DNV GL STRATEGIC RESEARCH & INNOVATION
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# ROGUE WAVES

## Impact on ships and offshore structures

SAFER, SMARTER, GREENER

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# CONTENT

# EXECUTIVE SUMMARY

Rogue waves have attracted considerable attention in academia, the shipping and offshore industries, and the media during the past two decades. These waves – also called freak, abnormal, or giant waves – are very steep and much larger than the surrounding waves. Several accidents involving ships and offshore structures have been reported due to such waves, and yet, as of today, rogue waves are not explicitly included in classification society rules and offshore standards. The occurrence of rogue waves presents the shipping and offshore industry with two important questions: should these waves be accounted for in design? If so, how best to account for them?

This position paper summarizes our latest knowledge on rogue waves and their impacts on marine structures in general and ships in particular. We also focus on research projects in which DNV GL has participated and that relate to rogue waves and their impacts on marine structures. We hope that this summary, together with our own insights, provides further understanding on the rogue wave phenomenon.

We also discuss how the state-of-the-art knowledge on rogue waves can be utilized to improve current design, as well as the planning and execution of marine operations. Finally, we propose future research activities that are needed to support the possible inclusion of rogue wave effects in ship and offshore structure design and operational procedures. The need for satisfactory warning criteria for rogue waves is emphasized.

The significance of severe sea state conditions may grow in some ocean regions in the future due to global warming. Therefore, taking rogue waves into account in the design and operation of marine structures may become an important part of adaptation to climate change.

# INTRODUCTION

The existence of exceptionally large waves – much higher, steeper, and more dangerous than those expected for a given sea state – has always been a part of maritime folklore. For centuries, sailors have reported giant waves, often described as 'walls of water', appearing from 'nowhere'. For a long time such events were believed to be mostly anecdotal, but in recent decades these waves, often referred to as rogue, abnormal, freak, giant, or extreme waves, have received considerable attention, both in the media and in the scientific community, and also in the shipping and offshore industries. The first real account of the rogue wave phenomenon in scientific literature was given by Draper (1964), while Mallory (1974) provided initial discussions on the large and abnormal waves in the Agulhas current off the south-east coast of South Africa. However, it is primarily during the last two decades that rogue waves have become the focus of wider attention, from industry and the scientific community, through larger research programmes, meetings, workshops, and conferences all dedicated to the rogue wave phenomenon.

One important factor that has led to increased interest in rogue waves is the emergence of reliable observations of such waves provided by wave measurements from, for example, oil platforms. One of the first, and probably best-known, reliable recordings of a rogue wave is the so-called New Year wave, also referred to as the Draupner wave, that was recorded at the Draupner platform in the North Sea on 1st January 1995. Whereas previous recordings of extremely large waves were often regarded as measurement errors, the validity of the Draupner wave was confirmed by damage to equipment due to the wave hitting a platform deck. Another important driver for research on rogue waves is the substantial increase in computational power in recent decades. This has enabled the study of rogue waves using numerical models describing realistic ocean conditions.

The motivation for investigating and understanding of rogue waves is obvious. Large waves represent a danger to ships and marine installations A number of ship accidents related to rogue waves have been reported. Public and media awareness of the dangers associated with extreme waves has also been increasing in recent years, largely due to incidents of rogue waves hitting passenger ships (e.g. Queen Elisabeth II in 1995, Caledonia Star and Bremen in 2000, Explorer, Voyager and Norwegian Dawn in 2005, Louis Majesty in 2010, and MS Marco Polo in 2014), some of which resulted in passenger fatalities (e.g. Louis Majesty and MS Marco Polo accidents). Recent hurricanes in the Gulf of Mexico have also shown how dangerous extreme sea states can be for marine structures. During Hurricane Katrina, 30 oil platforms were damaged or destroyed, nine refineries were closed, and oil production in the region was decimated. Such incidents have highlighted the need for improvements to reduce the risk of wave-related incidents. In the future, the significance of severe sea state conditions for ship traffic may even grow in some ocean regions because of the expected increase in the frequency and severity of extreme weather events associated with global warming (Bitner-Gregersen and Toffoli, 2015). Therefore, taking rogue waves into account in the design and operation of marine structures may become an important part of the adaptation to climate change.

Figure 1: Photographs showing some rogue wave incidents and rough wave conditions.

In academia, the main focus has been on understanding the physics behind the rogue wave phenomenon and determining the conditions under which such waves can be expected to occur more frequently. This has also received attention in the marine industry because of the possible effect on design and marine operations. The occurrence of rogue waves poses two important questions for the shipping and offshore industries: should these waves be accounted for in design? If so, how best to account for them?

Marine safety is one of the main concerns of the shipping and offshore industries in general, and of classification societies, as well as oil companies, in particular. The importance of including state-of-the-art knowledge about meteorological (temperature, pressure, wind) and oceanographic (waves, current) conditions in ship and offshore standards has received increasing focus in the last decades in several scientific and industrial international forums. There are potential safety, environmental, and economic advantages in utilizing the most recent knowledge about metocean descriptions in the operation and design of marine structures. Waves represent the dominant environmental load for most marine structures. Therefore, understanding, and possibly predicting, waves under various conditions is crucial with respect to design and operation of ships and marine installations. In order to achieve acceptance, a metocean description must be demonstrated to be robust and of adequate accuracy. As with most formal processes, updating codes and standards takes some time, and, consequently, updates may lag behind the state-of-the-art.

DNV GL intends to remain at the forefront of the development of rules and standards for design and operations of marine structures, and has therefore been an active participant in research on rogue waves. This research has been carried out in DNV GL Strategic Research and Innovation (SR&I) within projects funded by the by the European Commission (EC), the Research Council of Norway and the marine industry (Joint Industry Projects, JIP).

Offshore standards and classification society rules currently do not include rogue waves. This is due to a lack of full consensus about the probability of their occurrence, which is mandatory for systematic evaluation of possible revision of classification society rules and offshore standards (Bitner-Gregersen et al., 2003, ISSC, 2015). However, some of the DNV GL rules for design of superstructures of passenger ships that account for rogue waves have been revised as a result of the EC EXTREME SEAS project, which was coordinated by legacy DNV. Furthermore, it is worth mentioning that the oil company STATOIL has already introduced an internal requirement that accounts for rogue waves, in a simplified way, when designing the height of a platform deck (ISSC, 2013). This requirement is now under discussion for implementation in the revised version of the Norwegian standard NORSOK (2007).

This Position Paper provides a summary of the state-of-the-art knowledge on rogue waves and their impacts on marine structures in general, and ships in particular. The aim is to provide further insights for engineers into the rogue wave phenomenon and, at the same time, present the contributions that have been made to the field of rogue waves and their impact on marine structures by the projects in which DNV GL has participated. How these findings can be utilized to improve current design and operational procedures of marine structures is discussed. Finally, future research activities that are still needed to support the possible inclusion of rogue wave effects into ship and offshore structure design are proposed, and how to include them in planning and execution of marine operations, as well as for providing satisfactory warning criteria for these abnormal waves.

This position paper covers a wide-ranging subject area and cannot be exhaustive and mention all investigations carried out globally. However, the authors have attempted to provide the reader with a fair and balanced overview on the topic, describing the complexity represented by the rogue wave phenomenon and providing insights into the pro-active role played by the shipping and offshore industries in investigations of these abnormal waves.

# DNV GL ACTIVITIES ON ROGUE WAVES

Since the mid-1990s, DNV GL has been actively investigating the field of extreme and rogue waves, through literature reviews and participation in international conferences and workshops, as well as through affiliations with leading researchers in the field. In the 1990s, this topic was still relatively poorly understood. A significant step towards gaining further insights into rogue waves and their impact on marine structures was achieved in DNV GL through participation in international research projects with collaboration with wave specialists, as well as with experts on loads and responses. This research was partially or fully funded by the European Commission (EC) and the marine industry (Joint Industry Projects, JIPs). The projects include: the EC MaxWave (Rogue Waves – Forecast and Impact on Marine Structures) project, the EC Marie-Curie Network SEAMOCS (Applied Stochastic Models for Ocean Engineering, Climate, and Safe Transportation), the EC EXTREME SEAS (Design for Ship Safety in Extreme Seas) project, and the JIP CresT (Cooperative Research on Extreme Seas and their impacT) and its continuation JIP ShortCresT (Effects of ShorTCrestness on wave impact). The legacy DNV participated in these projects before merging with Germanischer Lloyd AG (GL). MaxWave, SEAMOCS, and EXTREME SEAS received appreciation from the EC, and EXTREME SEAS was on a shortlist of awarded projects. At present DNV GL coordinates the project ExWaCli (Extreme Waves and Climate change: Accounting for uncertainties in design of marine structures), funded partly by the Norwegian Research Council, that investigates occurrence of rogue waves in the future wave climate (Bitner-Gregersen, 2015).

## EC MAXWAVE PROJECT

The idea for initiating the MaxWave project arose during the 1998 COST 714 conference in Paris on directional wave spectra following an initiative from Prof. Douglas Faulkner. Ship accidents associated with bad weather were the main inspiration for starting the project. Single waves of abnormal height or groups of extreme waves were often reported by crewmembers of the ships involved in these incidents.

The project was funded within the Fifth Framework Programme in the period 2000 to 2003, and coordinated by GKSS Research Centre in Germany. It included four European Meteorological Offices (GKSS Research Centre, Norwegian Meteorological Institute, Meteo France, and UK Meteorological Office), three universities (Catholic University of Leuven, KU Leuven, in Belgium, Instituto Superior Técnico in Portugal, and Technical University of Berlin), two large research organizations (Institute of Hydro-engineering of the Polish Academy of Sciences and German Aerospace Centre), one small/medium size enterprise (Ocean Waves, Germany), and one Classification Society (DNV, Norway). A project Senior Advisory Panel (SAP) functioned as an entrance to international bodies and the project Expert Board brought knowledge from outside the project to the consortium. Prof. Faulkner was a member of the SAP of the project.

The aims of the MaxWave project were to provide a better understanding of the physical and statistical properties of rogue waves, to develop risk maps

and warning criteria for such extreme events, to investigate their impact on current design procedures, and to carry out a socio-economic assessment of possible revisions of the rules. A summary of the project content is given in Rosenthal (2004), and a summary of project results can be found in Rosenthal and Lehner (2008).

The project addressed theoretical aspects of extreme waves, as well as assessing traditional and new remote sensing techniques used to observe these waves. The theoretical considerations were limited to linear focusing of wave energy, and did not consider nonlinear effects, which were later found to be a main focus in research on rogue waves. Field data used in the project were supported by numerical data generated by the wave spectral model, WAM, which was implemented in meteorological offices participating in the project. The field and hindcast data were used to confirm the existence of rogue waves and to estimate their risk of occurrence. The MaxWave project also carried out some limited investigations addressing the impact of rogue waves on wave loads and responses, and discussed their consequences on the design of marine structures (Bitner-Gregersen et al., 2003).

MaxWave made a significant contribution to our understanding of rogue waves. However, due to the complexity of the topic several important questions remained to be answered. For example, too few data sets showing rogue wave events were available, which made it difficult to develop satisfactory physical and statistical models for prediction of these waves. Agreement about the probability of occurrence of rogue waves was not reached, and it was concluded that more research was required in order to investigate effects of these waves on marine structures (Bitner-Gregersen et al., 2003). Thus, completion of the  project called for further investigations that were of importance not only for the wave scientific community, but also for the shipping and offshore industries.

## EC NETWORK SEAMOCS

The need for further investigations of extreme weather events was also recognized by the EC, which fully funded the Marie-Curie Network, SEAMOCS (Applied Stochastic Models for Ocean Engineering, Climate, and Safe Transportation), within the Sixth Framework Programme. This was a four-year (2005-2009) research training and mobility network coordinated by the University of Lund, Sweden (SEAMOCS, 2009). The SEAMOCS Network partners included: Lund University, University of Sheffield in UK, University Paul Sabatier in Toulouse, France, KU Leuven in Belgium, Chalmers University of Technology in Sweden, Tallinn University of Technology in Estonia, Royal Netherlands Meteorological Institute, Swedish Meteorological and Hydrological Institute, and DNV in Norway. The SEAMOCS initiative linked meteorology and statistics with ocean and coastal engineering. The overall goal of the network was to increase marine safety, as well as to reduce the capital and operational costs of sea transport and major offshore installations. Central research topics for the SEAMOCS network were developing statistical spatiotemporal models on the global scale for metocean variables, including extreme values statistics, and developing nonlinear wave models and tools for studying the long-term effects of wave and wind climate on the design and operation of marine structures.

Research on nonlinear wave models, bringing theory and observations closer, in particular with respect to rogue waves, was of considerable interest to DNV, and the DNV SR&I participation in SEAMOCS concentrated primarily on this topic. In the first year of SEAMOCS, DNV SR&I collaborated with KU Leuven on second-order wave models. Later DNV hosted a post-doc from KU Leuven who brought to DNV a nonlinear wave code based on the HOSM (Higher Order Spectral Method) method (West et al., 1987), that was originally developed by the University of Turin, Italy. This code allowed the physics and statistical properties of waves to be studied beyond the second order, for the first time in DNV.

Through the SEAMOCS Network, DNV obtained further insights into some of the mechanisms that generate rogue waves and learnt that under some metocean conditions rogue waves may significantly change the distributions of the wave parameters that are currently used in the design and operation of marine structures.

## EC EXTREME SEAS PROJECT

Investigations in the MaxWave project and the SEAMOCS Network inspired DNV to propose a new EC project - EXTREME SEAS (Design for Ship Safety in Extreme Seas), (EXTREME SEAS, 2013). It was clear to DNV that several issues needed further investigation: generation of rogue waves was not fully understood, agreement about the probability of occurrence of rogue waves had not been reached, and systematic investigations on the impact of these abnormal waves on current design procedures were lacking.

EXTREME SEAS was a collaborative project funded within the EC Seventh Framework Programme (2009-2013). The project consortium consisted of two Shipyards (MEYER WERFT (MW) from Germany and Estaleiros Navais Viana de Castelo from Portugal), two Classification Societies (DNV and Germanischer Lloyd AG), one model basin (CEHIPAR in Madrid, Spain), one provider of meteorological services (Norwegian Meteorological Institute), one research institute (Institute of Applied Physics of the Russian Academy of Sciences, RAS) and four universities (University of Turin in Italy, Instituto Superior Técnico in Portugal, and University of Duisburg-Essen and Technische Universität Berlin (TUB) in Germany). TUB operated a model basin, which was also used in the project. EXTREME SEAS was coordinated by DNV, Norway.

A Senior Advisory Panel (SAP) was an observer in the project and supported the dissemination and exploitation of the project results. It consisted of IACS (International Association of Classification Societies), JCOMM (Joint Committee of Marine Meteorology of WMO), Color Line, and Carnival. The roles of IACS and JCOMM were, in addition to providing advice to the EXTREME SEAS Consortium, to bring the project results to the international level. MW, through their role as Chairman of the Technical Committee of EUROYARDS, which represents 6 major shipyards in 5 European countries, was the Exploitation Manager of the project.

The overall objective of EXTREME SEAS was to provide the technology and methodology necessary for safe ship design in extreme sea conditions. Another objective was to develop warning criteria for rogue waves that could be applied in the operation of marine structures, and to implement them in a marine weather forecasting system operated by the meteorological office in the consortium. The project also considered expected trends in storm intensities with the aim of helping the shipping industry adapt to climate change.

In order to achieve these objectives EXTREME SEAS studied the physical and statistical properties of extreme waves and developed advanced numerical and physical simulation models for wave-structure interactions. The investigations were supported by model tests that were used for validation of nonlinear wave models, and also used to enhance wave-structure interaction codes. Model tests were carried out in the basin of TUB and in the Spanish basin of Canal de Experiencias Hidrodinamicas de El Pardo (CEHIPAR). Field data used in EXTREME SEAS were collected at the Ekofisk field in the North Sea and from the Tallinn Bay of the Baltic Sea.

The case studies that were considered in EXTREME SEAS included container vessels, passenger ships, LNG carriers, and product and chemical tankers. However, the methodology and tools developed by the project are generally applicable to different ship types. Some weaknesses in the current design procedures for ship structures were highlighted.

The investigations carried out in EXTREME SEAS contributed significantly to improving our understanding of rogue waves, as well as their impact on ship structures. More systematic studies demonstrating the effects of rogue waves on wave-induced loads and responses were carried out for the first time.

## JIP CREST/SHORTCREST

Hurricanes Ivan, Rita, and Katrina in the Gulf of Mexico demonstrated the dangers of extreme sea conditions for all types of offshore structures, and drew considerable attention to the danger of extreme waves in the offshore industry. Proper accounting for extreme waves is necessary to ensure the integrity and safety of offshore platforms, and the question arose of whether rogue waves should be included in design within the offshore industry. Obtaining further insights into extreme waves and their impacts requires close cooperation between metocean specialists, wave modelling experts, hydrodynamicists, and reliability specialists. This resulted in initiation of the two-year JIP project CresT (Cooperative Research on Extreme Seas and their impacT) in 2008 (CresT, 2009), which continued as the ShorTCresT (Effects of ShorTCrestness on wave impact) JIP project. Both projects were coordinated by MARIN in The Netherlands and funded by oil companies, offshore engineering companies and classification societies. The project partners included SHELL from the Netherlands, Oceanweather Inc. and Forristall Ocean Engineering Inc. from US, Ocean Wave Engineering and Imperial College from UK, and DNV from Norway. DNV SR&I led the DNV participation in CresT, and ShorTCresT was run by DNV Oil&Gas.

The CresT project studied unidirectional waves, whereas the ShorTCresT project focused upon directionally spread seas. Model tests were carried out in the MARIN and Imperial College wave basins. A generic tension-leg platform (TLP) was defined and chosen as a case study in both projects. Two limit states, air-gap and water in deck, were considered.

The CresT and ShorTCresT projects analysed large amounts of field data collected by oil companies sponsoring the projects, and the focus was more on field data than in EXTREME SEAS. The projects did not use the nonlinear theoretical and numerical models that were studied in EXTREME SEAS.

