heading and wave direction are shown in Figures 7a. Given the same wave height, the ship's capsizing probability reaches a maximum when the wave direction is close perpendicular to the ship's heading. The ship's capsizing probability is higher with increasing wave heights (Figure 7b). The change in a ship's capsizing probability with the wave height and the angle between the heading and wave direction is shown in Figure 7c.

The ship capsizing probability under different wave and heading conditions at 1000 28th is shown in Figure 8. The Figure shows that ship capsizing probability is very different when the angle between ship's heading direction and wave direction is different. So, the RATC must consider the angle between ship's heading direction and wave direction. The ship's capsizing probability is small with stern waves or when the vessel is sailing head to sea.

## 4.3. Economy and safety route design

The ship's capsizing probability at different heading directions and times were calculated based on the forecast results from the numerical models. The alternative waypoints are shown in Figure 2, where the interval in the perpendicular direction of the original route is  $0.35^\circ$ . The ship speed through water kept constant. The routes of different acceptable capsizing probability and ship speed are listed in Table 3. To compare the model's superiority to the sector diagram typhoon avoidance method, the same experiment is done using sector diagram typhoon avoidance method. In figure 9, A, B, and C separately represent the location of the tropical cyclone center at 00:00, 06:00, and 12:00 on 28 July (UTC).  $H_1, H_2$  and  $H_3$  represent the ship's location at 00:00, 06:00, 12:00 on 28 July (UTC). The result of sector diagram typhoon avoidance method is Exp6. The ship's experimental RATCs are shown in Figure 10a.

Exp1~Exp3 (the ship has the same acceptable capsizing probability but different ship speed) are taken as a group which are used to test the ship speed's effect on the result. Although the speed in the Exp3 is higher (1kn) than Exp2, but the shipping time is only less 0.1 hour than Exp2. This is because that when the ship speed is higher the environment which it countered is different, it has to choose the route according to the changing environment. For Exp3 (Figure 10a), the ship have to travel long distance to avoid the higher risk area (capsizing probability). It shows that higher speed does not mean less shipping time as

expected. In the acceptable capsizing probability, the safety probability of the RATC is also different with ship speed. The middle speed (16kn) has the highest benefit-cost ratio. The benefit-cost ratio is no direct relationship with the ship speed. Exp3~Exp5 are taken as a group to test the effect of acceptable capsizing probability on the result. In this group, higher risk (capsizing probability) can reduce the shipping time. But it does not mean higher benefit-cost ratio. The benefit-cost ratio of Exp3 is the highest in this group, the risk is the middle one. Comparing with the Sector diagram typhoon avoidance method (Exp6), the model can reduce the ship's risk when avoid TC and the cost. When the ship speed is same, the benefit-cost ratio of RATC is higher than Sector diagram typhoon avoidance method (see Exp3-Exp7).

In Figure 10b, the ship's speed is 17kn and the acceptable capsizing probability of the ship is  $7 \times 10^{-4}$ . The blue line is the RATC before optimization while the red line is the route after optimization. Figure 10b shows that the optimal route can reduce more waypoints. Figure 11 indicates the ship's position at different times, colours as shown in the capsizing probability scale bar at the bottom of the figure, represent the ship's capsizing probability at several heading angles at different times. The RATC in different time can avoid the area of the high risk with changing environment.

Experimental results show that: the higher the acceptable capsizing probability level, the lower the cost of the RATC. Meanwhile, the higher risk to the ship must be considered. The higher ship speed does not mean the low time cost as expect. However, lower costs do not mean that the route's benefit-cost ratio is higher. The case study shows that the cost of a ship's RATC is related not only to the ship's speed, but also to the ship's the acceptable risk level. In same environment condition, the ship's risk is related with ship's performance. When ship's accept risk (acceptable capsizing probability) is chosen, the suitable ship speed can be make according to the benefit-cost ratio of the RATC. Compared to the Sector diagram typhoon avoidance method, the routes provided by this model are more safe and economical.

## 5. Conclusions

TC is the serious threat for ship sailing in ocean. How to choose a route to avoid TCs safety and economic is an essential subject for the sailor and ship company. The high accuracy forecasted environment data from numerical models is possible to guide RATC. The traditional methods to find RATC have some limits. For example, they don't quantify the risk according the ship's performance, but according the sailor's experience to estimate the ship's risk. In this paper, a safe-economical RATC was designed based on the dynamic forecast environment. In this proposed route design method, the limitations of the traditional methods



to find RATC are avoided or reduced. The ship's risk under heavy seas is quantified using the ship's capsizing probability where the ship's capability to resist wind and waves is considered. Although the accuracy of forecast environment data has improved compared with past, the forecast error is still needed to consider. In the model, when calculated the risk the effect of forecast errors are considered according to the error distribution. Ship speed loss is also taken into the model, which has a big effect on calculating ship's position with time.

