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Freak Waves: Clues for Prediction in Ship Accidents?

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ABSTRACT

Description of freak waves is not only important for design work but also for operational purposes it would be of benefit if warnings could be given to mariners. Meteo-centers already provide wave forecast based on spectral wave model. Although a spectrum gives some average description of the sea-state, it might contain additional information indicating an increased probability of occurrence of exceptional waves. To this end a database with 650 ship accidents was extracted from Lloyd's Marine Information Service database. Their study may help in identifying the ocean areas more prone to bad weather in general and abnormal waves in particular.

KEY WORDS: Freak waves; ship accidents.

INTRODUCTION

Air travel may be the fastest growing transport mode. However ships are two orders more efficient than air freight (in terms of cost per tonne mile) and hence continue to carry around 95% of the international freight (Faulkner, 2002). Owing to the increasing demands from developing countries, it is also expected that shipping freight may double in the next years and even more attention needs to be given to safety at sea. It is therefore necessary that warning can be given to avoid these cargos to encounter dangerous seas.

Although the forecasts are accurate, abnormal sea phenomena may appear suddenly. On September 28th 2000 the passenger ship "Oriana" was hit by a 17-meters wave (Howard, 2000). As reported by the Captain, the ship was handling the weather very well before an abnormal wave struck it. The incident ended without losses, but quite frequently the economic, human and environmental consequences are enormous.

Although several can be the causes of ship accidents, approximately 80% of shipping casualties are due to human errors in all phases of the process, i.e. design, constructions and operation (e.g. Gaarder et al, 1997). Nevertheless, accidents might occur due to unexpected sea conditions that might cause the unability to keep the ship under proper control. It is assumed that dangerous unexpected conditions will only occur if sea conditions are fairly rough. Looking at ship accidents reported as due to heavy sea conditions might therefore give us some clues as to why they could happen, which in turn may lead to possible warnings for mariners.

The objective of this study is to examine information related to the reported ship accidents that occurred in the last years due to heavy weather. This information concerns data about the ship themselves, but also other abut shipping density and sea-state.

The paper first presents a more detailed description of the ship accidents. The location of the area more prone to these events will be related to the shipping density. In the second part of the paper, the sea-state conditions that were obtained from numerical wave model analyses during the casualties are investigated.

The work is aimed by the need to find some common features or thresholds that might lead to a clear definition of risk – defined herein as probability of occurrence – for the encounter of abnormal sea-phenomena in general and "freak" wave in particular. In other words, the correlation between ship accidents and sea-state parameters is investigated to search for common features in the sea conditions during the selected casualties.

SHIP ACCIDENTS

Ships have greatly increased in size in the last five decades and quite often these cargo consist of hazardous materials, for which a safe handling and a safe navigation is required to prevent accidents leading to increase risk to life, property and environment. The memory of 37000-ton oil tanker "Erika" is still alive (December 8th 1999), when the "Prestige" accident happens. Sailing in monotonous seas the Erika's hull cracked and water was being taken on board. The next morning the Erika broke in two and started to sink. Thousands of tons of oil leaked from her cargo tanks. The huge blanket of oil drifted towards the Brittany coastline and one of the biggest environment disasters had started (Mangold, 2000). However, it is not just the environment, which causes concern. Because the vast majority of the world's trade is carried by sea, it is the total loss of ships, their valued cargo and lives as well as the collateral damage that is unacceptable.

Presently accidents still occur with severe and often less than severe weather conditions even though the forecasts are good and accurate. For this reason, it is also of concern to several meteo-centers to include the sea-state in marine weather forecast when it exceeds some threshold. Unfortunately some events occur in sea-states where the prevision of classical parameters does not reflect its. Also it does not give information about some specific and potentially dangerous phenomena such as the increase of the steepness in case of opposite wave direction to current flow or of cross seas, or abnormal waves.

Within the last decades some large ships have been lost, and in many cases the cause is believed to be a "freak" wave, which is individual wave of exceptional wave height or abnormal shape (Rosenthal 2002). The notation of "freak" waves was introduced to address single waves that are extremely unlikely as reported by the Rayleigh distribution of wave height (Dean, 1990). Precisely it is assumed that the wave height (from crest to trough) exceeds the significant wave height by a factor of 2 (Ochi, 1998).