# THEORETICAL BACKGROUND

## LINEAR DESCRIPTION OF WAVES

The building block of the standard representation of ocean waves is the single sinusoidal wave component:

$$\eta(\boldsymbol{x},t) = a\cos(\theta), \qquad \theta = \boldsymbol{k}\cdot\boldsymbol{x} - \omega t + \xi \qquad (1)$$

where $\eta(\boldsymbol{x},t)$ represents the vertical position of the water surface at the horizontal location $\boldsymbol{x} = (x,y)$ at time $t$. The wave amplitude is denoted $a$, $\boldsymbol{k} = (k_x, k_y)$ is the wave number, $\omega$ is the wave frequency and $\xi$ is a phase shift. For ocean waves on water of constant depth $h$, and  are related through the dispersion relation $\omega(\boldsymbol{k}) = \sqrt{gk\tanh(kh)}$, where $k = |\boldsymbol{k}|$ and where $g$ = 9.81 ms$^{-2}$ is the acceleration of gravity. The form of this dispersion relation reflects a very important property of water waves; namely the fact that they are dispersive. This means that wave components with different wavelengths travel with different propagation speeds.

The random model for ocean waves is constructed by representing the sea surface as a sum of elementary waves with different wavelengths, frequencies, and directions of propagation:

$$\eta(\boldsymbol{x},t) = \sum_j a_j\cos(\theta_j), \qquad \theta_j = \boldsymbol{k}_j\cdot\boldsymbol{x} - \omega_j t + \xi_j \quad (2)$$

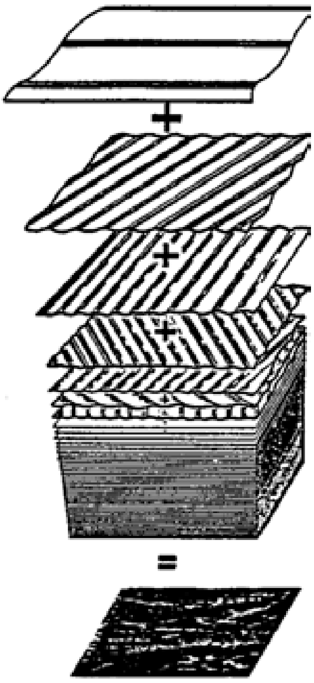

Figure 2: Conceptual illustration of the superposition of plane waves to form a random ocean surface. From Kinsman (1965).

To reflect the randomness of the sea surface $a_j$ and $\xi_j$ are typically assumed to be random variables.

From the representation (2), a number of properties of a random wave field can be derived. The standard parameter that represents the typical wave height in a wave field is the significant wave height $H_s$, which is traditionally defined as the average of the 1/3 highest waves in a stationary wave record. Nowadays, $H_s$ is often defined as four times the standard deviation of the surface elevation; $H_s=4\sigma$, where $\sigma$ is the standard deviation of the surface elevation, or alternatively the square root of the zeroth moment of the wave spectrum. These two definitions are equivalent for linear random waves with narrow wave spectrum.

## SECOND-ORDER DESCRIPTION OF WAVES

In reality, ocean waves are not described exactly by a linear formulation, and the representations (1) and (2) are valid only to leading order, under the assumption that the wave steepness is a small parameter. Wave steepness is essentially the ratio of wave amplitude to wave length. For a single wave component with amplitude a and wavelength $\lambda = 2\pi/k$, the wave steepness is normally defined as $\varepsilon = ak$. For a random wave field with significant wave height Hs and peak wavelength $\lambda_p = 2\pi/k_p$ , the steepness is often defined as $\varepsilon = k_p H_s/2$. Assuming that the wave steepness is small, nonlinear corrections to the representation (2) can be obtained from perturbation expansions in terms of $\varepsilon$.

The nonlinear counterpart of the single uniform wave (1) is the so-called Stokes wave, first derived by Sir George Stokes (Stokes, 1847). To second order in wave steepness, the Stokes wave is given by:

$$\eta(\boldsymbol{x},t) = a\cos(\theta) + \frac{a^2k}{2}\cos(2\theta), \qquad \theta = \boldsymbol{k}\cdot\boldsymbol{x} - \omega t + \xi. \quad (3)$$

The second-order Stokes wave has higher crests and shallower troughs than the linear wave (1), but the wave height is not changed to second order. The second term in (3) is a so-called bound, or locked, wave. This means that it is 'bound' to the 'free' wave represented by $a\cos\theta$, and is not allowed to propagate freely by itself. Therefore, bound waves do not affect the dynamics of wave evolution, but give merely a static modification of the shape of the surface.

The second-order generalization of the sum of wave components (2) was first derived by Longuet-Higgins (1963) for waves in deep water, and later by Sharma and Dean (1979) for waves in water of arbitrary depth. The second-order solution can be written:

$$\begin{aligned}\eta(\boldsymbol{x},t) &= \sum_j a_j \cos(\theta_j) \\ &+ \frac{1}{4}\sum_i \sum_j a_i a_j \,[K_{ij}^{-} \cos(\theta_i - \theta_j) + K_{ij}^{+} \cos(\theta_i + \theta_j) \qquad (4)\end{aligned}$$

where $K_{ij}^{-}$ and $K_{ij}^{+}$ are coefficients that can be found, for example, in Sharma and Dean (1979). The double sum in (4) contains all the second-order bound waves that arise from interactions between the free waves.

Today, the second-order wave description has become widely used in the offshore industry. DNV GL has an operative second-order wave code (Birknes and Bitner-Gregersen, 2003).

## HIGHER ORDER DESCRIPTION OF WAVES

The linear and second-order theories described above represent the first two steps in a hierarchy of increasingly accurate formulations of water waves. In the case of a single regular wave, the Stokes wave solution can be found to high order. The analytic expressions for the fifth-order Stokes wave on arbitrary depth can be found in Skjelbreia and Hendrickson (1960) or Fenton (1985) and can be calculated numerically to arbitrarily high order (Rienecker and Fenton, 1981). Higher order Stokes waves are often used in engineering applications, for example when studying wave impacts on structures.

For the more general case of a random wave field, represented to leading order by the sum of independent wave components (2), complications ensue at third order. Now the leading order wave amplitudes $a_j$ and phases $\xi_j$ are functions of time, and can no longer be assumed to be statistically independent. The different wave components can interact with each other, with the result that one component can transfer energy to other waves. This has the consequence that to third order or higher, explicit expressions like (4) are no longer valid, but the wave field must be described according to the governing partial differential equations. This opens for a wide range of new and interesting problems, and, in the context of rogue waves, an important question is whether the nonlinear dynamics of free waves can be responsible for changes in the statistical distributions that are not explained by second-order theory. This can have important implications for the design and operation of marine structures.

The very fundamental equations describing the motion of waves on the water surface in an 'exact' way are the Navier-Stokes equations. The Navier-Stokes equations describe the full dynamics of fluid flow, including waves on the fluid surface. They are, however, challenging to deal with, both theoretically and with respect to numerical simulations. Fortunately, in most practical applications, water waves can be well described by so-called potential theory, for which viscous effects are ignored. The full equations for potential theory are called the Euler equations. The Euler equations are, however, also quite complicated; they can be difficult to handle in their exact form and computationally demanding to solve numerically. One important and well-known method for solving the Euler equations numerically in a rectangular domain with constant water depth is the so-called Higher Order Spectral Model (HOSM), originally formulated by West et al. (1987) and Dommermuth and Yue (1987). In principle, HOSM does not contain any additional assumptions, except for the surface being single-valued (i.e., no wave breaking). However, in practice, a truncation of nonlinearity is always applied so that weak nonlinearity is implicitly assumed. HOSM is a relatively efficient numerical method, and has therefore been applied to the study of rogue waves. It has become particularly popular in recent years due to the increase in available computational power. HOSM has also been used in DNV GL in studies on rogue waves, and DNV GL currently has an operative HOSM code.

Traditionally, however, most of our understanding of wave dynamics has come from approximate models; that is, simplifications of the full equations that still capture important aspects of the problem.
In particular, for numerical investigation of rare events such as rogue waves, it is desirable to describe the sea surface over a large spatial area. Due to the computational burden of solving the full equations numerically, much of the work done on rogue waves has been carried out using approximate models. An important class of approximate models that has been widely used in rogue wave research is

the so-called Nonlinear Schrödinger (NLS) equations for water waves. NLS-type equations can be derived from the full Euler equations by assuming that the waves are weakly nonlinear (i.e., small wave steepness) and narrow banded (i.e., are described in terms of a narrow wave spectrum). For waves on deep water the so-called cubic NLS equation, valid to third order in bandwidth and nonlinearity, was first derived by Zakharov (1968) as a special case of the so-called Zakharov equation, which itself is a simplified model that assumes weak nonlinearity, but with no assumptions on the bandwidth. The cubic NLS equation for waves on constant finite depth $h$ was later derived by Davey and Stewartson (1974). For deep-water waves, Dysthe (1979) extended the cubic NLS equation to fourth order in wave steepness and bandwidth. Dysthe's equation is often referred to as the modified NLS (MNLS) equation, or Dysthe equation. Numerous other variants of NLS-type equations for water waves exist for various special conditions. The range of validity for various models for deep-water waves is illustrated in Figure 3.

## WAVE STATISTICS

Starting from the linear formulation (2), it follows from the central limit theorem of probability theory that the sea surface has a Gaussian (Normal) distribution. From this property, the distributions of other wave characteristics can be derived. In design and operations, the distributions of wave crest heights and wave heights are usually most important (see Figure 5 for definition of wave height and crest height in a wave record).

Longuet-Higgins (1952) showed that if the wave field is sufficiently narrow banded (i.e., can be represented by a narrow band of frequencies), the distribution of wave heights and crest heights are described by a Rayleigh distribution. According to the Rayleigh distribution, the probability that a wave height exceeds a certain value is given by:

$$P\,(H > cH_s) = \exp\,(-2c^2) \qquad (5)$$

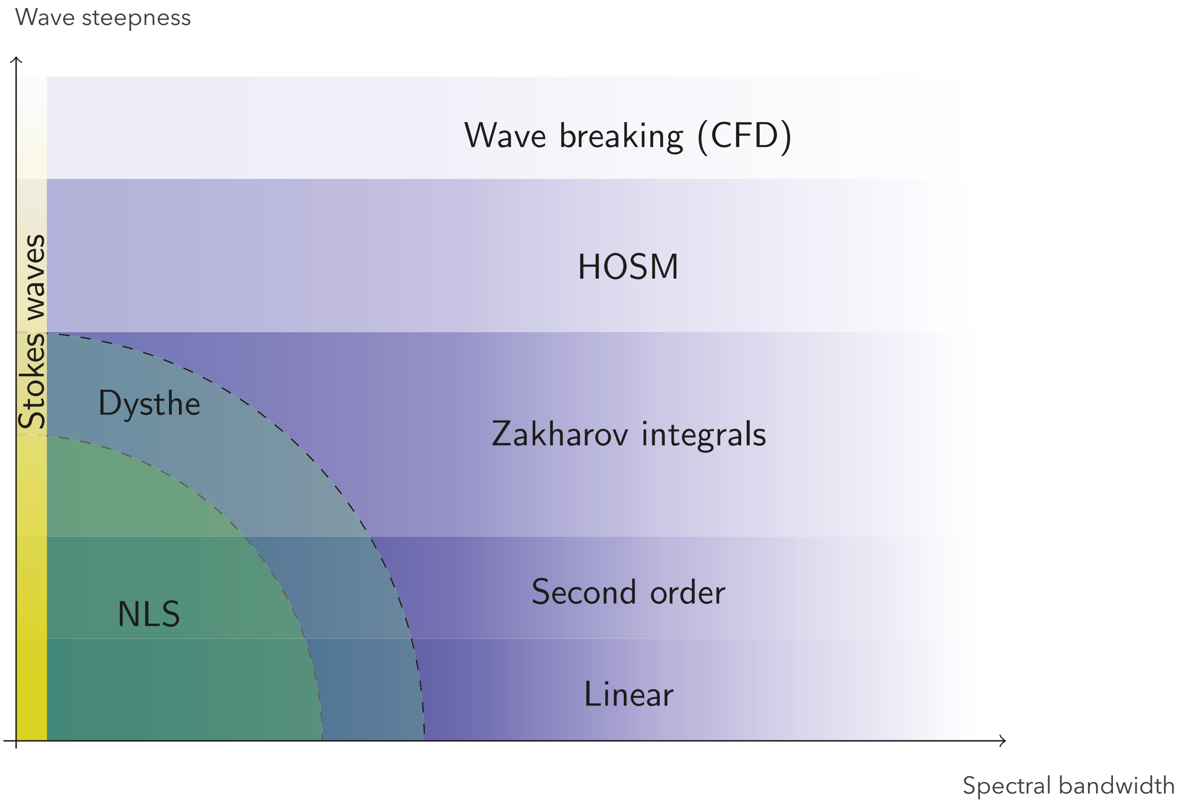

Figure 3: Range of validity of various approximate models for waves on deep water.

In reality, ocean waves are not always narrow banded, and observations will deviate from the Rayleigh distribution (Longuet-Higgins, 1980). For a more general formulation, wave-height statistics are often expressed in terms of Weibull distributions in the form:

$$P\,(H > cH_s) = \exp\,(-c^{\alpha}/\beta) \qquad (6)$$

where parameters $\alpha$ and $\beta$ are typically fitted with observational data. For example, Forristall (1978) analyzed 116 hours of hurricane-generated waves in the Gulf of Mexico, and found $\alpha = 2.126$ and $\beta = 0.52625$. This distribution has become widely used in the marine industry and has been shown to give reasonable results for other ocean regions also.

While second-order effects have a minor impact on wave height distribution, they have a significant impact on wave crest height distributions. The second-order modifications to the Rayleigh distribution of crests were derived by Tayfun (1980), who also derived a second-order distribution for the surface. The distribution of surface and crest heights according to linear (Gaussian and Rayleigh) and second-order (Tayfun, 1980) random wave theory are shown in Figure 4. Note that the second-order distributions predict significantly larger crests than the linear distributions.

As for the Rayleigh distribution of wave heights, the Tayfun distribution of crests is valid only for narrow-banded waves. Therefore, for realistic ocean waves, it common to use a more general Weibull crest distribution. By using simulations of the second-order random wave model (6) for many different wave conditions, Forristall (2000) suggested a two-parameter Weibull distribution for the crest heights, where the distribution parameters depend on the wave spectrum, as well as water depth. This distribution has been shown to fit quite well with measured data, and is currently the state-of-the-art distribution for second-order crest heights. It is, for example, used in design practice for offshore structures, DNV RP-C205 (DNV, 2014).

## DEFINITION OF ROGUE WAVES

In everyday language and in the media, terms like "rogue", "freak", or "giant" waves are often used as a synonym for 'large wave', often in the context of a wave-related incident. In the real ocean, rogue waves are waves that are very steep and much higher than the surrounding waves in a wave record, which is usually of 20-minute length; see Figure 5 for an extract of a wave record. In the scientific community, it is generally agreed that a rogue wave is a wave that is statistically unlikely to occur in a given sea state, based on averaged properties of that sea state. In this sense, a large and dangerous wave may not necessarily be rogue if it occurs in a very high sea state, and a rogue wave may not necessarily be very large if it occurs in a low sea state. However, in most cases the term rogue wave is used for waves that are both large in absolute measures and, at the same time, significantly larger than the surrounding waves in the sea state, and are thus unexpected.

There is currently no consensus on one unique definition of a rogue wave, but a common and simple approach is to define a rogue wave as a wave whose wave height or crest height exceeds some thresholds related to the significant wave height. A common definition is to apply the criteria (Haver, 2000):

$$\frac{H_{max}}{H_s} > 2 \quad \text{and/or} \quad \frac{C_{max}}{H_s} > 1.25 \qquad (7)$$

where $H_{max}$ denotes the zero-crossing wave height, Cmax is the crest height, and $H_s$ is the significant wave height, defined as four times the standard deviation of the surface, typically calculated from a 20-minute measurement of the surface elevation. Different variants of the crest criterion have been suggested in the literature, such as $C_{max}/H_s > 1.2$ (Haver and Anderson, 2000) and $C_{max}/H_S > 1.3$ (Tomita and Kawamura, 2000, Bitner-Gregersen and Hagen, 2004). It also should be noted that some authors use only one of the criteria given in (7). It has been suggested by Krogstad et al. (2008) that if both criteria are fulfilled the wave should be classified as a double rogue wave. As an example, the well-known Draupner wave was measured to have a crest height $C_{max} = 18.5$ m and wave height $H_{max} = 25$ m. The significant wave height in the 20-minute wave record in which it was observed was $H_s = 11.9$ m. Hence, for the Draupner wave, $H_{max}/H_s = 2.1$ and $C_{max}/H_s = 1.55$. Thus, the Draupner wave is classified as a rogue wave according to (7), or a double rogue wave according to Krogstad et al. (2008).

It should be noted that some authors have suggested that the wave height and crest criteria (7) are not sufficient for identifying rogue waves (see e.g. Guedes Soares et al., 2004). More advanced definitions of rogue waves could reflect mechanisms responsible for their generation (see the section

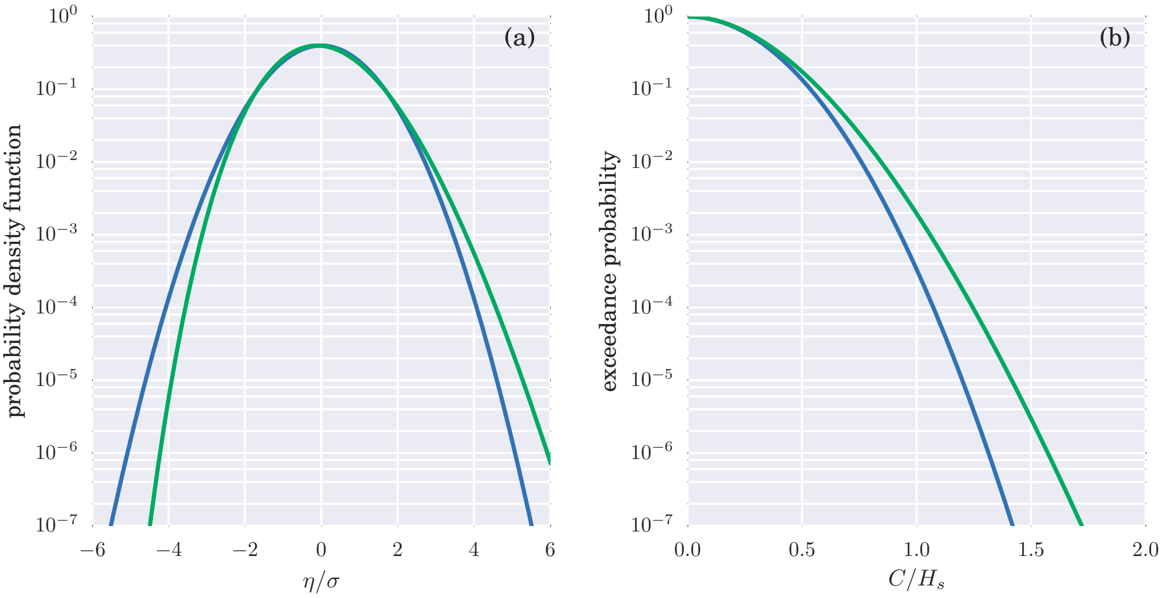

Figure 4: (a) Distribution of surface according to linear theory (Gaussian distribution, blue line) and second-order (Tayfun (1980), green line). (b) Exceedance probability for crest heights according to linear theory (Rayleigh, blue line) and second-order (Tayfun (1980), green line). The second-order distributions are shown for wave steepness $\varepsilon = k_c H_s/2 = 0.15$. Note that neither linear nor second-order distributions of wave parameters can be applied uncritically to nonlinear waves beyond second order, which is particularly relevant with respect to rogue waves.

