Global ship accidents and ocean swell-related sea states

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Abstract. With the increased frequency of shipping activities, navigation safety has become a major concern, especially when economic losses, human casualties and environmental issues are considered. As a contributing factor, the sea state ~~conditions~~ plays a significant role in shipping safety. However, the types of dangerous sea states that trigger serious shipping accidents are not well understood. To address this issue, we analyzed the sea state characteristics during ship accidents that occurred in poor weather or heavy seas based on a ten-year ship accident dataset. ~~The s~~Sea state parameters~~,~~ of a numerical wave model, i.e. ~~including the~~ significant wave height, ~~the~~ mean wave period and ~~the~~ mean wave direction, ~~obtained from numerical wave model data~~ were analyzed for the selected ship accident cases. The results indicate~~d~~ that complex sea states with the co-occurrence of wind sea and swell conditions represent threats to sailing vessels, especially when these conditions include ~~close~~ similar wave periods and oblique wave directions.

1 Introduction

The shipping industry delivers 90% of all world trade (IMO, 2011). It is currently a thriving business that has experienced increases in both the number and size of ships. However, due to the frequency of shipping activities, ship accidents have become a growing concern, as have the ~~following~~ associated destructive consequences, including: casualties, economic losses and various types of environmental pollution.

Investigations into the causes of shipping accidents show that over 30% of the accidents are caused by poor weather, and an additional 25% remain completely unexplained (Faulkner, 2004). Due to these dangerous uncertainties, accidents that involve poor weather and severe sea states should be further studied for shipping safety.

However, under changing weather conditions, the sea surface is too complex to predict, especially on ~~a small~~ short timescales (Kharif et al., 2009). The sea surface is composed of random waves of various heights, lengths and periods. Meanwhile, different kinds of waves emerge frequently~~,~~; among them, wind sea and swells are the two main types of ocean waves classified by wave generation mechanisms. Wind sea waves are directly generated by local winds, and when wind-generated waves propagate without receiving further energy from wind, ~~they gradually grow~~ they transition into ~~a~~ swells.

Meteorologists and oceanographers generally work with statistical parameters, such as the significant wave height (H_s), wave period (T, zero-crossing period) and wave direction (D), to represent a given sea state. Additionally, the wave spectrum, ~~that gives the~~i.e. the distribution of wave energy among different wave frequencies ($f, f = 1/T$) is analyzed in some studies to better understand wave dynamics. Note that a typical ocean wave spectrum with two peaks (e.g., one from ~~the distance~~ distal swells and the other generated by the local wind) ~~will be~~are much more complicated and variable.

~~Regarding~~ In terms of the sea state parameters, H_s is usually a practical indicator of the sea state during marine activities. Indeed, some studies, ~~have shown that accident areas coincide with the zones of the highest H_s, e.g., in~~ such as an analysis of ship accidents that occurred in the North Atlantic region (Guedes et al., 2001), have shown that accident areas coincide with the zones with the highest H_s. A high wave height is ~~no doubt~~ undoubtedly a threat ~~for~~ to ships, yet some ships wreck ~~at~~ in sea states characterized by relatively low wave heights and high wave steepness ~~sea states~~ (Toffoli et al., 2005).

A sea state with a narrow wave spectrum was observed during several major ship accidents, including the 'Voyager' accident (Bertotti and Cavaleri, 2008), the Suwa-Maru incident (Tamura et al., 2009), the Louis Majesty accident (Cavaleri et al., 2012) and the Onomichi-Maru incident (In et al., 2009; Waseda et al., 2014). Studies have assumed that the narrowed wave spectrum is primarily generated by the nonlinear coupling of swell and wind sea (or swell and swell) (Bertotti and Cavaleri, 2008; Tamura et al., 2009; Cavaleri et al., 2012; Waseda et al., 2012). During such wave couplings, the wave energy from one wave system (wind sea or swell) is enhanced and ~~transformed~~ transferred to the other wave system (usually a swell) (Tamura et al., 2009; Waseda et al., 2014). As a result, the wave energy transformation produces a steep swell, with a ~~large~~ high wave energy and extreme wave height (Bertotti and Cavaleri, 2008).

The oblique angle between two waves is another important condition involved in the interaction of wave systems. ~~Various~~ The traveling angles ~~have been discovered during~~associated with ship accidents~~,~~ ~~ranging~~ have varied from 10° (Onorato et al., 2010) to 60° (Tamura et al., 2009). The features noted above emerge individually or simultaneously ~~emerge~~ during ship accidents or ~~freakish~~ rare extreme sea states when swells and wind seas co-occur. Indeed, the co-occurrence of wind seas and swells can lead to dangerous seas, as demonstrated by the parametric rolling ~~that occurred for~~experienced by the German research vessel Polarstern (Bruns et al., 2011), ~~although~~ despite the absence of extreme wave heights ~~were not observed~~.

In previous studies of ship accidents, researchers focused on only one severe accident when discussing the sea state dynamics in detail or based their studies on ship accident data to perform statistical analyses of classical sea state parameters (e.g., H_s and T). To thoroughly investigate sea state parameters, we collected information on a large number of ship accidents and created a database for analysis. Additionally, we discussed the parameters in both wind sea and swell conditions. Statistical analyses were performed on data obtained from the International Maritime Organization (IMO). The data include ten years of ship accidents (2001 – 2010) and 755 cases caused by bad weather or heavy seas. Because swells with large wave energies can represent a threat to maritime activities, 58 cases in which swells were reported as an important factor in the ship accident were selected. The detailed information discussed above ~~are~~ is presented in section 2. Following an overview of the ship accidents (section 3), an analysis of the swell-related sea state conditions for these ship accident cases is presented in section 4. In section 5, two cases are illustrated to demonstrate the dynamic processes that ensue when wind sea and swell conditions occur during ship accidents. Finally, a summary and discussion are provided (section 6).

2 Data and Methods

2.1 Ship Accident Database

A ten-year (2001–2010) ship accident dataset was gathered from the Marine Casualties and Incidents Reports issued by the IMO. The dataset includes 3648 ship accidents, and each accident in the report includes the occurrence information, such as the accident time and coordinates, initial event, summary, casualty type, ship type, ~~etc~~among other factors. Since the primary information used in this study includes the accident time and coordinates, ~~after excluding the~~ events that failed to record these details were excluded, and ~~,~~ 1561 cases with exact geographical locations remained in the dataset.

According to the description of initial events, which provides clues regarding the accident causes recorded in the reports, those 1561 valid cases cover different kinds of cases triggered by natural factors and human factors. Because we focus on the events that occurred in natural weather-related conditions, cases with ~~the~~ descriptions such as fire or explosion, ~~–~~improper operations, ~~—~~and lost persons were eliminated from the 1561 cases, while cases with keywords such as strong wind/gale/cyclone or heavy seas/rough waves were kept. Although the proximal human factors resulting in ship accidents recorded in the IMO reports may have been indirectly related to dangerous seas or heavy weather, e.g., improper operations by crews, it would be exceedingly difficult to analyze the original factors case by case. Thus, distinguishing among trigger factors based on initial event keywords represents an optimal way of filtering the dataset. After this filtering, 755 weather-related accidents were obtained for the further analysis. An overview of these 755 cases is presented in section 3.

Furthermore, this study focuses on the cases that occurred in swell-related sea states. After examining all the summaries of the 755 cases, we ~~kept~~ retained 58 cases with clear descriptions of the swell ~~movement~~ motion during the ship accidents for the analysis of the swell-related sea states. ~~The~~ A detailed analysis is presented in section 4.

2.2 Numerical Wave Model Data

The ERA-20C numerical wave model data were obtained from the European Center for Medium-Range Weather Forecasts (ECMWF). The ECMWF uses atmosphere, land, surface, and ocean wave models and data to reanalyze the weather conditions during the last century. The ERA-20C products describe the spatio-temporal evolution of ~~the atmosphere (on 91 vertical levels, between the surface and 0.01 hPa), the land-surface (in 4 soil layers), and~~ ocean waves ~~(~~for 25 frequencies and 12 directions~~)~~. The accuracy is improved by validation with ERA-40 data and operational archive results. Compared to the ERA-Interim dataset (12 h), ERA-20C has longer reanalysis coverage (24 h) for single-point data (Poli et al., 2013). The Ocean Wave Daily data in the ERA-20C dataset are available from 1900–2010 every 3 hours at a grid size of 0.125°. The data provide 33 reanalyzed ocean wave parameters, and separate entries are included for swell and wind sea ~~conditions~~.

