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Towards the identification of warning criteria: Analysis of a ship accident database

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Abstract

A ship that founders presents a great disaster both from an economical and a human point of view. It is therefore of concern to meteorological centers to include sea state related parameters in marine weather forecasts when they exceed a certain threshold. At present a standardized warning system is not set up yet. To contribute towards the definition of adequate warning criteria, an investigation was undertaken of ship accidents reported as being due to bad weather. Sea state related parameters (i.e. meteorological centers' standard wave products) at the time of 270 accidents were analyzed and compared to known ship characteristics. In order to estimate a certain degree of severity, results were compared to wave climate variation. In particular the use of quantiles seemed to provide a reasonable description of dangerous seas.

Keywords: Ship accidents; Sea state parameters; Wave climate; Warning criteria; MaxWave

1. Introduction

During recent decades, ships have greatly increased in size and numbers [1]. Since often the cargoes contain hazardous materials, safe navigation is required to prevent accidents leading to increased risk to life, property and environment. According to Faulkner [1], there are two main sources causing ship loss. About 60% are due to operational causes (e.g. fire, collision, machinery damage), while the remaining 40% are characterized by design and maintenance causes (i.e. water ingress, hull breaking in two, and capsizing). Although many incidents may be related to human errors [2], accidents still occur due to unexpected and dangerous sea states, which can result in an inability to keep the ship under proper control.

To guarantee maritime safety, decision making must rely upon design and forecast criteria. The knowledge of extreme wave environments and the related wave-structure interaction is therefore required for the design of safe ships and offshore structures. Unfortunately accidents still occur under severe and sometimes less than severe sea conditions. Moreover, some events occur in sea states where the recourse to classical parameters i.e. H_{m0} and T_p [3] is insufficient. Also this may not provide information about some specific and potentially dangerous phenomena, such as the increase in wave steepness (when the wave direction is opposite to current flow [4]), or crossing seas [5] or abnormal waves [6]. It is therefore of concern to meteorological centers to include sea state related parameters in marine weather forecasts, when they exceed some threshold.

According to state-of-the-art statistical models, unexpected events (i.e. unexpected large crest height, unexpected severe combination of wave height and steepness), or unexpected group patterns are extremely rare. In order to reduce the overall risk of structural collapse, Norwegian standards require, for instance, a sufficient air gap to insure that a 10 000 year wave does not endanger the integrity of offshore structures (accidental limit state) [7,8]. Thus rare wave events occurring with an annual probability of exceedance of 10^{-4} are taken into account in the Norwegian offshore standards. Yet the bibliography or the occurrence of such events and their effects on ships and offshore structures is extensive [9]. The need

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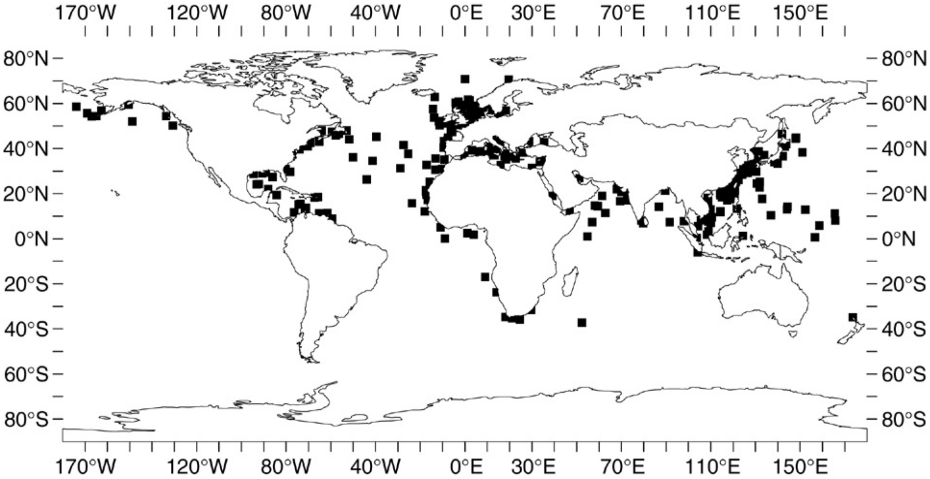

Fig. 1. Distribution of shipping accidents (1995–1999). Accidents were collected from Lloyd's Marine Information Service (LMIS).

to characterize unexpected wave phenomena for design and operation was therefore discussed in 1998 during the "Cost 714 — Conference on Applications of Directional Wave Spectra" [10], and consequently presented to the European Commission who authorized the undertaking of a research project better known as the "MaxWave" Project within the Fifth Framework programme [11].

A primary focus of the MaxWave project was the vital need for timely and accurate forecasts of dangerous sea conditions. In order to promote the use of sea state related parameters and warnings for dangerous sea states, updates to define specific products to improve the existing physical, statistical, and deterministic wave models [12] were established for the World Meteorological Organization (WMO) regulations and interaction with end users. At present a standardized warning system has not yet been set up. To contribute towards the definition of adequate warning criteria, an investigation of shipping accidents reported as being due to bad weather was undertaken. The present paper aims at providing an exhaustive analysis of the sea state characteristics (i.e. meteorological centers' standard wave products), which took place during 270 selected incidents in order to find whether a link between wave parameters and real casualties may be established. Note that, due to the very limited information available on ship accidents, it was outside the scope of this work and also not possible to study in detail which conditions lead to which failure mode considering current knowledge on the mechanics of ship behavior. We begin with a detailed description of the data sets and their limitations. The section following that gives the analysis of the sea conditions during accidents. Then we present correlations between structural and environmental characteristics and the observed sea states. We close with conclusions and recommendations.

2. Data sets

2.1. Ship accident database

The Lloyd's Marine Information Service (LMIS) operates a ship accident database regarded as the most reliable one. From it, about 650 incidents were extracted during the period from January 1995 to April 1999 (Fig. 1). The collected data set covers all reported casualties due to bad weather including total losses to all propelled sea-going merchant ships in the world of about 100 gross tonnage and above [13,14]. The classification of the accidents applies to the first event that has occurred and hence does not include other consequences that may have happened in the same accident. However, for some cases the very limited information given in the database does not allow us to confirm that the first event was bad weather. A synthesis of the above mentioned classification is given in Table 1.

Table 1
Classification of ship accidents related to 650 events

Class	
Foundered	36%
Water ingress	25%
Severe hull damage	16%
Capsize of intact ship	8%
Others	15%

Information collected from the Lloyd's Marine Information Service (period from January 1995 to April 1999).