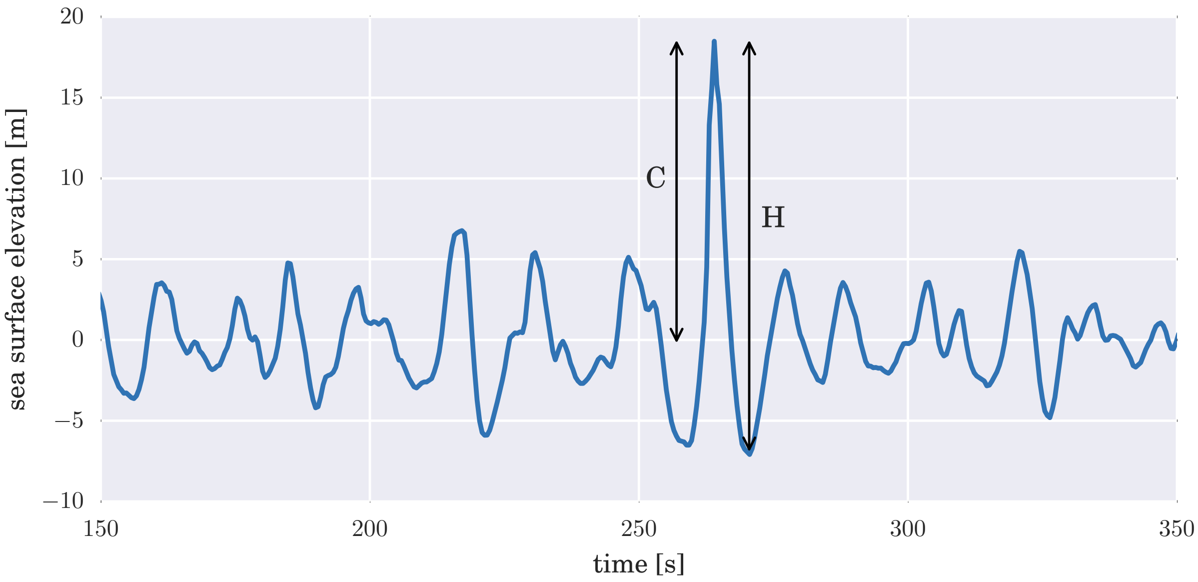

Figure 5: The New Year wave that was recorded at the Draupner platform on 1st January 1995. The maximum wave height and crest height are indicated.

below for a discussion of generation mechanisms of rogue waves). However, such advanced definitions would be more difficult to use in engineering applications.

## FIELD OBSERVATIONS OF ROGUE WAVES

There have been numerous visual observations and testimonials of rogue waves throughout history, as well as photographs of very large waves taken from ships. As described in Draper (1964), in 1826 the French scientist and naval officer Captain Dumont d'Urville reported having observed waves of up to 30 metres in height; a wall of water. At the time he was openly ridiculed for making such an outrageous report. One of the largest waves ever reported was said to have been observed from the USS Ramapo in the North Pacific in 1933. They estimated the wave to have a height of 34 metres. However, from purely visual observations it is obviously difficult to obtain accurate and reliable measurements of a wave, and such visual observations of rogue waves should be taken with some scepticism.

Today, there are many types of instruments that can measure the actual sea surface with some accuracy. These include wave staffs, wave buoys, and laser and radar altimeters. These are deployed at many locations throughout the world's oceans. In the past, due to storage limitations, only averaged sea state parameters were typically reported, and the time series of the surface were often discarded. Moreover rogue waves were often considered as measurement errors (outliers) and therefore removed from the time series. Keeping in mind that rogue waves are rare events and measurements are performed at single points, it is clearly difficult to obtain a large number of recordings of rogue waves. However, with increased data storage and data transfer capabilities, in recent years it has been possible to store full time series of surfaces, and more data on rogue waves are becoming available.

It should be noted that all devices for measuring sea surfaces have some uncertainty. Due to lateral movements, wave buoys tend to avoid high wave crests, and therefore often underestimate large crest and wave heights. On the other hand, laser altimeters can be sensitive to sea spray and can therefore be prone to overestimating crests.

The MaxWave project included a comprehensive study of field observations from different instruments, with data collected by wave buoys, laser, LASAR (array of lasers), marine radar (WAMOS), and satellites. Figure 6 shows the different wave instruments mounted in the Ekofisk field that were used in MaxWave. In addition, two container ships, the Grey Fox and the Northern Pioneer, were instrumented with marine radar to measure waves in the Agulhas current outside the coast of South Africa and in the Gulf Stream, respectively. This was prompted by the fact that abnormal waves often occur in areas where waves propagate into strong opposing currents. The Agulhas current is a well-known example (Lavrenov, 1998, Mallory, 1974), where waves travelling northeast from the southern Atlantic Ocean are focused by the southbound current and, as a result, the waves become steeper and shorter due to the wave-current interaction.

New methods to estimate individual wave height using WAMOS radar (Nieto Borge et al., 1999, Dankert and Rosenthal, 2004) and satellite Synthetic Aperture Radar (SAR) data (Schulz-Stellenfleth and Lehner, 2004) were also developed in the MaxWave project. These new methods enabled observations of individual rogue waves using radar and satellites for the first time. However, these measurement techniques still have important limitations. Firstly, they employ linear assumptions to invert the radar image to a sea surface. Secondly, only waves with lengths over about 100 metres can be detected by SAR. A map showing maximum single wave height, $H_{max}$, derived from three weeks of SAR data acquired in August-September 1996 is shown in Figure 7.

From SAR observations, the MaxWave project demonstrated that rogue waves mainly occurred in extended storm systems or in crossing sea states, where wave systems were arriving from different storm centres, and in moving fetch situations near the centre of the low. This has also been confirmed in investigations using the Lloyd's database of ship accidents. Toffoli et al. (2005) combined the 200 ship accidents in the database with wind fields and data from the spectral wave model, WAM, as well as from satellite data, to investigate the metocean conditions at the time of the accidents; see Figure 8. It was found that these accidents did not always happen in very high sea states; crossing seas and fast changing wind conditions were, however, typical. In a previous study using the same accident database, Guedes Soares et al. (2001) used visual observations of global wave climate (BMT, 1986) and demonstrated that ship accidents tended to occur in areas where the wave steepness was large.

As a part of EXTREME SEAS, Nikolkina and Didenkulova (2012) used literature review, analysis

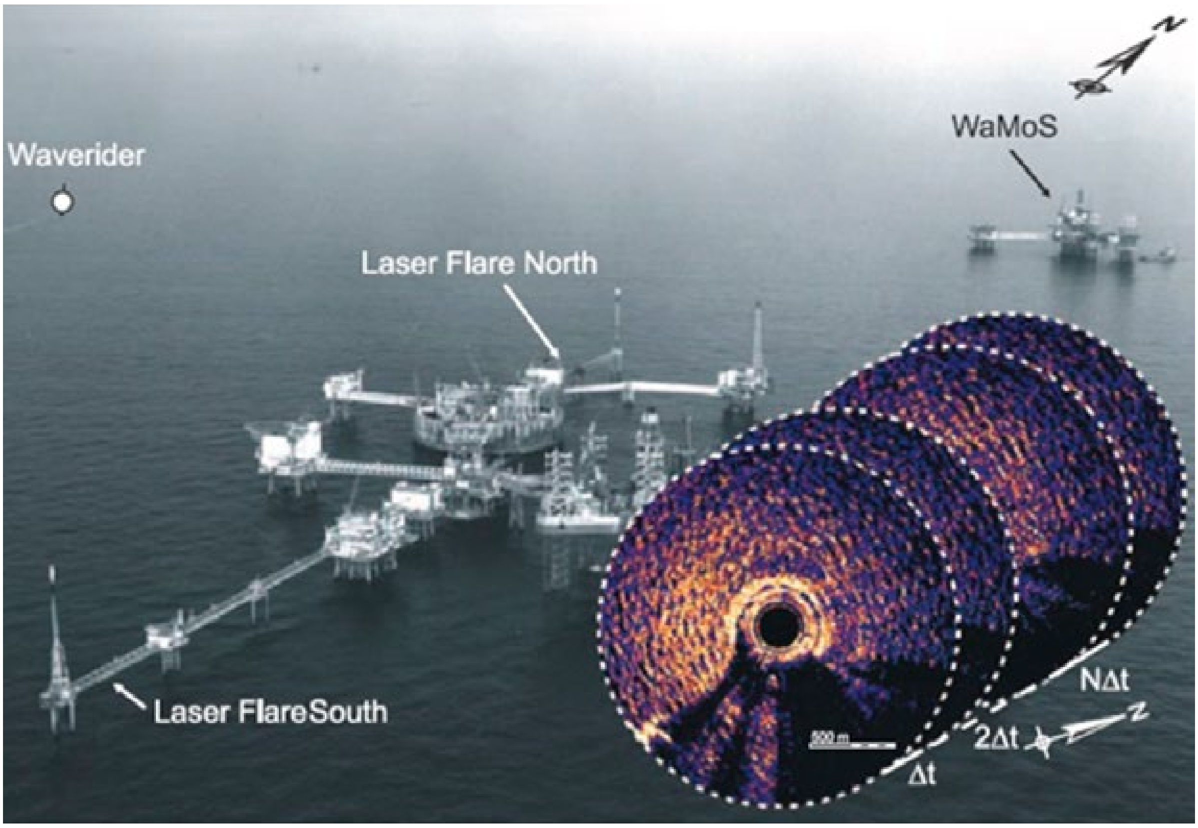

Figure 6: The Ekofisk platform with locations of in situ measurements and examples of WAMOS images.
After Rosenthal and Lehner (2008).

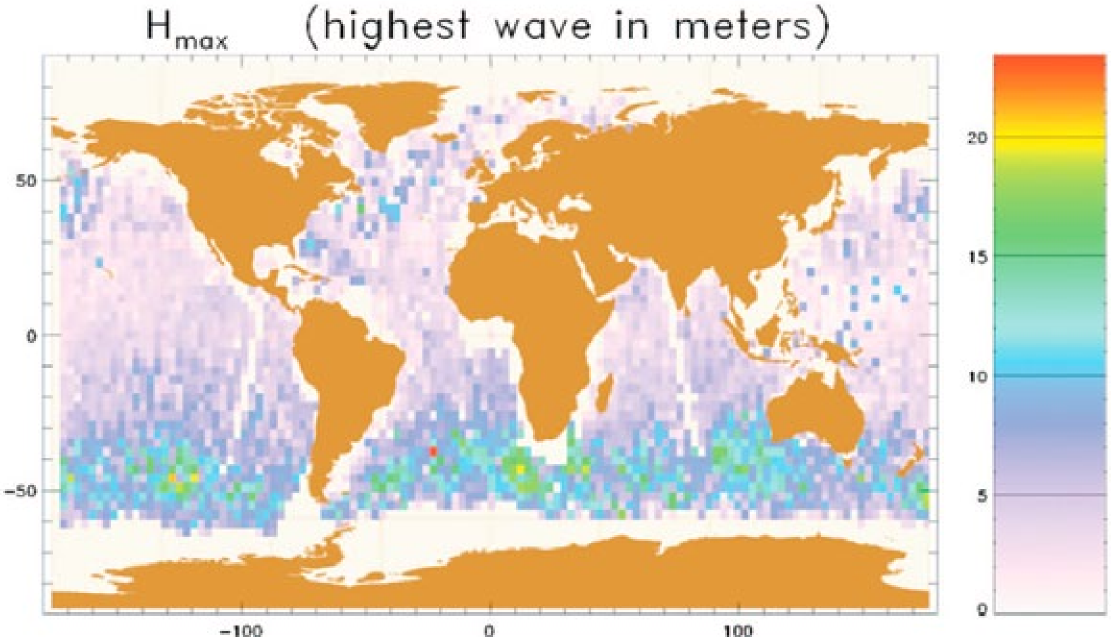

Figure 7: Map showing maximum single wave height, Hmax, derived from three weeks of ERS-2 SAR data acquired in August-September 1996. High waves occur in the high wind speed areas in the southern hemisphere and in the pass of Hurricane Fran in the Northern Atlantic. The highest wave was measured to be about 28 m and occurred in the South Atlantic to the north of a severe low in a moving fetch situation. After Rosenthal and Lehner (2008).

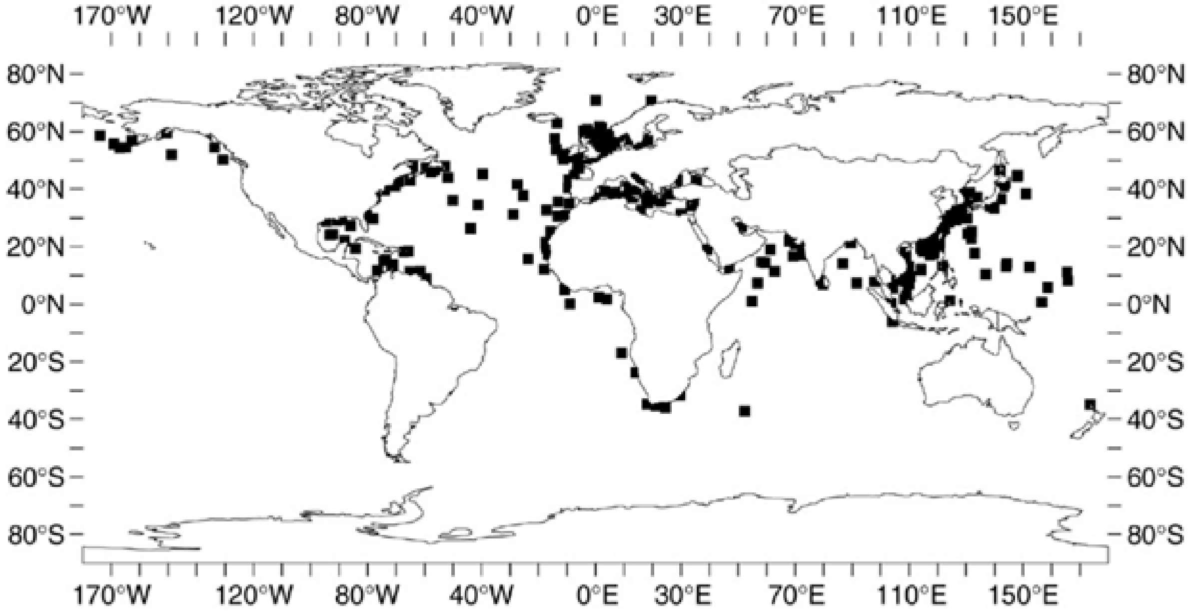

Figure 8: Distribution of shipping accidents (1995-1999). Accidents were collected from Lloyd's Marine Information Service (LMIS) (Toffoli et al., 2005).

| Wave parameters | Andrea wave | Draupner wave |
|---|---:|---:|
| $H_s$ | 9.2 m | 11.9 m |
| $T_p$ | 13.2 s | 14.4 s |
| $C_{max}$ | 15.0 m | 18.5 m |
| $H_{max}$ | 21.1 m | 25.0 m |
| $C_{max}/H_s$ | 1.63 | 1.55 |
| $H_{max}/H_s$ | 2.3 | 2.1 |

of existing databases, and information published in the media to show that rogue waves occur worldwide in the ocean, in both deep and shallow water. However, they are more frequent in some specific ocean regions.

A typical history of an accident reported by a ship's crew is that a huge wave destroys one or more windows on the bridge. The inflowing water damages the electronics, leading to stoppage of the engines. As a result, the ship turns parallel to the sea crests, resulting in an increased roll angle. This scenario was the case for the cruise ship Bremen, carrying 137 passengers, on 22nd February 2001 in the South Atlantic. The ship was hit by a rogue wave that damaged the bridge and knocked out the engines. Fortunately, the crew managed to make emergency repairs and restart the engines, bringing the ship back to safety. According to the European Medium Range Weather Centre ERA 40 data, the significant wave height was only about 5 metres and wind speeds were up to about 18 m/s at the time of the accident. Note that the ERA 40 data tend to underestimate significant wave height somewhat. Only two weeks later the Caledonian Star experienced a similar accident, west of the Falkland Islands, when the ship was hit by a rogue wave that was later estimated to have been almost 30 metres in height. At the time of the accident, the model showed 8 metre significant wave height and 22 m/s wind speed. Hence, in both these cases the sea state was well below the design value. It has been speculated that such a scenario was also responsible for the loss of container ship München in December 1978. Similar damage was also reported by the bulk carrier, Stenfjell, which arrived at Esbjerg (a harbour on West coast of Denmark) on the morning of 26th October 1998 with heavy weather damage to the wheelhouse, accommodation, and electrical installations, reportedly due to a rogue wave (Bitner-Gregersen and Magnusson, 2004). More recently, in March 2010, the cruise ship Louis Majesty also experienced similar damage due to a rogue wave breaking windows in the passenger dining room, causing two fatalities.