An acceptable risk level should be set according to the ship's characteristics and the company's risk tolerance. Based on the acceptable risk level and the benefit-cost ratio of different ship speed, the best speed to avoid TC can be figured out according to their benefit-cost ratio. According to the case study, comparing the traditional method (Sector diagram typhoon avoidance method), this model not only ensures the ship's safety but also reduces shipping costs. Using the model, companies and sailors can design RATC according to the ship's performance. It can increase the company's benefit within the ship's acceptable risk. There are some aspects needed to be considered in the future: (1) the joint effect of wind and wave will be included when calculating the ship's capsizing probability. In this paper, we only consider the wave's effect on ship's capsizing probability. The joint effect of wind and wave will be more accurate when calculating the capsizing probability. (2) the rapid growth of computing costs when increasing the spatial resolution of alternative waypoints will be addressed. When the alternative waypoints become more, there will be more calculation for the ship capsizing probability, the waypoint choice and the shipping time comparison. It is necessary to design an intelligence algorithm to solve the problem. (3) the comfort level of crew.

## Acknowledgement

This work is supported by the National Science Foundation of China (NSFC) through Grants 51209166 and D0512/40805063, self-determined and innovative research funds of WUT, State Key Laboratory of Tropical Oceanography (South China Sea Institute of Oceanology, Chinese Academy of Science).

## References

- Andrejev, O., Soomere, T., Sokolov, A., and Myrberg, K. : The role of the spatial resolution of a three-dimensional hydrodynamic model for marine transport risk assessment. *Oceanologia*, 53, 309-334, 2011.
- Azaron, A. and Kianfar, F.: Dynamic shortest path in stochastic dynamic networks: Ship routing problem. *European Journal of Operational Research*, 144, 138-156, 2003.

- 1 Aertssen, G.: Service Performance and Trials at Sea. Performance Committee of 12th ITTC.  
2 233-265,1969.
- 3 Bedard, R.: Feasibility of Using Wavewatch III for Days-Ahead Output Forecasting for Grid  
4 Connected Wave Energy Projects in Washington and Oregon. Electric Power Research  
5 Institute. Available at  
6 [http://oceanenergy.epri.com/attachments/wave/reports/Wave\\_Forecasting\\_Final\\_Report.pdf](http://oceanenergy.epri.com/attachments/wave/reports/Wave_Forecasting_Final_Report.pdf)  
7 ,78pp., 2008.
- 8 Bikdashi, M. Balachandran, B. and Nayfeh, A.: Melnikov analysis for a ship with a general  
9 roll-damping model. Nonlinear Dynamics, 6,101-124, 1994.
- 10 Chen, H.: A Minimum Cost Dynamic Program for Ship Routing under Uncertainty. PhD  
11 thesis, Department of Ocean Engineering, MIT, America, 163pp., 1978.
- 12 Chen, J.H., and Zhang, J.P.: Navigation Meteorology and Oceanography. Dalian maritime  
13 university press. Dalian, China, 303pp., 2004. (in Chinese)
- 14 Chu. P.C., Qi, Y.Q., Chen, Y.C., Shi, P., and Mao, Q.W.: South China Sea Wind-Wave  
15 Characteristics. Part I: Validation of Wavewatch-III Using TOPEX/Poseidon Data. Journal  
16 of Atmospheric and Oceanic Technology. 21,1718-1733, 2004.
- 17 Christiansen, M., Fagerholt, K., and Ronen, D.: Ship routing and scheduling: Status and  
18 perspectives. Transportation Science, 38, 1-18, 2004.
- 19 Delitala, A.M.S, Gallino, S., Villa, L., Lagouvardos K., and Drago A.: Weather routing in  
20 long-distance Mediterranean routes. Theoretical and Applied Climatology  
21 102,125-137,2010.
- 22 Falzarano, M., Shaw, S.W., and Troesh, A.W.: Application of Global Methods for Analyzing  
23 Dynamic Systems to Ship Rolling Motion and Capsizing. International Journal of  
24 Bifurcation and Chaos 2,101-115,1992.
- 25 Gu, J.Y.: Calculation of Ship Rolling Probability Using a New Path Integration Method.  
26 Journal of Ship Mechanics 10,43-52,2006a.
- 27 Gu J.Y.: Probability Analysis of Ship Nonlinear Roll-Motion Excited by White Noise. Journal  
28 of Ship Mechanics 10,18-25,2006b.
- 29 Gu, J.Y., and Miao, Z.H.: Numerical Simulation of Ship's Safe Probability in Stochastic  
30 Waves. Journal of Jiangsu University of Science and Technology (Natural Science Edition),  
31 19,6-11(in Chinese), 2005.
- 32 Guo, Y.Y., and Hou, Y.J.: Statistical Analysis of Ocean Wave Numerical Forecast Error.  
33 Marine Science, 34,65-68 (in Chinese), 2010.