For each individual case, a short description of the accident, some technical details (i.e. ship gross tonnage and ship age) as well as the time and geographical location are provided. Of the above 650 cases, only 49% (≈316 accidents) have a known exact location i.e. latitude and longitude. The remaining are known up to MARSDEN zone level i.e. a portion of the ocean extended over an area of 10° by 10° used to locate meteo/oceano observations [15]. Owing to the large surface that a MARSDEN zone covers, the latter were not considered. Furthermore, 46 incidents had missing information e.g. on the date. In the end 270 of 650 accidents (41.5%) were analyzed.

2.2. Sea state parameters

A globe-covering historical collection of sea surface parameters is provided by wave model results (hindcast). Although the wave spectrum cannot provide details about the instantaneous position of the sea surface, it may contain

Table 2
Wave parameters

Parameter	Formula	Reference
Significant wave height	$H_{m_0} = 4\sqrt{m_0}$	[3]
Energy wave period	$T_{m_{-10}} = \frac{m_{-1}}{m_0}$	[3]
Wave steepness	$\xi = \frac{2\pi H_{m_0}}{g T^2_{m_{-10}}}$	[3]
Mean directional spread	$\sigma = [2(1 - r_1)]^{1/2}$	[20]

additional information that points at dangerous conditions. Recently the European Center for Medium-Range Weather Forecasts (ECMWF) has given free access to the full data set of the new re-analysis undertaken in the ERA-40 project [16]. The latter is the name of a European project that aimed at reconstructing the world's weather during the last 45 years (the period from mid-1957 to 2002). This was done by running the ECMWF's integrated forecasting system with specifications very similar to those used operationally for weather forecasts, though with lower resolution than the current ones. The integrated forecasting system contains a wave model (WAM [17]), so that the main wave parameters are part of the ERA-40 results. The data is available every 6 h – at 0, 6, 12, and 18 UTC – on a grid covering the whole globe and with a resolution of 1.5° in both longitudinal and latitudinal direction [18]. Relying on this archive, sea conditions related to the selected accidents were retrieved. Because of the spatial resolution of the grid and the wave physics accounted for in the wave model, the results are not valid for coastal and shallow waters [18]. But since more than 90% of the incidents occurred in water depths of more that 50 m, it is considered that this should not have a large effect on the findings.

The two parameters most widely used to describe the sea state are the significant wave height and the mean wave period [3]. These classical values are not sufficient to evaluate the risk of dangerous wave events. However they likely lead to interesting results if they are used together with other parameters to investigate real casualties. The list of potentially important parameters is long. The analysis is limited to the ones given in Table 2.

In the formulas of Table 2, m_n is the nth-order moment of the wave spectrum [3], and g is the acceleration due to gravity ($\mathrm{m/s^2}$). The energy wave period ($T_{m_{-10}}$) [3] is one of the standard wave periods that are provided by the WAM model [17]. $T_{m_{-10}}$ is used due to the higher numerical stability provided by the spectral moment m_{-1}. The mean directional spread (σ) is the circular standard deviation [19] of the directional spreading function. The parameter r_1 that is used to compute σ is the first-order Fourier coefficient of the spreading function. In general r_1 is a function of frequency. Considering the whole spectrum, an average of the different r_1 can be used to compute the mean directional spread [20].

Two different types of waves usually characterize the sea surface: wind seas and swells. Whereas the first refers to waves still under the influence of the wind, the latter refers to waves that have already moved out of the generating area or are no longer affected by the wind. In comparison with wind seas, swells generally have longer crests and longer periods. For all parameters of Table 2, the total, the wind sea, and the swell components were collected. In addition the mean wave directions both for wind sea and swell were considered.

The time information at which the accidents occurred is limited to the day of the casualty (local time). Since the ECMWF ERA-40 provides data with respect to the Coordinated Universal Time (UTC), three days were investigated for each event: the day before, the day of the incident, and the day after. It was assumed that the accidents were most likely to have occurred during the worst sea conditions, and so the highest H_{m_0} and concurrent other parameters, as recorded at the nearest grid point, were analyzed.

2.3. *Wave climate*

Climate is by definition the synthesis of weather conditions in a given area characterized by long-term statistics (e.g. mean value and standard deviation) of the meteorological elements. In order to proceed a step further towards the definition of warning criteria, wave climate, as a reference level, is assumed for the interpretation of the actual wave parameters.

According to WMO, climate analysis should be preferably based on 30 years of data. For the present research, however, long-term statistics are computed over the whole 45 year period of the ERA-40 project as well as over the period from January 1995 to April 1999 covered by the accidents database. The climate data set consists of four different statistical variables computed for the ERA-40 wave parameters of Table 2. These are the mean value, the standard deviation, and the 0.8 and 0.9 quantile. The four statistical variables are computed for all of the 6 hourly values in each month. The analysis only focuses on those areas prone to shipping accidents (Fig. 2).

Generally speaking the 45 and 4.5 years statistics yield similar results (Fig. 3), though the latter provide slightly higher values. Furthermore, a large difference between the data sets is observed at the highest latitudes (Fig. 4). Different distributions of sea ice coverage and sea surface temperature, i.e. climate uncertainty, can explain these discrepancies.

On the whole, the global wave climate indicates that high wave activities are located at the highest/lowest latitudes. Ocean regions such as the North Pacific and North Atlantic reach maximum values of mean significant wave height of 4.5 m and wave steepness of 0.025 during the winter period (i.e. January). Note that mean wave steepness larger than 0.025 is often reported in areas of relatively low significant wave height. For example the China Sea, where approximately 15% of the accidents took place, is characterized by a mean significant wave height lower than 3 m and mean wave steepness larger than 0.025. Those regions (commonly tropical seas) are often prone to typhoons. However the coarse resolution of the ERA-40 wave model does not identify tropical cyclones [21]. Consequently, the values of the statistical parameters for regions of such storms may be too low.

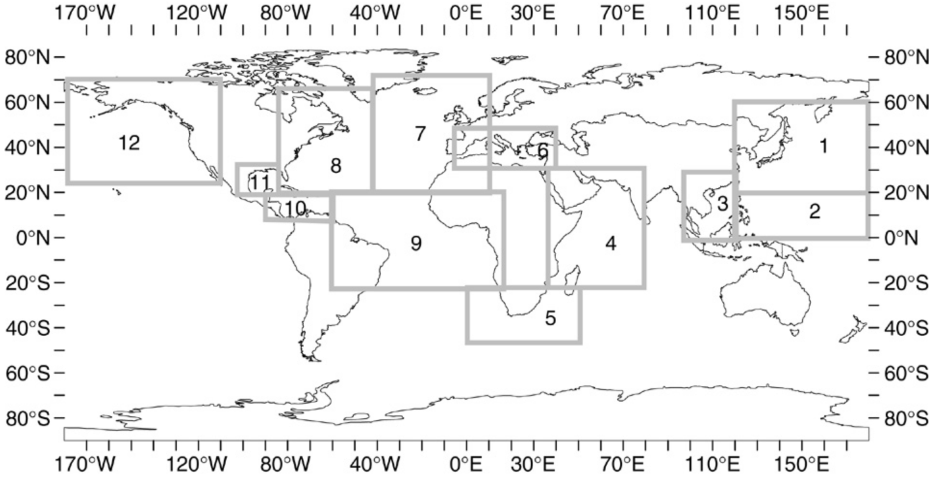

Fig. 2. Geographical regions considered for climate analysis: (1) Western North Pacific; (2) Western Central Pacific; (3) Indochina; (4) Western North India; (5) South Africa; (6) Mediterranean; (7) Eastern North Atlantic; (8) Western North Atlantic; (9) Equatorial Atlantic; (10) Caribbean; (11) Gulf of Mexico; (12) Eastern North Pacific.

