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A Domain-Based Model for Identifying Regional Collision Risk and Depicting Its Geographical Distribution

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Abstract: In recent years, the increasing volume and complexity of ship traffic has raised the probability of collision accidents in ports, waterways, and coastal waters. Due to the relative rarity of collision accidents, near misses have been used in the research to study the collision risk in the relevant water areas. However, the factor of near miss identification is usually limited to the relative distance between ships, and the instantaneous quantification and geographical distribution of collision risk is not paid enough attention. Therefore, this article proposed a domain-based regional collision risk model that can quantify the collision risk by detecting near miss scenarios. The proposed model is capable of quantifying the collision risk in the water area instantaneously and periodically and can be used to depict the geographical distribution of collision risks in combination with a grid method and the spatial interpolation technique. To validate the proposed model, some experimental case studies were carried out using automatic identification system (AIS) data from the Bohai Strait. The results show the capability and advantage of the proposed model in regional collision risk identification and visualization, which is helpful for maritime surveillance when monitoring and organizing ship traffic and may therefore contribute to the improvement of maritime safety.

Keywords: collision risk; ship domain; near miss; maritime traffic; geographical distribution

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1. Introduction

With the rapid development of the global economy, maritime trade has become more frequent in recent years, and maritime traffic demand is accordingly increasing, causing significant changes in ship traffic [1]. The changes to ship traffic are mainly reflected in the increasing volume and complexity of ship traffic, leading to an obvious increase in the probability of collisions, which have a serious impact on maritime traffic safety and cause serious loss of life, property, and environment [2,3].

In order to avoid collision accidents, the quantitative study of collision risk has always been an important concern of maritime traffic research. The objective of the study is to accurately and flexibly quantify the collision risk of ships in a specific water area, which is important for both the mariner and the maritime surveillance personnel. In the past, in order to study collision risk regionally, relevant scholars have often used historical data regarding collision accidents to approximately reveal the collision risk in a water area [4,5]. In addition, some scholars have built mathematical models to predict the probability of ship collision accidents in a specific water area. However, a collision is a rare event; in more cases, ships will pass each other at a very close distance. Although there is no collision in the end, this is still a very dangerous state and is known as a near miss. Compared with collision-related data, the consideration of near misses can reveal the potential collision risk in a water area more sufficiently, offering greater significance for maritime safety in practice. Therefore, in order to sufficiently and accurately reveal the collision risk of a water area, this paper aimed to propose a new domain-based model by which to quantify the regional collision risk and depict its geographical distribution through near miss identification.

2. The Literature Review

In maritime traffic research, a near miss refers to a special encounter scenario in which two ships ultimately pass very close to each other. To accurately detect near miss situations and to study the collision risk in a water area, scholars have considered various factors and have proposed multiple models. Barrat [6] has used near misses to quantify the collision risk in a water area. In order to estimate the number of near misses, the author presents the time difference as a variable and quantifies the collision risk by the number of times that the time difference is less than a certain value in a period of time. Goerlandt et al. [7] have proposed a method by which to detect near misses between two ships using ship domain. This method can identify critical encounters between ships in the AIS database. To reduce the collision warning frequency and the operators' workload, Fukuto and Imazu [8] use the distance at the closest point of approach (DCPA) and the time to the closest point of approach (TCPA) as thresholds by which to determine near miss scenarios. However, some scholars consider the use of DCPA and TCPA alone to be inadequate to fully reveal the collision risk during a ship encounter. In addition to the DCPA and TCPA, the relative distance between ships was also incorporated into the detection of collision risk [9]. In order to detect near misses, Zhang et al. [10,11] have built a vessel conflict ranking operator model based on AIS data, which considers the relative distance between ships, the relative speed, and the relative heading. The model can identify near miss scenarios in the water area without using expert knowledge. Yoo [12] has proposed a density map of near misses to reveal the risk in the South Sea of Korea. The near misses are determined under the conditions of DCPA < 0.1 nm, TCPA < 3 min, and ship distance < 0.3 nm. There are also some scholars using ship domain to determine near miss scenarios. Kim and Jeong [13] take the violation of ship domain as the condition with which to determine a near miss. The logistic regression method is used to evaluate the near miss index, and the risk in the Busan Port and Busan New Port is visualized accordingly. Yao et al. [14] have conducted a study on the characteristics of potential collision events in the Yangtze River estuary and adjacent waters based on a quaternion ship domain method, one which can detect non-accident critical events and provide information support for marine spatial planning and management. Cui [15] has analyzed the temporal distribution of near misses in the Qiongzhou Strait based on the concept of ship domain and conducted a kernel density analysis of ship positions in different encounter situations where near misses occur. Li et al. [16] have proposed an improved rule-aware time-varying collision risk identification model. The model considers the estimation of target ship motion and the corresponding uncertainty in the process of collision risk analysis, while also incorporating good seamanship. Xin et al. [17] have proposed a systematic traffic clustering method by which to find multi-ship encounters with a high collision risk. Further, the authors have proposed a new systematic multi-scale collision risk estimation approach. The approach is extended from the theory of the complex network and is able to capture the traffic conflict patterns in complex port waters [18]. Zheng et al. [19] have proposed a ship collision risk quantification method based on a generalized three-dimensional spatiotemporal ship domain model, which can consider both ship collision probability and collision consequence. Zhen et al. [20] have proposed a novel regional collision risk identification method based on the aggregation density of ship encounter clusters, one which can quantify the spatial and temporal regional collision risk distribution more intuitively and effectively. Zhou et al. [21,22] have proposed a near miss identification model based on a ship arena, which is a super ship domain, and studied the regional collision risk accordingly. A near miss is determined when the ship arena is violated by other ships.

Near miss research is carried out widely. However, research on the identification of near misses has mostly been conducted based on the relative distance between ships, which can only represent the relative difference in space and cannot characterize the actual spatial relationship or the potential collision risk. Meanwhile, the rules of collision avoidance are not considered sufficiently in detecting near misses. In addition, most of the current quantitative studies on collision risk based on near misses focus on the analysis and evaluation of the overall level of the collision risk in the water area but pay little attention to the spatial distribution and instantaneous collision risk regionally.

To overcome the above-mentioned problems, this article proposed a novel domain-based regional collision risk model, which was established by a new collision risk indicator. The model can reveal the potential collision risk in the water area more sufficiently and flexibly and depicts its spatial distribution accurately. The remainders of this article were arranged as follows: in Section 3, the regional collision risk model is established with the building of the new domain-based indicator. To validate the proposed model, some experimental case studies using the real AIS data from the Bohai Strait are discussed in Section 4. Some discussion of the advantages and disadvantages about the proposed model are made in Section 5. Our conclusions are drawn in Section 6, and some suggestions for future work about the proposed model are given.

3. The Domain-Based Regional Collision Risk Model

3.1. The Establishment of the Domain-Based Index

To model the regional collision risk model, the safety domain of the ships in the studied water area should be established first. The ship domain was established to identify the near miss scenario, which is a dangerous state of near collision between ships, so as to represent collision risk in the water area.

The ship domain is the safety zone around a ship when the ship moves in two-dimensional space. The concept of the ship domain was firstly proposed by Fujii [23] and was defined as "a two-dimensional area surrounding a ship which other ships must avoid—it may be considered as the area of evasion". Later, Goodwin [24] extended ship domain research to open water areas and defined the ship domain as "the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles". In modeling the ship domain, considering the influence of the Convention on the International Regulations for Preventing Collisions at Sea, which is commonly abbreviated as COLREG, the shape of the ship domain becomes an unequal sector geometry. In order to utilize the ship domain to conduct marine traffic computer simulation to study ship encounters and collision avoidance, Davis et al. [25] smoothed the boundary of the unequal sector ship domain model established by Goodwin to form a circular ship domain. To facilitate the subsequent calculation of the relevant index, the shape of the ship domain model established in this paper was selected as a circle, with reference to the smoothing boundary model proposed by Davis et al. [25], which can be expressed with the following equation.

$$SD(B_i) \leq R_{B_i}(i = 1, 2, 3, \cdots, n) \tag{1}$$

where B_i refers to the i-th bearing around the ship, R_{B_i} refers to the distance between the ship domain boundary at the i-th bearing around the ship, $SD(B_i)$ refers to the parameterization of the ship domain, and n refers to the number of bearings selected around the ship. Specifically, n bearings are divided within a 360-degree range centered on the ship, and the area with the range of R_{B_i} is regarded as the ship domain.

Considering the provisions on encounters in COLREG, ships coming from different bearings will cause different collision risks. To reflect this phenomenon, the center of the ship domain was moved a certain distance to the port side and stern side of the ship to highlight the danger of incoming ships on the starboard and bow side. The geometric center of the domain was an imaginary ship whose function was to mark the specific location of the ship domain in the water area, as shown in Figure 1. The displacement of the ship domain center was determined in a rotating coordinate system.