Several rogue waves that were recorded in the ocean have also been reported in recent years. One famous example is the Draupner wave shown in Figure 5. Another example is the so-called Andrea wave that was recorded at the Ekofisk field during the Andrea storm that crossed the central part of the North Sea on 8th – 9th November 2007 (Magnusson and Donelan, 2013). Table 1 shows the key parameters for the Draupner and Andrea waves. As seen in the table, both these waves can be classified as double rogue waves according to the criteria (7). Both these waves were recorded at oil platforms in the North Sea located in water depths of about 75 m.

In a recent extensive study carried out within the CresT project, Christou and Ewans (2014) analyzed large amounts of wave data provided by oil companies sponsoring the project and obtained from different sensors mounted on fixed-platforms: wave radars, wave staffs, optical lasers, and step gauges as well as some measurements from floating systems. The vast majority of the data was from Saab wave radars, and the results indicate that this instrument also provided the most reliable data. Several rogue waves were identified, but their percentage of the total number of recorded waves was relatively low . This could partly be due to the data control system used. It was concluded that instrumental recordings of rogue waves must be interpreted with care, and inspection of the full time series of the surface is usually necessary to confirm the validity of the recording.

Waseda et al. (2014) reported extreme waves recorded in 2009, 2012, and 2013 by point-positioning GPS-based wave measurements conducted by deep ocean (over 5,000 m) surface buoys moored in the North West Pacific Ocean. Two large rogue waves, exceeding 13 metres in height, were observed in October 2009 and three extreme waves of around 20 metres in height were observed in October 2012 and in January 2013. These extreme events were associated with passages of a typhoon and a mid-latitude cyclone. The authors suggested that direct measurements of extreme waves using GPS sensors might become an attractive alternative for observing extreme waves offshore.

# GENERATION MECHANISMS OF ROGUE WAVES

## SPATIAL FOCUSING

Spatial focusing of wave energy is a well-known effect in physics, for example in optics or from refraction of electromagnetic waves. In the case of ocean waves, focusing of waves coming from different directions or with different wavelengths can occur due to variations of the seabed bathymetry. When waves approach shallower water, the waves are refracted so that the crests align with the bottom contour lines. This can lead to focusing of wave energy and the formation of large waves at specific locations; for example, this is well known to occur behind small islands or underwater reefs. A photo showing wave refraction due to bottom variations is shown in Figure 9.

Another well-known effect that falls under the category of spatial focusing is wave refraction due to currents. Waves that propagate over variable currents will be refracted, such that focusing of wave energy can occur. A well-known example is the abnormal waves in the Agulhas current outside the southeast African coast. The occurrence of giant waves in this area has been well known for a long time (Mallory, 1974), and it has been shown that the jet-like structure of the current can lead to wave energy being trapped by refraction of waves, as illustrated in Figure 10.

The physical mechanism that causes geometrical focusing and can result in the formation of large waves is essentially described by linear wave theory, and is very well understood. However, in addition to linear focusing, nonlinearities can also play a role in the generation of rogue waves through wave-current interactions, see the section on nonlinear focusing below.

## TEMPORAL FOCUSING

Temporal, or dispersive, focusing of ocean waves is possible due to the dispersive nature of water waves. Dispersive means that waves with different wavelengths and periods travel at different velocities. For example, in deep water, long waves propagate faster than shorter waves. Therefore, waves of different scales may 'overtake' each other and produce a temporary high concentration of wave energy at a single location. Thus, by careful choice of an initial wave field it is possible to obtain a large wave at a specific time and location, and this

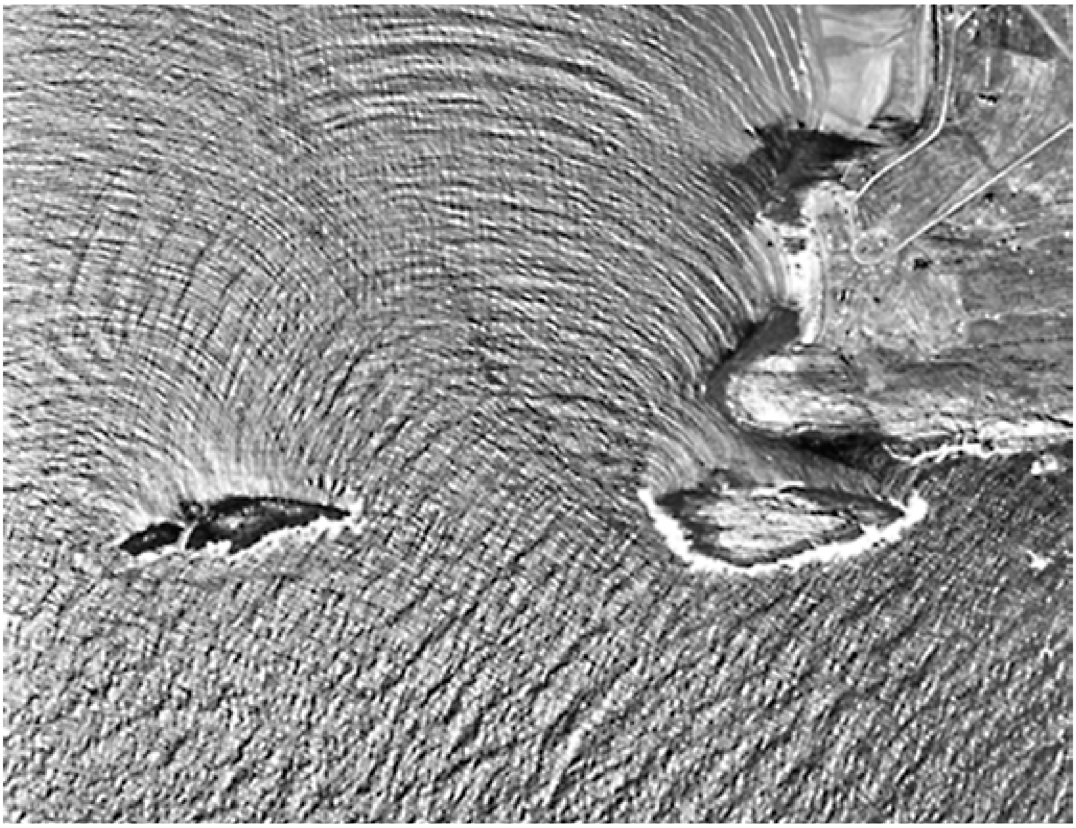

Figure 9: Example of wave refraction due to seabed bathymetry. Credit: Fjellanger Widerøe A/S

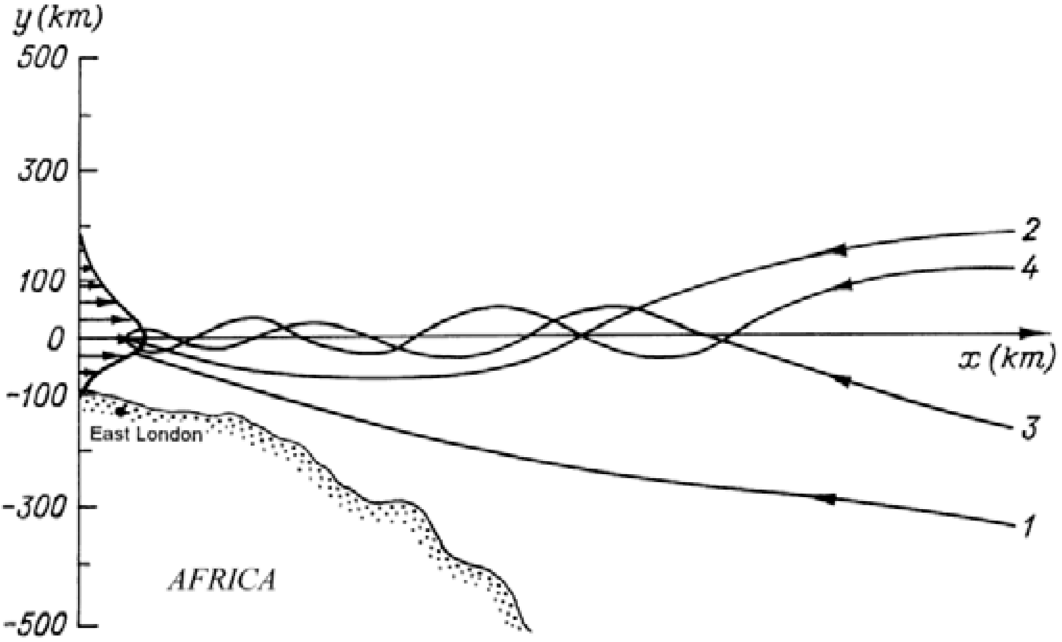

Figure 10: Illustration of wave refraction in the Agulhas current. The rays represent incoming waves that become trapped in the jet current. From Lavrenov (1998).

Figure 11: The ship Wilstar after an encounter with an extreme wave in the Agulhas current.

technique is frequently applied in wave tanks to produce large waves. Waves coming from different directions may also coincide and form large waves at certain locations.

These effects are results of linear superposition of wave components, and in the real random ocean, situations will occur where, by chance, the phase and directional configuration of the waves are such that large waves are formed. This effect is included in the linear statistical description (Gaussian sea surface) and is not expected to occur more often than predicted by linear random wave theory. Consequently, should rogue waves occur more often than predicted by linear (or second-order) theory, effects other than dispersive focusing are likely to be responsible.

### NONLINEAR FOCUSING

Nonlinear focusing is the mechanism that has received most attention in rogue wave research in recent years. As mentioned earlier, when going beyond second-order wave theory, the different wave components in the spectrum start to interact with each other. This facilitates energy transfer between different parts of the wave spectrum, and enables a wide range of possible effects that are not covered by linear and second-order descriptions.

The basic nonlinear effect that is believed to be responsible for the formation of rogue waves is the so-called modulational instability, also referred to as Benjamin–Feir instability after Benjamin and Feir (1967) who first described this effect for water waves. The essence of modulational instability is that small perturbations of a regular wave train can grow on behalf of the dominant wave and produce a short group of steep waves. Several exact wave solutions have been found that represent the effect of modulational instability. These solutions, for which energy concentrates locally are called breathers, are often viewed as basic examples of the rogue wave phenomenon. Such solutions have also been reproduced in wave tank experiments (Chabchoub et al., 2011). One of these breathers, the so-called Peregrine breather (Peregrine, 1983), is shown in Figure 12. Here, a weakly modulated regular wave (blue line) develops into a localized large wave (red line) due to modulational instability, before it evolves back into an almost regular wave train.

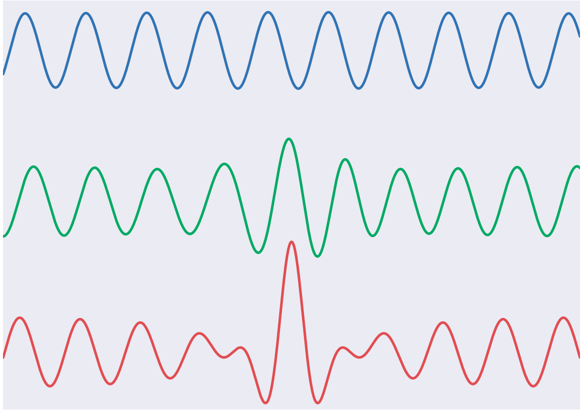

Figure 12: The Peregrine breather (Peregrine, 1983) at three different times during its evolution.

Although spontaneous generation of waves that are much higher than their surrounding neighbours can be modelled in terms of modulational instability, the conditions under which this effect occurs in realistic wind-generated wave fields in the ocean are not obvious. However, Alber (1978) and Crawford et al. (1980) showed that random waves can experience modulational instability provided that the ratio of wave steepness to relative bandwidth is sufficiently large. This latter inspired the definition of the so-called Benjamin–Feir index (BFI), defined as $BFI = \varepsilon/(\Delta\omega/\omega_p)$, where $\Delta\omega$ denotes the spectral bandwidth and $\omega_p$ is the peak frequency of the spectrum. It can also be shown that the strength of modulational instability depends on the directional spreading of the waves, in the sense that it is stronger for unidirectional waves than for short-crested waves.

Much of the research on rogue waves has concentrated on determining the conditions necessary for modulational instability effects to be active, both with respect to the shape of the wave spectrum (i.e., BFI and directional spreading), but also considering other environmental conditions such as crossing wave systems, current, variable seabed bathymetry, and special wind conditions. While the basic theory of modulational instability was developed in the 1960s and 70s, much of the work on this topic in recent years has been carried out using numerical simulations of three-dimensional wave models, as well as through experiments and field observations. Recent developments on these topics are discussed in the following sections.

# NUMERICAL AND THEORETICAL INVESTIGATION OF ROGUE WAVES

## SHAPE OF THE WAVE SPECTRUM AND OCCURRENCE OF ROGUE WAVES

One of the first works that addressed the effects of modulational instability on the occurrence of rogue waves in random sea states using numerical simulations was Onorato et al. (2001). They used the cubic NLS equation to simulate unidirectional random waves, and found that the probability of rogue waves depends on the ratio of wave steepness to spectral bandwidth, as suggested by the theoretical works of Alber (1978) and Crawford et al. (1980). This ratio was later named the Benjamin-Feir index (BFI) by Janssen (2003), who obtained similar results from numerical simulations using the more general Zakharov equation. Experiments with long-crested waves in a wave flume (Onorato et al., 2004) also confirmed the association between BFI and the probability of rogue waves for unidirectional waves.

Using NLS-type equations, Onorato et al. (2002) also performed simulations of directional wave fields, showing that the probability of occurrence of rogue waves depends not only on BFI, but also on the directional spreading of the waves. Using the Dysthe equation, Gramstad and Trulsen (2007) performed numerical simulations of a very large number of different wave conditions with different BFIs and directional spreading, showing that in order to obtain a notable deviation from second-order wave statistics, the wave field must have a quite narrow directional spreading. These works confirmed early experiments by Stansberg (1994), who noted that nonlinear modulation was weakened when the directional spreading of the waves increased. These results were later confirmed by large-scale experiments, some of which were a part of the EXTREME SEAS project, in wave basins at MARINTEK (Onorato et al., 2009a, Onorato et al., 2009b, Toffoli et al., 2010a) and University of Tokyo (Waseda et al., 2009). Based on these results, Waseda et al. (2009) and Mori et al. (2011) suggested generalized BFIs that also incorporate the effect of directionality, and more successfully parameterizes the observed occurrence of rogue waves. These relations have been used to suggest warning criteria for rogue waves, as discussed further in the section below on warning criteria.

Many of the first numerical investigations of rogue waves used NLS-type equations due to their low computational cost. In more recent years there has been a shift towards more advanced numerical models that do not suffer from the narrow-band assumptions of the NLS equation. One model that has been increasingly used for the investigation of rogue waves is the so-called Higher Order Spectral

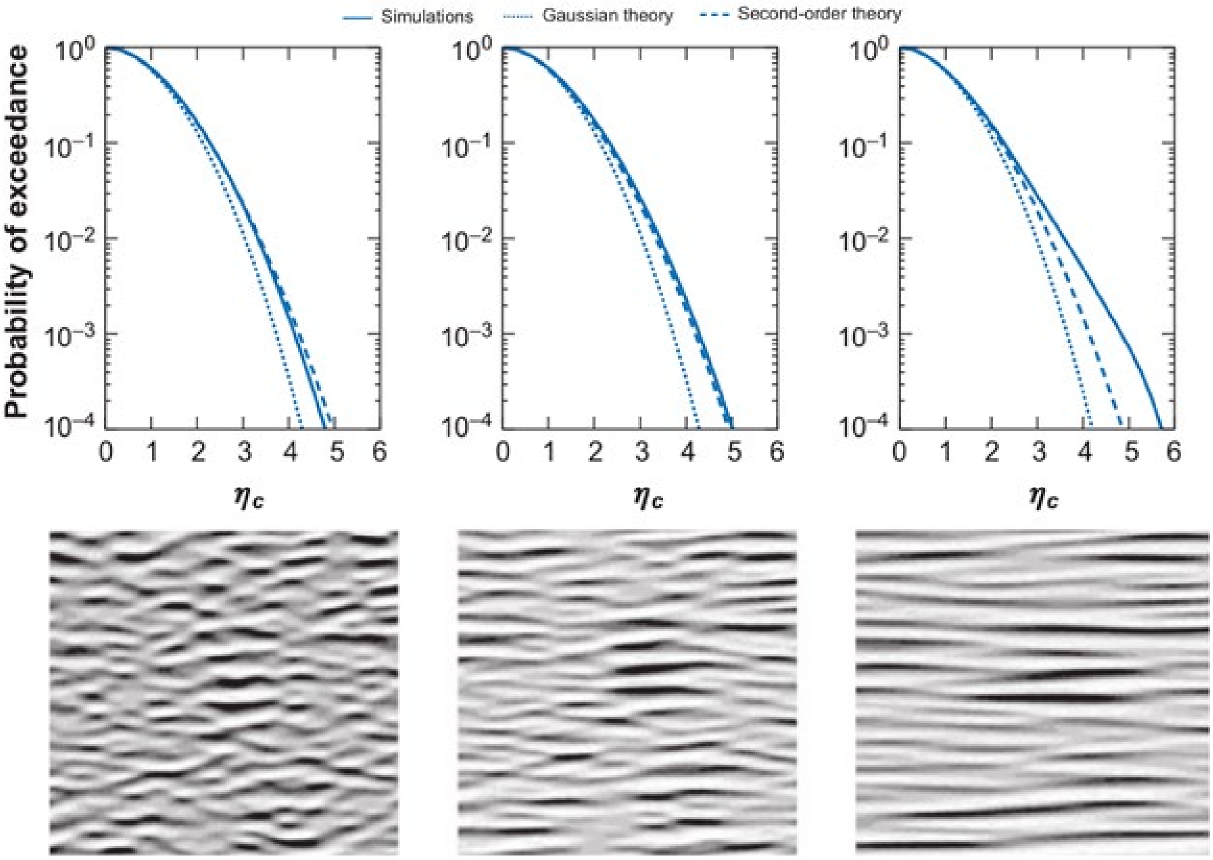

Figure 13: The dependence on wave directionality on crest statistics. Computer-simulated crest statistics and examples of sea surfaces for three different wave fields (from left to right: short-, medium-, and long-crested wave fields). Note the greater occurrence of high crests in the long-crested case. From Dysthe et al. (2008).

Model (HOSM). An early application of HOSM for the study of rogue waves was presented as a part of the SEAMOCS Network by (Toffoli et al., 2008b, Toffoli et al., 2008a) who obtained similar results as in the previous works that used NLS-type equations. A more recent extensive numerical study (Xiao et al., 2013) used HOSM to study how the occurrence of rogue waves depends on spectral parameters, also confirming the results of previous studies based on more simple NLS models.

