Analysis of Satellite AIS Data to Derive Weather Judging Criteria for Voyage Route Selection

M. Fujii

Marine Technical College, Japan Agency of Maritime Education and Training for Seafarers, Ashiya, Japan

H. Hashimoto & Y. Taniguchi

Graduate School of Maritime Sciences, Kobe University, Kobe, Japan

ABSTRACT: The operational limitations are discussed at the IMO as a part of the second generation intact stability criteria. Since it is a first attempt to introduce operational efforts into safety regulations, comprehensive discussions are necessary to realize practically acceptable ones. Therefore this study investigates actual navigation routes of container ships and pure car carriers in the trans-North Pacific Ocean in winter, because they are prone to suffer significant parametric roll which is one of stability failure modes. Firstly, interviews are made to shipmasters who have experiences to have operated the subject ships to identify major elements for route selection in the North Pacific Ocean. Secondly, sufficient number of actual navigation records is collected from Satellite AIS data to derive the weather criteria for the route selection in severe weather condition. Finally, shipmaster's on-board decision-making criteria are discussed by analysing the ship tracking data and weather data.

1 INTRODUCTION

The International Maritime Organization (IMO) is almost reaching to the finalization of the second generation of intact stability criteria (IMO 2017). It will be finalized by the Sub-Committee on Ship Design and Construction (SDC) till 2019. The criteria are defined in three levels: (Level 1) the largest safety margin but simplest calculation method, (Level 2) a medium safety margin but more complicated calculation method, and (Level 3) quite complicated direct stability assessment with the minimum safety margin. If a ship fails to pass the first and second level criteria, the ship should satisfy the direct stability assessment or change the cargo loading condition to adapt the criterion. Otherwise, the ship should be operated with operational limitations which have not been handled in the current intact stability criteria. The introduction of operational limitations is agreed upon at the sub-committee of SDC in principle.

Under the current intact stability criteria, a shipmaster needs to confirm whether the ship with current/expected loading condition satisfies the stability requirements in the regulation or not. If cleared, the shipmaster can sail the ship anywhere without any limitations. However, selection of navigation routes is limited according to the operational limitations in the second generation of intact stability criteria to guarantee the safety of ships. Therefore, impact assessment of the operational limitations on actual ship operation should be carefully investigated in terms of implementation.

Nowadays, weather routing algorithms are developed as for decision-making tools for masters to select an economical route with safety. Various weather routing algorithms for ship safety has been proposed (e.g. Krata & Szłapczyńska, 2012). In order to discuss the operational limitations, we try to assess influence of the operational limitations using a

navigation simulation for ocean-going ships (Hashimoto et al., 2016). The navigation simulation model was developed based on a weather-routing one developed by Kobayashi et al. (2011, 2015). However actual route-decision process of ships in severe weather is not clear enough whereas it is one of most important elements for the development of rational operational limitations. In this context, the navigation simulation is not only a simulation tool for route suggestion to captains, but to check the adaptation to the new stability criteria. Therefore, the navigation simulation should simulate ship routes with sufficient similarity with actual routes decided by captains by taking account of the preferred safety margin depending on the weather condition/forecast. The route decision-making criteria for regulatory purposes must be objectively. There are several researches in this direction (Vettor & Soares, 2015; Hayashi & Ishida, 2004), but they are not objective satisfactorily.

By following these situations, this study conducts an investigation of ship actual routes of ships served in Trans-north Pacific in winter. The subject types of ship are container ships and pure car carriers (PCC) who are assumed to be affected by the second generation intact stability criteria. Firstly, shipmasters who have operated container ships and/or PCCs are interviewed to determine the route selection criteria of the trans-North Pacific Ocean routes in winter. Secondly, Automatic Identification System (AIS) data received by satellites are used as one of most objective data to reveal actual navigation routes in severe weather condition to describe the relationship between the route selection and weather judging criteria. Finally, the shipmaster's on-board decision-making criteria are discussed by analyzing the tracking data of actual ships and weather data.