- 1 Hagiwara, H.: Weather routing of (sail-assisted) motor vessels, PhD Thesis, Technical  
2 University of Delft, Netherlands , 340pp.,1989.
- 3 He, H.M., Dong, G.X., and Jiang YX.: Approximate Estimation for Ship Speed Loss in Wave.  
4 Journal of SSSRI. 32,6-9,2009.
- 5 Holweg, E.J. : Mariner's guide for hurricane awareness in the North Atlantic Basin. United  
6 States: National Weather Service. Available at <http://www.nhc.noaa.gov/marinersguide.pdf>,  
7 (last access: 18 May 2012), 2000.
- 8 Hopkins, J.S.: The Accuracy of Wind and Wave Forecasts. Health and Safety  
9 Executive-Offshore Technology Report, London,1997.
- 10 Huang, Y.S., Wang, Z., and Li, H.T.: Calculation of the capsizing Probability of Ship at Beam  
11 Wind and Sea. Journal of Tianjin University, 34,651-654 (in Chinese) ,2001.
- 12 James, R.W.: Application of Wave Forecast to Marine Navigation. US Navy Hydrographic  
13 Office, Washington,1957.
- 14 Kaplan, R.: Lecture notes on nonlinear theory of ship roll motion in a random seaway[ A] .  
15 11th ITTC[C], Tokyo, 393,1966.
- 16 Li, C., Yang, B., and Zhang, Y.S.: Estimation methods of the ship's speed-loss in wind and  
17 waves. Ship science and technology 33,27-30 (in Chinese) ,2011.
- 18 Liu, D.G., Wang, D.Q., and Wu, ZL.: Safe-economic decision making model of ship's  
19 avoidance routing to tropical cyclone. Journal of Traffic and Transportation Engineering  
20 5,94-98 (in Chinese) ,2006.
- 21 Padhy, C., Sen, D., and Bhaskaran, P.: Application of wave model for weather routing of  
22 ships in the North Indian Ocean. Natural Hazards 44,373-385,2008.
- 23 Panigrahi, J., Tripathy, J., and Umesh, P.: Optimum tracking of ship routes in 3g-WAM  
24 simulated rough weather using IRS-P4 (MSMR) analysed wind fields. Journal of the Indian  
25 Society of Remote Sensing 36,141-158,2008.
- 26 Magirou, E.F., and Psaraftis, H.N.: Quantitative Methods in Shipping: A Survey of Current  
27 Use and Future Trends. Athens University of economics and business. Report  
28 No.E115,1992.
- 29 Maki, A., Akimoto, Y., Nagata, Y., Kobayashi, S., Kobayashi, E., Shiotani, S., Ohsawa, T.,  
30 and Umeda, N.: A new weather-routing system that accounts for ship stability based on a  
31 real-coded genetic algorithm. J. Mar. Sci. Technol., 16,311-322. DOI:  
32 10.1007/s00773-011-0128-z,2011.
- 33 McCord, M.R., Young-Kyun, Lee, and Hong Kam Lo.: Ship Routing through  
34 Altimetry-Derived Ocean Currents. Transportation Science 33,49-67,1999.