The establishment of relationships between the shape of the wave spectrum, in terms of BFI and directional spreading, and the occurrence of rogue waves, has been an important milestone in understanding rogue waves. However, the types of spectra for which significant increases in rogue waves are expected to occur less frequently in realistic ocean conditions. Nevertheless, a recent analysis of wave data from the Kvitebjorn platform in the northern North Sea (Waseda et al., 2011) found evidence that occurrence of rogue waves was associated with sea states with directional spreading of less than about 30°. This suggests that sea states with increased occurrence of rogue waves occur in realistic ocean conditions.

## CROSSING SEA STATES

Crossing sea states have been another research focus on rogue waves. Such sea states are common situations in the ocean and occur when two wave systems exist simultaneously. This can occur when local, wind-generated waves coexist with a system of swell that has been generated elsewhere. The two systems may have different energies, frequencies, and directions. In situations where the wind turns rapidly, generating a new local wave system, the two systems typically have similar peak periods, and may be separated only by their direction of propagation.

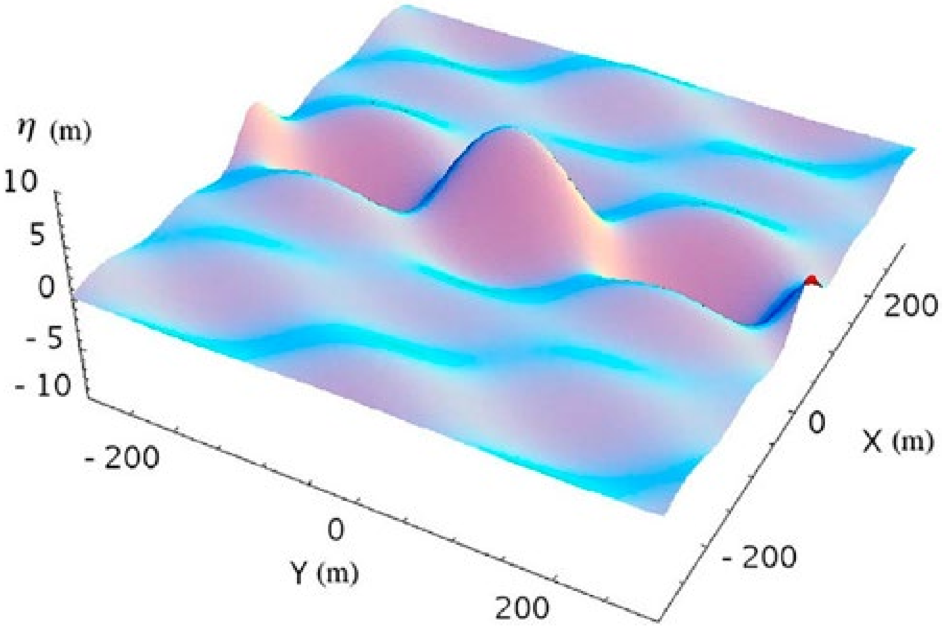

Figure 14: The surface elevation corresponding to a breather solution with the angle between the two wave systems equal to 50°; after Cavaleri et al. (2012).

Analysis of a database of ship accidents (Toffoli et al., 2005) found that many had occurred in crossing sea conditions. The sinking of the oil tanker Prestige in 2002, which has been suggested to be due to a rogue wave, happened in a crossing sea state (Trulsen et al., 2015). An accident that was analysed in the EXTREME SEAS project, in which the cruise ship Louis Majesty was hit by a giant wave, took place in a crossing sea (Cavaleri et al., 2012). It should be noted that a crossing sea could, in itself, create a difficult situation for manoeuvring a ship, as the captain must handle waves coming from different directions simultaneously.

From a theoretical viewpoint, crossing seas can be described by a set of coupled NLS (CNLS) equations, under the assumptions that the two systems are separated in direction or frequency, and that both systems are narrow banded and weakly nonlinear. Onorato et al. (2006) studied CNLS equations describing two wave systems with the same peak frequencies, but separated in direction. They found that the effect of modulational instability could be increased in crossing seas, but that this depends on the angle between the two wave systems. A more detailed analysis by Onorato et al. (2010) suggested that an increased probability of rogue waves was associated with angles between 40° and 60°. Cavaleri et al. (2012) discuss the crossing wave systems of the Louis Majesty accident in the framework of CNLS equations. Although the lack of measurements means it is impossible to establish the nature of the wave that caused the accident, a breather solution of the CNLS equation was suggested as a possible mechanism of occurrence of the rogue wave. In Figure 14 a breather solution corresponding to two wave systems crossing at 50° is shown.

The results on crossing wave systems have also been supported by laboratory experiments in the MARINTEK wave basin and by numerical simulations using HOSM (Toffoli et al., 2011a). However, the extent to which this result depends on spectral characteristics (e.g., wave steepness, bandwidth, directional spreading) of each of the wave systems is not totally clear. Nevertheless, recent numerical simulations by Bitner-Gregersen and Toffoli (2014) show that for systems separated by between about 40° and 60°, the increase in rogue wave occurrence persists, even when the individual wave systems are more broad-banded. In cases in which the two wave systems have different frequencies, these results may change. In fact, Gramstad and Trulsen (2010) investigated a case in which the two wave systems had very different frequencies, and did not find a clear change in rogue wave statistics. Cases where the two wave systems have only slightly different frequencies have been less studied, and further research is required to improve our understanding of the effects of crossing seas on rogue wave occurrence.

## SHALLOW WATER EFFECTS

When waves approach shallower water and the depth, $h$, becomes less than about half the wavelength, waves start to be influenced by the presence of the bottom, and their physical properties change quite substantially. Shallow-water waves are more asymmetrical, with higher crests and shallower troughs, than waves on deep water. In addition, waves on shallow water are only weakly dispersive, meaning that different wave components propagate at almost the same speed. The modulational instability, which is the main effect believed to be responsible for rogue waves in deep water, becomes weaker with decreasing depth. For unidirectional waves, modulational instability disappears when $kh = 2\pi h/\lambda < 1.363$. (Benney and Roskes, 1969). For waves in two horizontal dimensions, there may still be modulational instability for $kh < 1.363$. However, a wave packet can still grow due to modulational instability for $kh$ below this threshold, and this has been confirmed experimentally (Toffoli et al., 2013a), as well as in computer simulations (Fernandez et al., 2014). However, modulational instability is weaker than on deep water, and is therefore suspected to play a less important role in shallow water.

Nevertheless, rogue waves in waters of shallow depth have been observed and have been reported to be responsible for a number of accidents (Nikolkina and Didenkulova, 2011), and other effects could be important in shallow water. Variable bottom topography was discussed in the pervious section in the context of spatial focusing of wave energy. While this effect is linear and well understood, the combined effects of wave nonlinearity and variable bottom are more complicated. In some recent works, the statistical properties of random waves propagating over an underwater slope were considered, showing that the probability of rogue waves may increase on the shallow side of an underwater slope (Sergeeva et al., 2011, Trulsen et al., 2012, Gramstad et al., 2013). The case of more realistic directional waves still needs further investigation.

Figure 15: Extreme event produced in the Hannover wave tank.

Another important feature of shallow water waves is the existence of solitons. Solitons are isolated wave pulses that can propagate over long distances without changing their shape. Mathematically, such shallow-water solitons can be described by the Korteweg de Vries (KdV) equation that describes shallow-water wave dynamics. Interacting solitons have also been suggested as a possible mechanism for generation of rogue waves in shallow waters (Peterson et al., 2003).

## WAVE-CURRENT INTERACTIONS

Another situation that has been considered in the context of rogue waves, is the combined effect of wave nonlinearity and currents. As discussed in the previous section, waves propagating over a variable current may be amplified due to the effects of linear focusing. Moreover, waves propagating over an adverse current gradient, for example, an accelerating opposing current, will experience a growth in amplitude and a reduction in wavelength, leading to larger wave steepness. Hence, as a result of increased nonlinearity due to these linear mechanisms, nonlinear effects, such as modulational instability, may become more important. This effect has been suggested as a possible mechanism for generation of rogue waves in the presence of currents.

The case of random waves on variable current was studied numerically by Janssen and Herbers (2009), who considered weakly nonlinear waves propagating over a focusing current. They found that wave fields that were initially stable with respect to the modulational instability, could become unstable when the nonlinearity was increased due to the

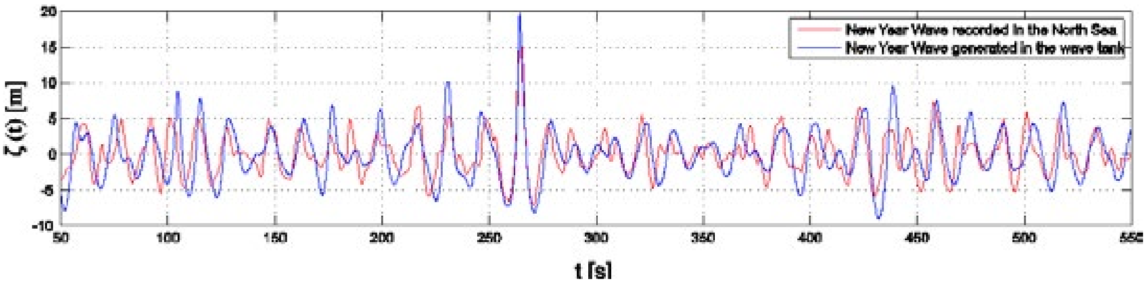

Figure 16: The New Year wave reproduced in the TUB tank. Comparison of the measured model wave train (scaled to full scale) at target position, and the recorded sequence at the Draupner platform.

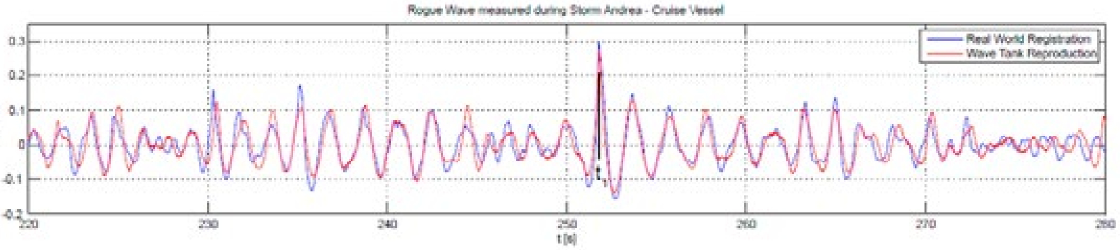

Figure 17: The Andrea wave reproduced in the CEHIPAR basin. Comparison of the measured model wave train at target position and the recorded sequence at the Ekofisk platform (scaled to model scale).

effect of linear focusing. This effect was, however, only observed for quite narrow band wave fields. Another study of nonlinear waves on currents was carried out by Hjelmervik and Trulsen (2009), who undertook numerical simulations using an NLS equation modified by the effects of current. They found that the probability of rogue waves could both rise and fall as an effect of the current, depending on the configuration of the waves and currents. The possible increase in rogue wave occurrence as a result of oblique and opposing currents was shown theoretically, experimentally, and numerically within the EXTREME SEAS project (Onorato et al., 2011, Toffoli et al., 2011b, Toffoli et al., 2013b).

The case of random waves facing an opposing current was recently studied experimentally by Toffoli et al. (2015). It was shown that more realistic random waves propagating in opposing currents could also destabilize, with a resulting increase in the occurrence of rogue waves. Interestingly, the increase in rogue waves was also observed for waves with more directional spread that normally obey near-Gaussian properties.

Generally, some evidence seems to support that in some situations the combined effect of wave nonlinearity and currents can lead to an increase in rogue wave occurrence. However, for a more complete understanding of the various mechanisms that are involved, including for which kinds of wave/current configurations such deviations should be expected in realistic ocean conditions, more research is necessary.

## EXPERIMENTAL INVESTIGATIONS OF ROGUE WAVES

Laboratory experiments have played an important role in research on rogue waves, and extensive laboratory tests of extreme and rogue waves have been carried out worldwide, both by academia and the marine industry, in order to improve our understanding of rogue waves, as well as to validate the theoretical and numerical nonlinear wave models used to describe them. Some of these experimental works have already been discussed. Here we focus primarily on experiments carried out within the projects in which DNV GL has been involved. The EC research projects, MaxWave and EXTREME SEAS, as well as the JIP projects, CresT and ShortCresT, included laboratory experiments. The EC SEAMOCS Network and EXTREME SEAS project also included experiments carried out within the EC-Hydralab III programme.

As a part of the MaxWave project, a method for generating extreme wave events in a wave tank was developed (Clauss et al., 2004). Historic wave records, including extreme wave events such as the Draupner wave, were reproduced in the wave tank. Figure 15 shows an extreme wave created in the Hannover tank by this method. This one was so high that it hit the laboratory ceiling.

In EXTREME SEAS, the laboratory experiments were carried out in tanks at Technische Universität Berlin (TUB) and at Spanish basin Canal de Experiencias Hidrodinamicas de El Pardo (CEHIPAR). The project also utilized model tests from others experiments in which the project partners were involved (the MARINTEK basin, the Danish Hydraulic Institute basin, the Australian Maritime College, and the Hannover wave tank). Experiments with both directional and unidirectional waves were carried out, and, in addition to water surface measurements, some experiments also included measurements of water particle velocities. Both the Draupner wave and the Andrea wave were reproduced in the model tanks; the Draupner wave in the TUB tank and the Andrea wave in the CEHIPAR basin (see Figures 16 and 17). The laboratory experiments in EXTREME SEAS were also used to validate numerical models such as the NLS equation, Dysthe model, and HOSM. Generally, it was found that the numerical nonlinear wave codes matched well with the experimental data, although they do not include forcing terms such as wind and wave breaking.

Model tests in the CresT and ShortCresT JIP projects were carried out in the MARIN and Imperial College basins. They included long-crested and short-crested waves, and were compared with field data. In ShortCresT, Buchner and Forristal (2012) demonstrated that short-crested basin waves and field waves show very similar behaviour. ShortCresT investigations of nonlinear waves generally confirmed findings from EXTREME SEAS. The final results of the ShortCresT project are summarized in Hennig et al. (2015).

It is interesting to note that the size of a wave basin does not have a significant effect on generated rogue waves and their statistics, as documented by Toffoli et al. (2011c) who compared wave experiments conducted independently in two different facilities, the MARINTEK ocean basin (Norway) and the directional wave basin at the Australian Maritime College (AMC). Although the basins are of different sizes and are equipped with different wave makers, the results obtained were very similar. The ShortCresT project also confirmed later that the size of the basin does not have an effect on generated rogue waves.

# STATISTICAL AND SPECTRAL DESCRIPTION OF WAVES

Statistical descriptions of extreme waves represent important input to design and operations of ships and offshore structures. In design, the linear or second-order statistical distributions discussed earlier are currently applied. However, analyses of numerical and field data have shown that the statistical properties of waves may deviate significantly from the linear or second-order statistics. The presence of a rogue wave in a time series changes the empirical distributions so that they significantly deviate from linear and second-order distributions. However, when only a 20-minute field time series is considered, it may be difficult to conclude whether or not the underlying distribution is different from linear or second order, due to sampling variability (the uncertainty associated with a limited amount of data) (Bitner-Gregersen and Hagen, 1990, Bitner-Gregersen and Magnusson, 2014). Therefore, numerical wave models that can generate very long time series are important tools for establishing the statistical properties of nonlinear waves.

As discussed in the previous section, modulational instability may increase the occurrence of rogue waves, if the waves are close to unidirectional. This will affect the statistics so that second-order models underestimate the probability of large waves (Toffoli et al., 2008b, Toffoli et al., 2008a). However, since modulational instability is suppressed when directional spreading is increased, the second-order wave model becomes more valid and the second-order, theory–based distributions (Tayfun, 1980, Forristall, 2000) are good approximations of the crest distribution (Socquet-Juglard et al., 2005, Toffoli et al., 2008b). This is demonstrated in Figure 18, which shows the crest statistics for different degrees of directional spreading compared with theoretical second-order distributions.

More systematic studies of statistical properties of nonlinear waves carried out in EXTREME SEAS (Toffoli and Bitner-Gregersen, 2011) have shown that effects of modulational instability can enhance the crest height for long-crested waves by up to 20 %, at lower probability levels, while the troughs become about 20 % deeper than second-order troughs. Numerically generated data have also allowed the study of short-term wave surface characteristics, like wave height, wave steepness, skewness, and kurtosis,

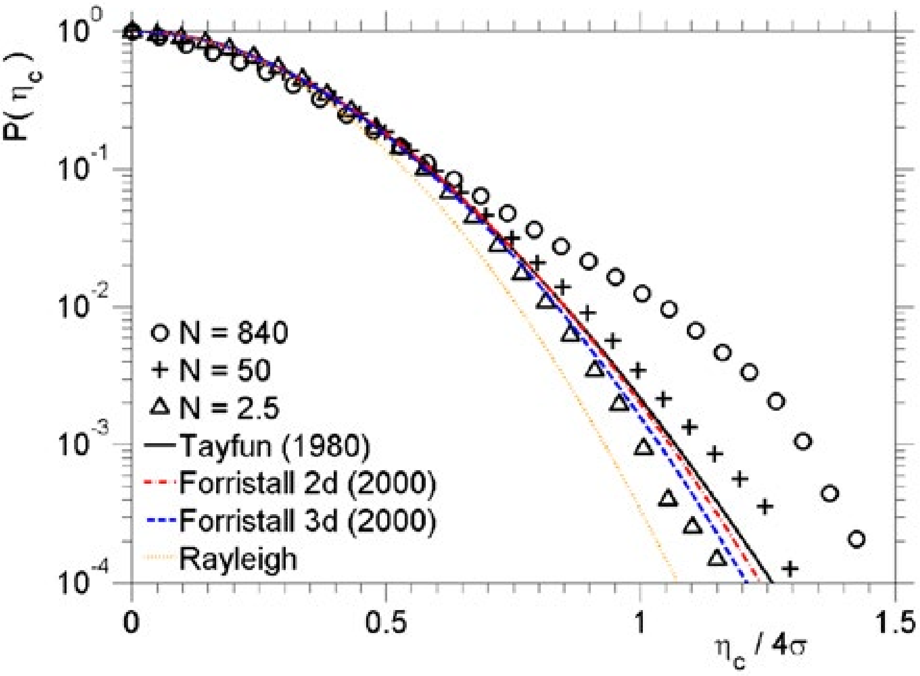

Figure 18: Distribution of wave crests derived from nonlinear numerical simulations of sea states with the directional spreading function $\cos^N(\theta)$ (where $\theta$ denotes wave direction, larger N means narrower directional spreading) and from commonly used distributions. After Bitner-Gregersen et al. (2008).