2 SHIPMASTER ON-BOARD ROUTE DECISION

The developed navigation simulation is based on a weather routing model. Even during actual navigation, a weather routing service is commonly used; this means that weather routing is a main method for correctly simulating practical navigation routes. However, the route decision is ultimately decided by the shipmaster. Hence, the shipmaster's intentions need to be included in the weather routing model.

In this study, shipmasters who were experienced with a container ship and/or PCC were interviewed to determine the weather criteria and limitations of the trans-North Pacific Ocean route in winter. Here, criteria refer to a standard for navigation without any restriction, and a limitation refers to a standard that does not allow navigation. The findings of the interviews are discussed below.

2.1 Route selection

The shipmaster basically selects a route according to the minimum distance and least ship motion considering the location of low-pressure areas. Along the eastbound route from Asia to North America,

shipmasters navigate by great circle sailing. The southern part of the great circle is selected to utilize the tailwind and following waves from a low-pressure. In addition, shipmasters generally select to navigate behind a low-pressure in the Gulf of Alaska. Along the westbound route to Asia, shipmasters head towards the Bering Sea, where the winds and waves are calm. If it is impossible to head north, a southern route is selected by Mercator sailing.

2.2 Information used for route selection

A shipmaster decides a route based on the weather forecast a week before sailing. At that time, navigation records of past voyages and the pilot chart are also referred to. Recently, recommendations from weather routing service are used; even in that case, the forecast accuracy is carefully considered.

2.3 Effects of wind and waves

The wave height criterion for container ships is normally 5 m. Shipmasters select a route where the forecast wave height does not exceed 6 m, but sometimes navigate areas where the wave height is 7–8 m.

In the case of PCCs, shipmasters feel that navigation is difficult when the wave height exceeds 4 m because of concerns over engine performance and ship motions, e.g. rolling and pitching. In addition, a PCC is affected by wind because of its large receiving area.

During racing and/or torque-rich are occurred, shipmasters consciously reduce the ship. Thus, the receiving direction of the wave is determined by considering the influence of the ship's speed and motion. Shipmasters normally avoid waves from dead ahead as much as possible.

3 EXAMINATION OF CONCRETE CRITERIA USING SATELLITE AIS DATA

Based on the above interview results, the criteria and limitations for the trans-North Pacific Ocean route in winter were loosely determined. However, the criteria need to be defined more concretely and numerically in order to add an algorithm that represents route decision-making by the shipmaster. Therefore, criteria were developed by investigating the tracking data of actual ships and weather data in addition to the interview results.

Presently, tracking data can be obtained from satellite-based AIS or the Long Range Identification and Tracking system (LRIT). In this study, the satellite-based AIS data were used, because the LRIT data are mostly used by governments, and the former is more focused on commercial use (Chen, 2014).

The satellite AIS data were obtained from exactEarth. The data included 100 container ships and 84 PCCs that were picked at random from the vessels that crossed the North Pacific Ocean from 1 December 2015 to 29 February 2016. The weather and sea

conditions were analysed by using National Centers for Environmental Prediction (NCEP) data.

3.1 *Interpolation of position data*

The intervals of the received AIS data varied from a few seconds to a few hours. Thus, in the analysis the position was estimated every 3 h starting from 00:00 UTC as calculated from the closest position.

The mesh of the weather data provided by the NCEP had longitudinal intervals of 1.25° and latitudinal intervals of 1.0°. Linear interpolation was performed to calculate the weather data at a ship's position at a given time.