3 Overview of Ship Accidents

In the ship accident dataset, 755 weather-related cases were distinguished and ~~expounded~~ discussed in section 2. Hereafter, we provide an overview on these 755 cases in terms of the initial events, ship types and spatial distribution. ~~Five types of initial events (Figure 1(a)) were assumed as weather-related ship accidents. The results show that the stranding/grounding type of accident ranks first in terms of frequency and accounts for 40.3% of all accident cases.~~ The initial event in the IMO reports describes the triggering behaviors of each accident. Based on these records, five types of initial events were selected for classification, which are stranding/grounding, hull damage, others, capsizing/listing and foundering/sinking, sorted from the largest proportion to the smallest (Figure 1(a)). The initial event labeled others in the classification includes report keywords such as 'machinery damage due to heavy weather', 'cargoes shifting due to rough seas' and 'fatalities in heavy weather conditions', which are all related to bad weather. Note that the classification shown in Figure 1 (a) is not based on a detailed trigger factor but a general result. For instance, when the ship accidents are classified as stranding/grounding or foundering/sinking, the vessels may have suffered from various types of dangerous seas or bad weather, including parametric rolling, extreme slamming, bending and torsional stresses, and/or green water on deck, all of which all can reduce a ship's stability and consequently cause stranding/grounding or sinking.

~~In addition, d~~Different types of ships respond differently when they encounter potentially dangerous sea conditions because of their ~~unique~~ different structures and functions. Among the 755 cases, general cargo vessel types experienced the highest proportion of accidents (32.3%) in rough weather and severe sea states, ~~and they are~~ followed by bulkers and fishing vessels. Collectively, these data highlight the types of ships that may require more attention during shipping activities (Figure 1(b)).

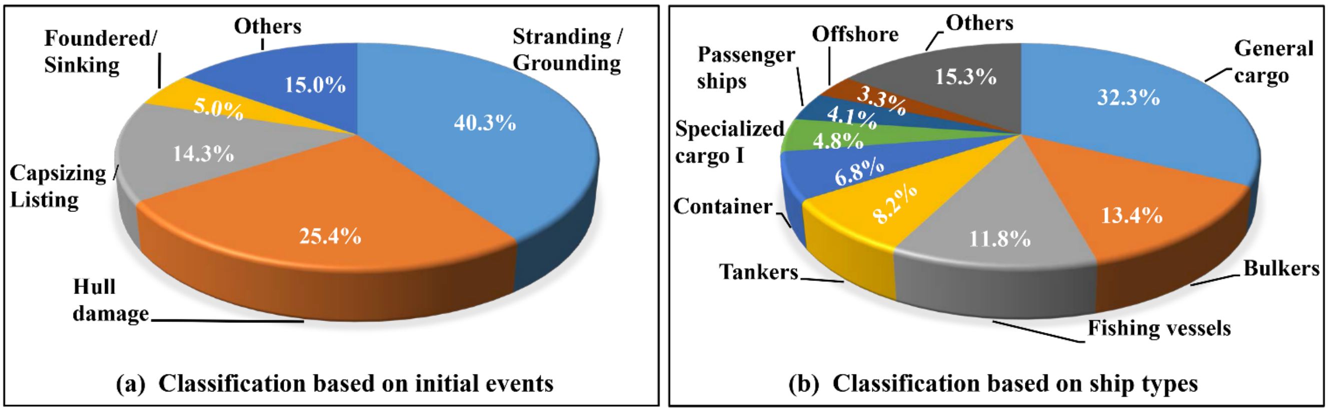

Figure 1. Classification of the 755 weather-related ship accidents based on initial events (a) and ship type (b). The accidents were recorded in the International Maritime Organization (IMO) database.

Figure 2 presents the spatial distribution of the 755 cases in terms of occurrence density. To construct the ship accident density graph, the research area was divided into 188,325 raster cells with a cell size of 50 km × 50 km. Then, a circle area with a radius of 500 km was defined as the region around each cell center. The number of ship accidents that fell within each region was summed and divided by the area of the region, which provided the ship accident density. Additionally, 58 ship accidents that occurred in swell sea states have been superimposed as blue dots. The areas of deeper colors in the map reflect a higher density of ship accidents. Clearly, these accidents are densely distributed in the North Atlantic Ocean, the North Indian Ocean and the West Pacific Ocean, which represent areas that coincide with the major shipping routes of Asian, European and North American countries.

Figure 2 shows that few accidents occurred in the open sea, although this result may have been related to the limited data recorded in the IMO database on severe open sea accidents that occurred from 2001–2010.

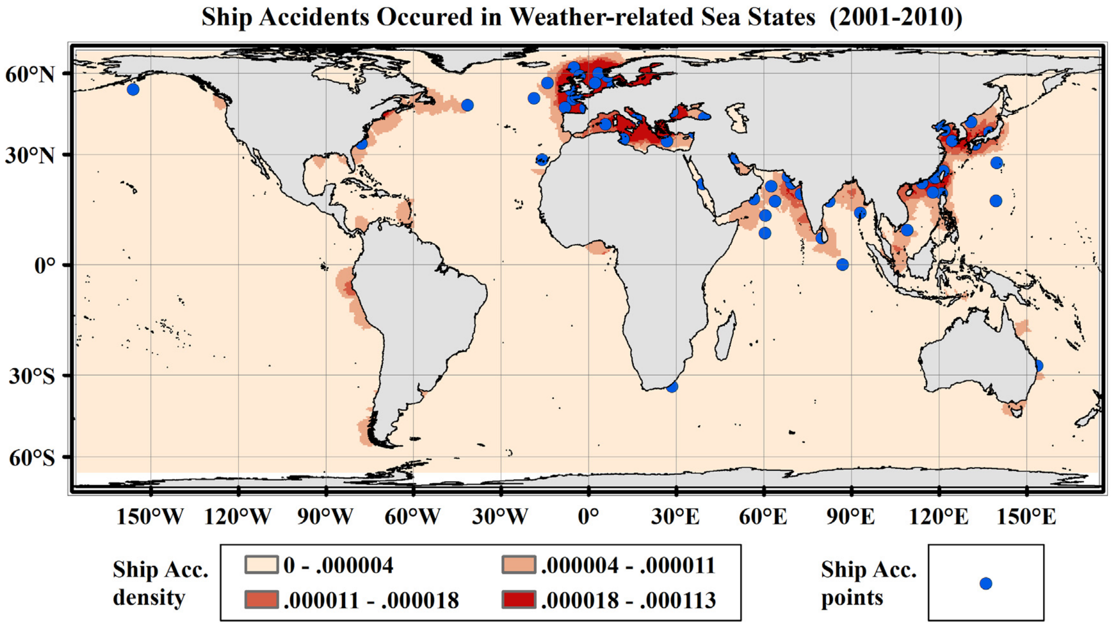

Figure 2. Geographical distribution of the ship accident density according to the 755 weather-related cases. The superimposed blue dots indicate the ship accidents (58 cases) that occurred in a swell sea state. ~~The figure was created in ArcGIS for Desktop software (version 10.2.0.3348).~~

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4 Analysis of the Sea State during Ship Accidents

As discussed in the Introduction section, the co-occurrence of wind sea and swell conditions is considered a potential causal factor that ~~can lead~~leading to dangerous sea states for ships. In this section, we focus on 58 swell-related cases to discuss the sea state characteristics associated with wind sea and swell ~~conditions~~. The sea states are described by three parameters: significant wave height, wave period and wave direction. Sea wind does have a significant impact on shipping safety, and in many cases, the high waves induced by wind can cause serious ship casualties. However, in this study, we focus on the impacts of sea state on shipping safety when both wind sea and swell are presented. Swells are long waves propagating far from their generation sources and are therefore no longer affected by the original sea wind. Consequently, in this study, the relation between sea wind and ship accidents was not considered.

4.1 Significant Wave Height

In terms of swell-related cases, both of the total sea wave height and swell wave height (H_{sw}) were analyzed. Moreover, the percentage of swell wave energy relative to the total sea energy was used in the analysis. Figure 3(a) shows the distribution of ~~those~~ these values. The bar chart indicates that almost half of the cases occurred in an H_s range of 0 m ~ 3 m, which is not high enough to warrant a rough-sea warning. However, the proportion of the swell wave energy (i.e., the ~~polygonal~~ line in the graph) within this range is greater than 50%; thus, when ships sail in relatively low sea states, the increased contribution of ~~the~~ swells may lead to dangerous sea states that threaten shipping safety. Along with an increase in H_s, the proportion of swell wave energy relative to the total sea energy remains at approximately 30%, which reflects the increasing contribution of wind sea to worsening sea conditions when H_s is greater than 3 m. In general, almost half of the swell-related cases occurred at H_s values smaller than 3 m, which suggests that high wave height is not the only critical factor that triggers ship accidents. Indeed, other parameters may also play pivotal causal roles in these accidents. Therefore, additional wave parameters, including the wave period and wave direction, are subsequently examined for these accidents.