- 1 Shen, D., and Huang, X.L.: Lasting Time before Capsize of Ship in Random Beam Waves.  
2 Shipbuilding of China 41,14-21 (in Chinese) ,2000.
- 3 Shi, X.H., Zhang, J., and Wang, S.: Analysis of rolling capsizing probability of warship under  
4 random wind and beam seas. Journal of Ship Mechanics 15,473-479 (in Chinese) ,2011.
- 5 Soda, T., Shiotani, S., Makino, H., and Shimada, Y.: Simulation of Weather and Ocean for  
6 Numerical Ship Navigation. Proceedings of the ASME 2011 30th International Conference  
7 on Ocean, Offshore and Arctic Engineering, Rotterdam, Netherlands, 19-24 June  
8 2011,1-8,2011.
- 9 Tang, Y.G., Gu, J.Y., Zheng, H.Y., and Li, H.X.: Study on the ship capsize in random beam  
10 seas using Melnikov method. Journal of Ship Mechanics 8,27-34 (in Chinese) ,2004.
- 11 Tang, Y.G., Liu, L.Q., and Zheng, H.Y.: Safe Basin Method of Predicting Survival  
12 Probability of Ships in Bow Seas and Quartering Seas. Journal of Tianjin University  
13 39,1021-1025 (in Chinese) ,2006.
- 14 Thompson, J.M.T.: Transient basins: a new tool for designing ships against capsize.  
15 Proceedings, IUTAM Symposium on the Dynamics of Marine Vehicles and Structures in  
16 Waves, London, 325- 331,1990.
- 17 Thompson, J.M.T, Rainey, R.C.T., and Soliman, M.S.: Mechanics of Ship Capsize under  
18 Direct and Parametric Wave Excitation. Philos. T. R. Soc. Lond., 338, 1–13, 1992.
- 19 Tolman, H. L.: Validation of WAVEWATCH III version 1.15 for a global domain. NOAA /  
20 NWS / NCEP / OMB Technical Note Nr. 213, 33 pp, 2002.
- 21 Wisniewski, B., Medyna, P., and Chomski, J.: Application of the 1-2-3 Rule for Calculations  
22 of a Vessel's Route Using Evolutionary Algorithms. TransNav - International Journal on  
23 Marine Navigation and Safety of Sea Transportation 3,143-146, 2009.
- 24 Wisniewski, B., and Kaczmarek, P.: Elements of Tropical Cyclones Avoidance Procedure.  
25 TransNav - International Journal on Marine Navigation and Safety of Sea Transportation  
26 6,119-122,2012.
- 27 Wu, J.L., Ma, X.X., Fan, Z.Z., Liu, D.G., and Liu, Z.J.: Benefit evaluation for ship's  
28 avoidance routing of tropical cyclone. Journal of Dalian Maritime University 36, 31-34 (in  
29 Chinese),2010.
- 30 Zhang,W.J., Wei, S.Y., Li, Q., Liu, D.G., and Liu, Z.J.: Multilevel decision method of ship's  
31 tropical cyclone avoidance route using multisource track forecast. Journal of Traffic and  
32 Transportation Engineering 10, 122-126 (in Chinese), 2010.

33

34

1 **Table1** The forecast error range division

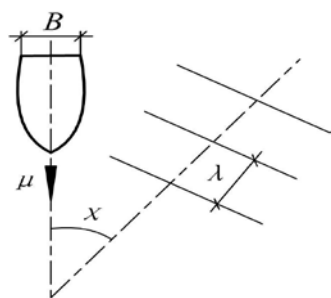
forecast error range(in meters)	[-2,-1.5]	[-1.5,-1]	[-1,-0.5]	[-0.5,0]	[0,0.5]	[0.5,1]	[1,1.5]	[1.5,2]
Probability in this error range	7.59e-4	1.6e-2	0.12	0.34	0.36	0.14	0.02	0.001

1    **Table 2** Parameter values of the ship

$L$	171.7m	$I_0$	$1.070*10^7 kg.m^2$
$B$	16.8m	$C_1$	0.871m
$\Delta$	8000t	$C_3$	0.013m
$B_1$	$1.070*10^7 kg.m^2 / s$	$\phi_{v1}$	-1.39rad
$B_2$	$1.070*10^7 kg.m^2$	$\phi_{v2}$	1.39rad
$\omega_0$	0.807rad/s	$T$	8m