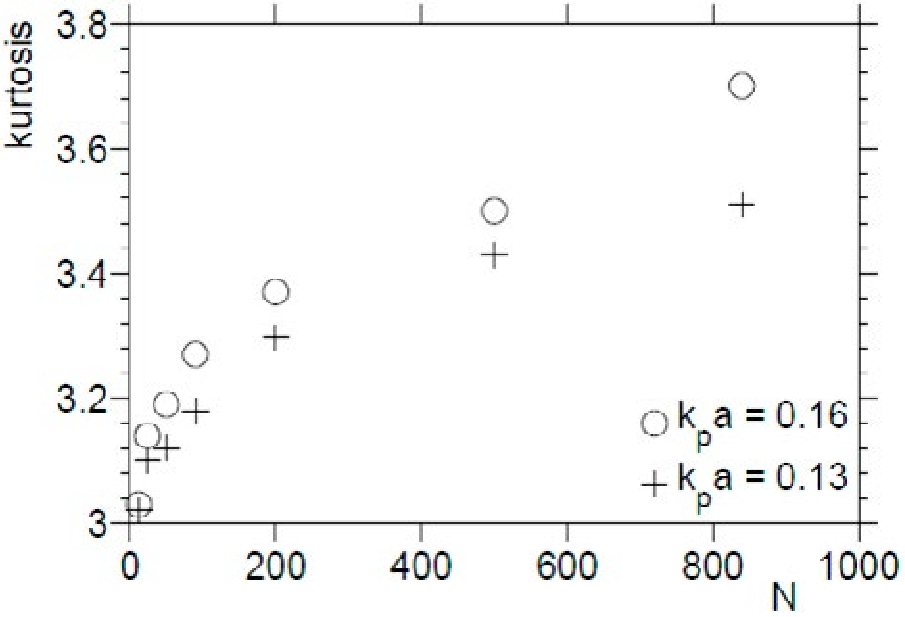

Figure 19: Kurtosis as a function of directional spreading coefficient, N, estimated from numerical simulations using HOSM. Kurtosis equal to 3 corresponds to the Normal distribution (linear wave model). From Toffoli and Bitner-Gregersen (2011).

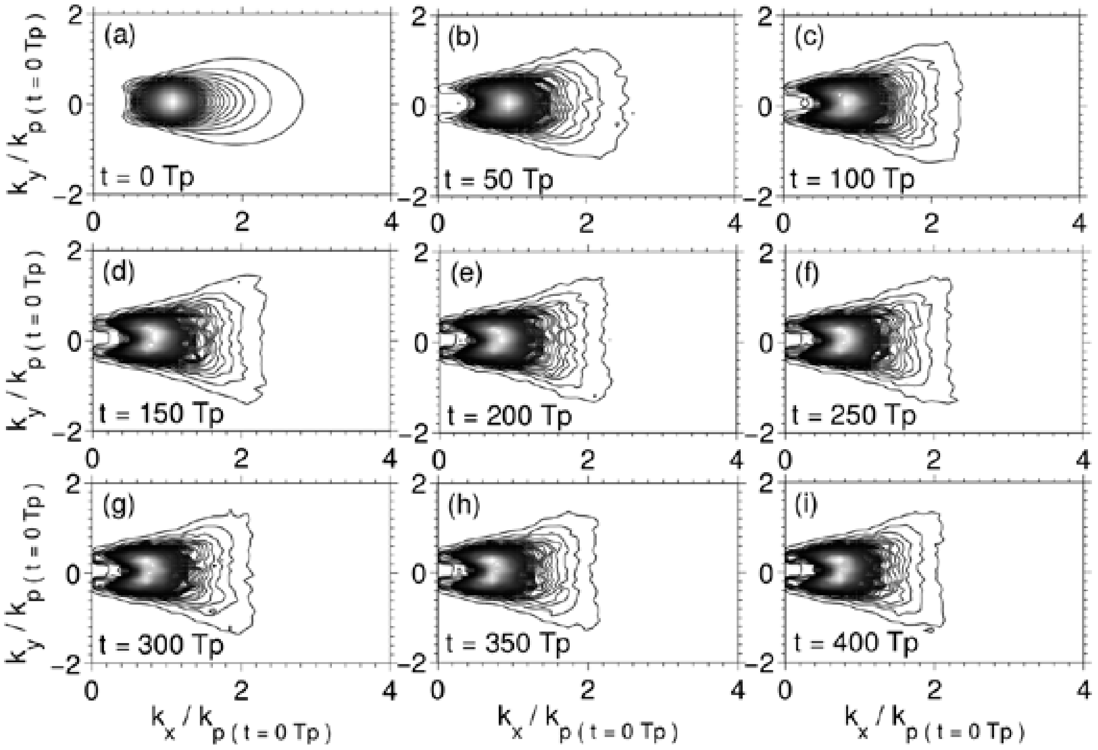

Figure 20: Temporal evolution of a directional spectrum (Toffoli et al., 2010b).

demonstrating again that directional spreading has a significant effect on wave statistics; see Figure 19. Skewness and kurtosis are third and fourth order moments of sea surface elevation, respectively. Both are commonly used as indicators of deviation from Gaussian statistics. Non-zero skewness indicates vertical asymmetry of the waves, which is primarily a second-order effect. Kurtosis may be used as an indicator of occurrence of rogue waves, and its value increases significantly when a rogue wave is present in a wave record.

In an attempt to include higher order effects in the statistical description of waves, Bitner-Gregersen and Toffoli (2012b) suggested a crest distribution based on empirical data and numerical simulations using HOSM. Similar to the Forristall (2000) distribution, it is based on a two-parameter Weibull distribution, where the Weibull parameters are modelled as functions of a generalized version of the BFI for directional sea states (Mori et al., 2011). The proposed distribution captures the tail of the crest distribution generally better than the Forristall (2000) distribution.

In current design practice, the wave spectrum is traditionally assumed to be constant and is usually modelled in terms of frequency spectra such as Pierson-Moskowitz, JONSWAP, Torsethaugen, or Ochi, with a unimodal directional energy spreading function, such as cosN(θ) (see e.g. DNV RP C-205). However, numerical experiments and field measurements have demonstrated that the wave spectrum evolves as a result of nonlinear effects. For example, a frequency spectrum may experience a broadening, as well as a downshift, of the spectral peak as a result of modulational instability. In the directional space, it has been shown that that nonlinear interactions spread energy outwards from the spectral peak along two characteristic directions, in qualitative agreement with a theoretical model proposed by Longuet-Higgins (1976). As a result, the directional distribution develops a bimodal form as the wave field evolves. These effects have also been shown in numerical simulations of NLS equations (Dysthe et al., 2003) and by HOSM simulations within SEAMOCS (Toffoli et al., 2010b). Examples of spectral evolution in HOSM simulations are shown in Figure 20. The bimodal shape of the directional distribution was also shown in field data by Ewans (1998), and resulted in a bimodal distribution being proposed that is currently used in the design of offshore structures.

# PROBABILITY OF OCCURRENCE OF ROGUE WAVES

Owing to recent research efforts, the occurrence of rogue waves, their mechanisms, and their detailed dynamic properties are now better understood. Despite these achievements, full consensus on the probability of occurrence of rogue waves has yet to be achieved. However, such consensus is essential to enable a systematic revision of offshore standards and classification societies' rules, which currently do not explicitly include rogue waves (Bitner-Gregersen et al., 2003).

Rogue waves that exceed the simplified wave height and crest criteria presented earlier are, even within the standard linear and second-order description of random waves, expected to occur from time to time due to the randomness of sea surfaces. Taking into to account the probability of occurrence of sea states in the North Sea scatter diagram and the second-order distribution of Forristall (2000), it has been shown by Bitner-Gregersen and Hagen (2004) that in a random 20-minute sea state, a wave satisfying $C_{max}/H_s$ >1.3 occurs with a probability of about $1.44 \cdot 10^{-3}$, corresponding to a return period of about 8 days. However, such a wave is not necessarily dangerous. Whether or not a wave is dangerous is case-dependent, and is different, for example, for design of offshore platforms than for operation of small fishing vessels. Simultaneous high and steep waves typically give high loads on marine constructions. According to the second-order model, the probability of occurrence of a wave with $C_{max}$ > 4.5 m and $C_{max}/H_s$ >1.3 is about $10^{-3}$, whereas the probability of occurrence of a wave with $C_{max}$ >8.5 m and $C_{max}/H_s$ >1.3 is about $10^{-4}$. In design, it is common to use the most probable extreme wave in a wave record of a given duration. The expected extreme depends on the duration of the wave record and a longer time series allows the capture of more extreme waves (Bitner-Gregersen, 2003, Bitner-Gregersen and Toffoli, 2012a). For example, the six-hour sea state duration that is commonly used in design today is insufficient to capture the Draupner wave when the second-order wave model is applied.

The second-order based probabilities of occurrence of rogue waves are already accounted for in current design practice, if a second-order model is applied. However, one important question that remains is how much these probabilities increase if higher order effects are taken into account.

As already mentioned, situations occur where significant deviations from second-order statistics have been observed, such as the case of narrow directional wave spreading, crossing seas, and other effects as discussed in previous sections, and the occurrence of rogue waves is closely related to the mechanisms generating them. Exactly how frequently such situations occur in the ocean is still a topic of investigation. In EXTREME SEAS, Bitner-Gregersen and Toffoli (2012a) analysed hindcast data from the North Atlantic and showed that sea states for which modulational instability may be active occur several times during the 20/25-year period used as return period for ship design. The highest sea state within the 10-year time period analysed by Bitner-Gregersen and Toffoli (2012a) ($H_s$ > 15m) was characterized by large wave steepness ($k_pH_s/2$ = 0.13) and narrow directional spreading, a condition that may trigger modulational instability. It is interesting to note that directionally spread seas may also include local long-crested waves and be characterized by conditions that lead to generation of rogue waves.

In another study, Bitner-Gregersen and Toffoli (2014) showed that crossing wave systems associated with increased occurrence of rogue waves also occur more often than once during the 20/25-year period in the North Atlantic and in the North and Norwegian Seas. These crossing sea states, which are characterized by two wave systems with approximately the same energies and peak frequencies, and a crossing angle of about 40°, were mainly observed in low and intermediate sea states. Increased rogue wave occurrence was observed not only when the two wave systems had very narrow directional distributions, but also for broader spectra. The occurrence of such sea states was shown to be location-specific, depending strongly on local features of wave climate.

In the MaxWave project several extreme waves exceeding the wave height criterion $H_{max}/H_s$ > 2.5 were detected in a global SAR data set acquired during the course of only three weeks (see Figure 7). More extreme waves ($H_{max}/H_s$ > 2) than expected from the standard Rayleigh theory were also found; these waves were especially detected in high sea states in the South Atlantic during southern winter.

# WARNING CRITERIA FOR EXTREME AND ROGUE WAVES

Forecasting extreme weather events as a part of the weather services provided by meteorological offices has always been welcome by the offshore and shipping industry, as safety at sea is improved. For the same reasons, the development of warning criteria for rogue waves has also been encouraged. Such criteria would have the potential to impact the planning and execution of marine operations, such that dangerous situations, where rogue waves occur, can be avoided.

Warning criteria for rogue waves need to reflect the mechanisms generating these waves. However, although such mechanisms have been identified, the development of warning criteria for rogue waves is more challenging. For some time ships have been warned against sailing in the Agulhas current off the southeast coast of South Africa when waves are travelling against the current, but introduction of other generation mechanisms of rogue waves into the warning criteria has been less successful. A first important step towards this was made in the MaxWave project.

In the MaxWave project, Savina et al. (2003), in cooperation with the Joint Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Maritime Safety Services, suggested the inclusion of significant wave height, as well as a warning for dangerous sea state/rogue waves, in the weather forecasting systems. Meteo France implemented a warning system for rogue waves on a pre-operational basis that included two parameters: one index combining directional spreading and significant wave height, and a second index being a product of the average wave steepness and the significant wave height (Savina et al., 2003). The system was intended to optimize routing of fast ferries in the Mediterranean and was planned for evaluation by end-users. However, it was found that the criteria did not fully reflect the occurrence of rogue waves, and did not cover all aspects of their occurrence.

Later, several authors have studied the associations between spectral wave parameters and the occurrence of rogue waves, and the BFI was proposed as a good indicator of the occurrence of rogue waves (see Onorato et al. (2001), Janssen (2003), Mori and Janssen (2006), Mori et al. (2011)).

In EXTREME SEAS, the University of Turin, the Norwegian Meteorological Institute, the Institute of Applied Physics at RAS, and DNV worked on the development of warning criteria for rogue waves. These warning criteria included several of the known mechanisms generating rogue waves that are described earlier. It was agreed that BFI was one indicator of rogue waves. Two wave systems crossing at a 40-60° angle and with similar frequencies and energies, were also proposed as a part of the warning criteria (Toffoli et al., 2011a, Bitner-Gregersen and Toffoli, 2014), as well as information about current (Onorato et al., 2011).

The warning criteria based on BFI were implemented at the European level by the European Centre for Medium-Range Weather Forecasts (ECMWF), in collaboration with the University of Turin. These warning criteria have also been under validation in the Norwegian Meteorological Institute. This has shown that some improvements are still necessary for the warning criteria to be fully satisfactory.

The criteria for crossing wave systems proposed in EXTREME SEAS were used to provide a possible explanation of the Louis Majesty ship accident that occurred in the Mediterranean on 3rd March 2010 (Cavaleri et al., 2012). The ship was hit by a large wave that destroyed some windows at deck number five and caused two fatalities. Using the WAM wave model, a detailed hindcast of the local wave conditions was performed. This revealed the presence of two comparable wave systems, with almost the same frequency, arriving from the southeast and the northeast. The wave conditions at the time of the accident are shown in Figure 21. The size of the possible rogue wave was estimated using the breather solution of the coupled NLS equations as a prototype of the rogue wave generation, see the section on crossing seas.

Coupling of spectral wave models with numerical phase-resolving models, such as NLS or HOSM, could be utilized in the future to provide warning criteria for rogue waves, as demonstrated by, for example, Bitner-Gregersen et al. (2014b).

The development of a satisfactory warning system for rogue waves and its implementation in the design and operational procedures of ships and offshore structures still remains a high priority topic within the scientific community and the marine industry.

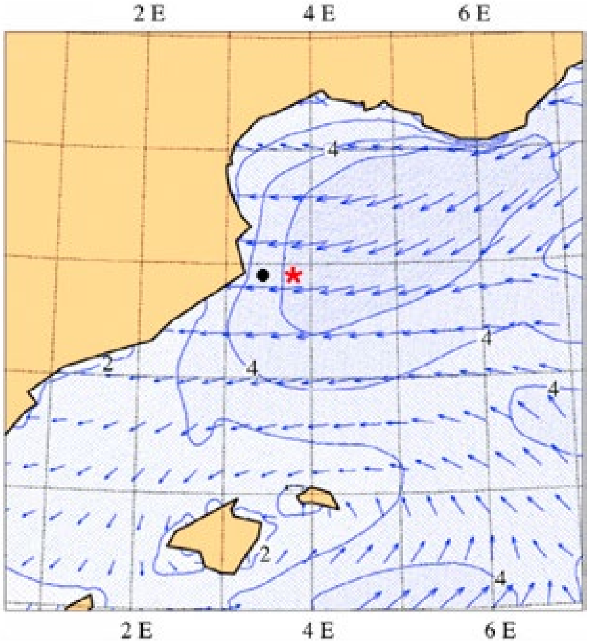

Figure 21: Significant wave height and wave direction at 14 UTC 3rd March 2010. Isolines at 1 m intervals. The star indicates the ship location at the time of the accident and the dot indicates a nearby wave buoy. After Cavaleri et al. (2012).

# IMPACT OF ROGUE WAVES ON LOADS AND RESPONSES

The recognition of the existence of rogue waves has caused concern regarding the impact that these waves may have on ships and offshore structures. Preliminary investigations have shown that forces caused by rogue waves could be significant, encouraging further investigation of the topic.

The MaxWave project conducted studies addressing the effect of rogue waves on wave loads and responses, and discussed their consequences on the design of marine structures. Instituto Superior Técnico in Portugal (Fonseca et al., 2001) proposed a simplified method using measured sea surface elevations containing abnormal wave events as input to their Strip Theory Code, and DNV in Norway (Pastoor et al., 2003) demonstrated how such measured wave records can be used as input to the DNV 3D Panel code.

The DNV approach was applied to the Draupner wave record as a case study. The wave record was approximated as a linear irregular sea surface, and used as input to the 3D Panel code. This method is able to reproduce the surface elevation exactly, but fails to give the correct fluid velocities and pressures. Although the approach was based on simplified assumptions, it enabled the study of different phases of a cruise ship encountering the Draupner wave. Five different phases of the cruise ship meeting the Draupner wave are shown in Figure 22. The orientation and speed of the ship in the first phase, prior to encountering the rogue wave, are very important and determine how the ship will be affected by the wave crest in the next phase. In Phase 2, the ship encounters a 'wall' of water, leading to a severe impact loading on the superstructure and slamming on the flared bow section. In Phase 3, the ship is expected to be set back due to a large impact loading on the superstructure; this means that the ship passes through the wave more slowly than its initial forward speed. In Phase 4, the foreship climbs out of the wave. At this stage, the initial speed and the subsequent speed reduction in the previous phases are important as they determine the extent to which the ship is able to climb out of the wave. The wave steepness is also of significance in this phase, because a steep slope will result in considerable immersion of the foreship, depending, of course, on the size of the following wave trough. In the last phase, Phase 5, the bow impact loading when the ship re-enters the water is important. Large flare in the foreship will result in greater slamming loads. A second aspect of interest in this phase is the immersion. Slender bow sections would be expected to immerse deep into the water, whereas a large flared ship will be significantly decelerated, thereby limiting the submergence. Large flare will prevent large immersions and hence prevent green water events, but at the cost of high wave loading on the bow, in combination with large vertical accelerations.