4.2 Mean Wave Period

Figure 3(b) depicts the relationship between the occurrence of specific ship accidents and wave period differences (bar charts) ~~from~~ between swells and wind sea (ΔT, i.e., the mean period of the swell minus the mean period of the wind sea). Furthermore, the mean wave period of the total sea (T, solid line) is also plotted in the graph. Approximately two-thirds of the cases occurred in sea states where ΔT was less than 3 seconds (s) and the value of T approached 7 s, which represents a close wave period for swell and wind sea conditions in most cases. In other cases, the value of T was larger than 8 s when ΔT was larger than 3 s. ~~Overall~~On the whole, an upward trend can be observed with an increase in ΔT, except for a slight fluctuation between 4 s and 5 s. Overall, a close mean wave period (ΔT <3 s) between swell and wind sea in a co-occurring sea state is an important factor for shipping accidents.

4.3 Mean Wave Direction

As noted in the Introduction, previous theoretical studies and ship accident analyses have indicated that crossing sea states (particularly crossing swell and wind sea states) may induce high waves and generate dangerous sea conditions. To investigate this issue further, the mean wave direction differences between the swell and wind sea (ΔD, i.e., the absolute value of the mean swell direction minus the mean wind sea direction) for all the swell-related ship accidents have been analyzed. Approximately half of the cases (55%) exhibited ΔD values less than 30° (Figure 3(c)), and the values of ΔT (indicated by the solid line superimposed on the bars) within this range were approximately 3 s before decreasing to 1.8 s at ΔD values ranging from 30° to 40°. During swell and wind sea interactions, the rate of change in swell energy under the influence of wind sea energy (Tamura et al., 2009) reaches a maximum at approximately 40°(Masson, 1993). The ΔD range of 30° to 40° for the lowest value of ΔT (1.8 s) demonstrates ~~the~~ strong coupling between two waves. However, 45% of the accidents were associated with ΔD values larger than 30°. An angle of 30° appears to be a critical point for ship accidents because a rising trend in the ΔT line begins at this point. As the angle increases, the ΔT values decrease to below 3 s, and the sea state can be more easily transformed into a crossing sea state (Li, 2016; Onorato et al., 2010), which could pose a risk for ships.

Figure 3(d) is identical to Figure 3(c) except that the wave steepness of the total sea (S) has been added to the bar chart. In the present study, the wave steepness of the total sea is calculated via $S = 2\pi\, H_s / gT^2$. Along with an increase in ΔD, a rising trend in wave steepness can be observed, although a slight fluctuation appears from 40°~50°. Wave steepness appears to be positively correlated with ΔD, particularly when ΔD ~~is~~ of approximately 50°. This condition is associated with a crossing sea state with a close wave period. Overall, large direction angle and wave steepness values appear to generate dangerous sea state conditions.

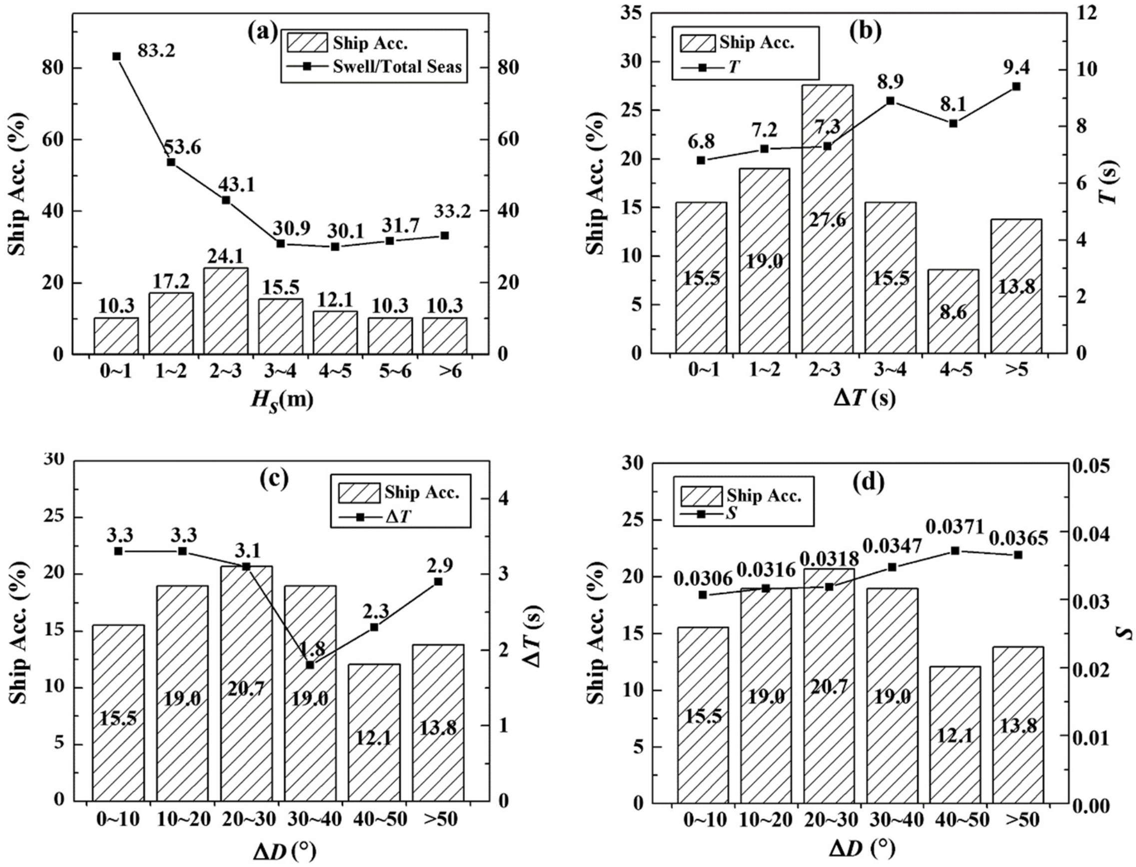

Figure 3. Incidence rate of ship accidents: (a) at different significant wave heights (H_s, bar chart) and the proportional change in swell energy in the total sea (polygonal line); (b) with wave period differences (ΔT, bar chart) and the mean wave period (T, polygonal line); (c) with wave direction differences (ΔD) and ΔT; and (d) with ΔD and the value of the wave steepness of the total sea (S)

5 Sea States of Typical Cases

Based on the statistical analysis of the sea state characteristics presented above, we preliminarily conclude that close wave periods and oblique angles between co-occurring wind sea and swell conditions play important causal roles in ship accidents. In this section, two cases are presented to reveal the dynamic processes underlying co-occurring wind sea and swell conditions during ship accidents. One case occurred ~~under~~ in a relatively low sea state, while the other case occurred ~~at~~ in a high sea state. ~~Detailed sea state conditions for the two cases are presented in Figures 4 and 5. The first column in each figure indicates the wave model results 3 hours before the accident, whereas the second column indicates the results at the time closest to the occurrence of the accident.~~

The first ship accident case occurred at approximately 20:30 UTC on February 24th, 2009. The Korean tug CHONG JIN capsized at 34°8′ N, 124°131′ E. To thoroughly investigate the possible cause of this accident, the sea state is analyzed in detail. Figure 4 shows the time series of the sea state and sea surface wind at the accident location over 24 hours. At the top of the graph, wind vanes and numbers represent the sea surface wind direction and wind speed. The lines in the middle of graph represent significant wave heights of the swell (blue), wind sea (green) and total sea (grey), respectively. The mean wave period of the swell and wind sea are annotated in the same colors as the wave height. The wave directions of the swell and wind sea are also presented at the bottom of the graph.