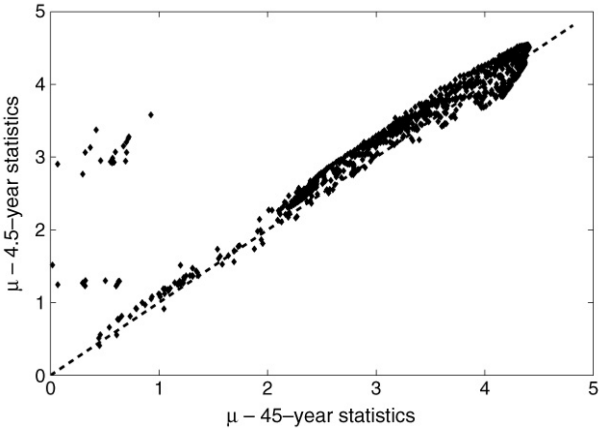

Fig. 3. Scatter plot of mean significant wave height from 45 and 4.5 years statistics for the month of January in the Eastern North Atlantic for all nodes of the ERA-40 wave model grid.

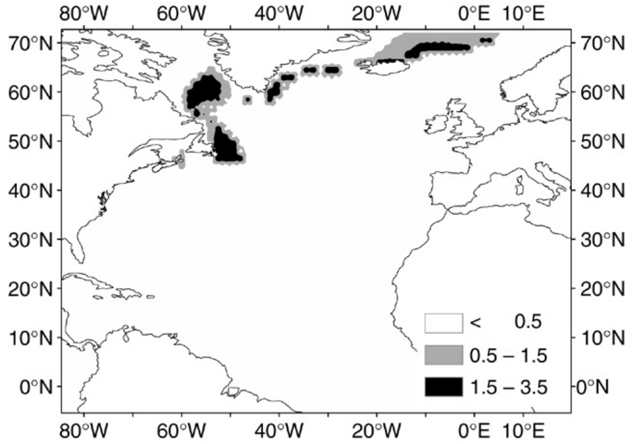

Fig. 4. Location of major differences (|bias| > 0.5 m) between 45 and 4.5 years statistics on the month of January.

3. Sea states during the accidents

3.1. Significant wave height

The significant wave height is representative of sea severity. During incidents, it is therefore expected that relatively high values will be recorded. Toffoli et al. [22] found, however, that rather low significant wave heights occurred during those ship accidents, which have been reported as being due to bad weather. Note that [22] used the global wave analysis sets of the ECMWF operational wave model. About 80% of those incidents took place within January 1995 to June 1998, when the model was run with a spatial resolution of 1.5°.

The current analysis, which is based on the ERA-40 wave data set, leads to similar conclusions. In particular, it is remarkable that two accidents out of three were observed in a sea state with significant wave height lower than 4 m (upper panel in Fig. 5). The model resolution of only 1.5° is possibly leading to an underestimation of the sea state. For example, severe conditions such as tropical storms are not adequately represented. But on the total of 270 selected incidents, only 10% occurred during cyclones (mainly in South-East Asia (Fig. 6)). Although more severe sea conditions may be expected for those cases, the underestimation due to tropical storms should not lead to significantly different findings.

As a validation of the observed low significant wave height, a crosscheck analysis was undertaken using a satellite radar altimeter (RA). The RA is a vertically pointing pulsed radar used to make accurate measurements of the heights of the waves that appear in its footprint (i.e. significant wave height) [23]. Measurements were collected from the archives of both the European Space Agency's ERS-1 and ERS-2 missions and the US/French TOPEX-Poseidon mission at each accident's nearest satellite footprint. Fig. 7 shows the correlation between the significant wave heights that were measured by satellite radar altimeter and the ones calculated by the wave model. Although some measurements show a significant deviation from the model results, which can partially be explained by a slightly different location (both in time and space)

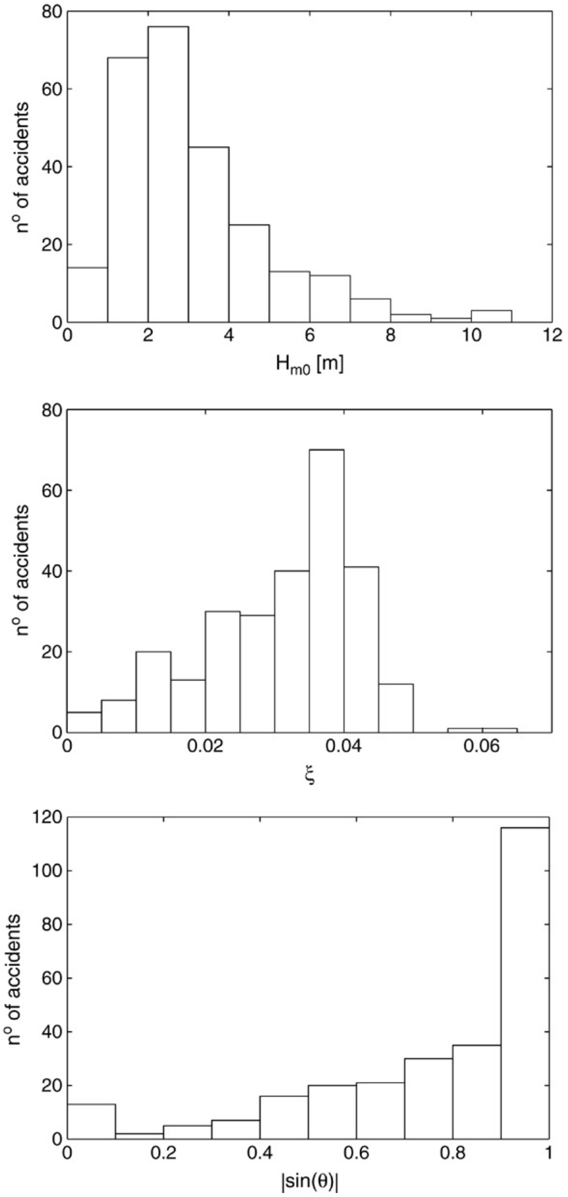

Fig. 5. Histogram plots: maximum significant wave height (upper panel); wave steepness (middle panel); $|\sin(\theta)|$ where θ is the difference between the mean wave direction of wind sea and swell (lower panel). $|\sin(\theta)|$ larger than 0.866 indicates crossing seas.

between the accidents and the satellite footprints, generally good agreements between the RA measurements and the model calculations confirm the occurrence of rather low sea states.