1 **Table 3** Experimental results

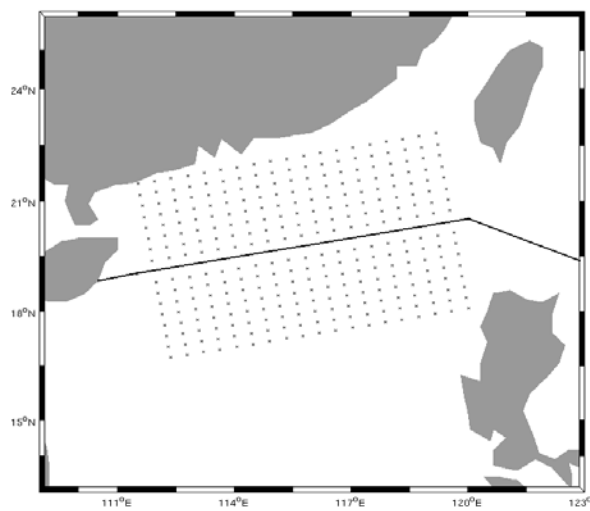
No.	Ship speed (kn)	Acceptable capsizing probability $P_a$	Maximum wind in the sailing (m/s)	Maximum wave in the sailing (m)	Shipping time (hour)	Safety probability	Cost (thousand dollar)	Logarithm of Benefit-cost ratio $\lg(Ra)$
Exp1	15	0.001	18.1	5.2	46.6	0.9991	81.37	-2.858
Exp2	16	0.001	17.8	5.3	41.6	0.9992	76.60	-2.884
Exp3	17	0.001	20.1	4.4	41.5	0.9991	79.71	-2.867
Exp4	17	0.002	20.1	4.4	40.7	0.9980	78.17	-2.875
Exp5	17	0.0007	20.1	4.4	41.5	0.9993	79.71	-2.867
Exp6	17	/	20.7	4.2	40.9	0.9959	78.56	-2.866



1

2 **Figure 1** The wave encounter angle

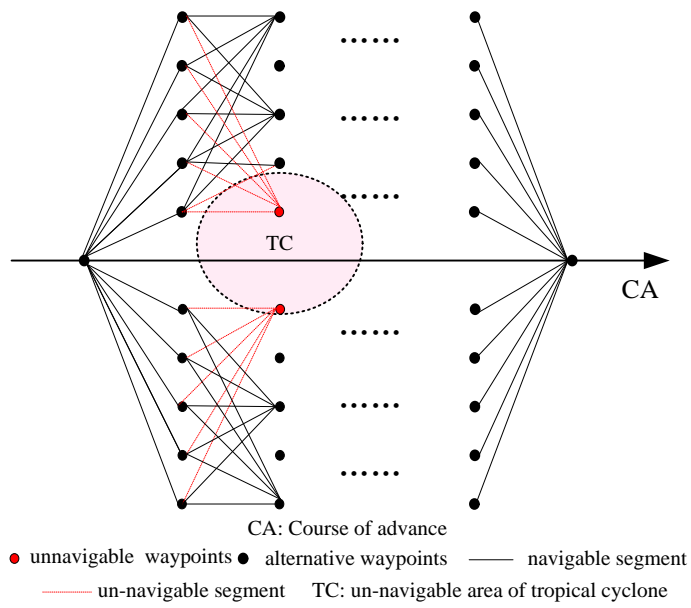




1

2 **Figure 2** Sketch of alternative waypoints

1



2

3

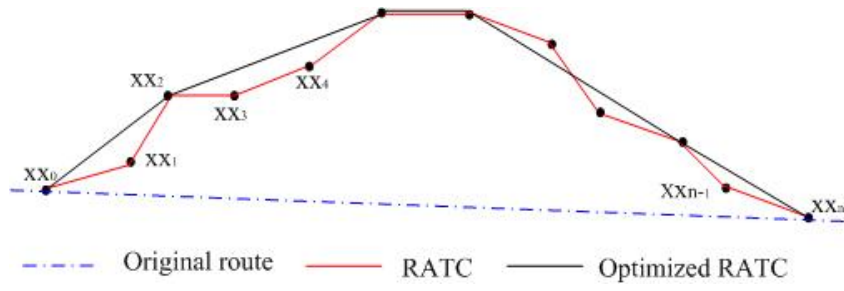
**Figure 3** A route designed to avoid TC

4

(The un-navigable waypoint is the point that all segments cannot reach)