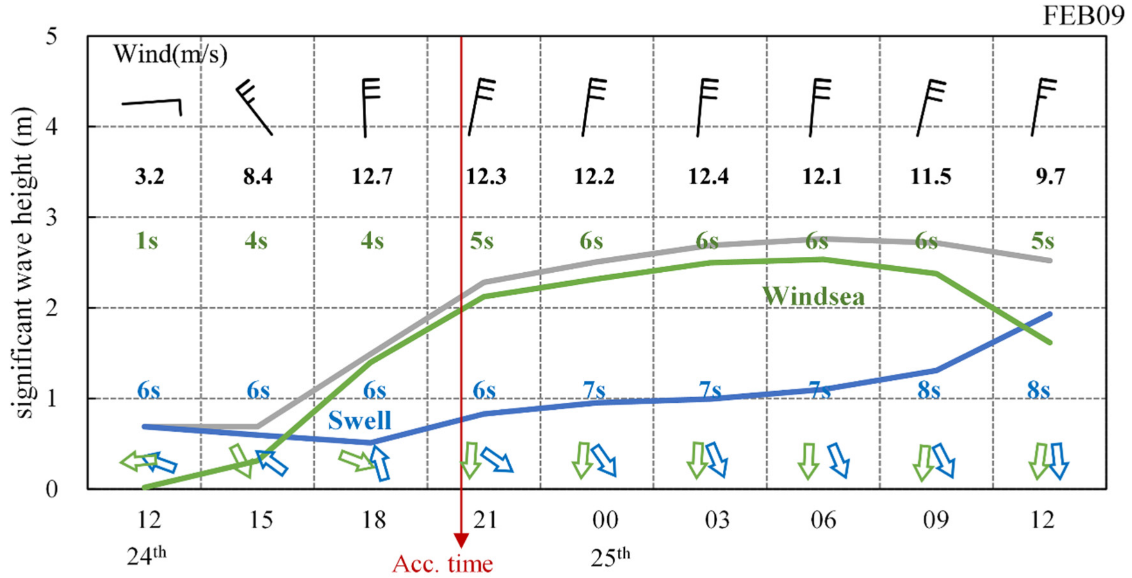

Figure 4. Time series of sea surface wind and sea state at the ship accident location over 24 hours for the case occurred at 20:30 UTC on February 24th, 2009. At the top of the figure, wind vanes and numbers indicate wind direction and wind speed at the accident location. Three polylines that in grey, green and blue colors represent the significant wave height of total sea, wind sea and swell, respectively. The numbers in green and blue colors are the mean wave period of wind sea and swell. At the bottom of the figure, the arrows that in green and blue color indicate the mean wave direction of wind sea and swell, respectively.

At 12:00 UTC on February 24th, approximately 8 hours before the ship accident, the sea was low with an H_s of 0.7 m. The dominant wave was swell moving to the northwest, and the wind sea was fairly slight. At 15:00 UTC, the wind sea began to develop rapidly due to sudden changes in the wind field (the wind direction changed from east to northwest, and the wind speed increased from 3.2 m/s to 8.4 m/s). Along with the continual growth of the wind sea, the difference between T_{sw} and T_{ws} decreased. The wave directions of the wind sea and swell at this moment were almost opposite. Soon thereafter, at 18:00 UTC, the wind speed rose continuously and reached 12.7 m/s, while the wind direction tended to the north. The H_{ws} reached 1.4 m, while the H_{sw} was still less than 1 m. When the accident occurred (close to 21:00 UTC), the swell direction was distinctly different from that at 18:00 UTC, as it had shifted from southeasterly to northwesterly. As the sea became rough, both H_s and H_{ws} increased rapidly by 2 m. Similar growth occurred in the wave periods, specifically, from 5.7 s to 6.2 s for the swell and from 4.3 s to 5.4 s for the wind sea. As the wave period of the wind sea became close to the swell, the difference between them (ΔT) decreased to 1 s.

Figure 4 shows variations in the sea state at the accident location, while sea state in the vicinity of the accident is presented in Figure 5. The diagrams in the first column show the wave model results at 18:00 UTC, 3 hours before the accident, whereas the second column are the results at 21:00 UTC, close to the accident occurrence time. From top to bottom, the sea state parameters are H_s, ΔT and ΔD. Within three hours of the ship accident occurrence, the H_s increased slightly by approximately 0.5 m across a large area proximal to the accident location. Due to the growth of the wind sea forced by local wind (refer to Figure 6), the wave period difference ΔT decreased by approximately 2 s in the area. The most distinct variation in sea state in the area is ΔD. At 18:00 UTC, the swell direction in the area was southeasterly, propagating from other areas to the ship accident location. However, after three hours, the swell direction changed to northwesterly, opposite the direction three hours before. Based on the wave direction of the wind sea in the area, we find that the northwesterly swell system (at 21:00 UTC) likely transformed from a fully developed local wind sea after the wind direction turned to the north at 15:00 UTC. Consequently, ΔD narrowed greatly from 187° to 59° at 21:00 UTC, further decreasing to 30° at 3:00 UTC on February 25th.

The change in the wind is considered a key factor in this accident. The turning point appeared at 15:00 UTC on the 24th, when the sea wind changed significantly in terms of both magnitude and direction. Afterwards, the continuous force of the sea wind induced the growth of the wind sea. The "old" wind sea was transformed into a young swell, which led to a marked decrease in ΔD. The closer wave period and narrower direction angle between the wind sea and the swell produced a resonance effect. Some experimental studies suggest that a swell with the same direction as the wind will play a role in suppressing the growth of a wind sea (Philips and Banner, 1974; DoneJan, 1987). As the swell direction tends to be the same as the wind direction, the development of a wind sea is suppressed. Meanwhile, the lower ΔD and ΔT provided conditions for wave energy transformations from the wind sea to the swell (Masson, 1993). Closer wave periods and narrower wave spectrum provide ideal conditions for the transformation of wave energy, and the resulting energy-enhanced swell represents a great threat to shipping safety.

Based on the analysis presented above, we found that the crossing sea state of swell and wind sea may have triggered the accident. Moreover, the swell that had a significant impact on the ship accident was transferred from the local wind sea instead of the "old" one that propagated from a distant storm. In the numerical wave modeling, discrimination of "swell" and "wind sea" occurs in the post-processing step through wave spectral partitioning. This spectral partitioning arbitrarily divides the two-dimensional wave spectrum into wind sea and swell components (Gerling, 1992; Hanson and Phillips, 2000) based on some criteria, and the integrated wave parameters of the corresponding wind sea and swell are subsequently derived. These swell and wind sea values are useful for depicting the trend of a sea state and can significantly contribute to many applications, such as forecast and analysis of surface wave conditions in shipping lanes and coastal areas, as in the statistical analysis and the case study presented above. However, spectral partitioning may have trouble distinguishing among the essential attributes of a wave field when both wind sea and swell or multiple swell systems are present (Hanson and Phillips, 2000).

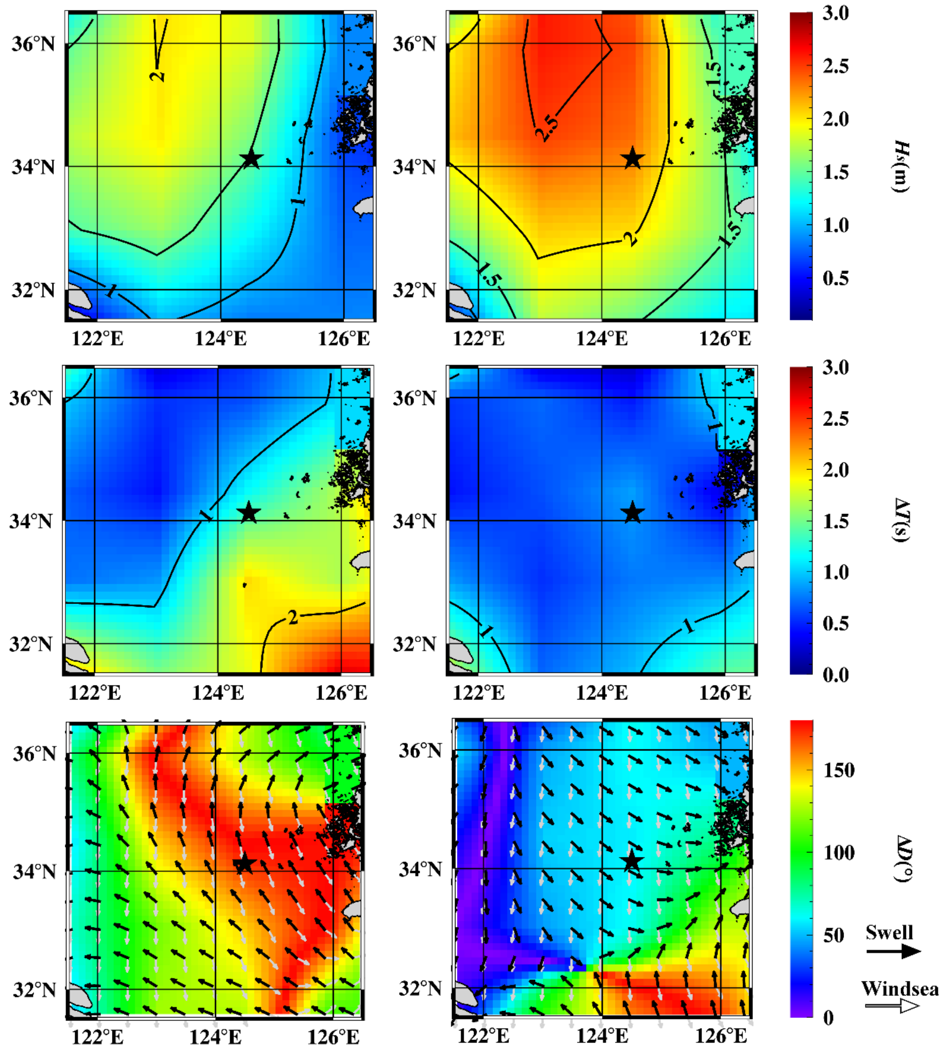

Figure 5. The sea state in the vicinity of the case that occurred on February 24th, 2009. The left and right columns are the model results at 18:00 and 21:00 UTC, respectively. The first, second and third rows in the figure are H_s, ΔT and ΔD, respectively. The accident location is marked with a black star. Arrows in the plots of the third row represent the wave directions of the swell (black) and wind sea (light grey).