3.2. Wave steepness

Gunson et al. [24] and Olagnon and van Iseghem [25] address the wave steepness as a parameter that points at an enhancement of risk of extreme waves. Steeper sea states might yield dangerous dynamic effects due to ship motion (e.g. slamming), even though the significant wave height is not particularly large.

Considering the selected accidents, the joint distribution of the significant wave heights and the related energy periods shows the existence of an upper bound limit corresponding to a wave steepness of 0.0450 (Fig. 8). The Pierson–Moskowitz spectrum [26] is often used as a model spectrum for fully developed seas. This spectrum is characterized by having constant steepness. It has a value of 0.0346 if the formulation of Table 2 for wave steepness is used. It was observed that many cases (3 accidents out of 5) occurred during sea states characterized by wave steepness between 0.0300 and 0.0450 (middle panel in Fig. 5). The value of 0.0346 was exceeded by approximately 130 accidents (48%). Only 20% of these accidents occurred at a significant wave height larger than 5 m (Fig. 9).

Table 3
Following, opposing and crossing seas

Angles	Sea	Angles
330°	Following	30°
150°	Opposing	210°
60°/240°	Crossing	120°/300°

Angles follow the geographical convention: 0° indicates the North direction.

The presence of strong ocean currents (e.g. the Gulf current, the Agulhas current, or the Kuroshio current) can generate strong horizontal shear leading to refraction of the waves and focussing of wave energy when waves run opposite the current direction [4]. Since the integrated forecasting system at ECMWF does not take into account surface currents, sea states at locations with strong currents might be steeper than the ones hindcasted.

In general, it is expected that the wind sea component is characterized by higher steepness. Fig. 10 indicates that less steep sea states were correlated with a large contribution of swell to the total sea, or in other words steeper sea states were associated to wind seas. However, steeper wind seas (i.e. $\xi_{\mathrm{windsea}} > 0.0450$) were generally associated with rather small values of significant wave height (Fig. 9 lower panel). In contrast, as the wave height enlarged, the wind sea steepness seemed to reach the asymptotic value of 0.0346. Since the model is tuned to reach large wave heights for long fetches and long duration, i.e. near full development, this asymptotic behavior is not unexpected.

3.3. Crossing seas

During heavy sea conditions, ships usually travel perpendicular to the crests, and with very low forward speed. However, they may be in trouble when they have to face two (or more) wave trains coming from different directions. Under this condition, the entire hull would be exposed to wave impact. It is therefore supposed that crossing seas may be dangerous to ships.

When wind seas and swells are traveling in the same direction within a range of ±30°, we refer to following seas. The condition of opposing seas can be reported in the case when the wind sea and the swell directions are in opposition (±30°), while a perpendicular direction between the wave trains (±30°) is recorded as crossing sea. Table 3 illustrates the bounds for different seas.

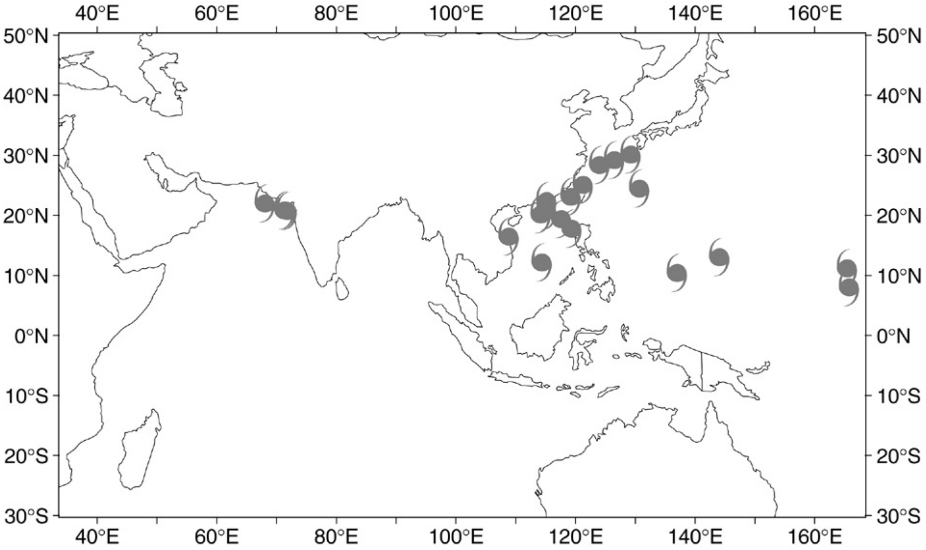

Fig. 6. Location of ship accidents that occurred during tropical typhoons.

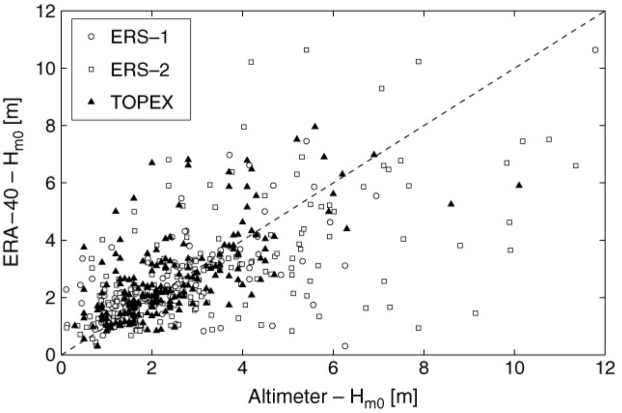

Fig. 7. Correlation plot of significant wave height recorded from altimeter radar and from wave model.

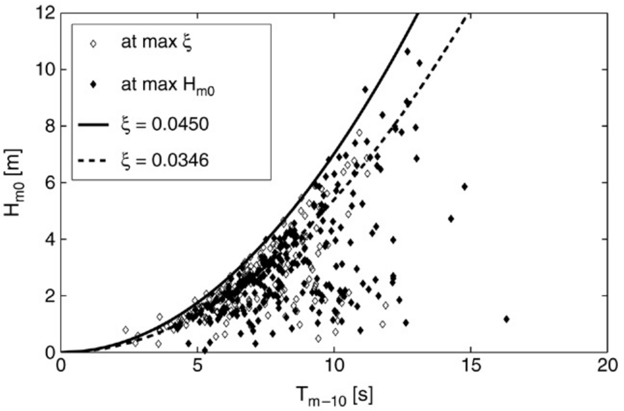

Fig. 8. Scatter plot of significant wave height versus energy period. The distribution is upper bounded by a wave steepness equal to 0.0450 (solid line). The dashed line indicates the steepness corresponding to a fully developed sea.