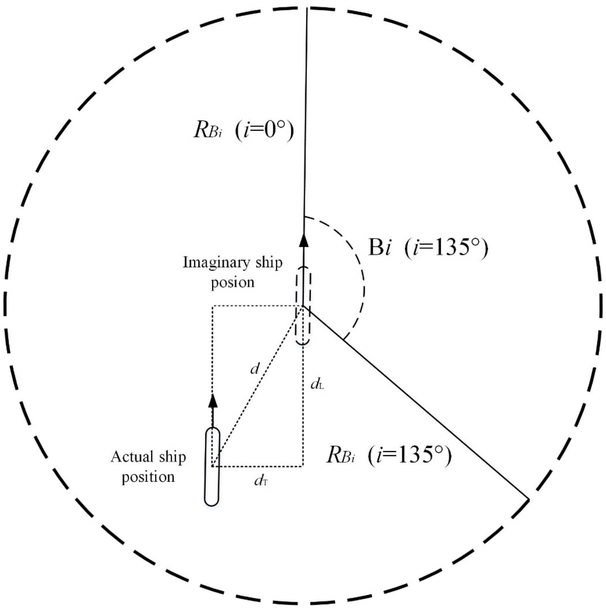

Figure 1. Illustration of the ship domain in this article.

Based on the established ship domain, two domain-based indexes were built to identify the near miss scenario. The first index was the Ship Domain Overlapping Index (SDOI), which was actually a coefficient for scaling up or down the domain size and was first proposed by Liu et al. [26]. The ship domains of the two encounter ships will be tangent when the sizes of domain are multiplied by this coefficient simultaneously. An example of an SDOI larger than 1 is shown in Figure 2.

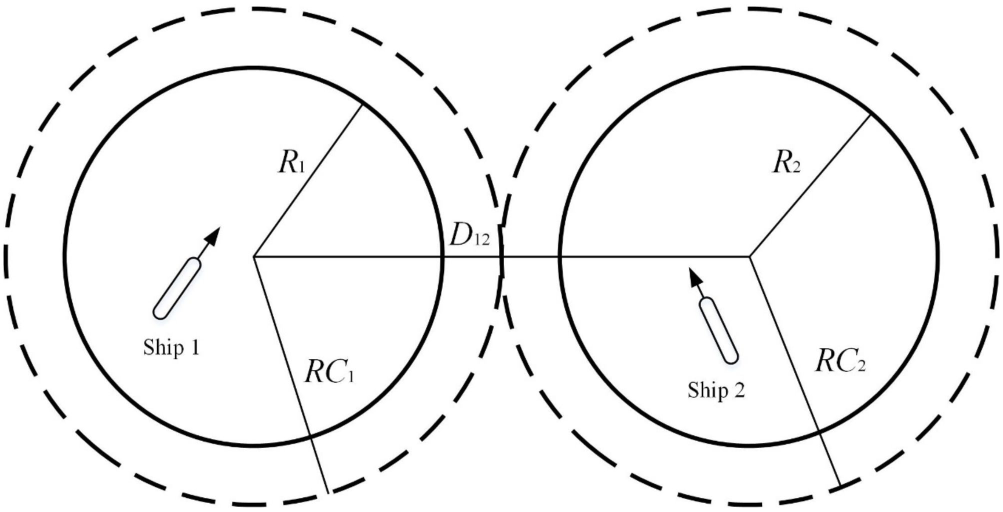

Figure 2. Illustration of the Ship Domain Overlapping Index.

When the SDOI equals 1, the ship domains are just tangent; that is, the two domains start to violate each other, which indicates the collision risk has reached a certain level. After that, as the SDOI continues to get smaller and the ship domains begin to intersect, the situation becomes more and more urgent. Given these circumstances, the SDOI is improved in this article to better represent the relative spatial relationship between two ships. The improved index was named the Ship Domain Overlapping Rate (SDOR). The SDOR refers to the ratio of the overlapping area to the respective areas of the two ship domains after the domains begin to overlap, as shown in Figure 3.

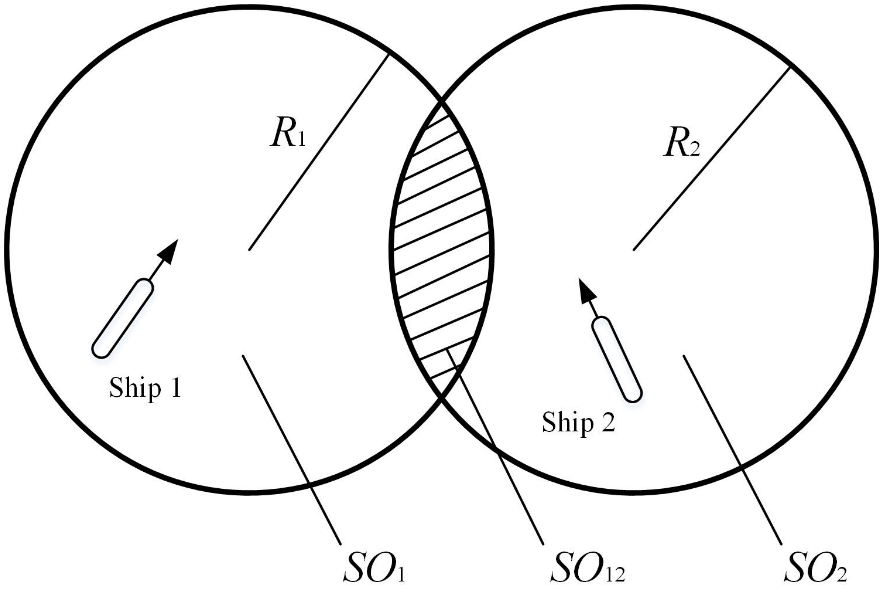

Figure 3. Illustration of the Ship Domain Overlapping Rate.

With the increase of the ratio of overlapping areas to the respective areas of the two ship domains, the domain violation becomes more serious, and the situation becomes more urgent. The average value of the two ratios can represent the collision risk under this domain violation situation, which can be expressed as follows:

$$SDOR_{ij} = \left(\frac{SO_{ij}}{S_i} + \frac{SO_{ij}}{S_j} \right) / 2 \tag{2}$$

where SO_{ij} refers to the overlapping area between the ship domain of Ship i and Ship j, and S_i and S_j are the domain sizes for Ship i and Ship j. Compared with the SDOI, when the two ship domains violate each other, the SDOR can better represent the collision risk between two ships, especially if the sizes of the two ships areas are different.

3.2. Identification of the Near Miss Scenario

According to the SDOR between two ships established above, the near miss scenario in the water area could be identified by combining it with two traditional collision avoidance parameters.

When the ship domains begin to overlap and gradually intersect, the value of the SDOR begins to be generated. At this time, the risk of collision is still low. With the further overlap of ship domains, the collision risk between two ships gradually increases. Therefore, the SDOR can be used as a threshold to judge a near miss scenario. The threshold of the SDOR for identifying a near miss scenario can be set according to the actual traffic situation and the research demand. Two traditional collision avoidance parameters are also taken as the threshold of near miss identification. The two traditional collision avoidance parameters are the distance to the closest point of approach (DCPA) and the time to the closest point of approach (TCPA), which can indicate the risk of collision in the spatial and temporal aspects, respectively, and are widely used in collision risk quantification research. With the reduction of the DCPA and TCPA, the urgency of the ships in the spatial and temporal aspects will increase, and the collision risk will increase accordingly. According to the relevant research and collision avoidance practice, the threshold of the DCPA is first set to 2 nautical miles and the threshold of the TCPA is first set to 10 min. When the DCPA between two ships is less than or equal to 2 nautical miles, the TCPA is less than or equal to 10 min, and the SDOR is greater than or equal to the threshold value, the encounter of two ships is judged as a near miss scenario. Compared with the DCPA and TCPA, which are objective parameters that predict the collision risk between ships, the

SDOR can better represent the current spatial relationship between them and consider the impact of collision avoidance regulations, which is more suitable for determining collision avoidance practices.