5

1

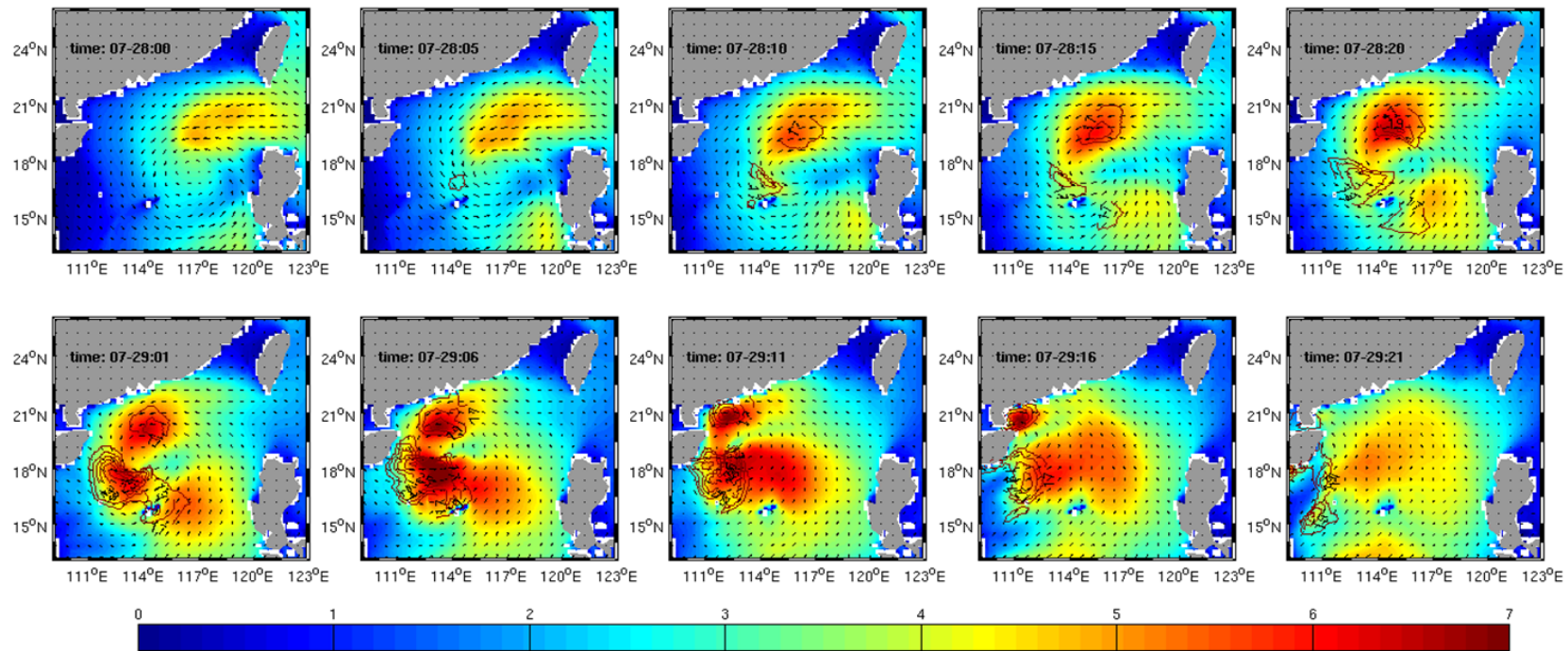


3      **Figure 4** Optimized RATC

1



1

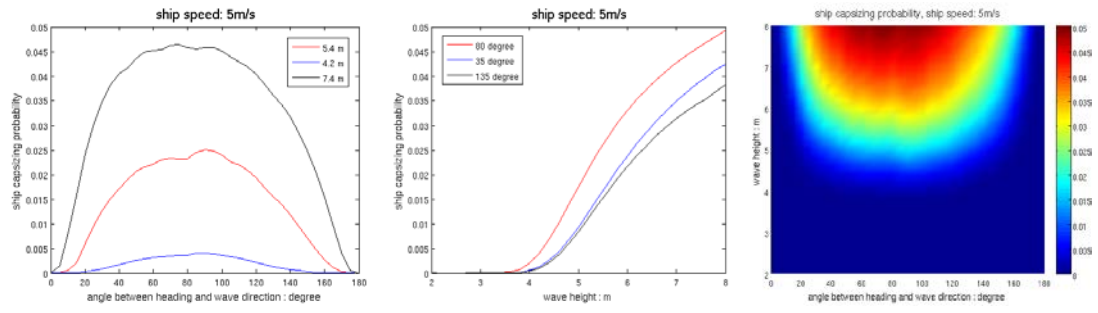


Wave height : m

2

3 **Figure 6** The forecast wind and wave conditions

1

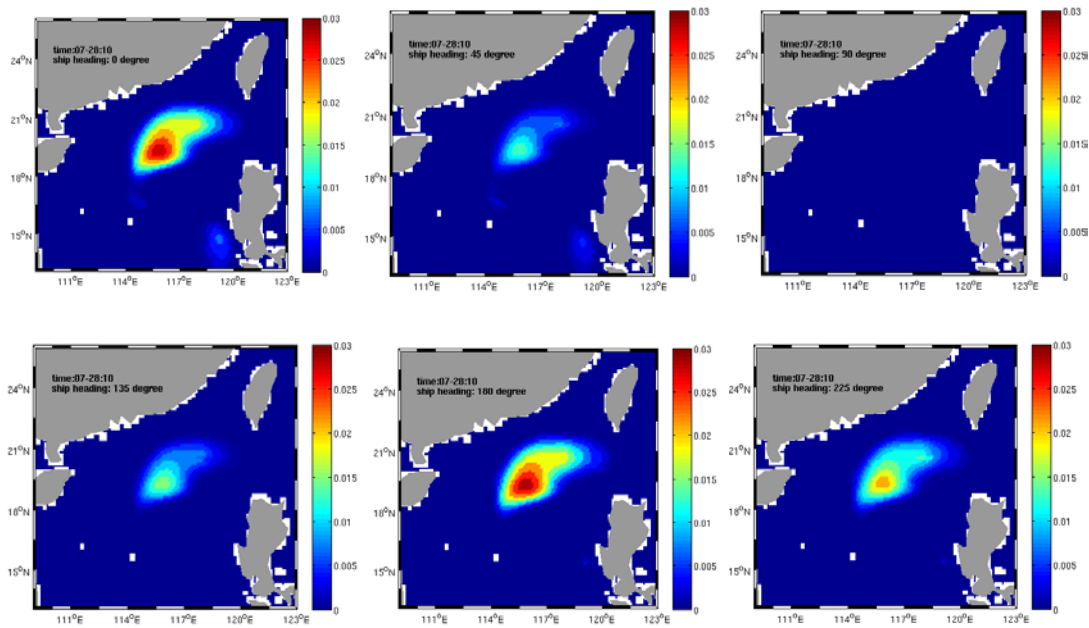


2

3 **Figure 7** The change of ship's capsizing probability