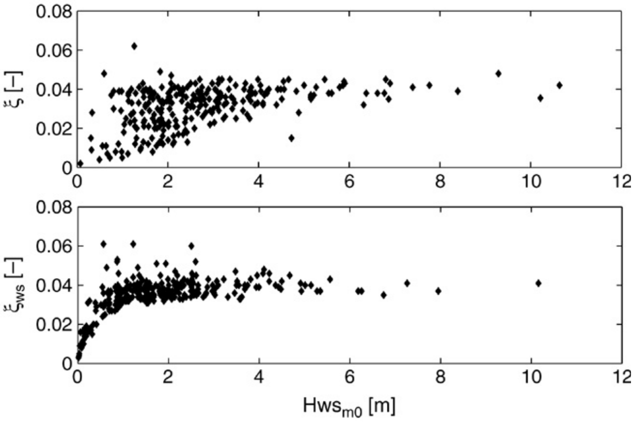

Fig. 9. Correlation plot of wave steepness and wave height: total sea (upper panel) and wind sea (lower panel).

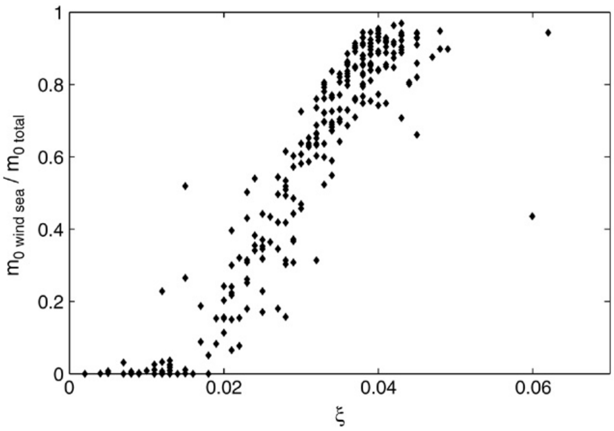

Fig. 10. Correlation plot of wave energy and wave steepness. The Y axis is the ratio of the energy of the wind sea to the energy of the total sea. Highest values correspond with dominant wind sea.

According to the above mentioned definitions, crossing seas satisfy the condition $|\sin(\theta)| \geq 0.8660$, where θ indicates the angle between the wind sea and swell mean direction. Crossing seas (also known as beam seas) were observed for one accident out of two (lower panel in Fig. 5). If the definition of following, opposing, and crossing seas is shifted from a range of ±30° to

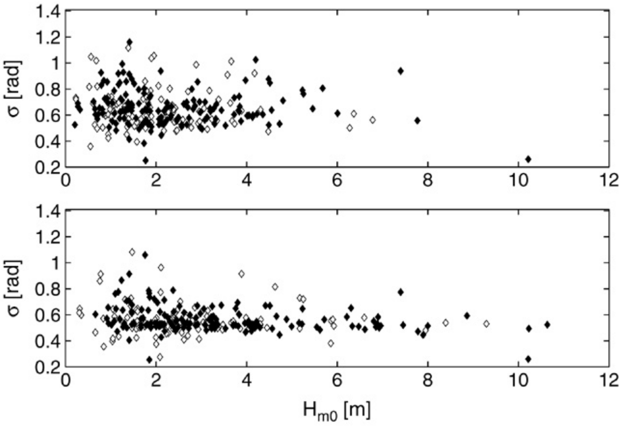

Fig. 11. Correlation between the mean directional spread (σ) and the significant wave height: at the time of the maximum mean directional spread (upper panel) and at the time of the maximum significant wave height (lower panel). Accidents, for which the maximum spreading was recorded before the maximum significant wave heights are plotted as black diamonds.

±45°, the number of reported beam seas increases to almost 70% of the cases.

Since the exact time of the accidents is unknown, crossing seas and large wave heights were assumed as two possible independent causes. As a consequence, the first did not necessarily occur when the latter was encountered. In particular, crossing seas were generally observed before the maximum significant wave height. In contrast, the angle between wind sea and swell reduced as the highest significant wave height was approached.

The above mentioned classification is based only on wave directions, and hence no information about the wave energy is included. In term of wave impact, the energy of wind sea and swell has to be considered. To this end, the selection of crossing seas is limited to those sea states, which are characterized by a ratio of wind sea energy to total energy ($\frac{m_{0\text{windsea}}}{m_{0\text{total}}}$, where m_0 is the zero-order moment of the wave spectrum) between 0.2 (i.e. swell significant wave height equal to two times the wind sea significant wave height) and 0.8 (i.e. swell significant wave height equal to half the wind sea significant wave height). Considering this additional feature, only 53 accidents ($\approx$20%) satisfied the identification criteria for crossing seas. The number of cases slightly increases (up to 26%) if a range of ±45° is used to select wave trains along perpendicular directions.

The sea surface is represented by superimposed directional components [27]. Therefore the mean wind sea and swell direction might not be sufficient to describe the mean propagation of ocean waves. To better integrate the directional information of the wave spectrum, the directional spread was investigated (see Table 2). It takes a value equal to 0 for a unidirectional spectrum and $\sqrt{2}$ for a uniform spectrum. When $|\sin(\theta)|$ and the mean directional spread (σ) are compared, then the crossing sea corresponds with σ between 0.6 and 0.8.

In general, the mean directional spread was not observed below the limit of 0.4 (for $\approx$98% of the accidents), which corresponds to a spreading angle of 25°. The analysis of the angle between wind sea and swell (i.e. θ) indicates that different wave trains tend to assume similar directions as the sea state becomes more severe. The magnitude of the mean directional spread was found to decrease towards a value of 0.5 with an enhancement of significant wave height (see Fig. 11 lower panel). In particular, the reduction of spreading was observed to occur during growing sea state conditions for approximately 60% of the selected cases. Accidents for which the maximum directional spread was recorded before the maximum wave height are represented as dark diamonds in Fig. 11.