3.2 *Handling errors in satellite AIS data*

As shown in Figure 1, the AIS position data sometimes jumped to an unreachable point. Such data needed to be excluded from the analysis. The reason for the position jump could not be determined. Thus, in this study, a distance between neighbour positions was used to judge if an error had occurred. Figure 2 shows the system flow.
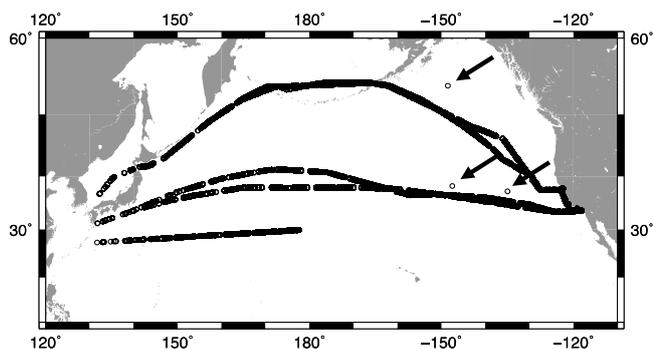
Figure 1. Error data included in satellite AIS data.
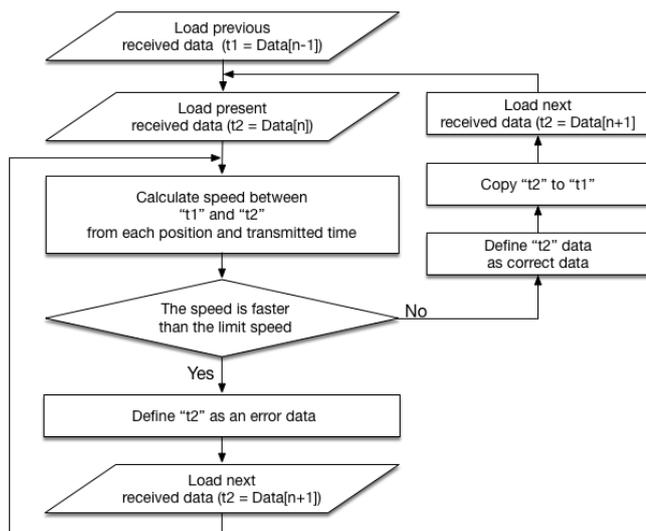
Figure 2. System flow for error judgement.

The distance is defined by the ship's speed data (SOG) transmitted by AIS from each vessel. Table 1 presents the number of corresponding data, average speed, and standard deviation, and Figure 3 shows the probability density distribution of SOG. All SOG data obtained for this study were calculated except

when the speed was below 0.5 kn, which means that the vessel was not sailing. As indicated in Figure 3, the SOGs followed an almost normal distribution. Therefore, the limit distance was defined from 3σ of SOG data. This means that the AIS data were regarded as an error if the speed between neighbor positions was greater than the limit speed which is calculated by the data received time and the limit distance.

Table 1. Details of SOG data.

	Number of data	Mean (kn)	SD	3σ
Container	3,505,445	17.93	3.19	27.49
PCC	1,560,487	15.98	2.89	24.66
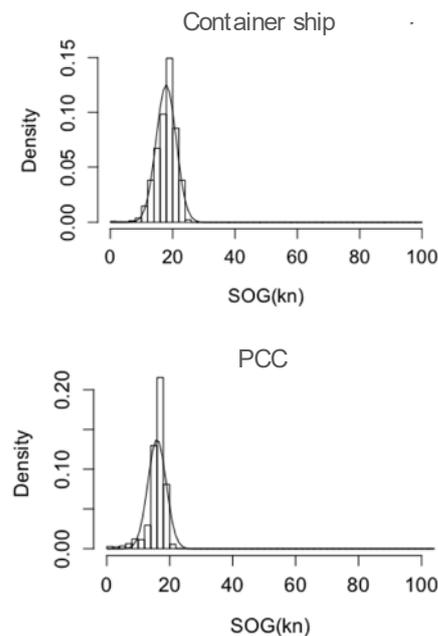
Figure 3. Probability density distribution of SOG from AIS data.