In the MaxWave project, a method based on measured sea surface elevations containing abnormal wave events as input data to a wave-structure interaction code was compared with model test data, and showed good agreement when applied to predicting the bending moment of a Floating Production Storage and Offloading (FPSO) platform (Clauss et al., 2004).

EXTREME SEAS was the first project to investigate the impact of rogue waves on ship structures more systematically, by using both model tests and numerical simulations. The case studies addressed by EXTREME SEAS included a container vessel, a passenger ship, an LNG carrier, and a product and chemical tanker. Ship behaviour in extreme and rogue waves was investigated by the numerical sea-keeping codes enhanced/developed within the project: Strip Theory code, 3D Panel code, and computational fluid dynamics (CFD); see Figure 23. The numerical results were validated by model tests carried out in TUB and CEHIPAR. Figure 24 shows a comparison of a model test and numerical modelling using DNV's 3D Panel code, WASIM. Some impressions from the model tests are shown in Figure 25 and Figure 26. The ships were instrumented to measure motions and wave-induced loads. At the TUB, breather solutions of the NLS equation were successfully reproduced in a wave tank with the help of the University of Turin and, for the first time, used in sea-keeping tests (Clauss et al., 2012). This provides new perspectives on the methodology of examining ships and offshore structures in rogue waves.

One of the main issues when performing these experiments is reducing sampling variability, that is, the uncertainty due to the limited data. Therefore, model tests must be repeated a sufficient number of times. Furthermore, in a sea state characterized by a high BFI, modulational instability occurs typically after between 10 and 30 wave lengths from a wavemaker. Thus, a scale of model tests should be considered carefully in order to be able to generate rogue waves.

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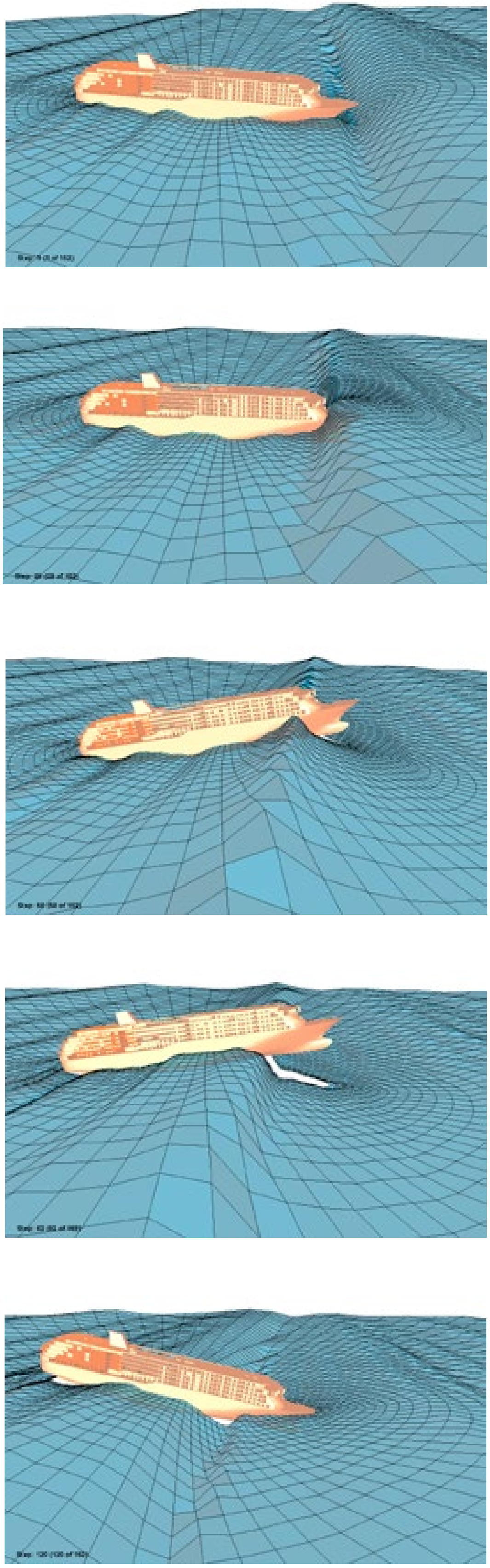


Figure 22: Five phases of a cruise ship encountering the Draupner wave (Pastoor et al., 2003).

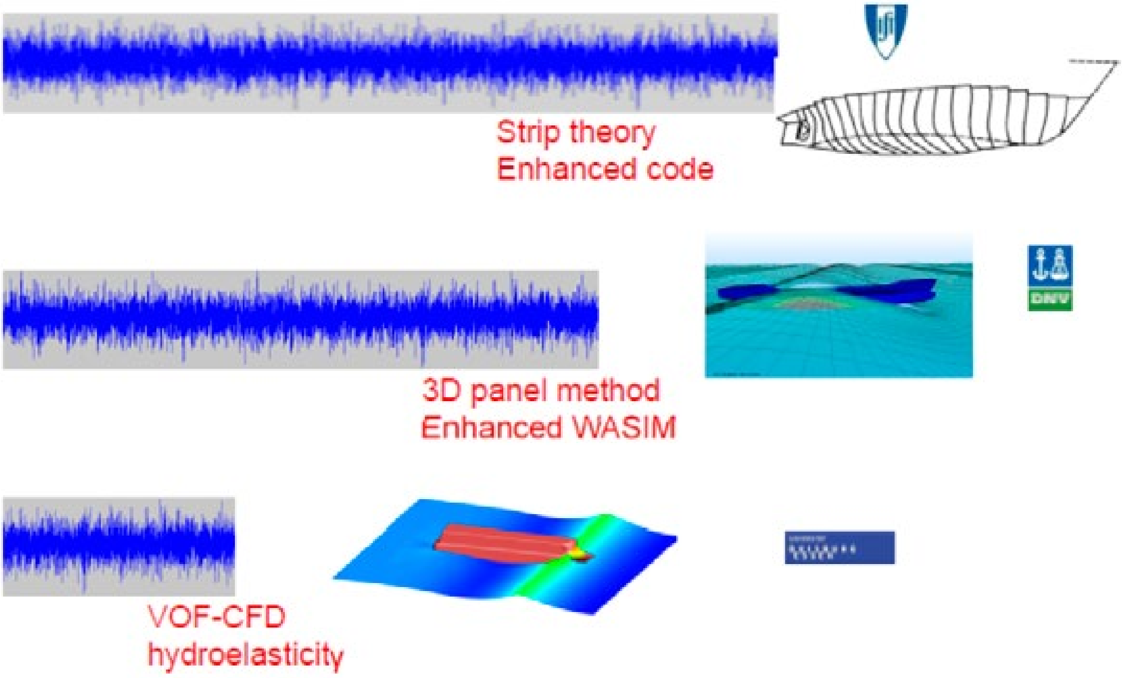


Figure 23: The numerical codes considered in the EXTREME SEAS project.

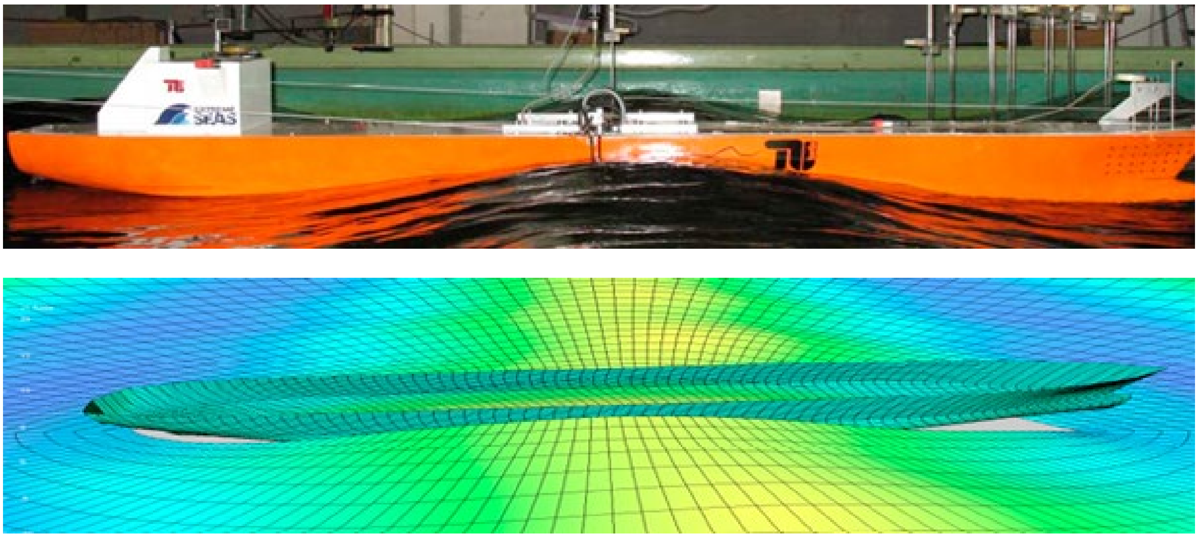


Figure 24: Comparison of model test of a tanker carried out in TUB, and WASIM simulations performed by DNV.

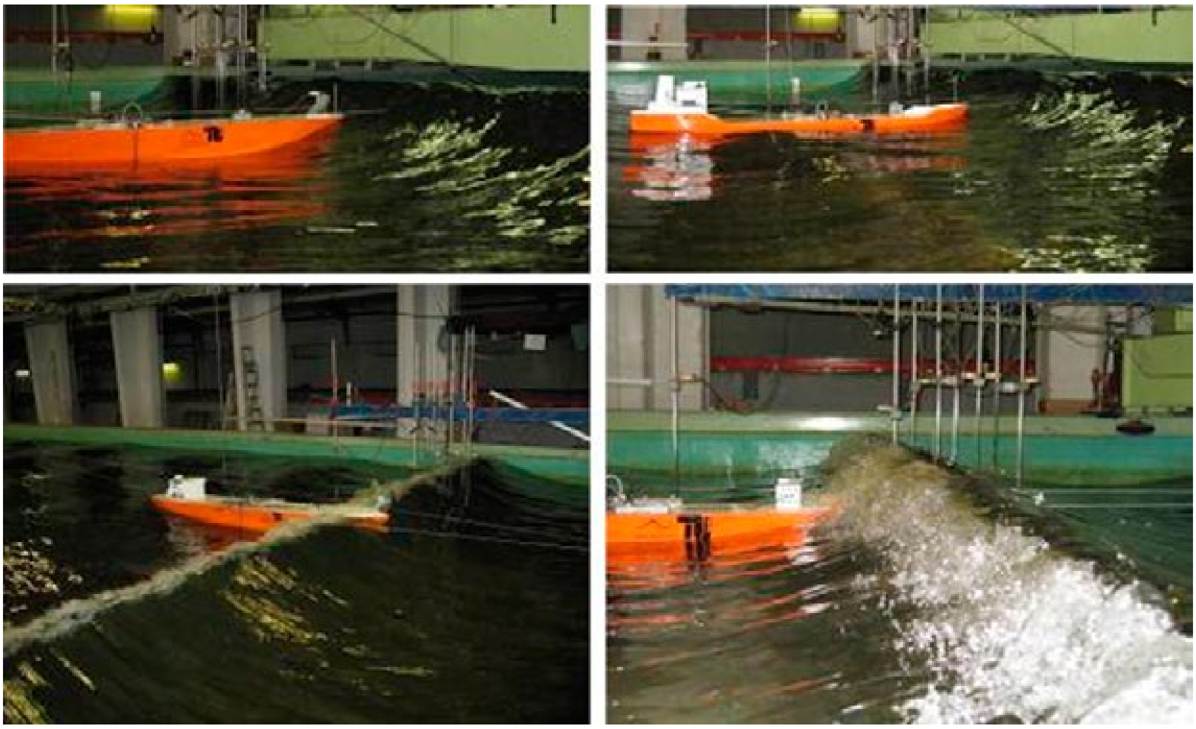


Figure 25: Impressions of the model tests carried out in TUB; LNG carrier (left column), chemical tanker (right column).

Figure 26: Impressions of the model tests carried out in CEHIPAR; cruise ship.

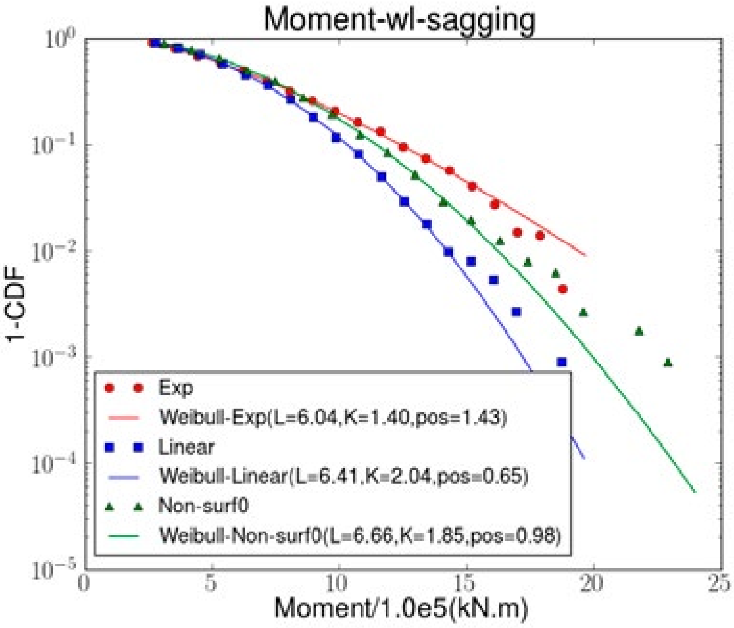


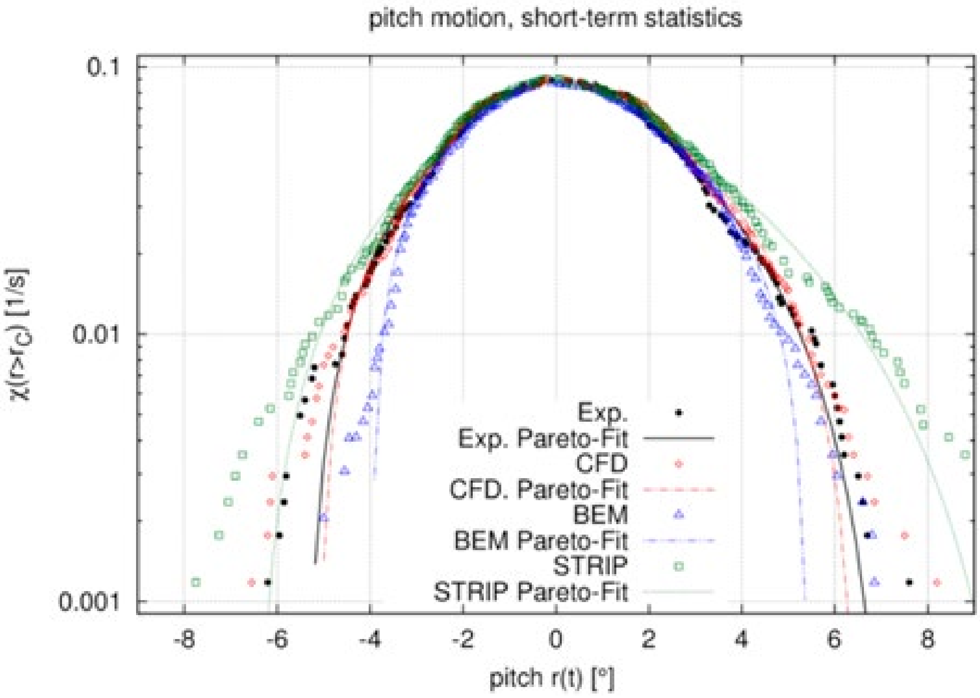
Figure 27: Wave-bending moment in rogue waves for the LNG carrier; experimental data and numerical simulations carried out by linear 3D Panel code with linear wave input, but some nonlinear response corrections. After Guo et al. (2013).

It was demonstrated that rogue waves have a significant impact on wave-induced bending moment (sagging and hogging), slamming, and ship motions such as heave, pitch, and surge. The Strip Theory and 3D Panel codes were not able to capture the effects of rogue waves impact satisfactorily, as there were significant deviations from the model tests, as shown in Figure 27 and Figure 28. While the CFD-based approach gave better predictions than the two other methods, it was still not completely satisfactory. These investigations represent a significant step forward in investigations of the impacts of rogue wave on ship structures, and also identified future research needs.

In EXTREME SEAS, the German ship yard Meyer Werft (MW), in collaboration with legacy GL Hamburg and the University of Duisburg-Essen, investigated the impact of rogue waves on a cruise ship built by MW, with particular focus on the ship's superstructure. The analyses showed significant impact loads from rogue waves on the superstructure (see Figure 29). Redesign of the superstructure was proposed in EXTREME SEAS, and it was documented that should such a redesign be implemented then the total price for a cruise liner would increase slightly, but operational costs would remain unchanged. The proposed redesign of the superstructure is now under implementation in the DNV GL rules for passenger ships.

The methodology and tools developed in EXTREME SEAS, although applied only to four ship types, are also applicable to other ship types. The investigations demonstrated that further research is still needed to provide wave-structure interaction tools that can satisfactory predict the impacts of rogue waves.

It is crucial that the design of offshore structures ensures that, for example, platform decks are safe from green water events, and that extreme wave induced loads do not endanger structural integrity. In the CresT and ShorTCresT projects, particular focus was on an extreme sea state that the platform Marco Polo in the Gulf of Mexico experienced during Hurricane Rita. This sea state was applied in an analysis of the behaviour of a generic tension-leg platform (TLP) system defined by the project. It was shown that loads and motions of the TLP, as well as the air-gap, were significantly affected by very steep waves such as rogue waves (Hennig et al., 2015).