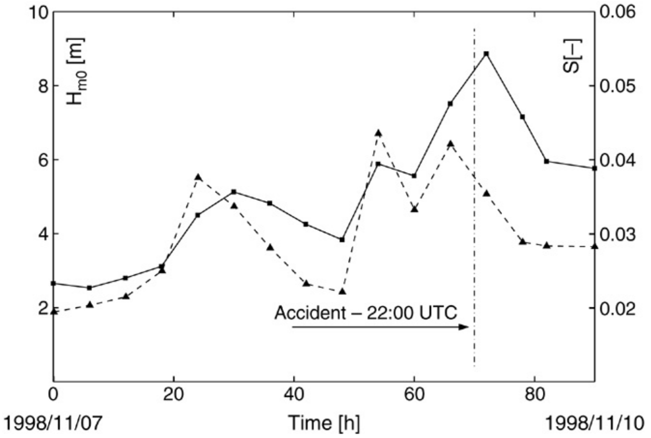

Fig. 12. Schiehallion FPSO accident: 1998/11/09 22:00 UTC. Time-dependent plot of significant wave height (solid line) and wave steepness (dashed line).

3.4. Rapid developments in the sea state

Olagnon and van Iseghem [25] and Toffoli et al. [5] indicate that rapid developments of the sea state may lead to dangerous conditions. For instance, rapid developments of the sea state were observed when the Schiehallion FPSO was damaged by an extreme wave on November 9th, 1998. An area of the bow, 20 m above the water line and above the main deck level, was pushed in by 0.25 m as reported by Gorf et al. [28]. The time history of the significant wave height and wave steepness, which were obtained from the ERA-40 data set, clearly show a sharp peak at the estimated time of the accident, i.e., 22:00 UTC (Fig. 12). Note that the wave steepness was already decreasing when the peak of significant wave height occurred.

To extend the investigation to all cases, developments in the sea state were computed as an enhancement factor of the wave parameters: $Z_{6\text{h}} = |\frac{\zeta_i - \zeta_f}{\zeta_i}|$, where ζ represents a generic wave parameter, and subscripts i and f refer to initial and final i.e. six hours later. Rapidly changing conditions were consequently defined when the variation in magnitude of a given wave parameter overcame the threshold value of 0.2 (i.e. $Z_{6\text{h}} > 0.2$) within a 6 h period.

According to the above enhancement factor, rapid developments were observed quite often throughout this investigation. Enhancement larger than 0.2, for instance, characterized three accidents out of five, both in terms of significant wave height and wave steepness (total sea component). On the other hand, rapidly changing conditions of the wind sea components were encountered during more than 80% of the events.

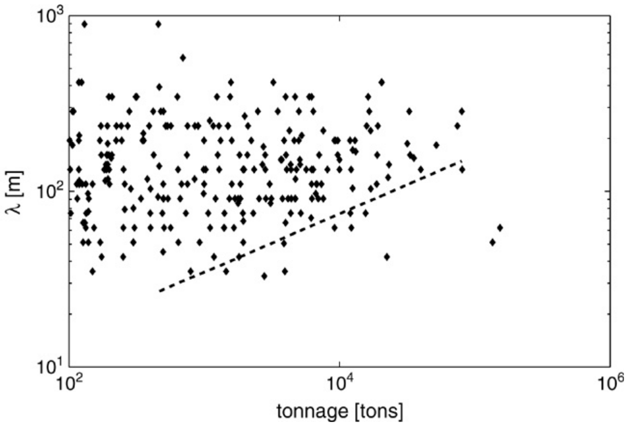

Fig. 13. Scatter plot of the wavelength versus ship gross tonnage. A lower limit exists for wavelength equal to half the ship length (dashed line).

4. Accidents and related sea conditions

Toffoli et al. [22] suggested that an interpretation of wave forecasts should be given for each type of ship and for each individual ship, since vessel responses in a sea state depend on the ship type and ship dimensions. Due to lack of information, the ship gross tonnage represents the only parameter that can be related to the ship size. Nonetheless, any significant correlation between the parameters of Table 2 and ship tonnage were not found.

In order to derive additional information on the ship size, tables provided by Tsinker [29] were used to estimate ship length as a function of tonnage. Considering that specific ships are vulnerable to particular wavelengths, it was observed that only a few cases of accidents occurred with wavelengths lower than half the ship's length. The correlation between the wavelength, computed using the linear dispersion relation (deep water approach) [3], and the ship gross tonnage (Fig. 13) confirms, in that respect, the existence of a lower bound at half the ship length (dashed line).

Different types of ships seem to have different types of accidents (see Table 1 for accident's type classes). For instance, fishing vessels were mainly listed as capsized whilst fishing or loading fish. For these cases, the significant wave height that were hindcasted were not particularly severe. However the angular difference in the wind sea and the swell headings reported was nearly 90°.

Frequently, accidents were associated with a combination of causes e.g. water ingress and capsizing. Synchronous ship motion (pitch and roll) may introduce extreme response to container ships and their security system, for example, leading to failure, loss of containers, and ship capsize [30]. This phenomenon is likely in head seas, even with moderately high waves [30]. Although the significant wave height was recorded as sometimes larger than 9 m, accidents to container ships also happened with relatively low waves ($H_{m_0} \leq 4$ m), and wave angular spread between 25° and 30° with respect to the mean wave direction (i.e. following or head seas). In contrast, more severe sea states ($H_{m_0} > 4$ m and $\xi > 0.03$) were recorded during accidents with bulk carriers. These ships are particularly vulnerable to accidental ingress of water. The combined load of cargo and water leads to excessive stresses on the hull structure with consequential breaking up of the vessel and rapid sinking [31]. This category was mainly observed with following seas.

5. Severity of the sea states

5.1. Wave heights and periods

The wave parameters recorded at the time of ship accidents revealed the occurrence of apparently rather low sea states. Relying on the Lloyd's Register database and on numerical model results [13,16], the hindcasted sea conditions were tested against wave climatology. The corresponding monthly climate was collected at the nearest grid point and assumed to be representative of the surrounding area.

The sample mean represents the most basic descriptive element for any set of measurements. However it can be dubious if relied on as a threshold for risk assessment. The current analysis indicates that only 32 accidents out of 270 took place in sea states with significant wave height lower than the monthly mean (Fig. 14 upper panel). Similar findings were observed, also, for the wind sea component (Fig. 14 middle panel). In contrast, however, the swell components were relatively well related to the mean values, even though some accidents occur during extreme swell heights (Fig. 14 lower panel).

The wave parameters at the time of ship accidents are representative of bad weather conditions. It is therefore expected that these parameters can reach relatively high values. The analysis of the related quantiles confirms this assumption. By definition the q-quantile of a random variable X is any value x such that $P(X \leq x) = q$. In particular it is observed that the q-quantiles approach provides a more adequate estimation of potentially dangerous sea states if the q factor increases (e.g. Fig. 14). About 65% of the accidents were characterized by H_{m_0} higher than the 0.9-quantile and 74% by H_{m_0} higher than the 0.8-quantile.

As observed for the significant wave height, the spectral mean periods also deviate from the monthly mean. Approximately 64% of the total cases analyzed (170 accidents) occurred with waves of periods larger than the reference mean. In contrast, these cases appear to be upper bounded by the 0.9-quantile (Fig. 15 upper panel), while the 0.8-quantile seems to provide a relatively good agreement between the accidents' sea states and the wave climate.