There are several reasons why these wave phenomena may occur. Often extreme events can be explained by the presence of ocean currents (e.g. Agulhas current) or bottom topography that may cause focusing of wave energy in a small area. On the other hand, it is believed that in the open ocean – away from non-uniform currents or bathymetry – these waves can be produced by nonlinear self modulation of a slowly varying wave train (Janssen, 2002).

The European research program "MaxWave" aims at investigating the occurrence and properties of rogue waves, demonstrating impact of rogue waves on current design structures for ship and offshore structures and developing improved forecast product including warnings for extreme waves. The present investigation is expected to contribute mainly to the latter.

MEANS OF INVESTIGATION

Five years (1995 – 1999) of ship accidents due to bad weather, collected from the Lloyd's Marine Information Service (LMIS) and Lloyd's casualty reports have been studied. The location of ship damages as well as losses due to severe weather are shown in figure 1. Although only a few accidents are categorized as being caused by freak waves (e.g. Gunson et al, 2001), it does not mean that other ship accidents under severe weather were not due to freak waves. Therefore all accidents under severe weather were considered when wave and wind fields were retrieved from the ECMWF-archive.

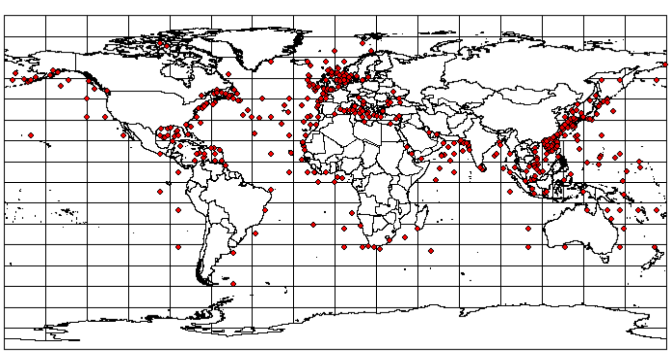

Figure 1. Worldwide ship accidents (1995-1999) due to severe weather. Source: Lloyd's Marine Information Service (LMIS) casualty database.

The study of the ship accidents in heavy weather can help in identifying the ocean area more prone to bad weather conditions in general and to abnormal waves in particular. However, due to the complexity of the sea-state, the analysis done addresses not only the classical wave parameters (from the wave energy spectrum), but also the geographical and technical parameters (i.e. ship characteristics).

TECHNICAL DATA SETS

Ship Accidents Database

The data covers all reported serious 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. It should be noted that the category "bad weather" applies to the first event that occurred, and does not record other consequences that may have occurred in the same accident. The Lloyd's database is recognized as the most reliable one among the existing databases. It was developed in 1979 in response to the shipping community's growing need for more detailed information on reported casualties and demolitions. The database is continuously updated based on reports received daily from Lloyd's Agents and Lloyd's Register Surveyors, situated in over one hundred and thirty countries all over the world. All information received from the surveyors is accuracy checked (Bitner-Gregersen & Eknes, 2001).

Ship Density

Whenever a ship is using a radio transmission outside harbors, the location (in space and time) is recorded as well as the so-called "call sign'. The call sign is a name used by ships for radio transmission and it is better than the ship's name because a call sign is always the same while a ship's name can include spaces, lower cases/upper cases and can slightly differ depending upon who indicates the ship's name. Although ships can change names and also call signs, most of the time the same call sign is used for a long time by a given ship. Therefore it can be addressed as a ship's indicator.

As the call sign is a unique name, it can be used to define the ship density that represents a geographic index of usage. The ship density is defined as an index of 100 if 8 call signs can be counted in an area of 500 X 500 km^2 per day.

The ship density data set covers the period 2000 – 2001 (ship track data were made available by JCOMMOPS). The index was calculated as an average over the month and it refers to a single MAR zone, which is an area of 10°X10° (Fig.2). The MAR zone defines an area that differs from the ship density definitions. Therefore a adjustment factor was applied.

Note that the ship density includes all ships and is thus not consistent with the accident database, which contains ships of 100 gross tonnage and above. The information we have at this moment does not permit us to make this consistent.