It should be noted that the thresholds for the three indexes are not fixed and can be adjusted according to the different traffic situations or different safety standards required. In general, the encounter of two ships is identified as a near miss scenario when the following equations are satisfied.

$$DCPA_{ij} \leq \gamma_{DCPA} \ (i,j = 1,2,3,\cdots,n) \tag{3}$$

$$TCPA_{ij} \leq \gamma_{TCPA} \ (i,j = 1,2,3,\cdots,n) \tag{4}$$

$$SDOR_{ij} \geq \gamma_{SDOR} \ (i,j = 1,2,3,\cdots,n) \tag{5}$$

where $DCPA_{ij}$, $TCPA_{ij}$, and $SDOR_{ij}$ refer to the DCPA, TCPA, and SDOR between Ship i and Ship j, and γ_{DCPA}, γ_{TCPA}, and γ_{SDOR} are the thresholds for judging a near miss scenario. When the thresholds of the DCPA and TCPA are further increased, and the threshold of the SDOR is further reduced, it means that the two ships are identified as near miss ships earlier; that is, a higher safety standard is adopted. On the contrary, when studying narrow waterways or traffic separation schemes, ships mostly maintain a relatively close distance due to the width of the water area, and the thresholds can be loosened to a certain extent by lowering the thresholds of the DCPA and TCPA and raising the threshold of the SDOR.

3.3. The Identification of Collision Risk and Its Spatial Distribution

After identifying the near miss scenarios in the water area, the regional collision risk can be represented. Specifically, after identifying all near miss scenarios, the studied water can be divided into grids, and the near miss scenarios in each grid can be counted. According to the numbers of near miss scenarios in each grid per unit time, the regional collision risk can be identified as follows:

$$CR_{Grid_k} = \frac{NearmissCount_{Grid_k}}{TimeInterval} \tag{6}$$

where $Grid_k$ $(k = 1,2,3,\cdots,K)$ refers to the k-th grid in the water area, and K refers to the number of grids. $NearmissCount_{Grid_k}$ refers to the number of near miss scenarios in the k-th grid, and $TimeInterval$ refers to the time interval for counting the number of near miss scenarios. CR_{Grid_k} refers to the collision risk index of the k-th grid in the time period of $TimeInterval$, and it can be used to visualize the collision risk distribution in the water area. This is because a near miss is an event that occurs more frequently than an actual collision, and is close to an actual collision, as shown in Figure 4.

On the basis of the near miss results, the collision risk situation in the water area can be visually represented, so as to help maritime surveillance operators rapidly find the regions with high collision risk and pay more attention to them in traffic monitoring.

In addition, the SDOR and SDOI can be combined to identify the instantaneous collision risk. The change of the spatial relationship of the ship domains is divided in to two stages. The first stage is the phase of ship domain separation. In this stage, the collision risk can be identified by the SDOI, and the value of the SDOI is greater than 1. The second stage is the ship domain intersection stage, where the SDOR can be used to identify the collision risk. The SDOR is 0 at the beginning of this stage and increases with the overlapping of the domains. Therefore, the instantaneous collision risk between two ships can be expressed by the following equations.

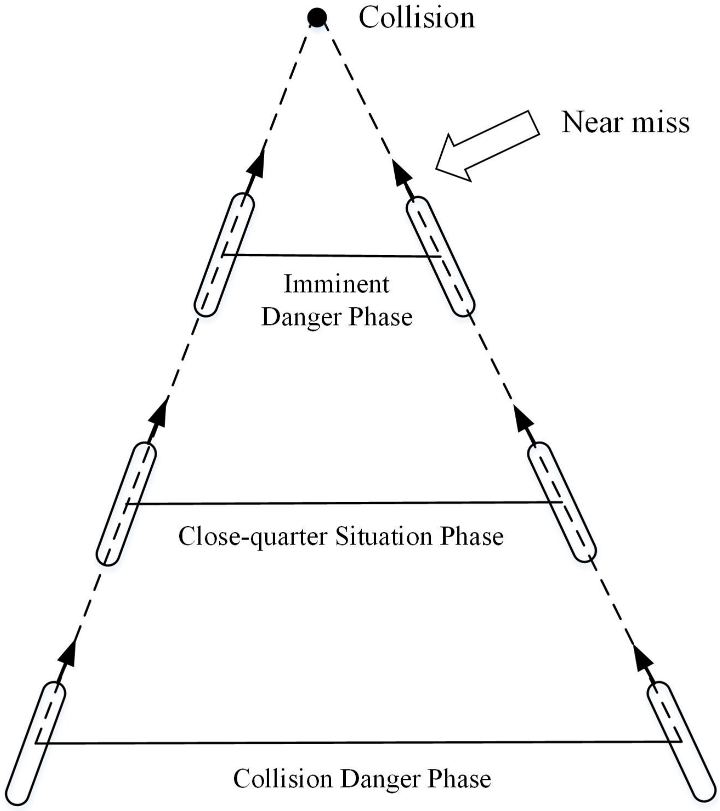

Figure 4. The near miss situation in the ship encounter process.

$$CR_{ij} = \begin{cases} a_{sep} \cdot e^{b_{sep} \cdot SDOI_{ij}} \text{ if ship domains are seperated} \\ a_{int} \cdot e^{b_{int} \cdot SDOR_{ij}} \text{ if ship domains are intersected} \end{cases} \tag{7}$$

$$CR_{Grid_k}{}' = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} CR_{ij}}{A_n^2 - n} \tag{8}$$

where CR_{ij} refers to the instantaneous collision risk between Ship i and Ship j, and a_{sep} and b_{sep} are the parameters of the negative exponential function when the ship domains are separated. a_{int} and b_{int} are the parameters of the negative exponential function when the ship domains are intersected; these parameters can be obtained by presetting the extreme encounter scenarios. $CR_{Grid_k}{}'$ refers to the instantaneous collision risk of the grid, and n refers to the number of ships in the grid. The value of $CR_{Grid_k}{}'$ can be generalized to the various grids in the water area, so as to represent the geographical distribution of the collision risk visually. In addition, based on the collision risk value of each grid and the ship positions, the thermal map of the collision risk distribution in the water area can be generated by using spatial interpolation technology. This can be used as an alternative to the spatial distribution map of collision risk in grid form, with better visibility.

4. Case Study

To validate the effectiveness of the proposed regional collision risk model, several experimental case studies were carried out in the Bohai Strait. The location of the studied water area was between 37.9° N and 38.7° N and 121.9° E and 122.2° E, as shown on the ship trajectories map depicted in Figure 5. The trajectory map is the spatial distribution of all ship traveling routes in the water area within a specified period. It represents the degree of ship traffic congestion and collision risk in the water area through the spatial distribution of ship travelling lines, and it also reveals the traffic flow situation and the overall encounter situation in the water area. It can be clearly seen that a main traffic flow (approximately in the southeast–northwest direction) and a crossing traffic flow (approximately in the north–

south direction) existed in the studied water area, and the two traffic flows intersected close to the center of the studied water area. As one of the three biggest straits in China, the Bohai Strait has a large traffic volume and complicated traffic situation [27]. The large volume and the complex situation of ship traffic make these waters crowded and busy. Close-quarters situations can easily unfold, thus increasing the collision risk and making it more difficult to mitigate the risk by utilizing collision avoidance maneuvers.

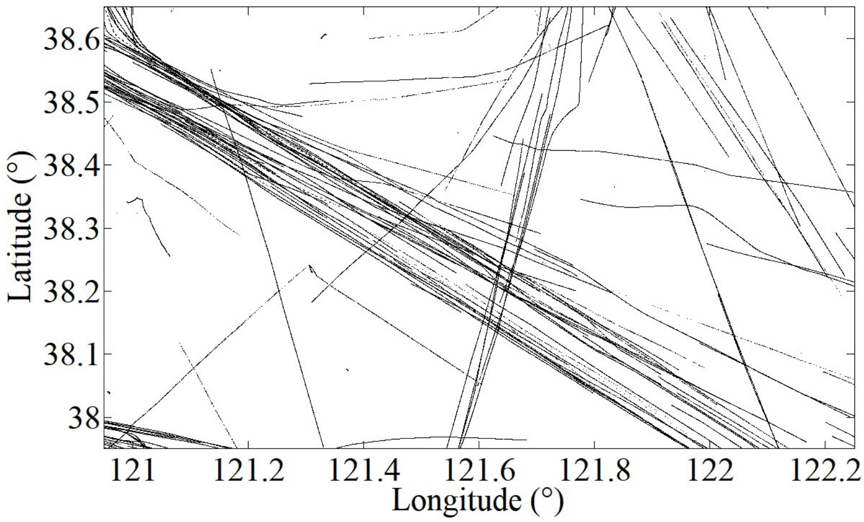

Figure 5. The ship trajectories map of the studied water area (3 h).

The case studies were carried out by using the AIS data from the Bohai Strait. AIS data contains 27 different messages; the dynamic information in Message 1 and the static information in Message 5 were mainly used in the case studies. Before using the AIS data, it was cleaned to remove anomalous information, and then the data were stored in a database. In addition, to identify the near miss or collision risk between ships, the parameters derived from the AIS data for each ship had the same timing. Therefore, the data were interpolated before being input into the model, as the AIS devices of different ships broadcast information with different time intervals.