In terms of wind sea components, the 0.9-quantile is exceeded by almost half of the cases (Fig. 15 middle panel). The effect on the relative strength of the contribution of the wind sea and swell components to the obtained mean period makes, however, the interpretation of these data rather difficult.

5.2. Wave steepness

The ratio of the significant wave height to the square of the energy period, i.e. the wave steepness, indicates that more

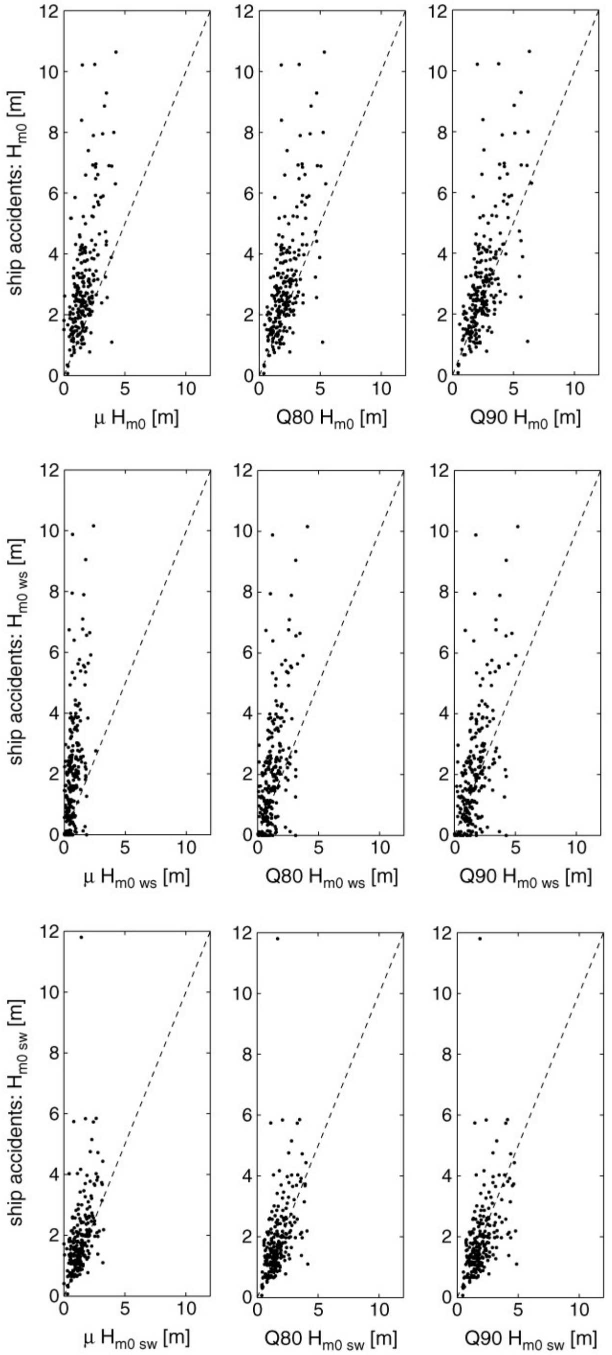

Fig. 14. Observed significant wave heights versus climate mean, 0.8-quantile, and 0.9-quantile significant wave heights: total (upper panel); wind sea (middle panel); swell (lower panel).

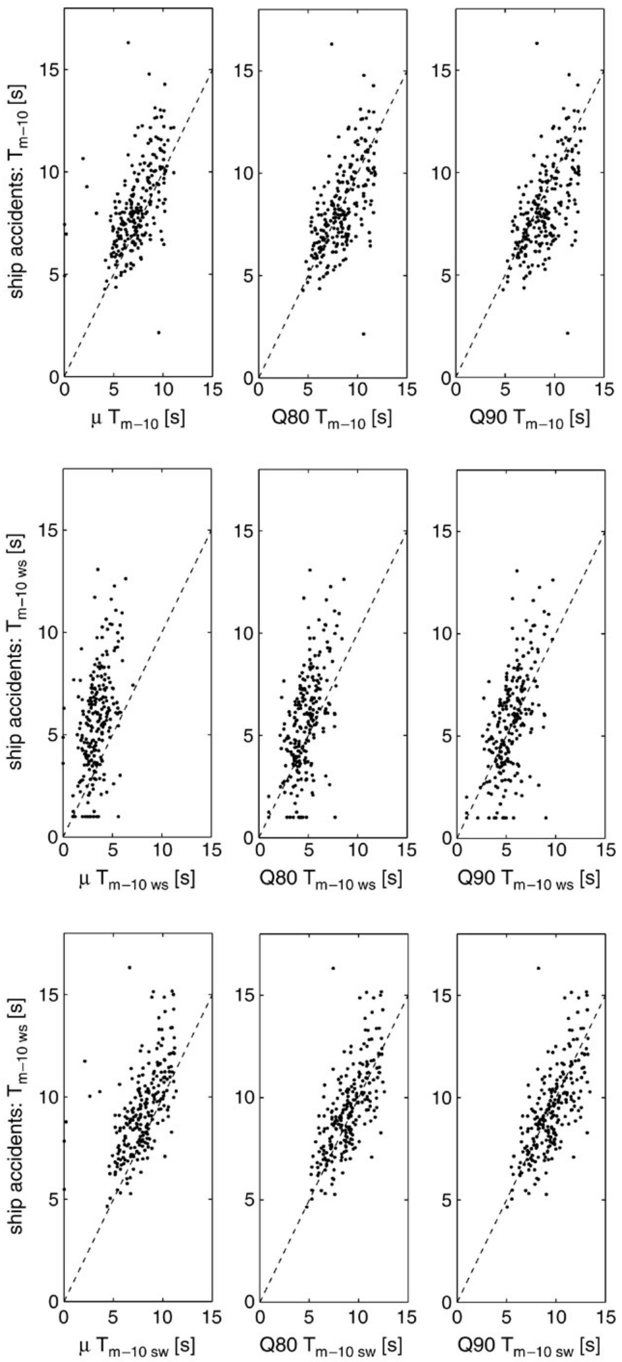

Fig. 15. Observed energy periods versus climate mean, 0.8-quantile, and 0.9-quantile energy periods: total (upper panel); wind sea (middle panel); swell (lower panel).

than 50% of the incidents took place in sea states characterized by steepness larger than 0.035 (fully developed seas). The comparison of the accidents' sea states with the related wave climate indicates that, in general, the hindcasted steepness exceeds not only the monthly mean (Fig. 16), but also the related 0.9-quantile. In particular, the values of the latter seem to represent a lower bound for steepness greater than 0.02 and an upper bound otherwise. Similar conclusions can be derived for the wind sea and the swell components.