Sea-State Parameters

In order to construct the sea-state during each of the ship accidents, the ECMWF data set, see Persson (2002), has been queried. The wave model that is used to produce ocean wave analysis at ECMWF is the WAM model, which describes the rate of change of the wave spectrum due to advection, wind input, dissipation due to white capping and non linear wave - wave interaction.

Data were collected for a specified space and time window. When the casualties' location was known, an area of 3° X 3° was defined. When the location was not known exactly, the entire MAR zone (in which the accident took place) was investigated. On the other hand, the time window covered a total period of three days: the two days before the event and the day of the casualty.

The data set that was available contained the full 2D wave spectra and some integrated parameters such as the significant wave height, mean period, mean direction (all of them for wind sea and swell), the peak period, etc… from the wave model analysis. The data availability was at 12 GMT for casualties that occurred before June 28th 1998, while after this date, the data were available at 0, 6, 12 and 18 GMT.

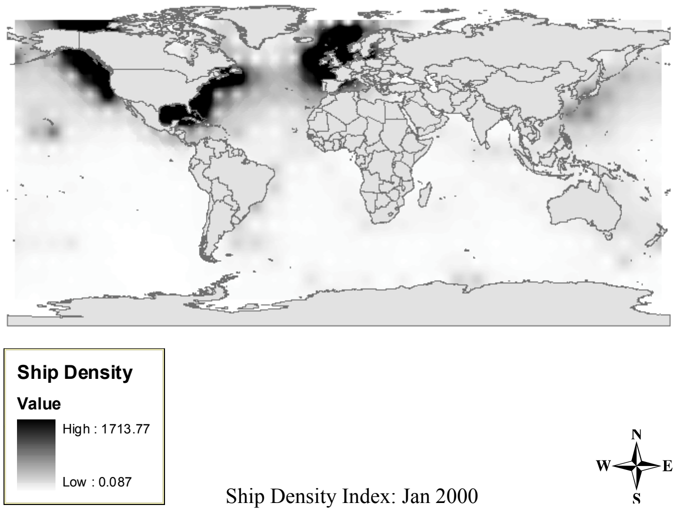

Figure 2. Ship Density Index: the distribution is representing the month of January 2000.

ANALYSIS OF CASUALTIES

Accident Types

The main causes of ship losses over the last two decades are due to "operational" causes (60%) and "design and maintenance" causes (40%), see Faulkner (2002).

In conditions of heavy sea, accidents may occur as a combination of different events (e.g. took water, capsized and sank). They can be classified as follow:

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

Geographical Distribution

The ship accidents geographical distribution follows the ship density. In other words, a high number of accidents were recorded in those areas of high ship transit. More precisely, the casualties occurred in the North Sea, along the North American coast and both in the East and South China Sea.

Figure 3 shows the density of the casualties. This density was defined addressing index 1 for each accident that occurred in an area of 500 X 500 km^2.
It is not a surprise that only 6% of the casualties were recorded in the Southern Hemisphere.

Seasonal Distribution

Due to generally more severe weather in winter compared to the other parts of the year, extreme phenomena occur as expected more often in the winter period. The seasonal distribution extracted by the ship accident database confirms this assumption. Figure 4 shows the time distribution histogram. It only contains the casualties that occurred in the Northern Hemisphere. However, the same conclusion may be derived from the Southern Hemisphere's casualties.

The winter season (from December to February) is characterized by 35% of the events, and more than 60% of them are placed in the period between October and March. Nevertheless it is remarkable to mention that about 16% of the cases are recorded between June and July (early summer).

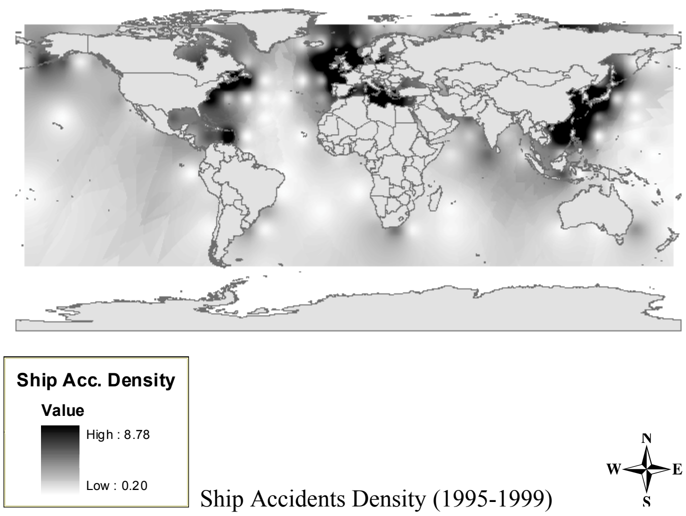

Figure 3. Geographical distribution: ship accidents per MAR zone – period 1995-1999.