In this article, the threshold of the SDOR for identifying a near miss scenario was set as 0.25. When the SDOR between two ship was 0, it meant that there was no overlap between the ship domains. As the domains continued to overlap, the value of the SDOR increased from 0. At the beginning, the ship domains had just begun to overlap, indicating that a collision risk had begun to appear. When the SDOR was 0.5, it meant that on average, half of each ship's domain was covered by another ship. Usually, under such circumstances, the two ships themselves have a very high possibility of intruding into the other ship's domain. This constitutes a situation of imminent danger, and the chance of collision avoidance is relatively small. The two ships may pass each other at a very small distance only by achieving sufficient coordination. Based on the abovementioned two important phases, this article took 0.25 as the threshold to determine the near miss scenario; that is, a collision risk had been generated but had not developed into the most urgent danger situation. At this time, a quarter of each ship's domain has been violated on average, creating a relatively urgent situation.

Firstly, experimental case studies were carried out to validate that the proposed domain-based model was capable of identifying the collision risk in a specified water area. After processing and inputting the AIS data, the proposed model was used to quantify the collision risk in the studied water area for 1 h, from 1300 to 1400 on 24 June 2022. The results are shown as a grid map in Figure 6. In the grid map, the collision risk in each grid is represented by different colors, where dark red represents high collision risk and dark blue represents low collision risk.

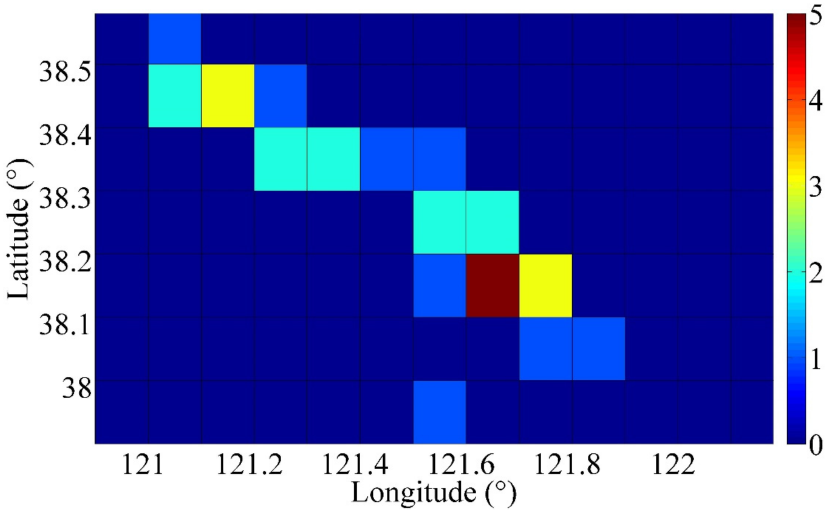

Figure 6. The grid map of collision risks in the studied water area (1300 to 1400, 24 June 2022).

In the studied water areas, collision risks were mainly distributed in the grids from northwest to southeast, which was consistent with the location and direction of the actual main traffic flow shown in Figure 5. Due to the large traffic flow and ship density in the main traffic flow, the collision risk at the location of the main traffic flow was greater than that in other water areas with sparse traffic flow. This was also shown by the grid map in Figure 6. In addition, the ship densities were also calculated and depicted in a grid color map in Figure 7.

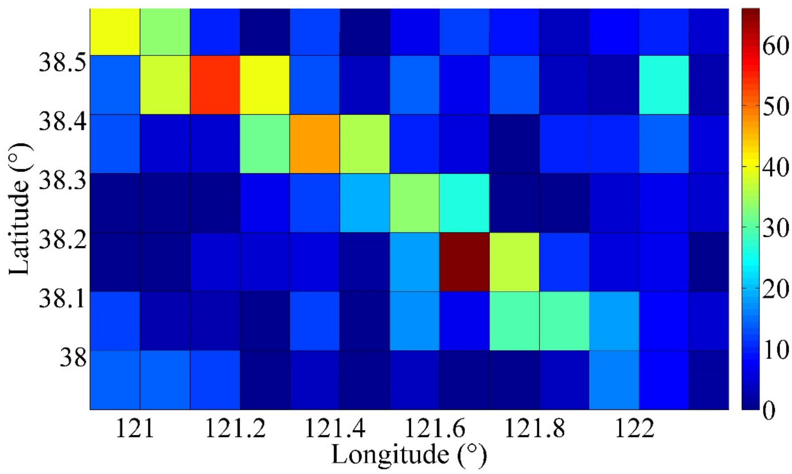

Figure 7. The grid map of ship densities in the studied water area (1300 to 1400, 24 June 2022).

Grids with a high ship density in the density grid map were also distributed from northwest to southeast in the studied water area, which was similar to the results in Figure 6. The correlation degree between the abovementioned two maps was calculated on a two-dimensional level, and the result was 0.8154, which indicated that the collision risk map and the density map had a relatively strong correlation. As the ship density can reflect the busyness and the risk of collisions of ship traffic to some extent, the proposed model in this paper effectively quantified the collision risk in the studied water area and depicted its spatial distribution through the form of a grid map.

We also selected the previous hour and the next hour of the above time period to carry out the same experimental case studies. For the previous hour, 1200 to 1300 on 24 June 2022, the grid map of collision risks obtained by the proposed model and the grid map of densities obtained through ship traffic data statistics are shown in Figure 8. For the next hour, 1400 to 1500 on 24 June 2022, the grid map of collision risks obtained by the proposed model and the grid map of densities obtained through ship traffic data statistics are shown in Figure 9.

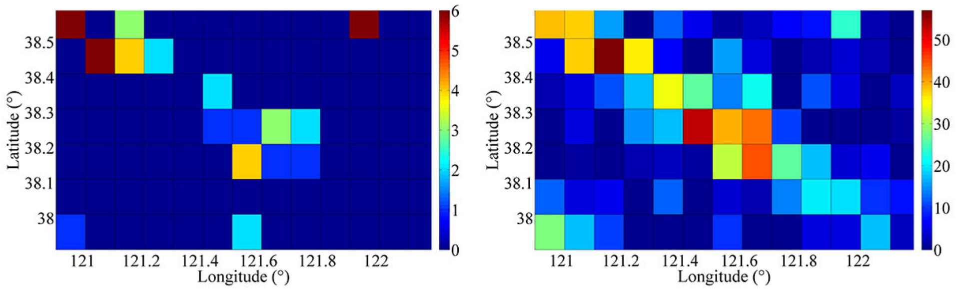

Figure 8. The collision risk map (**left**) and ship density map (**right**) for 1200 to 1300, 24 June 2022.

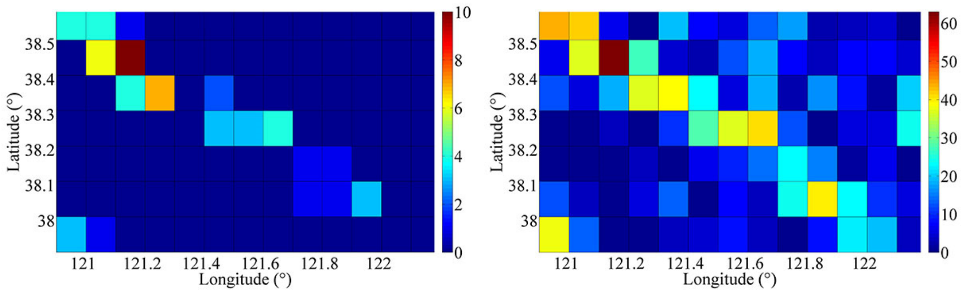

Figure 9. The collision risk map (**left**) and ship density map (**right**) for 1400 to 1500, 24 June 2022.

The collision risks and ship densities depicted by Figures 8 and 9 presented similar location characteristics, where the high collision risk and high-density regions were all located from northwest to southeast in the studied water area, which is also the location of the main traffic flow in the Bohai Strait, as shown in Figure 5. Therefore, the same conclusion can be drawn; the proposed model can effectively identify the collision risk in the studied water area and depict its spatial distribution.

Case studies were also carried out in the extended time periods of 1300 to 1500 on 24 June 2022 and 1200 to 1500 on 24 June 2022. For the two time periods, the collision risks were calculated by the proposed model and presented by grid maps. Then, the collision risk maps were compared with the ship density maps for the same periods to examine the correlation degree, and the results are shown in Table 1. For the period of 1300 to 1500, the correlation degree between the collision risk map and ship density map was 0.8200, which was higher than the result for the 1300 to 1400 period (0.8154). For the period of 1200 to 1500, the correlation degree between the collision risk map and ship density map was 0.8220, which was a further increase.