5.3. Mean directional spread

The mean directional spread gives information as to how the wave energy is distributed over the directions. It assumes zero value for an unidirectional spectrum and $\sqrt{2}$ for a uniform spectrum. Its analysis revealed a reduction of the spreading towards the value of 0.5 as the significant wave height enhances. As indicated in Fig. 17, those values reflect relatively well the monthly mean. The 0.9 (and even the 0.8) quantile, in contrast, produces an upper limit.

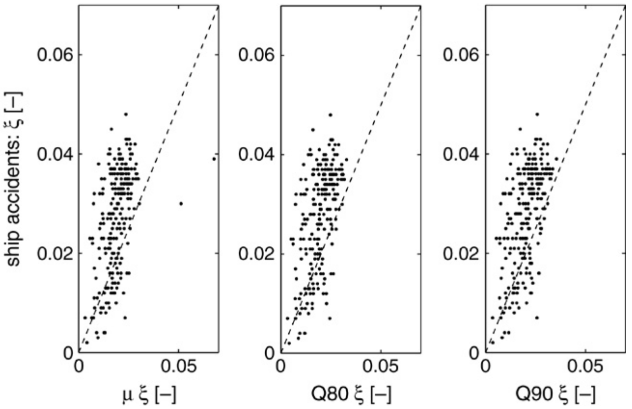

Fig. 16. Observed wave steepness (total sea) versus climate mean, 0.8-quantile, and 0.9-quantile wave steepness.

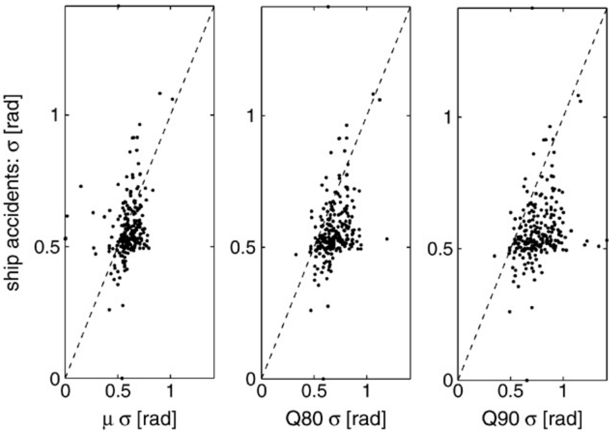

Fig. 17. Observed mean directional spread versus climate mean, 0.8-quantile, and 0.9-quantile mean directional spread.

6. Conclusions and recommendations

To contribute to the definition of warnings criteria, wave fields retrieved from the ECMWF ERA-40 archive were used in the analysis of ship accidents, which were collected from the Lloyd's Marine Information Service. Assuming that dangerous sea conditions occur in fairly rough sea states, only incidents due to bad weather were investigated. About 270 accidents were consequently looked at in order to find whether it is possible to establish a correlation between hindcast parameters and real casualties.

The analysis of wave parameters shows that relatively low sea states occurred during the selected cases. Also the wave steepness (total sea) appeared to be rather low, even though the reference limit of $\xi = 0.0346$, i.e. the steepness of a fully developed sea, was exceeded in approximately 50% of the total accidents. Interestingly to note, however, is the fact that relatively high steepness was observed during moderate wave heights. Large steepness was usually correlated with a large contribution due to wind sea.

A possible explanation for those apparently low sea states can be related to the coarse resolution (i.e., 1.5° both in latitude and longitude) of the wave model. Strong tropical storms such as typhoons are therefore not adequately represented. Also, the effect of ocean currents is not included in the ECMWF wave model product with consequently a possible underestimation of the real sea state (e.g. wave height and steepness). Radar altimeter data were analyzed to crosscheck the hindcasted sea conditions. Despite the above mentioned limitation, quite a good agreement was found between wave model and satellite observations (RA).

Despite the fact that the classical parameters like wave heights and periods are not exhaustive for the analysis of dangerous sea states, their time dependent development were shown to play an important role. Rapid changing of the sea states was observed frequently during accidents, especially in terms of wind sea components.

There are indications that wave trains traveling along different directions in general and crossing seas, in particular, should be seen as possibly dangerous conditions. Classification of the sea states by mean direction may, however, lead to a misinterpretation of the wave impact effect, as no information about the wave energy is involved. The investigation of the mean directional spread, in that respect, showed a tendency of the wave energy to focus over a small range of directions as the worst sea state conditions were approached.

Information about the ship characteristics and about the expected sea state needs to be combined. In particular it was observed that accidents occurred when the wavelength was systematically above half the ship length. Each ship (captain) should therefore interpret the marine forecasts with respect to their ship type and loading state.

It is not easy to produce firm conclusions on the above findings. In particular, important details like the exact time of the accidents are missing. However, considering the impact that ship accidents have on human lives and environment, more detailed descriptions are needed to establish satisfactory warning criteria. In that respect, it could be of great benefit to have a ship's data-recording device, i.e., black box on board storing the information needed to improve safety of ship operations. We believe that in combination with a detailed hindcast of the sea state conditions great progress could be made.

In order to move a step further towards the standardization of warning systems, the observed sea states were compared with wave climatology calculated on the basis of the ERA-40 archive. A climate analysis provided description of regional weather characteristics in terms of probability of occurrence of a certain sea state variable. Monthly climate data were collected at the nearest grid points in the vicinity of the accident. The investigation indicates that for most of the cases the observed sea states were relatively severe when fitted to the climate data for the same location. For example, both the significant wave height and wave steepness were observed above the related mean values. The 0.8- or even 0.9-quantile seems to give a good description of dangerous seas. The use of quantiles to indicate different levels of risk for regional occurrence of dangerous sea states should be investigated further.

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Appendix A. List of acronyms and symbols

A list of acronyms and symbols that were used throughout the paper are included in Tables 4 and 5.

Table 4
List of acronyms

Acronym	
ECMWF	European Center for Medium-Range Weather Forecasts
ERA-40	ECMWF Re-Analysis project
LMIS	Lloyd's Marine Information Service
RA	Radar Altimeter
UTC	Universal Time Coordinates
WAM	Wave Modeling
WMO	World Meteorological Organization

Table 5
List of symbols

Symbols	
H_{m_0}	Significant wave height
g	Acceleration due to gravity
m_n	nth order moment
Q_{80}	0.8-quantile
Q_{90}	0.9-quantile
r_1	First order Fourier coefficient
$T_{m_{-10}}$	Energy wave period
$Z_{6\text{h}}$	Enhancement factor
ζ	Generic wave parameter
θ	Angle between wind sea and swell mean direction
λ	Wavelength
μ	Mean value
ξ	Wave steepness
σ	Mean directional spreading

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