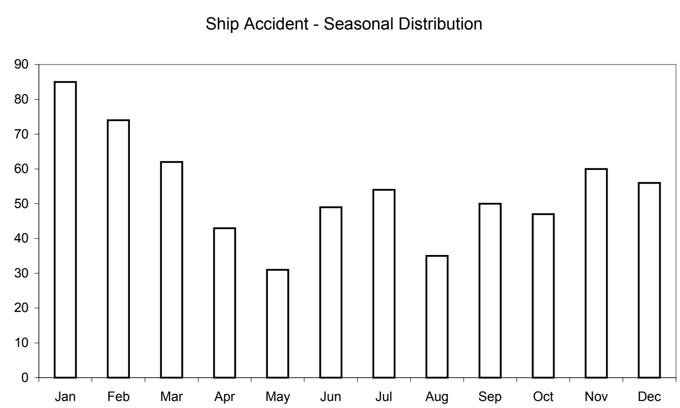

Figure 4. Seasonal distribution of ship accidents – period 1995-1999.

Geographical Density of Risk

Nowadays the forecasts are quite accurate and often they also include warnings concerning the sea-state. It is therefore believed that shipping routes avoid more dangerous areas. With this in mind, the ship density index was put forward as a normalizing factor to provide a first evaluation for the risk of occurrence of ship accidents. More precisely, the risk density was described by the ratio between the ship accident density and the ship density. This definition should not be seen as the ultimate definition for risk since only one parameter – the ship density – is considered. Figure 5 reports this distribution.

The analysis indicates that the Southern Hemisphere seems to be more prone to casualties than the Northern one. Nonetheless, the risk density is remarkable in all-South Asia regions, and part of the Mediterranean Sea. On the other hand, the North Atlantic appears less severe. The high number of accidents in the North Atlantic was balanced by intensive shipping activities.

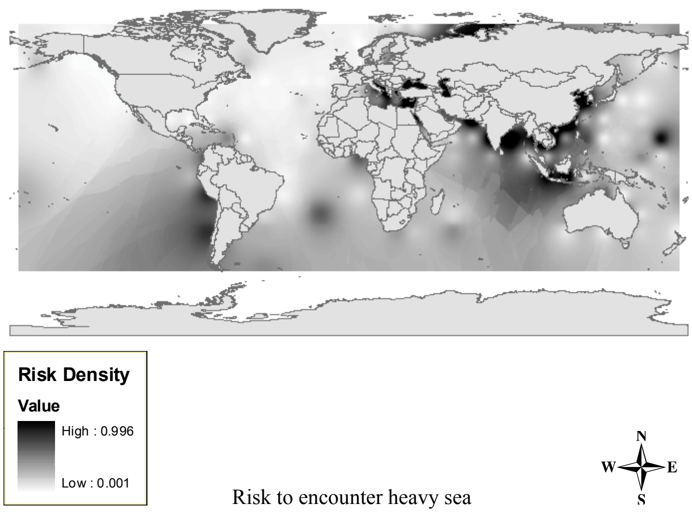

Figure 5. Risk to encounter ship accidents due to heavy sea. The risk concerns only the casualties and the shipping densities**.** Its values were normalized by means of the highest one.

ANALYSIS OF THE SEA-STATE

Parameters

The two parameters most widely used to describe the sea-state are the significant wave height and the mean wave period (WMO, 1998). These two classical values are not conclusive to evaluate the risk of extreme events. However, they might lead to interesting results together with other possible parameters if combined with real casualties.

The list of potentially important parameters is long. The analysis is limited to the ones give in Table 1.