4 DATA EXTRACTION AND DEFINITION OF THE TRANS-NORTH PACIFIC OCEAN ROUTE

The AIS data obtained in this study included ships that navigated the North Pacific Ocean during the period in question, even if it was only once. This means that vessels that navigated the North Pacific Ocean only once and then navigated other areas were included in the data. Therefore, navigation data for the target area (north of 10° N, between 130° E and 110° W) were extracted. In order to analyse eastbound and westbound voyages, departing and arriving lines were set on the Asian and American sides, as shown in Figure 4.

In general, when a vessel navigates the North Pacific Ocean from the Asian side to the American side by great circle sailing, the departure point from the great circle is set off Japan. Therefore, the limit line on the Asian side (i.e. west-side line) was defined at 143.5° E. The limit line on the American side (i.e. east-side line) was defined as from 60° N, 140° W to 0° N, 112.5° W off continental America because ports are located widely distributed from the northwest to

southeast. However, vessels may navigate just on the east-side line because the line was drawn diagonally. Hence, the limit line was divided into latitudinal intervals of 1°, and the longitude was calculated at every latitude. The calculated longitude line every 1° was used as the east-side limit line for judgement.

In this study, eastbound vessels were defined as passing the west-side line first and then passing the east-side line. Westbound vessels did the opposite. The analysis of the voyages used valid data between the AIS data which was first received after a vessel entered the area and the AIS data that was first received after the vessel left the area.
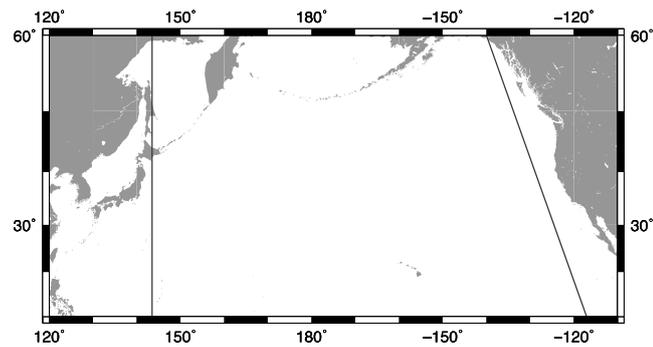
Figure 4. Departing and arriving lines.

5 ANALYSIS RESULTS

5.1 Route comparison for container ships and PCCs

Table 2 presents the number of trans-North Pacific Ocean voyages during this period. The numbers of voyages by container ships and PCCs are different because the container ships operated the same route according to a schedule, but the route of the PCCs was not fixed.

Table 2. Number of voyages across the North Pacific Ocean.

	Eastbound	Westbound	Total
Container	164	111	275
PCC	22	15	37
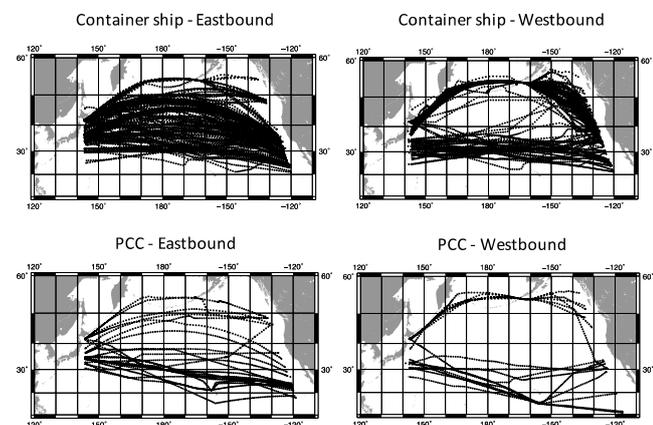
Figure 5. Plotted routes for each type of ship.

Figure 5 plots the eastbound and westbound routes of each type of ship. When traveling east, both container ships and PCCs navigated the centre of the North Pacific around a latitude of 40° N. On the other hand, when traveling west, the ships followed two routes: through the Bering Sea and around 30° N. In addition, the eastbound routes of the both types of ship showed almost the same trend. However, for the westbound route south of 40° N, the PCCs headed much further south than the container ships.