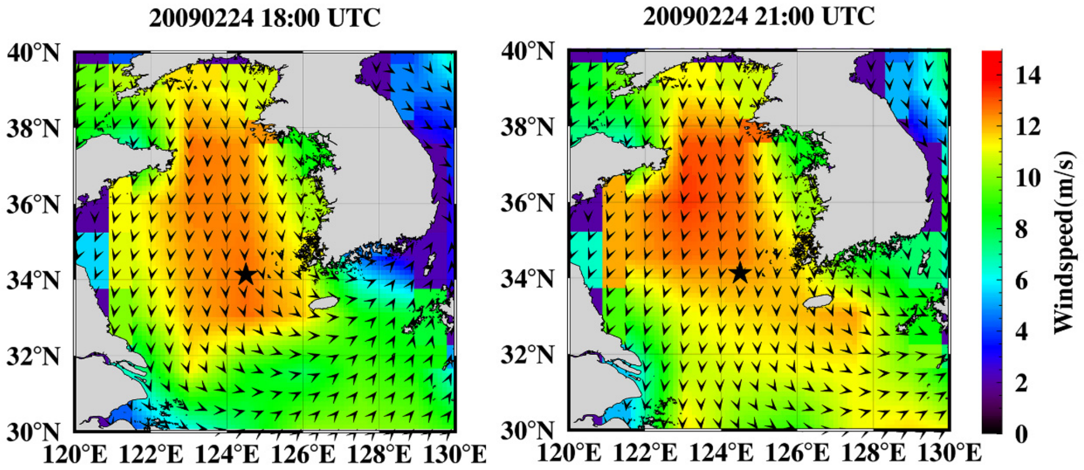

Figure 6. The sea surface wind fields at 18:00 UTC (left) and 21:00 UTC (right) of the first case that occurred at 20:30 UTC on February 24th, 2009. The accident location is marked with a black star. The arrows represent the sea surface wind directions.

In ~~another~~ the second case, a bulker carrier with a gross tonnage of 36,546 sailed from Davant, United States, to Hamburg, Germany, on ~~10~~ January 10, 2010, and at 14:45 UTC ~~and~~ encountered extremely poor weather, with westerly winds of more than 20 m/s and southwest waves of more than 9 m. As a result, t~~T~~he ship was seriously damaged~~, and the crew was seriously injured~~ at 46°14′ N, 41°29′ W. The time series of the sea surface wind and sea state over 24 hours for this case are presented in Figure 7. The lines, symbols and numbers in the figure have the same meanings as those presented in Figure 4.

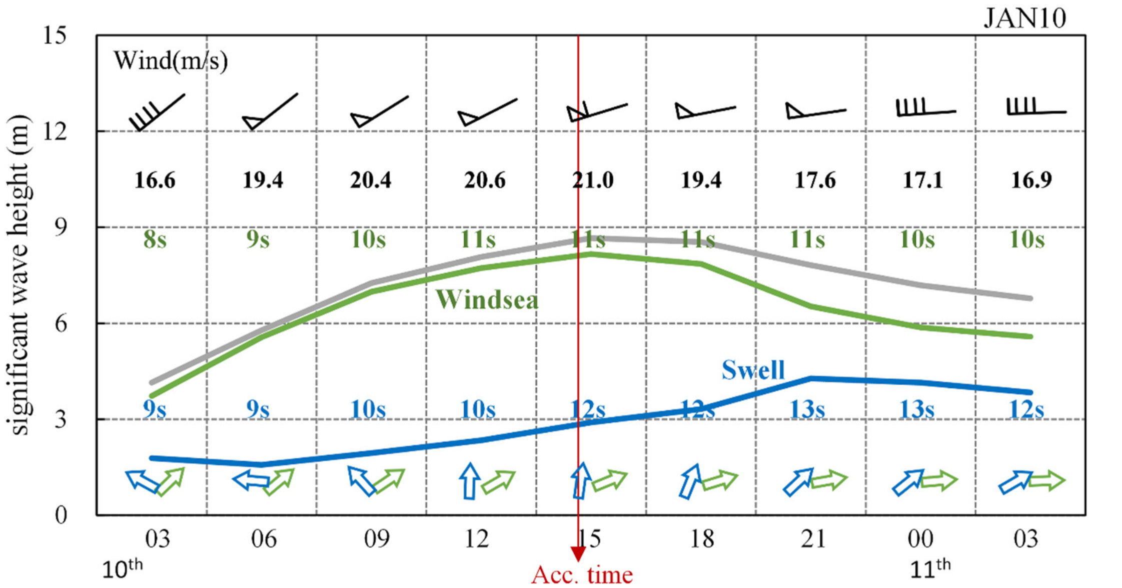

Figure 7. Time series of sea surface wind and sea state at the ship accident location over 24 hours for the case that occurred at 14:45 UTC on Jan. 10th, 2010. The lines, symbols and numbers in the figure have the same meanings as those presented in Figure 4.

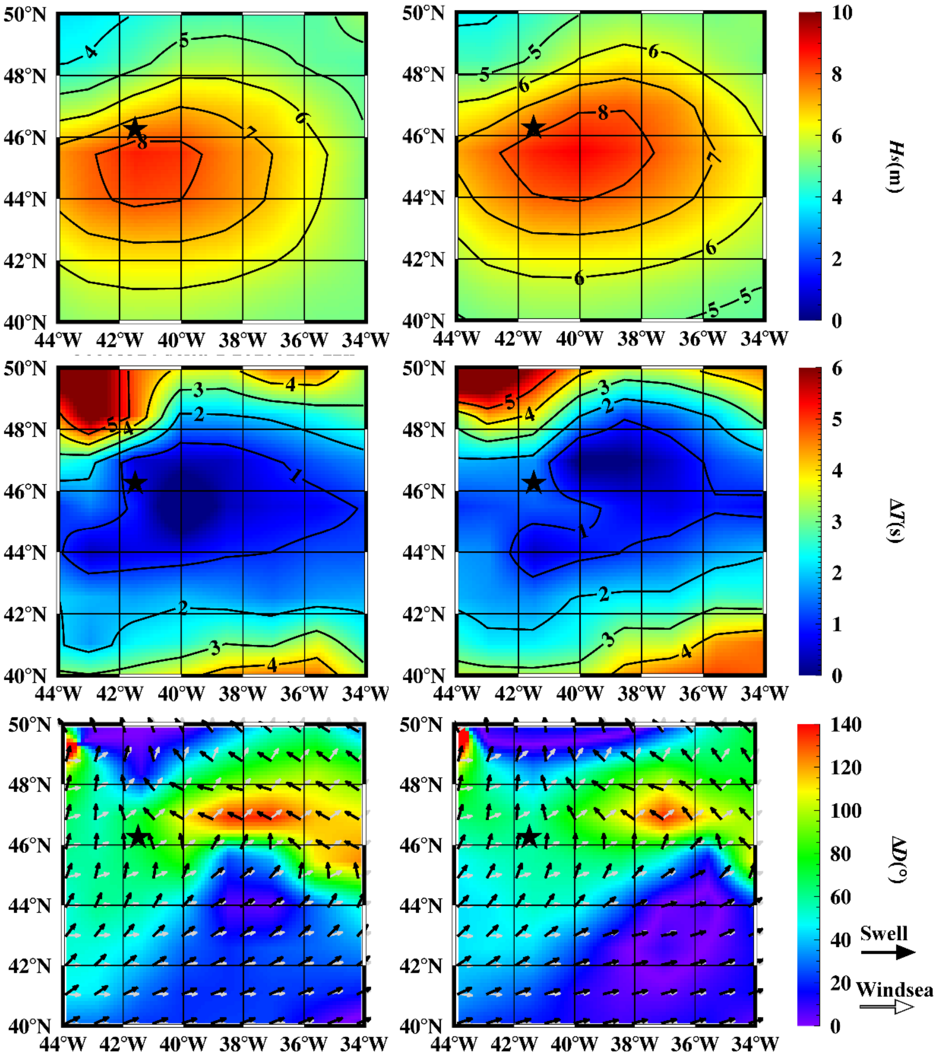

Figure 8. The sea state in the vicinity of the case that occurred on January 10th, 2010. The left and right columns are the model results at 18:00 and 21:00 UTC, respectively. The first, second and third rows in the figure are H_s, ΔT and ΔD, respectively. The accident location is marked with a black star. Arrows in the plots of the third row represent the wave directions of the swell (black) and the wind sea (light grey).