Table 1. The correlation degree between the collision risk map and density map for different time periods.

Time Periods	1 h	2 h	3 h
Correlation Degree	0.8154	0.8200	0.8220

The above results showed that with the extension of the time period, the correlation between the collision risk map and ship density map increased, which indicated that with the increase of the research period and amount of data, the proposed model can achieve a better effect in representing the collision risk in the studied water area.

In addition to the daytime time periods, we also chose a nighttime time period to carry out the experiment. The chosen time period was 0100 to 0200 on 24 June 2022, and the collision risk map obtained from the proposed model is shown in Figure 10, together with the ship density map of this time period. The collision risk map also presented the same traffic characteristics of the density map and the trajectory map.

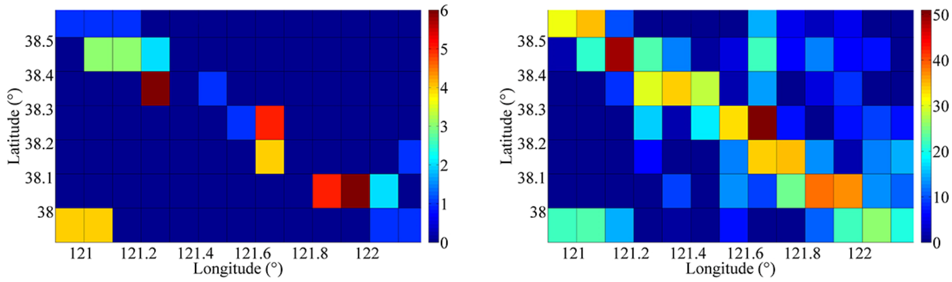

Figure 10. The collision risk map (**left**) and ship density map (**right**) for 0100 to 0200 on 24 June 2022.

Alongside studying the collision risk within specific hours, the experiment was also conducted for the course of a day. After inputting the data, the average collision risk of the 24 h of 24 June 2022 and the map of the ship density were depicted in Figure 11.

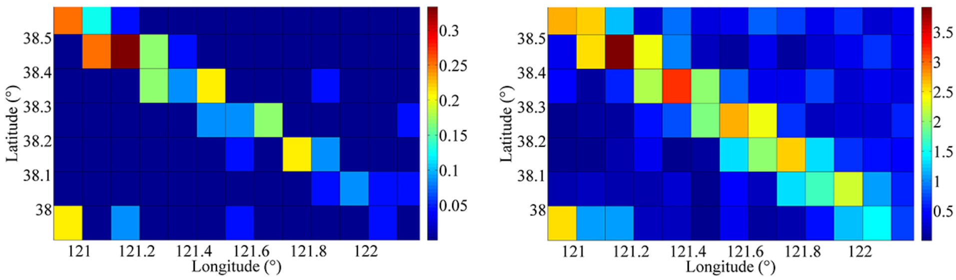

Figure 11. The collision risk map (**left**) and ship density map (**right**) for the 24 h of 24 June 2022.

Figure 11 also shows that the collision risk identified was distributed from the northwest to the southeast of the studied water area, which conformed to the information revealed by the density map and trajectory map. The correlation degree between the collision risk map and density map was calculated as 0.8513, which put more emphasis on the positive correlation between the collision risk map and the collision risk situation than can be characterized by ship density.

To further validate the proposed model, the scope of the data was further extended. We selected the data from 16 June 2022 to 30 June 2022, 15 days in total, to investigate the collision risk in the studied water area. The collision risk map obtained by the proposed model was depicted in Figure 12, together with the ship density map. The correlation degree between the two maps was calculated as 0.8322.

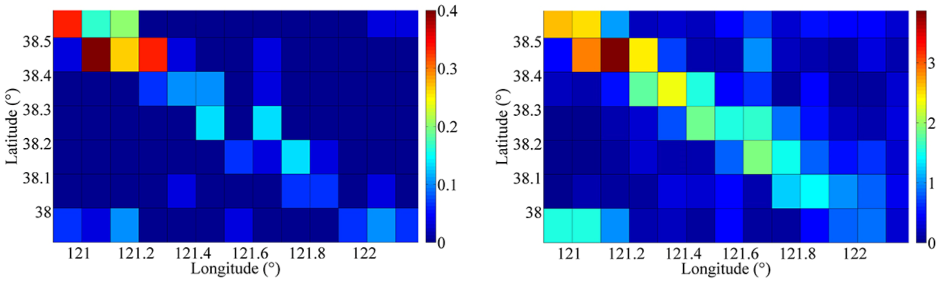

Figure 12. The collision risk map (**left**) and ship density map (**right**) from 16 June 2022 to 30 June 2022.

After expanding the amount of data, the collision risk map still showed that the collision risk situation was indicated by the actual traffic in the studied water area and had a high consistency with the collision risk situation represented by the ship density map. This demonstrated the effectiveness of the proposed model in identifying the collision risk regionally.

Additionally, we used the methods in [14,22] to identify the collision risk in the studied water area within a 15-day period for comparison. The resultant maps are depicted in Figure 13.

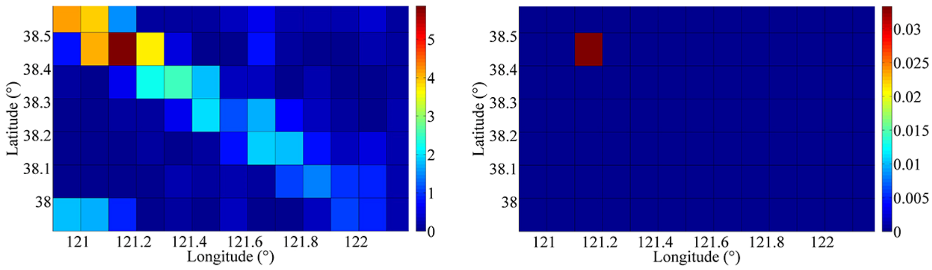

Figure 13. The collision risk maps depicted by using the methods in [22] (**left**) and [14] (**right**) from 16 June 2022 to 30 June 2022.

A case study was carried out to prove the capability of the proposed model in identifying the instantaneous collision risk. Three timing moments were selected for the case study: 1200, 1300, and 1400 on 24 June 2022. For the three timing moments, the collision risks were calculated by the proposed model and depicted in thermal maps, which are shown in Figure 14.

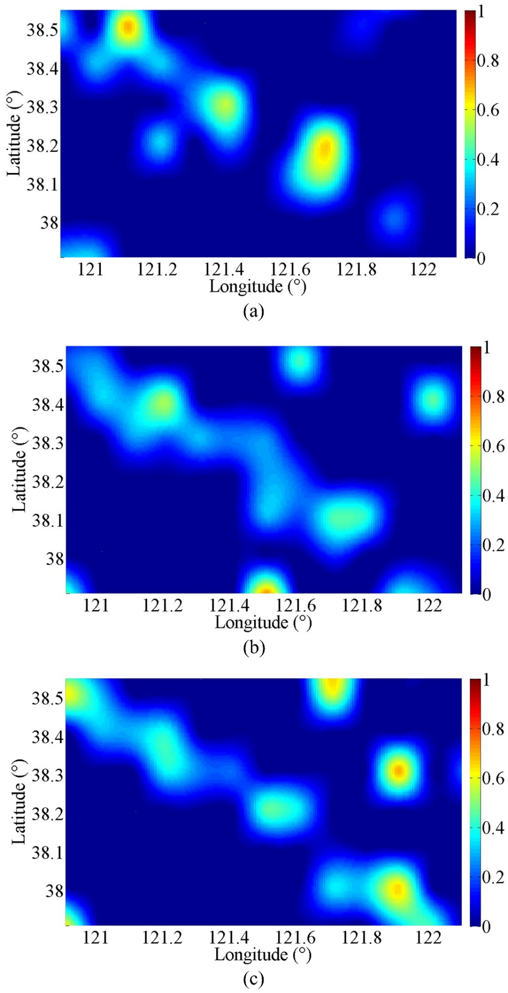

Figure 14. The thermal maps of collision risk in the studied water area at (**a**) 1200, (**b**) 1300, and (**c**) 1400.

It can be observed from the figure that the collision risks were mainly distributed in the region from northwest to southeast, which was the location of the main traffic flow in the studied water area as shown in Figure 5. As the traffic volume and traffic density are large, the location of the main traffic flow was expected to have a relatively higher collision risk than other regions. This was well represented by the collision risk map drawn by the proposed model, demonstrating the effectiveness of the proposed model in identifying the instantaneous collision risk. Meanwhile, the collision risk map was compared with the ship density map at the corresponding timing moments to check the correlation between them, so as to verify that the proposed model can reflect the traffic risk of collision in the studied water to some extent. Table 2 shows the correlation degree results between the collision risk maps and the ship density maps obtained at the three timing moments. The results showed that strong correlations exist between them, further illustrating the effectiveness of the proposed model in identifying the instantaneous collision risk.