5.2 Encountered waves and direction

Table 3 presents the average wave height. The container ships encountered an average wave height 0.5 m higher than the PCCs. Figure 6 shows the probability density distribution of the wave height. The wave distribution of the container ships slowly decreased from 3 m to 8 m. However, the distribution decreased sharply for the PCCs. This is consistent with the interview results, i.e. navigating in areas with wave heights of over 4 m by PCC is difficult.

Table 3. Average wave height.

	Number of data	Mean (m)	SD	2σ	3σ
Container					
All data	21,705	3.53	1.29	6.11	7.40
Eastbound	12,423	3.74	1.26	6.25	7.50
Westbound	9,282	3.26	1.28	5.83	7.11
PCC					
All data	3,501	3.05	0.97	4.98	5.95
Eastbound	2,141	3.16	0.98	5.12	6.10
Westbound	1,360	2.86	0.92	4.70	5.62
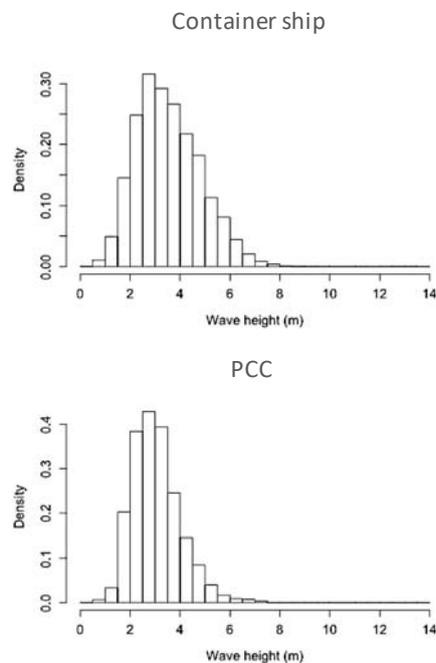
Figure 6. Probability density distribution of the wave height.
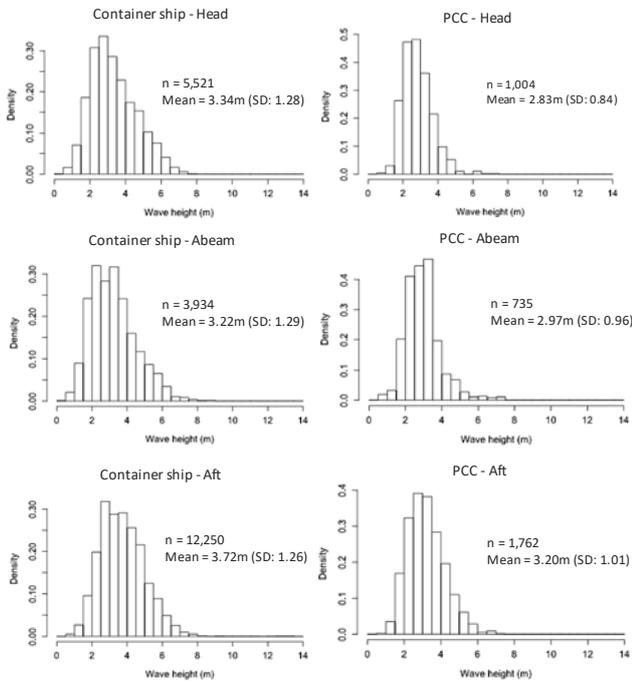
Figure 7. Probability density distribution of the wave height for each encounter direction.

According to the interview results, the wave height criterion is 5 m for container ships, and 4 m for PCCs. These figures indicate an average speed of almost 1σ for each vessel type.

Figure 7 shows the probability density distribution of the wave height for each encounter direction. A value of 0° means dead ahead. 'Head' refers to a range between 60° starboard and 60° port from the bow. 'Abeam' refers to a range of 60° to the head and 60° to the aft on both the port and starboard sides. 'Aft' refers to a range of 60° to each side from directly aft. For the container ships, the trend in the density was almost the same in all directions, and the density decreased with an increasing wave height. The highest average wave height came from the aft, and lowest came from the head. For the PCCs, the head and aft densities decreased sharply above a wave height of 3.5 m. However, the aft waves showed a gradually decreasing trend. The wave heights for the

PCCs were highest from the aft direction and lowest from the head direction.