Table 1: Wave parameters considered in the analysis

Parameter	**Formula**	**Reference**
Significant Wave Height	$H_S = 4\sqrt{m_0}$	(Ochi 1998)
Spectral Peak Period	$T_P = \frac{2\pi}{\{\omega \vert \max S(\omega)\}}$	(WMO, 1998)
Spectral Mean Period	$T_{m-1} = \frac{m_{-1}}{m_0}$	(WMO, 1998)
Average Wave Steepness	$S_P = \frac{2\pi H_s}{g T_P{}^2}$	(WMO 1998)
Mean Directional Spread	$\sigma = \sqrt{2(1-r_1)}$	(Bidlot, 2001)
Spectral Bandwidth	$\nu = \sqrt{\frac{m_2 m_0}{m_1^2} - 1}$	(Longuet-Higgins, 1983)

In the formulas above of Table 1, m_n is the nth-order moment of the spectrum (WMO, 1998), ω is the angular frequency, g the acceleration due to gravity (m/s^2), and r_1 is the first-order centred Fourier coefficient.

In addition the 10-*m* wind speed was also considered. It is essential for defining the surface stress, which is the basic force that leads to ocean waves.

Sea-State

One Set of Parameter per Day

The sea-state parameters were analyzed in correlation with 250 ship accidents (40% of the available casualties). The values were observed at 12 GMT the day of the accident. Although the time of the accidents was not known, it was assumed that this sea-state is representative for the time of the accident. Therefore rapid changes on the day or before the day of the accidents cannot be observed. The wave parameters were evaluated from a full 2D wave spectrum. Table 2 reports exceedance levels found by the investigation.

Table 2: Accidents exceeding a given threshold – Parameters at 12 GMT.

Parameter	**Threshold**	**Accidents**
Significant Wave Height	< 5 *m*	87%
Spectral Peak Period	8 *s* < T_p < 18 *s*	63%
Spectral Mean Period	4s < T_P < 12 *s*	77%
Average Wave Steepness	< 0.03	79%
Mean Directional Spread	0.5 < σ < 0.75	60%
Spectral Bandwidth	0.3 < ν < 0.4	80%
10 *m* Wind Speed	< 10 *m/s*	53%

Figures 6 to 8 show the histogram-plots for the significant wave height, the average wave steepness and the 10 *m* wind speed.

An encounter with a steep wave condition can be disastrous, even for a large ship. An example is given by the FPSO "Schiehallion". The ship (80000 tons) was located 60°21' N and 4°4' E when it sustained heavy weather damage above the waterline around 22 GMT on November 9th 1998. The reported damage was not caused by a wave of extreme height, but by a wave of exceptional steepness. Wave model hindcast results showed steepness values of about 0.04 (Gunson et al, 2001). Note that average wave steepness extracted from the Pierson-Moskowitz spectral formulation (Pierson-Moskowitz, 1964) is characterized by a constant value S_P equal to 0.0295.

The propagation characteristics of an ocean wave field can be obtained from the circular standard deviation of the directional distribution function, and it is usually referred to as the directional spread (σ). The parameter is a function of the first-order centred Fourier coefficient of the directional distribution (r_1), and it takes values between 0 and $\sqrt{2}$, where the value of 0 corresponds to unidirectional spectrum and the value of $\sqrt{2}$ to uniform spectrum (Bidlot, 2001).

The spectral width (bandwidth) parameter can be used as a measure of the irregularity of the sea-state (WMO, 1998). Irregular wave patterns may be observed if $\nu \approx 1$, while $\nu \ll 1$ is indication of regular waves (narrow spectrum).

It is hard to define a real threshold above which one can assume warnings for shipping, as nowadays ships are designed to sail in extreme seas. Nevertheless, the present study shows that a high number of casualties occurred in a low sea-state condition. Note again that the sea-state parameters calculated refer to the 12 GMT the day of the accident.