1

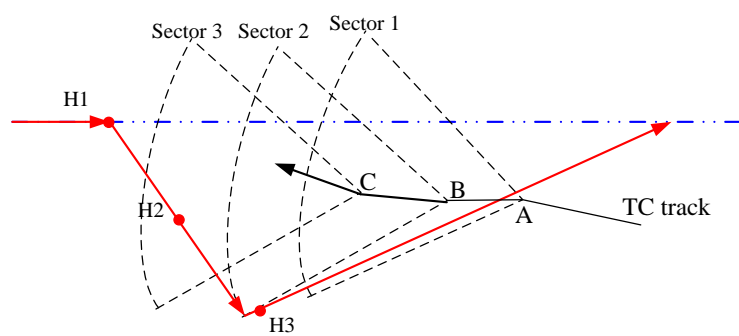
2



3

4 **Figure 8** The ship's capsizing probability at different ship headings on 28 July 2011, 10:00  
5 (UTC)

1

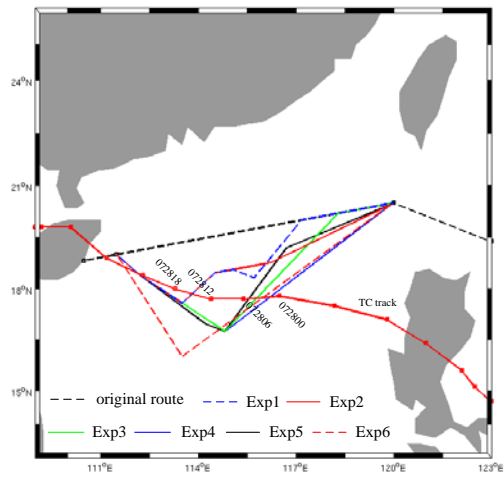


2

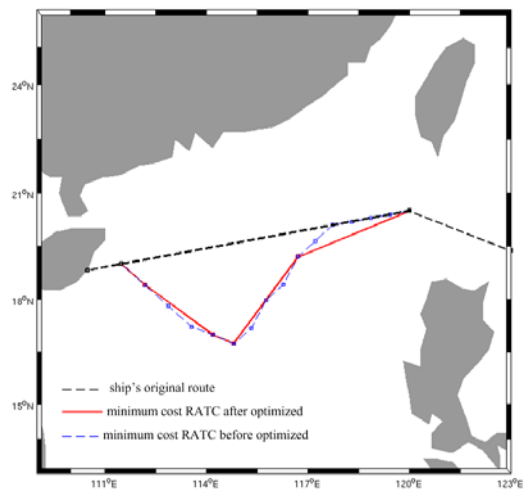
3 **Figure 9** Sector diagram typhoon avoidance method