For both container ships and PCCs, the average wave height from the head was 5% less than the average height for all voyages, and the average wave height from the aft was 5% greater.

Table 4 presents the proportion of the encounter direction for each wave height category. The proportion of wave heights from the head suddenly decreased over 7 m, and the abeam waves increased instead. In addition, the total number of data over 7 m decreased. Thus, waves coming from the head should be limited to around 7 m. In the case of PCCs, head waves should be limited to around 5 m because the total number of data was less over 5 m than below 5 m.

5.3 Eastbound and westbound trends

Table 5 presents the average speed data for eastbound and westbound ships, and Figure 8 shows the encounter wave direction. As shown in Figure 8, both container ships and PCCs mainly encountered aft waves when eastbound. On the other hand, westbound ships encountered waves from diagonally in front. The container ships received waves from both port and starboard; however, the PCCs only received waves on the starboard side. This may be because of the difference in voyage areas. We analysed trends for four areas in the North Pacific Ocean, as shown in Figure 9. Area 2 received waves diagonally from the port front, and other areas received waves from the starboard front side. That means that westbound container ships may not navigate in a zigzag fashion to avoid bow waves based on only these data.

Table 5. Average speed for eastbound and westbound ships

		Mean (kn)	SD
Container	Eastbound	18.74	2.60
	Westbound	16.26	3.21
PCC	Eastbound	15.79	2.49
	Westbound	16.69	2.42

Table 4. Proportion of encounter direction by wave height.

Wave height (m)		≤2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Container									
Head	%	33.51	29.02	23.42	20.83	23.52	22.40	12.98	NA
	#	707	1,777	1,420	903	495	157	17	0
Abeam	%	30.90	19.37	18.11	12.55	14.16	12.41	18.32	40.00
	#	652	1,186	1,098	544	298	87	24	4
Aft	%	35.59	51.61	58.46	66.62	62.33	65.19	68.70	60.00
	#	751	3,160	3,544	2,888	1,312	457	90	6
PCC									
Head	%	35.59	33.64	25.80	18.66	5.10	22.22	16.67	NA
	#	147	479	289	75	5	6	1	0
Abeam	%	20.82	22.12	21.79	14.18	14.29	29.63	66.67	NA
	#	86	315	244	57	14	8	4	0
Aft	%	43.58	44.24	52.41	67.16	80.61	48.15	16.67	NA
	#	180	630	587	270	79	13	1	0
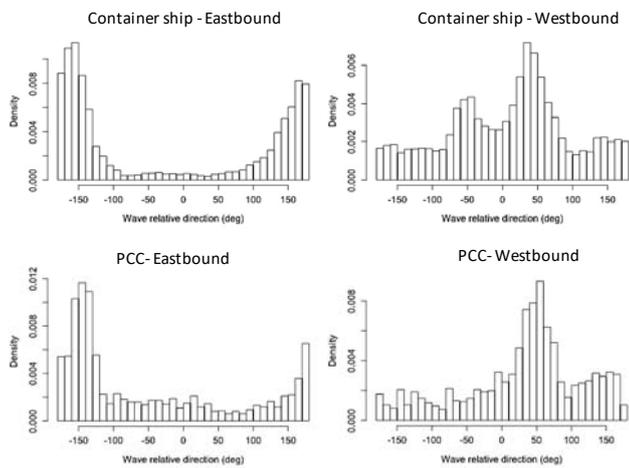
Figure 8. Probability density distribution of the wave direction for eastbound and westbound ships.
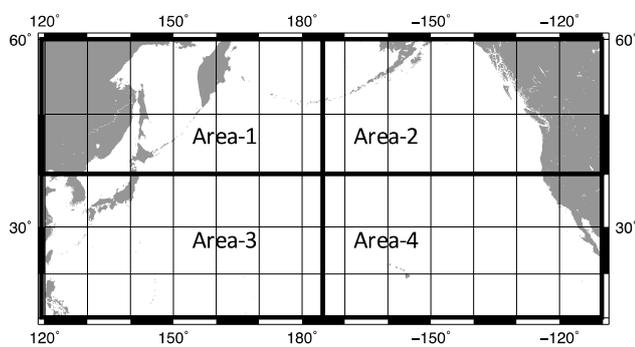
Figure 9. The North Pacific Ocean divided into four areas.