Table 2. The correlation degrees between the collision risk maps and ship density maps for the daytime scenarios.

Timing Moment	1200	1300	1400
Correlation degree	0.7037	0.7868	0.7182

In addition, we also selected three nighttime timing moments for further experiments: 0000, 0100, and 0200 on 24 June 2022. Utilizing the proposed model, the instantaneous collision risk distribution of the three moments are depicted in Figure 15. The correlation degrees between the collision risk maps and the ship density maps were calculated as shown in Table 3.

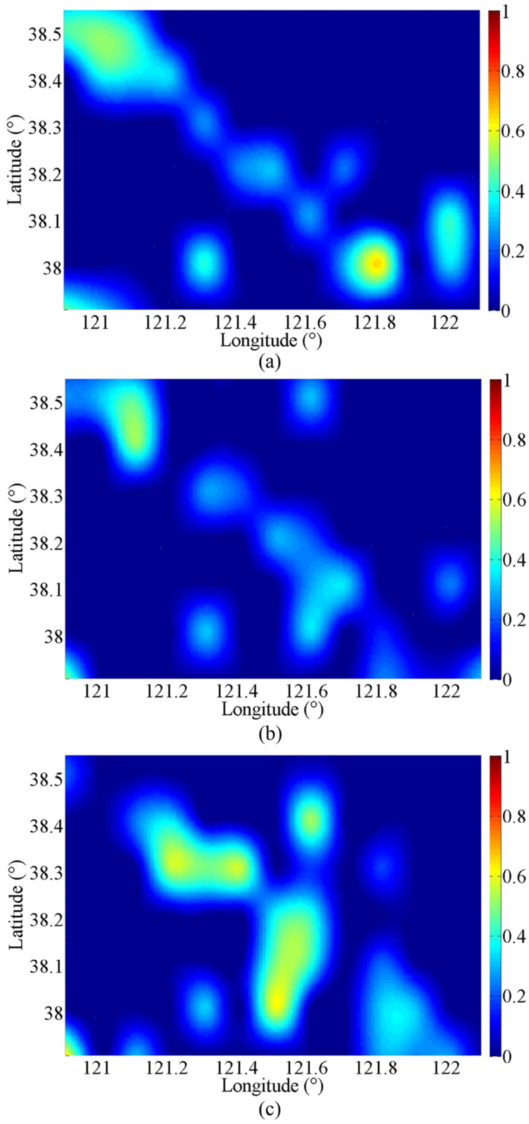

Figure 15. Thermal maps of the collision risk in the studied water area at (**a**) 0000, (**b**) 0100, and (**c**) 0200.

Table 3. The correlation degrees between collision risk maps and ship density maps for the nighttime scenarios.

Timing Moment	0000	0100	0200
Correlation degree	0.7743	0.7838	0.7946

The collision risks were still mainly distributed in the regions of main traffic flow, and the correlation degree results indicated a strong correlation between the collision risk maps and the ship density maps, which explained the effectiveness of the proposed model for identifying the instantaneous collision risk at night.

Furthermore, to validate the effectiveness of the proposed model in identifying the instantaneous collision risk, the data range was extended to 15 days. After applying the proposed model, the geographical distribution of collision risks is depicted in Figure 16.

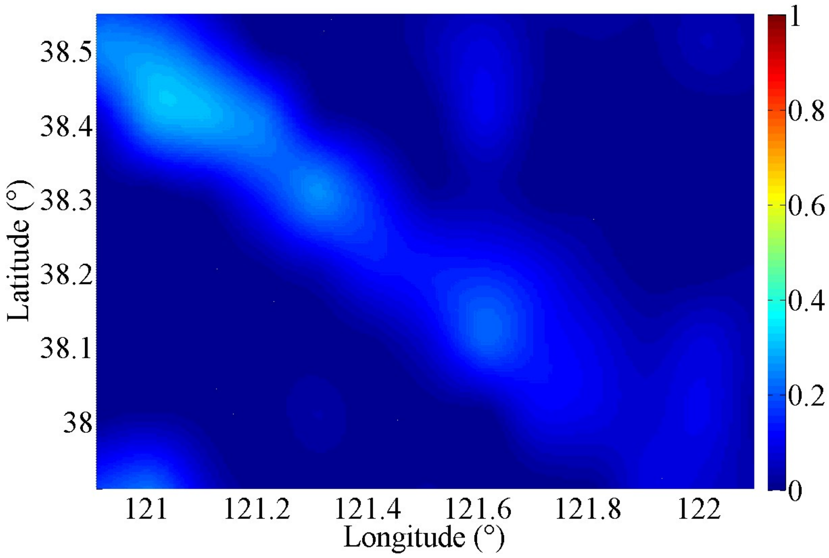

Figure 16. The thermal map of collision risk in the studied water area from 16 June 2022 to 30 June 2022.

It can be observed from the figure that collision risks were still distributed at the main traffic flow locations in the studied water area. Meanwhile, the correlation degree between the resultant collision risk map and the ship density map within the 15 days was calculated as 0.7548, which also represented the strong correlation between the results and the collision risk situation reflected by the ship density. Therefore, it was proven that the proposed model was capable of identifying the instantaneous collision risk in the water area.

5. Discussion

In this paper, a domain-based regional collision risk model was proposed. The proposed model was able to identify the collision risk in a studied water area and depict its geographical distribution. To establish the proposed model, a novel ship collision risk indicator called the ship domain overlapping rate (SDOR) was built. This indicator can represent the collision risk between two ships through considering their relative position and overcomes the problem that the collision risk between two ships cannot be sufficiently represented by the ship domain overlapping index when the parameters of the two ships are different. It should be noted that although the SDOR was modeled in a two-ship encounter scenario, it can also be used in a multi-ship encounter scenario. In a multi-ship encounter scenario, the multi-ship encounter can be divided into several two-ship encounters, and for each scenario, the SDOR between two ships can be obtained. Then, the SDORs of any two ships can be linearly combined to obtain the SDOR of multiple ships. In addition, the SDOR can incorporate the influence of the relative bearing and the regulations of COLREG. In this research, the SDOR was used in combination with the traditional collision avoidance parameters of the DCPA and TCPA to identify near miss scenarios, so as to represent the collision risk in the studied water area. Apart from quantifying and describing the distribution of the collision risk in the studied water area over a period of time, the proposed model can also calculate and depict the spatial distribution of the instantaneous collision risk, so that maritime surveillance operators can better grasp the collision risk in a water area in real time.

To validate the proposed model, experimental case studies were carried out and discussed in Section 4 using AIS data from the Bohai Strait. Firstly, the proposed model was validated to identify the collision risk in the studied water area over a period of time. Time periods of different lengths were selected. The ship density and ship trajectory were used to check the results because of their ability to reflect the traffic risk of collision. Secondly, the proposed model was validated to identify the instantaneous collision risk. Different instantaneous scenarios were selected, and the results were also compared with the ship density. The abovementioned experimental results demonstrated the effectiveness of the proposed model in identifying the collision risk. In the experimental case studies, ship density was used to validate the effectiveness of the proposed model in identifying the collision risk. However, as a basic maritime traffic indicator, ship density is unable to reveal the collision risk sufficiently and accurately alone. For example, in the scenario of Figure 14a, if we represent it as a grid map, the collision risks can be depicted as in Figure 17. Examining the grids of row 1 column 1 and row 4 column 6, the former grid has a ship density of 6 and the latter grid has a ship density of 7, but the collision risk of the former gird is higher than that of the latter grid, because there were no near misses in the regions of the latter grid, while four near miss scenarios occurred in the former grid. This was also the case in row 4 column 9 and row 2 column 3, where, although the ship density increased, the collision risk decreased. The above results also showed that the proposed model in this paper was more accurate in the identification of the collision risk than the ship density.