1

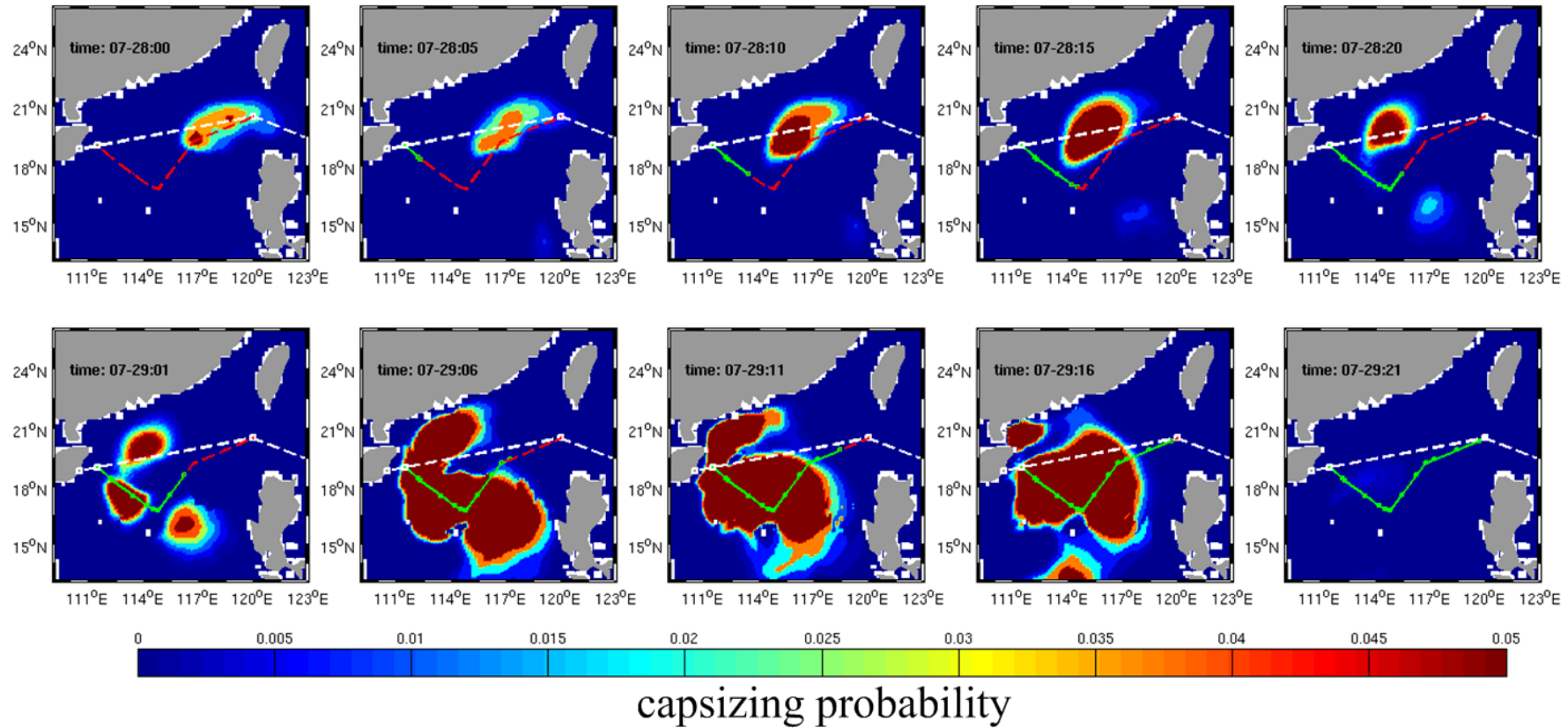


2



3 **Figure 10** (a) Experimental routes (b) The route before and after the optimization experiment  
4 Exp5

1



2

--- The route that ship will sail      — The track that ship has sailed

3 **Figure 11** Ship position and the capsizing probability at different times