Figure 10 plots the ship position for wave heights over 5 m for container ships and over 4 m for PCCs. These wave heights were selected based on the opinions of shipmasters. The eastbound voyages are widely distributed. On the other hands, the westbound voyages mainly distributed around the Gulf of Alaska. Here it can be seen that Eastbound voyages that mainly receive aft waves are allowed to navigate for a long stretch of time even under rough sea conditions. However, the westbound voyages that receive head waves could be allowed to navigate only a short time. It can be determined that the navigation period for high waves is related to the ship motion.
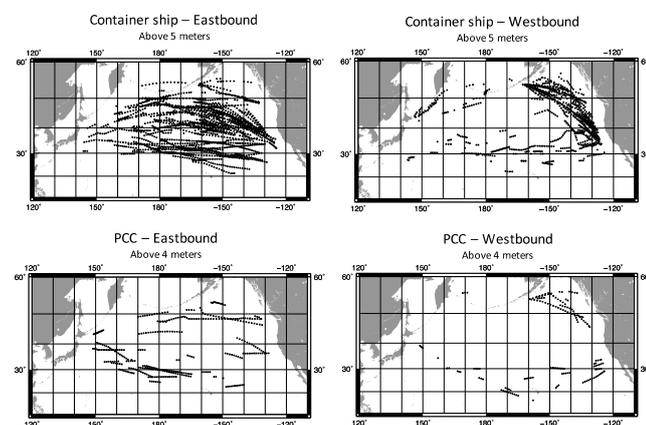
Figure 10. Plotted ship positions for >6 m wave height encountered by container ships and >4 m wave height encountered by PCCs.
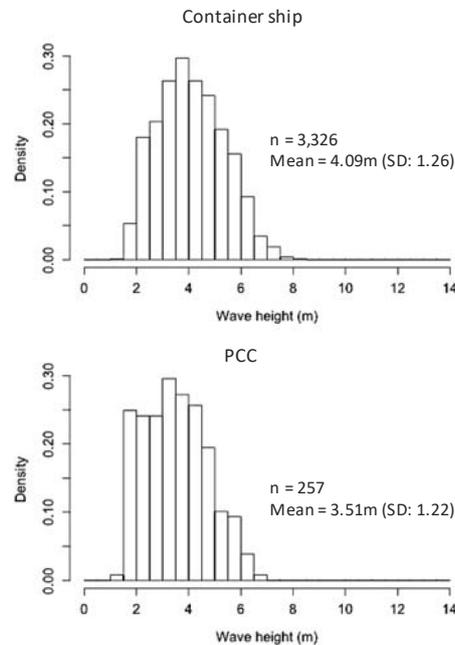
Figure 11. Wave height in area north of 30°N and east of 165°W.

Figure 11 shows the density of encountered wave heights in the area north of 30° N and east of 165° W. The average wave height was 0.5 m higher than the average height for all voyages. For PCCs, the high density zone reached around 5 m. For container ships, the density was not significantly reduced. However, the wave height increased as a whole. If the criterion is 1σ of the average speed like other areas, it would be around 5.5 m. Thus, the shipmasters' wave criterion may have become more lenient temporarily during navigation of this area. The criterion can be determined to be 5.5 m for container ships and 5 m for PCCs.