~~The sea state at this point was relatively high. From the perspective of wave height, the modeled H_s, H_{ws} and H_{sw} values between 12:00 UTC and 15:00 UTC increased from 8.08 m to 8.66 m, from 7.72 m to 8.16 m and from 2.34 m to 2.90 m, respectively. In addition, the wave periods increased from 10.5 s to 12.1 s for the swell and from 10.7 s to 11.1 s for the wind sea over three hours at this site. Evidently, the rising rate of the swell period was higher than that for the wind sea period, which produced a contour line of 1 s in the ΔT graphs. Concurrently, the waves in this case can be divided into two distinct areas according to the wave directions. The high ΔD area and low ΔD area were located in the northerly and southerly directions,~~

~~respectively. The boundary of the two areas at 50°~60° of *ΔD* was close to the accident area, thereby reflecting the fluctuating propagation angle and interactions between the two waves. These features, which are related to changes in the wave direction, were identical to those of the first case described above. In the present case, high waves (approximately 9 m) may have been a factor that threatened shipping activities. However, the decisive causes of the accident were likely related to the decreasing wave period and wave direction changes due to the co-occurring wind sea and swell conditions.~~

Based on the sea surface wind field on January 10th and 11th over a large area in the vicinity of the ship accident (not shown here), the area was experiencing an extra-tropical cyclone. The H_s (over 8 m) and sea surface wind speed (higher than 20 m/s) presented in Figures 7 and 8 also reveal the bad weather situation when the ship accident occurred. From 3:00 UTC until the approximate time of the ship accident, the wind sea grew under the force of the continuously increasing sea surface wind speed, as evidenced by the increases in H_{ws} and T_{ws}. The time at which the ship accident occurred, i.e. approximately 15:00 UTC, likely corresponds to a turning point in the wind sea growth. Before then, the H_{ws} continuously increased from 3.7 m at 3:00 UTC to 8.2 m at 15:00 UTC. Simultaneously, the T_{ws} increased from 8 s to 11 s. After the turning point, both the wave height and wave period of the wind sea started to decrease gradually. More interesting is the variation in the swell in the area. At the ship accident location, both H_{sw} and T_{sw} gradually increased from 3:00 UTC until 21:00 UTC on January 10th. However, the time series of the mean wave direction of swell shown in Figure 7 suggests that the swell situation was very complicated. At 3:00 and 6:00 UTC on January 10th, the easterly swell was the dominant swell system. The mean wave direction of the swell subsequently gradually turned to southerly and southwesterly, leading to a decrease in the ΔD from 107° (3:00 UTC) to 59° (15:00 UTC).

The sea state maps shown in Figure 8 can better resolve the variations over the course of a few hours. The H_s graph clearly shows that the higher wave area increased in size within 3 hours. The ΔT map suggests that the swell and wind sea had a close mean wave period of less than 1 s in a large area surrounding the ship accident location. In fact, the ΔT derived from the time series presented in Figure 7 suggests that it retained a quite small value of 0 ~ 1 s for approximately 15 hours. The ΔD graphs show that at least two swell systems existed in the area, with one being southerly/southwesterly and the other being southeasterly. This situation led to a high ΔD area and a low ΔD area. The boundary of the two ΔD areas at 50°~60° was close to the accident area. Based on both Figures 7 and 8, the ΔD was becoming smaller during the event, not only in the location of the ship accident but also across a large area. The time series of the swell wave direction may misleadingly suggest that the swell direction changed suddenly within a few hours. However, this was probably not the true situation. As stated in the analysis of the first case, discrimination of the swell and wind sea in the wave model post-processing step is an arbitrary process. The wave model product used in this study only provides one swell component, which cannot represent the complete swell state in a complicated situation. In this case, as mentioned above, the area was experiencing an extra-tropical cyclone that not only featured a rotational wind field but also moved in a certain direction, thereby generating swells propagating in various directions. Thus, multiple swell components might have co-existed in certain observation locations. However, spectral partitioning cannot resolve the complete swell components as only one (dominant) swell system was retained in the wave product, such as that used in this study. This situation can lead to misunderstanding data suggesting that the swell direction changed suddenly.

Nevertheless, in the present case, large waves (higher than 8 m) may have been a factor that threatened shipping activities. The additional causes of the accident were likely related to the decreasing wave period and wave direction changes that led to co-occurring wind sea and swell.

6 Summary and Discussion

The present study is motivated by a desire to thoroughly evaluate the sea state conditions during ship accidents. It aims to establish more accurate and effective maritime warning criteria and better understand the mechanisms underlying extreme waves. To this end, ten years of ship accidents that occurred in rough weather or sea conditions were chosen from the IMO ship accident database and then analyzed.

Based on the selected 755weather-related accident cases, an accident occurrence density map was generated. The ship accidents presented a dense distribution in the North Atlantic Ocean, the North Indian Ocean and the West Pacific Ocean because of the associated severe weather and sea state conditions, and the locations of these accidents coincided with major shipping routes. In terms of ship type in the casualty reports, the most frequent ships involved in these accidents included general cargo ships, bulkers and fishing vessels. Of the reported initial events, stranding/grounding and hull damage were the most prominent.

Strong winds and high waves can cause heavy sea states, which are indeed the primary risk factors for maritime activities. However, the potential dangers of swells with relatively low wave heights are generally underestimated. Notably, our analysis of the 58 swell-related accidents indicated that 52% of the cases occurred in relatively low sea state conditions with H_s values smaller than 3 m~~,~~; and ~~the~~ that swells provided the dominant wave energy in these conditions. A further analysis of these accidents suggested that co-occurring wind sea and swells, especially when ~~certain conditions occur,~~ the differences in their mean wave periods and mean wave directions meet certain conditions, may lead to hazardous seas and pose a risk to shipping activities. Among the 58 swell-related ship accidents, approximately 62% of the cases have ΔT values of less than or equal to 3 s. Interestingly, for all these cases, the averaged ΔT for different ΔD is approximately 3 s and is smallest, i.e., 1.8 s, when ΔD is between 30° and 40°. When ΔD is between 30° and 40°, the crossing sea state has a high potential of being composed of a wind sea and a swell transformed from the local wind sea, as was the situation in the first case. Overall, the statistical analysis reveals that ΔT values less than 3 s and ΔD values smaller than 60° are two important factors of crossing seas that can lead to wave interaction between the wind sea and the swells, consequently generating dangerous seas that threaten shipping safety. Therefore, this finding can potentially be used as a warning criterion in forecasts for shipping lanes.

~~Our analysis of the wave period and wave direction demonstrated that two types of sea states can generate severe sea states. In the first state, ΔD is less than 30°, and the values of ΔT are all slightly great than 3 s. This case is the most likely angle interval for two coupling waves to establish an extreme sea state (Onorato et al., 2010) because this scenario produces a large~~

~~rate of wave amplification and generates unstable wave surfaces and perturbations. Although close wave period conditions are not present, the small difference angle between two wave systems has the strong possibility of forming violent seas. In the second state, as *ΔD* increases, *ΔT* reaches a minimum value of 1.8 s at 30° ~ 40° and is still less than 3 s when *ΔD* is large than 40°. Additionally, the nonlinear coupling between two waves reaches a high level as *ΔD* increases. Meanwhile, the quasi-resonance occurs between two waves due to the close wave period. Therefore, with increasing wave energy transformation, waves can grow rapidly, become violent and threaten ships. Consequently, the resonant nonlinear interaction will result in a narrow wave spectrum and likely lead to an abnormal sea state under the influence of modulation instability. In addition, the rising value of wave steepness as *ΔD* increases indicates that the situation is worsening.~~

According to the report records, many ship accidents have occurred in offshore areas yet few have occurred in open sea areas. Although the accuracy of the model data is fairly high, the coastline resolution used in the dataset is relatively coarse. As a result, a bias may exist in the offshore areas. Therefore, the diagrams shown in the statistical analysis appear to be somewhat noisy. On the other hand, even under the same sea state, different ship types should respond differently. This phenomenon may also lead to a variety of statistical results in a variety of situations. Nevertheless, the statistical results still reveal noteworthy characteristics of dangerous sea state conditions.