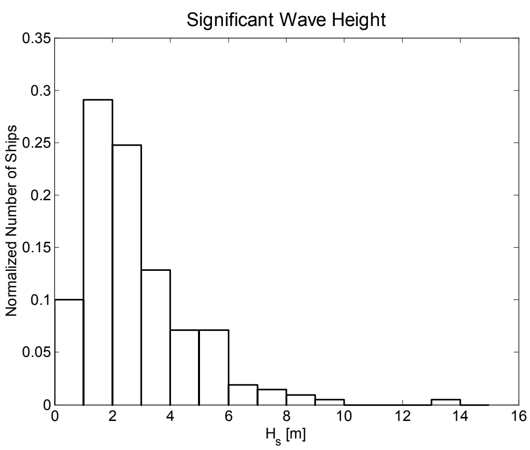

Figure 6. Significant wave height histogram. Data referred at 12 GMT. The normalization of the y-axes lead to an area under the histogram equal to 1.

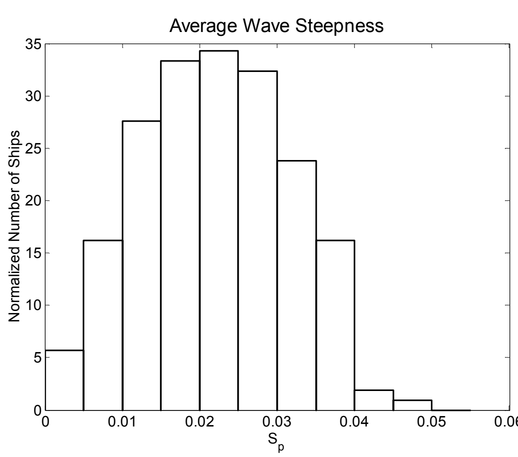

Figure 7. Average wave steepness histogram. Data referred at 12 GMT. The normalization of the y-axes lead to an area under the histogram equal to 1.

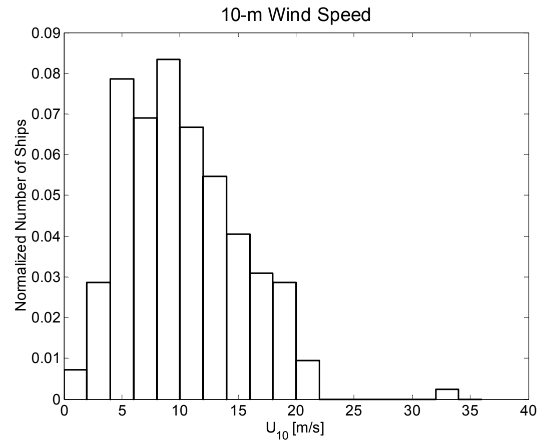

Figure 8. 10-*m* wind speed histogram. Data referred at 12 GMT. The normalization of the y-axes lead to an area under the histogram equal 1.

Four Sets of Parameters per Day

About 40 accidents of the 250 analyzed cases (16%) occurred in the period after June 28th 1998. For them, the data were recorded every six hours, and hence "rapid" changes in the parameters can be observed. The analysis of these 40 accidents covered two days before and the day of a casualty. In this period a sharp increase of the significant wave height, average wave steepness, and wind speed was observed in the last 24 hours (e.g. Fig. 9 shows the significant wave height for an event that occurred off Nova Scotia). None the less, the sea-state appeared again to be rather low. However, an average wave steepness equal to 0.03 was overcome in 46% of the cases, which represents more than double the quantity observed at 12 GMT.More detailed research has to be done to sea whether next to having values for certain parameters of the sea-state also an indication of the gradient (in time and in space) is needed.

On the other side, a flat line was usually observed for the mean directional spread and the bandwidth parameter. However, for several cases a sharp peak was observed for the bandwidth parameter.

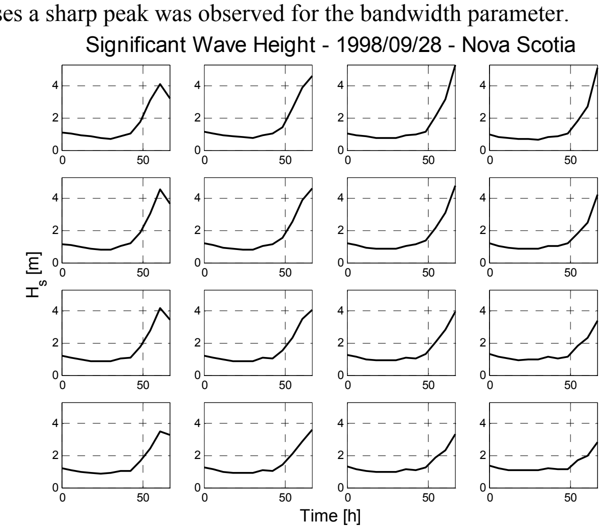

Figure 9. Evolution in time of the significant wave height. It reports the parameter in the retrieval grid points (mesh of 1°X1°). The casualties can be located between the four middle plots.