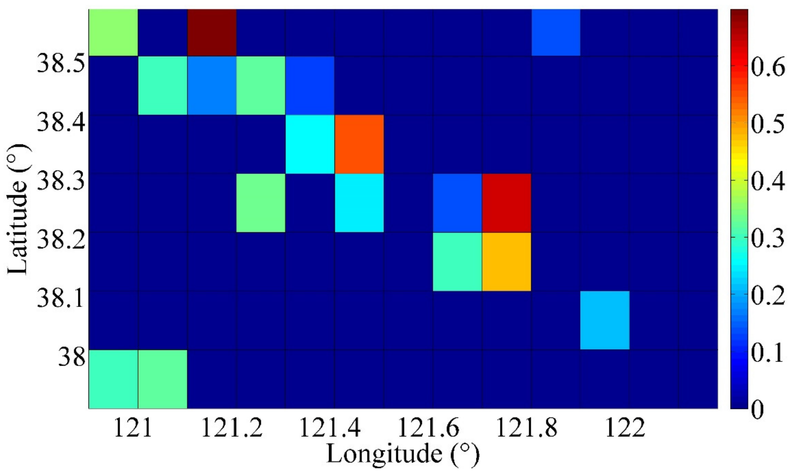

Figure 17. The grid map of the collision risk at 1200 on 24 June 2022.

When the scenario was extended to 15 days from 16 June 2022 to 30 June 2022, the abovementioned situation also occurred in the grid of row 7 column 12 and row 4 column 8 of the collision risk map depicted in Figure 18. The above results also showed that the proposed model in this paper was more accurate in the identification of collision risk than the ship density.

To further validate the advantages of the proposed model, other comparison experiments were carried out by using AIS data from the Bohai Strait. The comparison methods were two traditional models used for identifying the collision risk or near misses. The proposed model was first compared with the regional collision risk model in [22], which also identified the collision risk in a studied water area based on near misses.

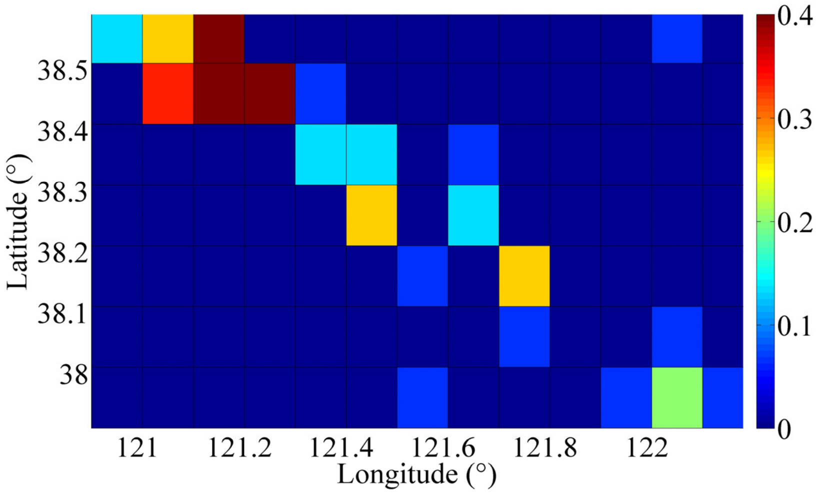

Figure 18. The grid map of collision risk at 1200 from 16 June 2022 to 30 June 2022.

The model distinguished the near miss situation by judging whether a ship had invaded the area of other ships, and then identified the collision risk accordingly. The identification ultimately relied on the judgement of the relationship between relative distance and the size of the area. The collision risk in the studied water area for 1300 to 1400 on 24 June 2022, identified by this model, are shown in Figure 19. The high collision risk regions were also located from northwest to southeast in the studied water area, which was very similar to the distribution map in Figure 6 obtained by using the proposed model in this article. However, it can be seen from Figure 19 that the number of near misses obtained by [22] was much higher. This was because it adopted a high threshold to distinguish a near miss scenario. Since the radius of the area proposed by Davis et al. [22] was approximately 2.7 nm, such a threshold was obviously higher for judging near miss scenarios, and some scenarios that were relatively safe would have been included. If the experiments were extended to a 15-day period, the resultant collision risk map is depicted in Figure 13 (left). Compared with the collision risk map in Figure 12, the average near miss results obtained by [22] were also much higher than those of the proposed model, which was also because of the high threshold adopted.

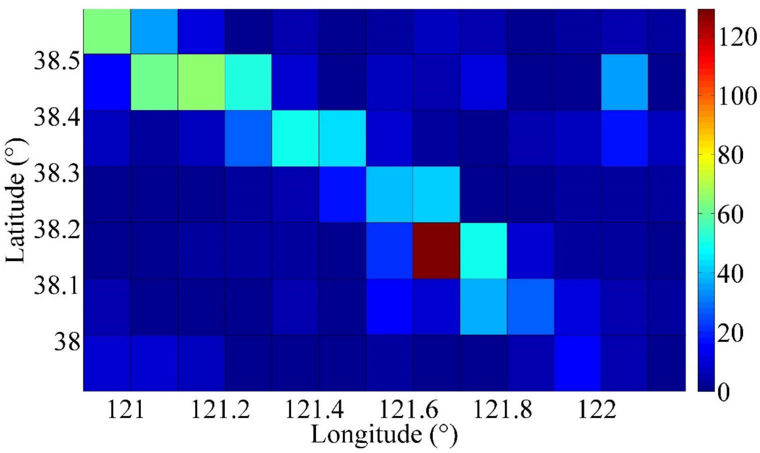

Figure 19. The collision risk map obtained by applying the model in [22].

For some specific situations, this model was unable to fully recognize the collision risk. Taking the scenario in Figure 20 as an example, as Ship 1 was within the range of the area boundary, it was judged as a near miss ship. Ship 2, as it was outside the area boundary, was not judged as a near miss ship. In fact, Ship 1 had almost passed the main ship and the collision risk between them was small, while Ship 2, although far away from the main ship, had a higher collision risk because it was at risk of a head-on encounter with the main ship, and the DCPA between them was very small. The model in [22] found it difficult to fully and accurately identify the collision risk in such situations, while the proposed model, which additionally considered the traditional collision avoidance parameters on the basis of the SDOR, had an advantage in collision risk identification in such scenarios.

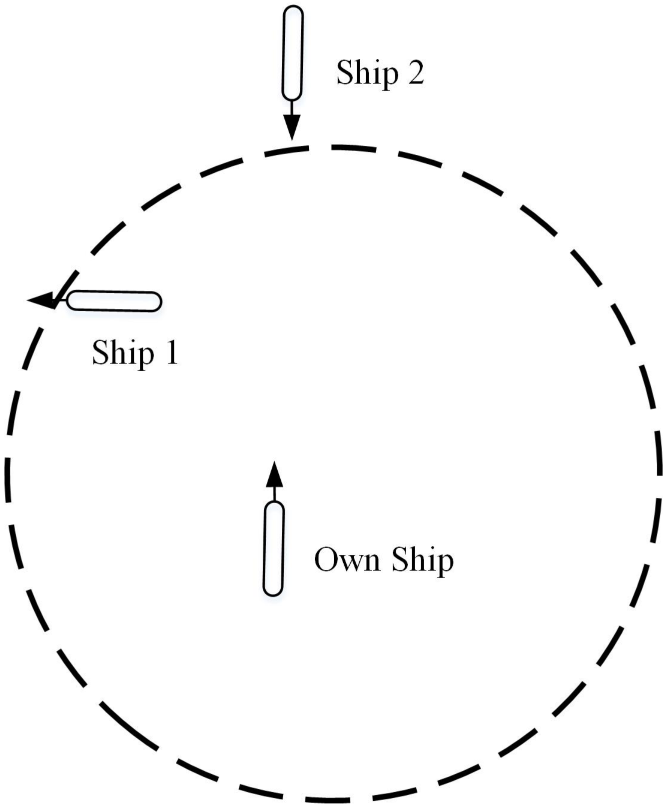

Figure 20. An example scenario of ship encounters.

In addition, the proposed model was also compared with the near miss model proposed in [14]. The model was used to calculate near misses at 1300 on 24 June 2022, and the distribution map is shown in Figure 21. Only one near miss occurred in the grid of row 5 column 8, while the rest of the area was completely safe. The model proposed in this article was also used to calculate the collision risk at this moment and the distribution map is shown in Figure 14b. By comparing the two figures, we found that the model in [14] only determined a near miss by the threshold of the impact factors of the collision risk, and thus studied the collision risk in the water area. In other words, it only determined whether there was a near miss or not. As a result, the potential collision risk in the studied water area for an instantaneous scenario could not be fully identified due to the small number of near misses. Even if this near miss scenario was not formed in some areas, there would still be some potential collision risks, as shown in Figure 14b. The proposed model in this article not only identified the collision risk over a period of time, but also considered the identification of the instantaneous collision risk. The SDOR index established in this paper to identify near misses can be used to calculate and describe the spatial distribution of the instantaneous regional collision risk in a studied water area, highlighting the advantage of the proposed model in identifying the instantaneous collision risk. The proposed model was not limited by the statistical period and can allow maritime surveillance operators to better understand the collision risk in a water area in real time. When the experiment was extended by using a larger range of data, from 16 June 2022 to 30 June 2022, a similar phenomenon was observed in the near miss map, depicted by using the method in [14], as shown in Figure 22.