The sea states of the two case studies meet the general conditions of a possible occurrence of dangerous waves based on the statistical analysis, whereas they also presented different situations. In the first case, the overall sea state was relatively low, at 2.0 -2.5 m. However, the sea surface wind direction changed significantly approximately 6 hours before the accident. The gradually enhanced northerly/northwesterly wind forced the growth and development of a wind sea, which later transformed into a swell. The “new” swell therefore had a markedly different direction from that present approximately 6 hours before. The freshly generated swell and wind sea both had smaller *ΔT* and *ΔD* values, producing favorable conditions for coupling between the swell and the wind sea and leading to possible generation of waves dangerous to ship safety. In the second case, the overall sea state was quite rough, with an H_s higher than 8 m. Although the sea surface wind speed increased gradually before the accident occurred, the sea surface wind direction remained southwesterly. On the other hand, although *ΔT* remained quite small (approximately 1 s) for more than 12 hours, *ΔD* exhibited significant variation, decreasing from more than 100° at 9 hours before to approximately 60° when the accident occurred. A plausible explanation is that the area was experiencing an extra-tropical cyclone, which had a rotational sea surface wind field and also moved continually. This cyclone therefore generated swells that propagated to multiple directions. Detailed analysis of the sea states associated with these two specific cases further demonstrates that both oblique wave directions and similar wave periods between the wind sea and the swell are two key factors of crossing seas that can lead to the generation of sea state dangerous to shipping safety.

~~The dynamic wave interactions presented in the two specific cases analyses demonstrated that the oblique wave directions (40° ~ 60°, listed in the cases) and the narrow wave periods between wind sea and swell led to the increase in the wave height, which could be an indicator of wave energy transformation and worsening sea state. This result is consistent with the explanation given in the previous paragraph.~~

~~Although the accuracy of the model data were validated using ERA-40 and operational archive results (Poli et al., 2013),~~

~~the present wave model results were retrieved on a global ocean scale rather than on an individual basis; therefore, deviations may exist compared to the actual sea states. Nevertheless, the results indicate noteworthy characteristics of dangerous sea state conditions.~~

Finally, ship safety could be improved if the major contributors to dangerous sea states are identified and monitored, especially ~~in high incidence areas for ships~~ along major shipping lanes. In future work, the use of multisource data will undoubtedly provide a more complete description of these complex phenomena.

Acknowledgments

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Responses to reviews

We would like to thank the reviewers for their evaluation of this study and the helpful suggestions and comments. Comments are responded on a point-by-point basis. Please check the revised manuscript for the details. We hope this revised version could satisfy the reviewers and be acceptable for publication in NHESS.

Responses to Reviewer 1

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It is an interesting paper investigating the correlation between ship accidents and certain sea states, co-occurrence of wind sea and swell, in particular. It is well known that ships are endangered in high seas, depending on their size. Therefore, the IMO recommends ship owners to take advantage of ship routing services. However, accidents also occur unexpectedly at moderate sea states and thus it makes sense to dig deeper in the available data base. From this point of view, I find this paper is worth being published. However, I have some major concerns and proposals of improvement:

- The wave model data set ERA-20c used is not suitable for this study, therefore acquire a high resolution data set
- Discuss the typical cases in terms of time series in addition to the 2-dim- representation
- Include interpretation of wave spectral partitioning
- Include some discussion on ship behavior in rough seas

Under these conditions, the paper will be acceptable, otherwise, I would have to reject the paper.

Response: Thank the reviewer for the positive comments. We have made a major revision following the reviewers' comments.

- *The wave model data set ERA-20c used is not suitable for this study, therefore acquire a high-resolution data set.*

The detailed answer for this question presented in the point by point answers. Please refer to the response for comment 2.

- *Discuss the typical cases in terms of time series in addition to the 2-dim-*

representation

Time series of sea states for the case studies have been added to the revised manuscript. Please refer to Figure 4 and Figure 7 of the revised manuscript.

- *Include interpretation of wave spectral partitioning*

For the first case study, interpretation of wave spectral partitioning has been added to the revised manuscript. Please refer to the last paragraph in Page 10.

- *Include some discussion on ship behavior in rough seas*

We didn't discuss ship behavior in rough seas in details, as the present study focuses on investigating sea states impacts on ship accidents. Some general discussion on this was added to the revised manuscript. Please refer to the first paragraph in Section 3.

Comment 2: Numerical Wave Model Data:

Page 3, line 24-25:

The Ocean Wave Daily data in the ERA-20C dataset are available from 1900–2010 every 3 hours at a grid size of 0.125°ERROR. The spatial resolution is 1.5° ……

Response: The ERA-20C data with various spatial resolution (from the lowest 3° by 3° to the highest 0.125° by 0.125°) are available. We used the ERA-20C data with the highest resolution of 0.125° by 0.125° for this study. The following figure shows the screenshot of the data downloading interface (at http://apps.ecmwf.int/datasets/data/era20c-wave-daily/type=an/)

But we also noticed that the ERA-20C data with the highest resolution of 0.125° by 0.125° should also have some biases, particularly when the reviewer pointed out that the modeled wave height of the first case (presented in the original manuscript). We had also checked that case again and confirmed this point. The detailed explanation why the modeled wave height of the first case has such distinct bias was presented in the interactive discussion panel. On the other hand, spatial resolution of coastline used in the ERA-20C data is rather low, which can lead to that the model results seem to be very smooth in the offshore area, i.e. they don't represent fine structure of sea state in the offshore areas. We have added some discussions on this point in Section 6.

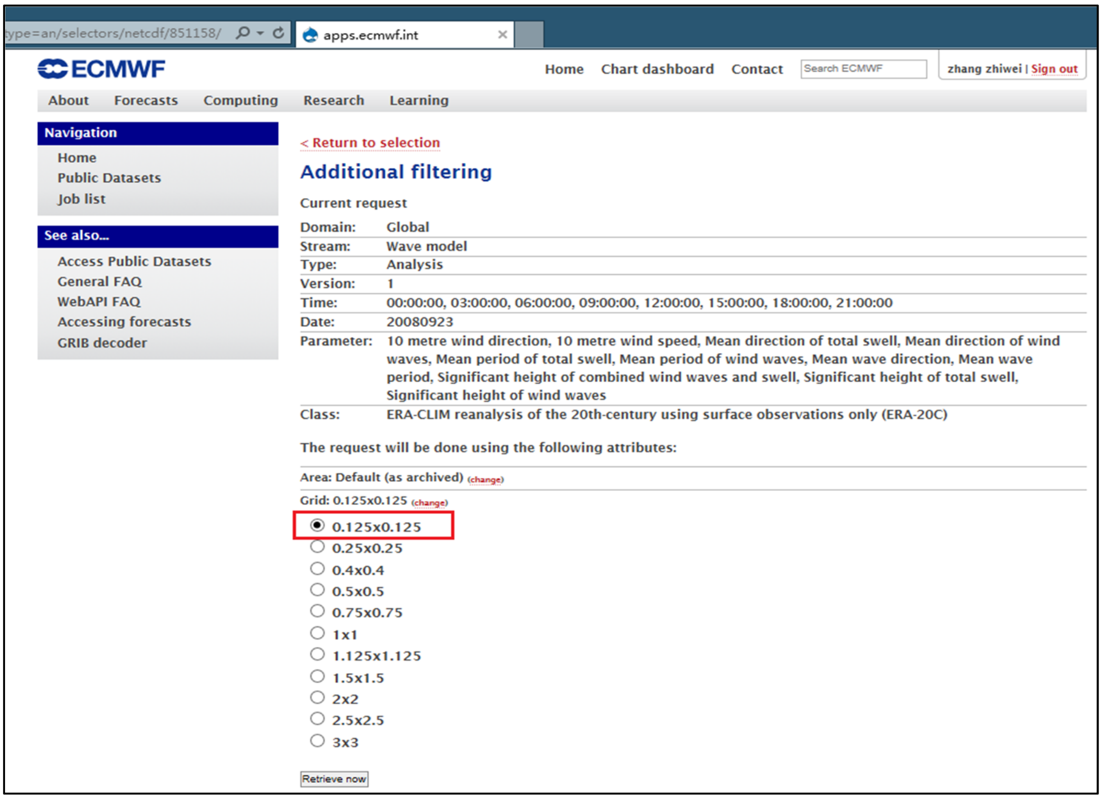

Fig.R1 The download interface of ERA-20C data

Comment 3: Overview of Ship Accidents

The section describes the large variety of ship types and accidents. It is clear that each case would deserve a distinct study taking into account the ship's properties. Since this will hardly be possible, some discussion on ship's behavior in heavy seas would be helpful at this point. The authors already mention parametric rolling, but a lot other dangerous incidents may occur, like extreme slamming, bending and torsional stresses, green water on deck and emerging propellers (both reducing ship's stability).