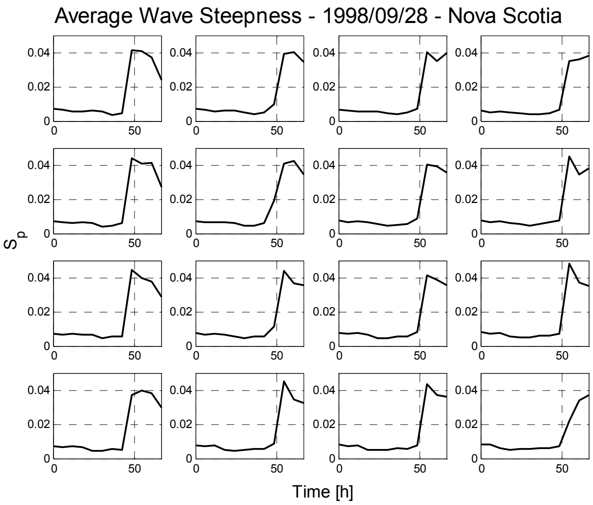

Figure 10: Evolution in time of the average wave steepness. It reports the parameter in the retrieval grid points (mesh of 1°X1°). The casualties can be located between the four middle plots.

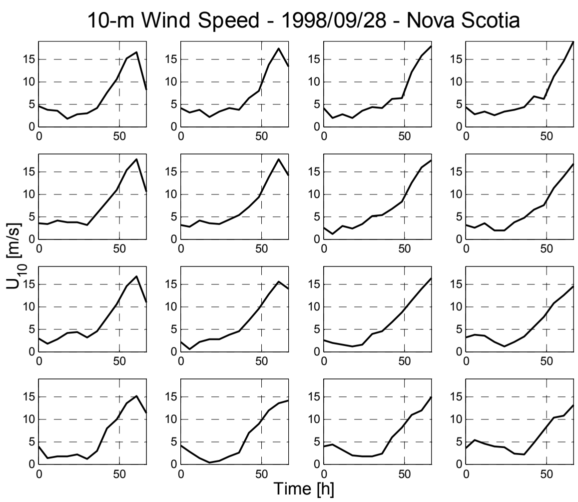

Figure 11: Evolution in time of the 10-m wind speed. It reports the parameter in the retrieval grid points (mesh of 1°X1°). The casualties can be located between the four middle plots.

Wind Sea and Swell Separation

The wave parameters discussed before do not take into account the directions of wind sea and swell. Under this consideration, the mean direction for wind sea and swell were observed on the day of the accidents (wind sea and swell separation had been performed by ECMWF's WAM model). The Cartesian plane was divided in four sectors: "following sea" between 315° and 45°, "cross-sea" between 45° and 135°, and between 225° and 315°. Also the "opposite sea" between 135° and 225° was detected. This distinction gives the following results:

- Following Sea: 53% of the cases;
- Cross Sea: 38% of the cases;
- Opposite Sea: 9% of the cases.

The definition above covers quite a large directional range. It was intended to categorize each entry of the entire data set.

If the directional range for a particular category changed from 90 to 45 degrees (e.g. cross-sea between 67.5 and 112.5 degrees and between 247.5 and 292.5 degrees), the number of cross-sea cases also decreases to half. In other words only 19% of the cases then satisfy the condition of cross-sea. However, the analysis for the entire three-days data set shows that very often the condition of cross-sea changes to the condition of opposite sea when approaching the day of the events.

Since conditions of cross-sea and opposite sea are believed to be dangerous for ships, it is remarkable that only about 50% of the cases were reported in such conditions.

One clear example of cross-sea is shown in Figure 12. The swell that was coming from South South-West crossed the wind sea coming from West with an angle of approximately 90°.

We noted that about 60% of the cases of cross-sea are located in those areas where a high risk to encounter ship accidents were detected (see Fig. 5).