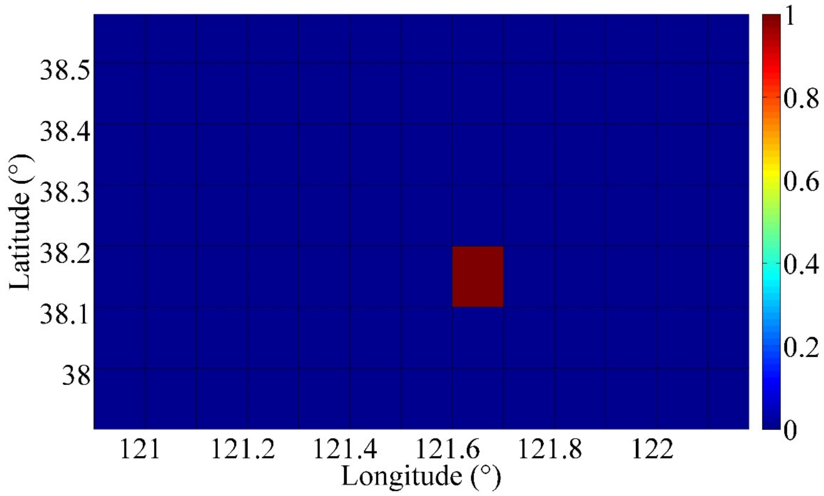

Figure 21. The near miss map obtained by applying the model in [14] at 1300 on 24 June 2022.

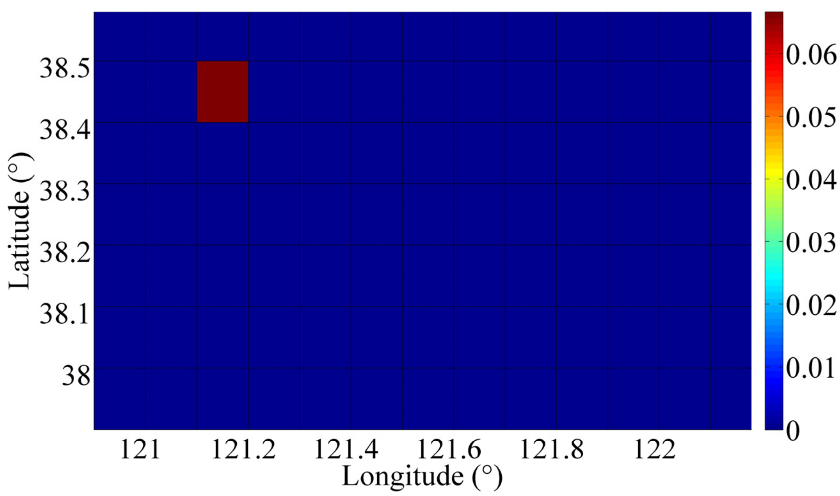

Figure 22. The near miss map obtained by applying the model in [14] from 16 June 2022 to 30 June 2022.

In the above discussion, several similar methods or indexes were compared with the model proposed in this article: the traditional ship density index, the macroscopic collision risk model based on area, and the near miss identification method, in order to study the risk in an identified water area. These methods or indexes can characterize the collision risk in a water area, but there are differences between them, and each has advantages and disadvantages.

The traditional ship density is one of the basic indexes of collision risk representation in a water area. In general, the greater the density of ships, the greater the risk of collision, because a high ship density will make the distance between ships relatively small and increase the difficulty of collision avoidance. The advantage of using ship density to characterize the collision risk lies in its simplicity, because as a basic ship traffic parameter, it is relatively easy to obtain and calculate. However, this simplicity also has the disadvantage of the limited accuracy of collision risk quantification. This is because ship density can only estimate the danger from the perspective of ship quantity, without considering the ship collision geometry. This was proven through the experiments in Figures 17 and 18, where the traditional ship density was compared with the proposed model, and the results showed that the proposed model identified the regional collision risk more accurately. For the method in [22], near miss scenarios were identified based on the ship arena, and the collision risk was characterized by near miss situations. Its advantage is that the mariners' consideration of collision avoidance stages is incorporated into the collision risk modelling in the area, because the area is a super ship domain set up to avoid invading the safety domain of ships. However, due to the relatively large scale of the area and the lack of the consideration of other crucial collision avoidance parameters, the intrusion of its boundary to determine near miss scenarios will cause more situations to be judged as near misses than have occurred in reality. In the experiments represented in Figures 13 (left), 19 and 20, it can be seen that many more near miss scenarios were identified by this method, but this does not mean that these situations were actually high collision risk situations. In other words, compared with this method, the model proposed in this article based on the SDOR and SDOI determined the near miss scenarios more accurately, and thus better represented the collision risk. For the study in [14], the near miss scenarios were determined based on two traditional collision avoidance parameters and the distance between ships. The advantage of this method was that it is more rigorous and accurate in determining near miss scenarios, as three threshold conditions needed to be met at the same time. A near miss scenario was identified by these thresholds based on a large amount of data and could indeed identify noteworthy locations with a high collision risk in the water area. However, this method also had limitations. Due to its strict criteria for near miss identification, when it was used to identify instantaneous risk, because of the limited number of samples for a specific moment, most of the encounter scenarios were identified as safe, and only a few near miss scenarios were identified. For these safe encounters, many of their actual collision risk levels were not 0, but this was difficult to identify through this method. This was illustrated by the experiments represented in Figures 13 (right), 21 and 22 which showed that, compared with this method, the proposed model was able to identify the instantaneous regional collision risk more adequately.

In summary, this article made the following three main contributions. First, a new collision risk SDOR was proposed based on the ship domain in this article, which was able to characterize the potential collision risk between two ships through the relative relationship between their ship domains. Secondly, a near miss identification method was proposed. The SDOR is combined with the traditional collision avoidance parameters of the DCPA and TCPA as the standard parameters for determining near miss scenarios, so as to identify near misses in the water area more accurately, and thus characterize the regional collision risk more sufficiently. Thirdly, combining the SDOR and SDOI, this article proposed an identification method of instantaneous regional collision risk distribution, which was not limited by the statistical period, and which could further depict its geographical distribution in the water area. The method will be helpful for maritime surveillance operators to comprehensively grasp the collision risk situation in a water area in real time.

However, the proposed model also had some limitations. Firstly, in modeling the ship domain overlapping rate, the ship domain was established in a circular form, where the ship moved at a certain distance from the center of the domain. In reality, the shape of the ship domain will vary according to the type of water area. An elliptical domain is often used in waterways and a rectangular domain is sometimes used in narrow channels. The accuracy of the model could be further enhanced if the shape of the domain could be dynamically adjusted according to the water type. Secondly, in the proposed model, the influence factors of the collision risk were considered mainly to include the static and dynamic factors of the ship; the factors related to the traffic environment were not considered sufficiently, such as wind, waves, visibility, traffic facilities, etc. These factors also have some impact on the collision risk level. Thirdly, if the scope of the studied water area was further expanded, the computation efficiency of the proposed model would be limited to some extent. Due to the large scope of the studied water area, the identification of near misses between any two ships will increase the computation workload significantly. It would be better to classify the ships spatially before the model computation so as to improve the computation efficiency of the model.

6. Conclusions

In this article, a novel domain-based regional collision risk model was proposed. To establish the proposed model, a new domain-based indicator was built to represent the collision risk between ships and was used to identify near miss scenarios in the water area in combination with two traditional collision avoidance parameters. The proposed model was able to identify the collision risk in the water area instantaneously and periodically and could be used to depict the geographical distribution of the collision risk when combined with the grid method and spatial interpolation technique. To prove the effectiveness and advantages of the proposed model, experimental case studies were carried out using real AIS data from the Bohai Strait. The results showed that the proposed model could quantify and visualize the regional collision risk effectively and gain more accurate collision risk results compared with other relevant studies. By utilizing the proposed model, maritime surveillance operators could more rapidly and accurately understand the collision risk in a water area, which would be helpful for the enhancement of maritime safety.

The proposed model could be further improved in the future. Firstly, rather than the circular domain established in the proposed model, the domain shape could be adjusted dynamically according to the type of water area so as to make the model more accurate. Secondly, traffic environmental factors, such as wind, waves, visibility, and traffic facilities, could be incorporated to further improve the accuracy of the results. Thirdly, to improve the computation efficiency of the proposed model in a larger water area, it would be better to take some measurements to classify the ships spatially first, such as by using spatial clustering techniques before model computation.

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