Response: Thank the reviewer for the valuable suggestion. The initial event in the IMO reports describes the triggering behaviors of each accident. According to initial event, we have divided five types in terms of ship behaviors. In order to facilitate statistics, the classification is not based on a detailed trigger factor but a general result. It is no doubt that the ship behaviors in rough seas mentioned by the reviewer can induce stranding/grounding or foundering/sinking. We have added some discussion on this point according to reviewer's suggestion. Please refer to the first paragraph of Section

3.

Comment 4: Analysis of the Sea State during Ship Accidents

(1) “With the statistical evaluation in this section the authors attempt to find evidence of a relation between ship accidents and crossing seas (wind sea and swell), characterized by small ΔT<2s, directional spread of 30 - 40°.

Indeed, a tendency in this direction can be recognized, but there is a lot of noise in the data, which remains unexplained. Some portion of this noise is probably due to the coarse data grid. The rest should be explainable by the large variety of ships and different kinds of causes for accidents (see 3.).”

Response: Thank the reviewer for pointing out of the noise data question. With respect to the used ERA-20C data, as we response to Comment 1, it does have a grid size of 0.125° × 0.125°. But the coastline used in the dataset has relatively low coarse resolution. As a result, some biases should exist in the offshore areas. On the other hand, even encountering the same sea state, different ships should respond differently. This phenomenon may also lead to a variety of statistical results in a variety of situations. We have added some discussions on this point. Please refer to line 9 -14 in page 16 of the revised manuscript.

(2) “Human errors may also cause accidents, even in moderate sea states. A discussion of this issue should be included here.”

Response: Thank the reviewer for pointing it out. We missed this point in the previous manuscript. But as stated above that we would like to focus on sea state studies, we just mentioned it in the revised manuscript, while don’t expand it for a detailed discussion. Please refer to the sentences in line 12 -15, page 3 of the revised manuscript.

(3) “Wave steepness values between 0.03 and 0.04 are surely not hazardous for ships at all, but steepness of individual waves will probably increase the average steepness. The positive correlation between steepness and the spread between sea and swell propagation is interesting: Is there some theoretical explanation for this phenomenon?”

Response: It is a good question. When we found this interesting feature, we also tried to find some theoretical explanation, but we have not solved it yet. This remains our further study.

Comment 5: Sea States of Typical Cases

(1) "It should be mentioned that the distinction between wind sea and swell is an artificial construction. Mariners usually think of swell as a wave system originating from a distant storm, travelling into the local wind field. Crossing seas of this type are not very frequent but very hazardous. The sea states discussed in this section and presumably most of the other 753 cases do not involve a "classical" swell. Crossing seas with angles of 30-40° between directions of wind sea and swell are typically generated by rapidly moving low pressure systems, particularly in the vicinity of cold fronts with sudden changes in wind direction. Consider a storm with high wind sea: If the wind changes direction, a new wind sea is generated and the "old" wind sea is transformed to "swell". This partitioning of wave systems is done by the wave model post processing."

(2) Figures 4 and 5 are difficult to interpret, I could hardly follow the arguments in the text. The coarse 1.5° model grid creates strange rectangular wiggles of contours. Furthermore, I miss date and time in the legend.

(3) "In order to thoroughly investigate the cause of accidents I suggest a local description in terms of time series like the ones I include here, based on the operational ECMWF Global WAM."

Response: We did a major revision with respect to the case study.

First, As the reviewer pointed out, the modeled wave height of the first case was wrong. We had confirmed this point and explained why the modeled wave height has such distinct difference from the operational WAM results. This has been presented in the interactive discussion panel and is not presented here anymore. Therefore, the original case was replaced with the other one of the 58 swell-related cases. This is presented in Section 5.

Second, By coincidence, the new case of crossing sea state of wind sea and swell fits very well with the reviewer's consideration on crossing sea state. The new case does indicate a “new” swell system transformed from local wind sea and the local wind sea eventually composes of a crossing sea state which is a great threaten to the ship safety.

Third, interpretation of spectral partitioning on this case was also added. Please refer to the last paragraph of page 10.

Fourth, analysis of the second case was re-written.

Fifth, Time series of sea state and wind field of the two cases at the accident locations are presented in Figure 4 and Figure 7, respectively.

Sixth, The two-dimensional sea state diagrams were updated to exclude swell period maps for better interpretation. Please refer to Figure 5 and Figure 8 of the revised manuscript.

Comment 6: Minor revisions

(1) Page 2, line 5: A high wave height is ~~no doubt~~ undoubtedly a threat 5 for ships, yet some ships wreck at relatively low wave heights ~~and~~ but high wave steepness sea states (Toffoli et al., 2005).

Response: It is done as suggested.

(2) Page 2, line 28-29: The detailed information discussed above ~~are~~ is presented in section 2.

Response: It is done as suggested.

(3) Page 3, line 22: “ERA-Interim” has not been described so far.

Response: “ERA-Interim” have revised to “ERA-Interim dataset (12 h)”

(4) Page 5, line 1: The number of ship accidents ~~that fell within~~ inside each region was summed …

Response: It is done as suggested.

(5) Page 6, line 2: As discussed in the Introduction ~~section~~, the co-occurrence of wind sea and swell conditions is considered a potential causal.

Response: It is done as suggested.

(6) Page 8, line 4: a small ΔD area in the northerly direction and a large ΔD area in the southerly direction. seen from the ship's position? This is hardly recognizable on the map of fig 4!

Response: Please check whether the new Figure 5 yields better visual interpretation.

Responses to Reviewer 2

Comment 1: Abstract: -sea state conditions play a significant role in shipping safety. should be sea state. remove the condition.

Response: The suggestion has been followed in the revised manuscript.

Comment 2: The sea state parameters, including the significant wave height, the mean wave period and the mean wave direction, obtained from numerical wave model data were analyzed for selected ship accidents. This sentence is fuzzy. Please rewrite it.

Response: The sentence was revised as: "Sea state parameters of a numerical wave model, i.e., significant wave height, mean wave period and mean wave direction, were analyzed for the selected ship accident cases." Please refer to Page 1, line 13 - 14.

Comment 3: Introduction -wave period (T) cross-zero wave period or other types of wave period?

Response: Yes. It is cross-zero wave period. It was clarified in the revised manuscript. Please refer to Page 2, line 1.

Comment 4: Date and method -the ERA-20C products describe the spatio-temporal evolution of the atmosphere (on 91 vertical levels, between the surface and 0.01 hPa), the land-surface (in 4 soil layers), and ocean waves (for 25 frequencies and 12 directions). I understand you want to describe the high-quality of ECMWF-20C data, however, waves are used in this study. Thus the atmosphere and soil are useless here.

Response: Yes. The sentence is a little bit lengthy and we have revised as: "The ERA-20C products describe the spatio-temporal evolution of ocean waves for 25 frequencies and 12 directions." Please refer to Page 3, line 23 - 24.

Comment 5: I wonder why not analysis the relation between ship accident and winds?

especially in poor weather, wave should be related with wind.

Response: It is a good question. Sea wind does have significant impact on shipping safety and in many cases the high waves induced by wind can cause serious ship casualties. However, in this study, we would like to know impacts of sea state when both windsea and swell present on shipping safety. Swell are long waves propagating far away from generation sources and therefore are not effected by sea wind anymore. Therefore, in this study, we didn't investigate relation between sea wind and ship accidents. We have clarified this point in the revised manuscript. Please refer to Page 6, line 6 - 10.

Comment 6: 4.1 Wave Height Here, the variable is not coincident with description above. Following the manuscript, SWH is right!

Response: The suggestion has been followed. Please refer to Section 4.1. of the revised manuscript.

Comment 7: Figure 4 the figure at forth row should be replotted due to the colors does not overlap with x axis and y axis

Response: Thank the reviewer for pointing the slight offset of the two plots. We have modified the offset in the new figure. Since the figure 4 in the old manuscript has been replaced by Figure 5 of the revised version. Please refer to the third row of Figure 5 in Page 11.

Comment 8: Figure 5 the arrow is out of area

Response: Starting points of the arrows are the grids where the model data are available. The boundary (axis limits) of the plots are the same as the grids, therefore, it is unavoidable that some arrows are beyond the plots. In the revised manuscript, there are three figures that contain the arrow graph (i.e. Figure 5, 6 and 8). Then the situation of arrow out of area still exist in the three figures.