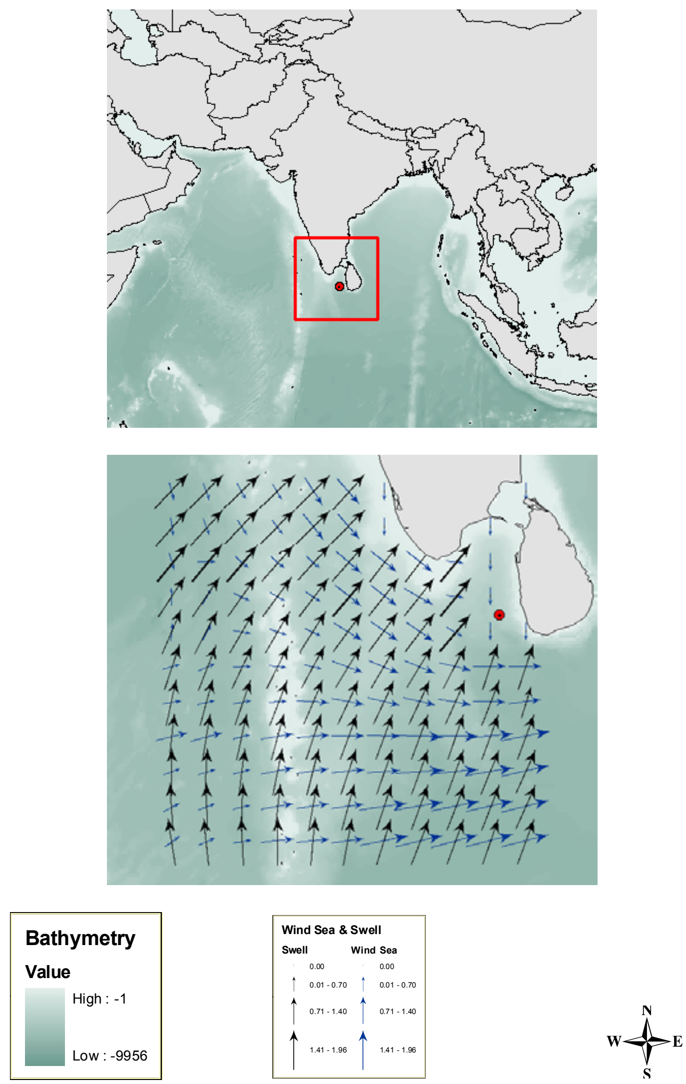

Figure 12. Wind Sea and Swell mean direction – Cross Sea condition. The length of the arrows is made proportional to the significant wave height.

CONCLUSIONS

Ships that founder represent a great disaster both from an economical and a human point of view. Moreover the environmental collateral damages may be enormous. Therefore it would be of great benefit if warning might be given to mariners.

Data on ship density as well as wave and wind field data (retrieved from the ECMWF-archive) were used in the analysis of ship accidents due to heavy weather. About 250 accidents were consequently looked at.

The combination of the shipping density and the density of ship accidents allows to define those locations in which there is an increased risk (probability of occurrence) worth. Nevertheless, the density cannot be assumed as the only parameter for consideration and hence the sea-state conditions were added. Surprisingly, the investigation showed that in most of the cases the casualties occurred in rather low sea-state (according to wave model analysis). This can be caused by the fact that data are referred to a fixed time (12 GMT). The present analysis has several limitations and therefore the results should be used with care. Further investigations are necessary in order to reach a firm conclusion. A cross-check of model data with altimeter data (Topex-Poseidon campaign) will for example be done.

The study indicates that the classical spectral parameters (H_S and T_P) are not sufficient to point at possibly extreme wave phenomena. However processes that form huge waves such as interaction between waves and currents (e.g. Agulhas Current) are usually not adequately represented in operational forecast products.

Cross, opposing or following seas may play a role, but the current results do not allow to draw firm conclusions.

There are indications that rapidly changing conditions can create dangerous situations. An adequate time resolution of wave parameters is therefore needed to understand the importance of gradient information in developing warning criteria for operational purposes. Important to remark in that respect is that all ships react differently to a certain sea-state and that an interpretation of wave forecast will be needed for type of ship and possibly for each individual ship.

ACKNOWLEDGMENTS

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