5.4 Relation between the wave height and ship speed

During the actual operation of merchant ships, the speed may be decreased depending on the sea conditions. This is decided by the shipmaster depending on the main engine performance and ship motion. According to the interview results, a shipmaster decreases the engine revolution when racing and/or torque-rich conditions are expected.

Figure 12 shows a scatter plot of the relation between the wave height and ship speed. For a container ship that received an aft wave, the ship speed stayed almost the same ($r = 0.0202467$) even at high wave heights. On the other hand, for a container ship that received a head wave, the ship speed gradually decreased ($r = −0.2780084$) as the wave height increased.
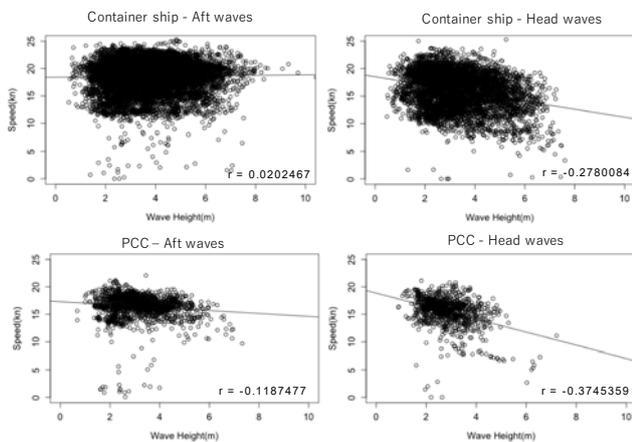
Figure 12. Scatter plot of the relation between the wave height and speed.

In the case of PCCs, the ship speed gradually decreased with aft waves ($r = -0.1187477$) even at large wave heights. The speed with head waves decreased ($r = -0.3745359$) with an increasing wave height. These results include the effect of the current, dirt on the bottom, winds and waves, and reduced engine revolution. Hence, it is difficult to clarify the reason why a ship's speed decreases. However, the deceleration rate of PCCs was much greater than container ship. This result agrees with the shipmasters' opinion that the speed of a PCC should be immediately decreased in rough seas.

6 CONCLUSION

In this study, tracking data of actual ships traversing the trans-North Pacific Ocean route in winter were analysed to determine the relationship between the route selection and weather judging criteria, with a particular focus on waves. Based on the results, the following weather judging criteria were determined:
- Based on the tracking data and interview results, the average wave height encountered by container ships is 3.53 m; the wave criterion for the North Pacific Ocean in winter should be 5 m, which is almost the same as 1σ.
- The average wave height encountered by PCCs is 3.05 m. The wave criterion for the North Pacific Ocean in winter should be 4 m, which is almost the same as 1σ.
- For both container ships and PCCs, the average heights of head were 5% less and aft waves were 5% greater, compared with the average wave height for all voyages.
- Head waves for container ships should be limited to around 7 m. Head waves for PCCs should be limited to around 5 m.
- Eastbound voyages that mainly receive aft waves are allowed to navigate for a long stretch of time even under rough sea conditions. However, westbound voyages that mainly receive head wave could be allowed to navigate only a short time.
- In the area north of 30° N and east of 165° W, the average wave height is 0.5 m higher than the average height for all voyages. In addition, the high density zone reaches around 5.5 m for container ships and 5 m for PCCs. The

shipmasters' wave criterion may become lenient temporarily when navigating this area.
- PCCs decelerate much more under head sea conditions than container ships.

The results of this study are based on 3 months of AIS and weather data. Thus, the criteria may differ at other times of the year depending on the changing climate. However, at present there is no standard for developing an algorithm to represent a shipmaster's on-board decision-making. These results can contribute to the development of the operational limitations in the second generation of intact stability criteria. It remains as a future work to propose an algorithm that represents the route decision/selection by shipmasters with the preferred safety margin for the navigation simulation based on the outcomes of this study. To assess the impact of operational limitations on actual ship operation is expected as a future work using an updated navigation simulation based on the outcomes of this study.

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