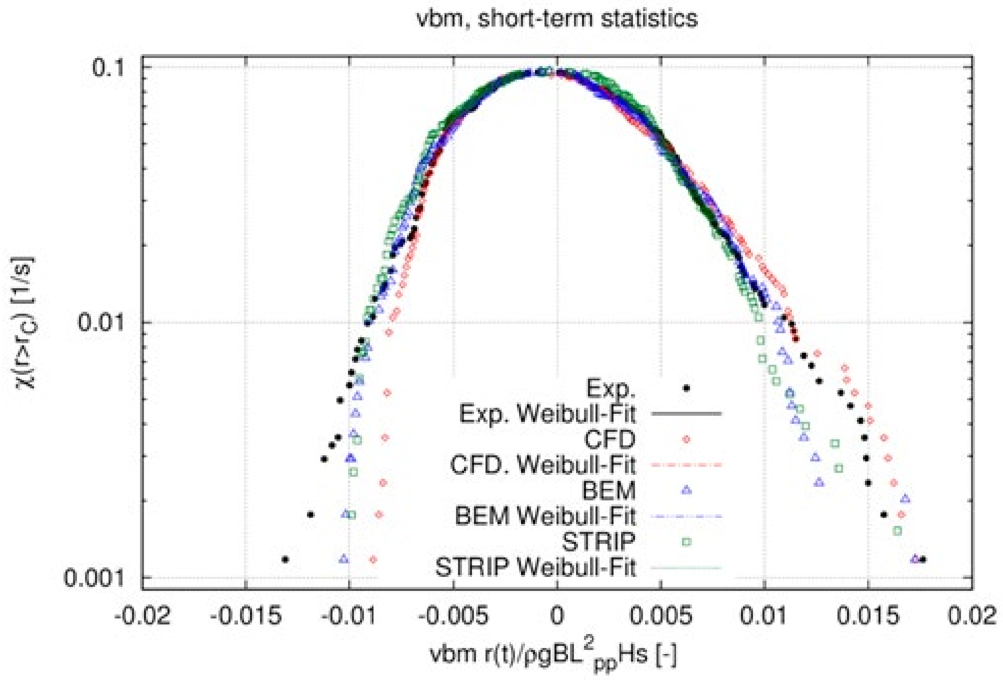


Figure 28: Outcrossing rates for pitch and vertical bending moment of the cruise ship obtained by three different numerical methods; irregular sea state with $H_s$=12.5 m, $T_p$=12.22 s, and wave steepness ε=0.089 (Ley, 2013).

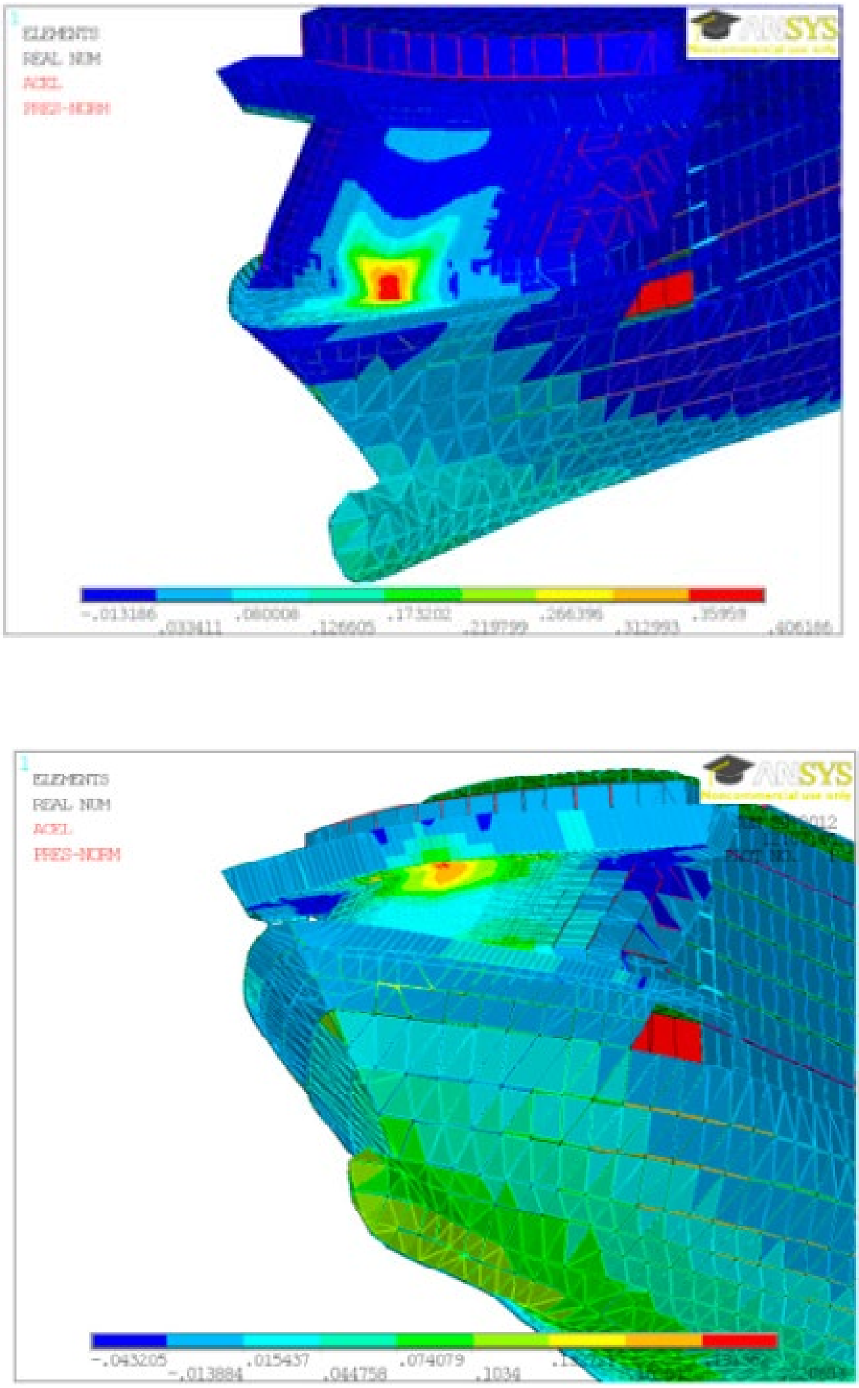


Figure 29: The cruise ship analysed in EXTREME SEAS by MW.

# CURRENT DESIGN PRACTICE AND MARINE OPERATIONS

The majority of ocean-going ships are currently designed to the North Atlantic wave environment, which is regarded as the most severe. Visual observations of waves collected from ships in normal service and summarized in the British Maritime Technology Global Wave Statistics (GWS) atlas (BMT, 1986) are used for ship design and operations. The average wave climate of four ocean areas in the North Atlantic, with some correction introduced due to inaccuracy of the zero-crossing wave period (Bitner-Gregersen et al., 1995), is recommended by the International Association of Classification Societies (IACS, 2000) for ship design.

The traditional format of classification society rules is mainly prescriptive, without any transparent link to an overall safety objective. In 1997 and 2001, IMO developed Guidelines for application of the Formal Safety Assessment (FSA) methodology in rule development, which allows provision of risk-based goal–oriented regulations (IMO, 1997, 2001). Structure Reliability Analysis (SRA) can be utilized in this process. Although wave data and wave models are not explicitly used by classification society rules for general ship design, they are needed in rule calibration when FSA methodology is applied. For some less-typical designs, classification society rules require or recommend some type of dynamic load analysis that makes use of wave data and wave models. Classification rules permit the design of ships for restricted service in terms of geographical zones and the maximum distance that the ship can operate from a safe anchorage; in which case, reduced design loads apply. Many aspects of the design, approval, and operation for a restricted service require detailed knowledge of local weather conditions. Although open to all ship types, in principle, the use of such restricted service is, in practice, mainly confined to high-speed vessels.

In the design process, international standards are followed to calculate ship structural strength and ship stability during extreme events, with a return period of 20 or 25 years; the Ultimate Limit State (ULS) check corresponding to the maximum load carrying resistance. Checks in the Accidental Limit State (ALS), which correspond with the ability of the structure to resist accidental loads and to maintain integrity and performance due to local damage or flooding, cover grounding, collision, fire, and explosion. An extreme weather event check is not included in ALS for ships.

Unlike ship structures, offshore structures normally operate at fixed locations and often represent a unique design. As a result, platform design and

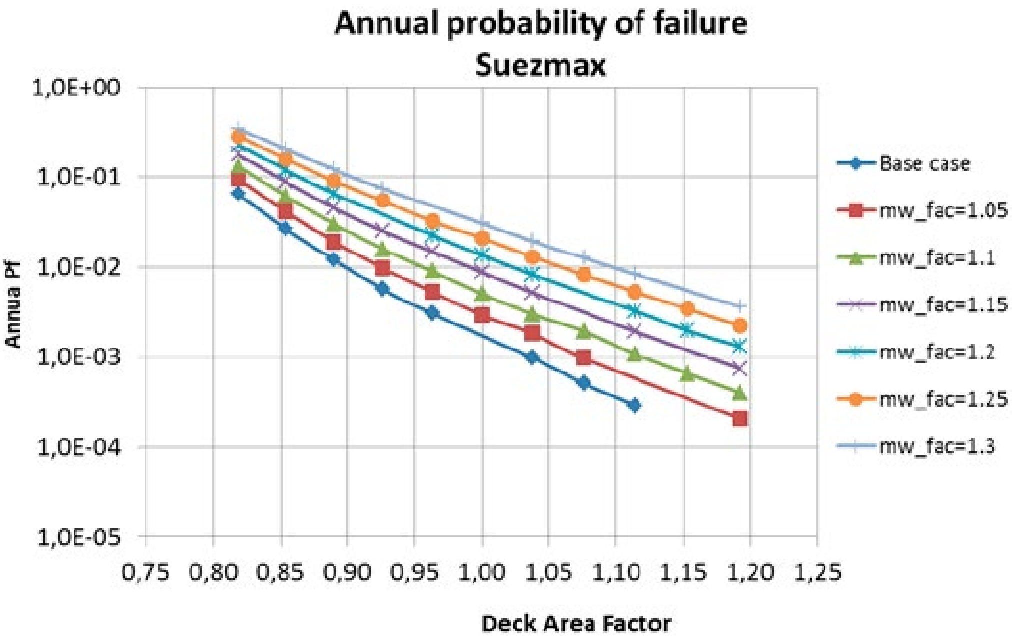


Figure 30: Annual probability of failure for net scantling for Suezmax. Base case compared with the effects of rogue waves (Bitner-Gregersen and Hørte, 2013).

operational conditions need to be based on the location-specific metocean climate. Note that FPSO systems are designed for the North Atlantic wave environment, unless a location-specific wave climate is proven to be more appropriate. Instrument-recorded data were traditionally regarded as superior to model-derived data. However, due to limited availability of measurements and improved hindcasts, the latter have become increasingly relied upon in design and operations during the last decade. SRA is widely used in the development of offshore standards.

Offshore structures (including FPSOs) follow a different approach to that of ship structures, and are designed for the 100-year return period (ULS). The Norwegian offshore standards, now under revision (NORSOK, 2007), take into account extreme severe wave conditions by requiring that a 10000-year wave does not endanger the structural integrity (ALS).

The shipping industry commonly uses linear regular and irregular waves as input to numerical codes for calculation of ship loads and responses in a sea state, while second-order irregular waves are currently applied by the offshore industry when analysing structural loads and responses. Both linear and second-order wave models are unable to capture very steep waves, such as rogue waves. There has recently been an increase in the use of CFD tools in the analysis of marine structures, which requires proper descriptions of very steep waves and the sea states in which they occur. This can only be obtained from nonlinear wave models beyond second order.

Rogue waves are currently not explicitly included in classification societies' rules and offshore standards, due to the lack of a consensus about the probability of their occurrence. It is worth mentioning that an oil company, STATOIL, has already introduced an internal requirement that, in a simplified way, accounts for rogue waves (ISSC, 2013). This requirement is now under discussion for possible implementation in the revised version of the Norwegian standard, NORSOK. However, an open question still remains; what impact will rogue waves have on current design practice?

The main concern of the shipping and offshore industries is how the safety level currently used in design will be affected by presence of rogue waves. In order to investigate changes in safety level, the

IACS Common Structural Rules for Tankers, CSR, (IACS, 2010), which address hull girder collapse of tankers in sagging conditions, were considered in EXTREME SEAS (Bitner-Gregersen and Hørte, 2013, Bitner-Gregersen et al., 2014a). The analyses included the same ships as considered by IACS (2010): Suezmax, Product Tanker, VLCC 1, VLCC 2, and Aframax. In order to account for rogue waves, a simplified approach was applied in which the annual extreme vertical wave bending moment was scaled by a constant factor of between 5 and 30 %. This reflects the findings of Guo et al. (2013), based on comparison of model tests (with rogue waves present), and numerical simulations (with linear irregular waves adopted as input in development of the CSR for Tankers). Guo et al. (2013) showed that the increase in the wave bending moment depends on both the ship type and the sea state.

The investigations showed the same overall trend for all the ships analysed; the probability of failure increased typically by between 50 % and 100 % when the extreme bending moment was increased by 5 %, compared with the Base Case representing the CSR for Tankers. These results indicate that the reliability level is maintained when the deck area is increased by a similar percentage as the increase in the extreme wave bending moment (see Figure 30). In the study, the deck area was increased following a relatively simple formula in which both the stiffeners and the plate thicknesses were modified, but not the frame spacing or the number of stiffeners. It might be possible to increase hull girder strength in a more optimal way using less steel.

Within EXTREME SEAS, the Portuguese shipyard, ENVC, demonstrated innovative designs for three vessels recently built by ENVC (Ro-Pax Ferry, Heavy-Lift Container, and Asphalt Tank Carrier). It was shown that the extra building costs related to accounting for rogue waves could be marginal or none, depending on the initial design and use of high-strength steel (Miranda et al., 2013). Maintaining the same safety level and reducing costs when accounting for rogue waves is still a topic requiring further investigations.

The research carried out in the CresT and ShorTCresT JIPs showed that for two limit states, air-gap and water in deck, rogue waves will impact on the reliability level for the generic TLP platform (Bitner-Gregersen, 2011, Hagen, 2011, Hennig et al., 2015).

# CONCLUSIONS AND RECOMMENDATIONS

Many research efforts in the last decade have contributed to our understanding of the mechanisms generating rogue waves and their detailed dynamic properties. Consistency in results between numerical phase-resolving models and experimental data has been documented. However, forcing terms, such as wind and wave breaking, are typically not included in nonlinear wave models used today. Furthermore, rogue waves observed in the ocean have been successfully reproduced in model basins. Field measurements show that rogue waves can occur worldwide, in both deep and shallow water, but some locations seem to be more vulnerable than others. Rogue waves have been observed in low, intermediate, and high sea states, but they appear to occur more frequently in low and intermediate sea states. Today, the nonlinear effect of modulational instability is regarded as one of the main mechanisms responsible for generation of rogue waves, and sea states with narrow directional spreading, as well as crossing wave systems, are suspected to be associated with modulational instability and hence increase the probability of rogue waves occurring. Waves travelling in oblique and opposing currents are also known to produce large waves.

The simple definitions of rogue waves, such as the crest criterion, $C_{max}/H_s > 1.2\text{-}1.3$, and the wave height criterion, $H_{max}/H_s > 2$, are now commonly accepted and widely used. Using such definitions, rogue waves are not so rare. The second-order wave model, which in many cases gives a satisfactory description of the probability of rogue wave occurrence, shows that we may expect rogue waves to occur about once every 8 days. However, a rogue wave is not necessarily dangerous, as this depends on the specific case and is, for example, different for the design of offshore platforms and the operation of small fishing vessels. If, in addition to the crest or height criteria, a requirement of the severity of the sea state is included (e.g., $H_s > 8$ m), then the corresponding occurrence probability is reduced. However, recent investigations indicate that for typical $H_s$ values used in the design of ships and offshore structures, rogue waves may be expected to occur more often than once within the design return periods.

It has also been shown that sea states for which second-order statistics are no longer valid, such as narrow wave spectrum, crossing seas with waves of similar frequencies and energies and a crossing angle of 40-60°, or special cases of wave-current interactions, may occur more often than once within the design return periods of ships and offshore structures. There are also indications that there will be an increase in wave steepness in the future climate, and this may also suggest more rogue waves (IPPC, 2013, Mori et al., 2013, Hemer et al., 2013, Bitner-Gregersen and Toffoli, 2015). However, this topic still needs further investigation and is being addressed in the ongoing Norwegian Research Council project ExWaCli (Extreme Waves and Climate change: Accounting for uncertainties in design of marine structures).

Studies so far have demonstrated that rogue waves may have a significant impact on loads and responses of ships and offshore structures. In order to be able to investigate this impact properly it is recommended that the shipping industry introduces nonlinear waves as input to the wave-structure interaction codes for ships. This will require further development of existing codes. In DNV GL, this topic is already being addressed through the project "HOSM in Sea-keeping", in which nonlinear irregular wave input to the DNV GL 3D Panel code, WASIM, is being implemented, following an approach originally suggested in EXTREME SEAS.

The offshore industry also needs tools that can be used for assessment of loads and responses in situations with rogue waves; use of the second-order wave model is not sufficient. Furthermore, increasing use of CFD in ship and offshore structure analysis will require proper descriptions of very steep waves that can be obtained from nonlinear wave models. Very steep nonlinear waves will have a significant impact on water particle kinematics, for which proper descriptions are very important for design and marine operations. Thus, the implementation of nonlinear wave models in the shipping and offshore industries is essential for studying the effects of such waves.

Rogue waves affect both global and local loads of ships and offshore structures, and, consequently, their design. Although high rogue waves are the most dangerous regarding structural integrity, low and intermediate rogue-prone sea states are also expected to impact on the operation of ships and offshore structures, and may also impact weather-restricted design, as well as design of local loads.

The existing margins in the classification rules and offshore standards should be evaluated before firm decisions are reached regarding inclusion of rogue waves in rules and standards. Retaining the current safety level in rules and standards during this process is crucial. In addition, costs associated with accounting for rogue waves should be kept low through the introduction of innovative designs.

The existing warning criteria for rogue waves are still not fully developed and nor are they sufficiently reliable. The development of warning criteria remains a high priority topic within the scientific community, and for the ship and offshore industries. Such criteria will increase safety at sea and affect the planning and execution of operation of ships and offshore structures.

# REFERENCES

ALBER, I. E. 1978. The Effects of Randomness on the Stability of Two-Dimensional Surface Wavetrains. Proc. R. Soc. Lond. A., 363, 525-546.

BENJAMIN, T. B. & FEIR, J. E. 1967. The Disintegration of Wave Trains on Deep Water Part 1. Theory. J. Fluid Mech., 27, 417-430.

BENNEY, D. J. & ROSKES, G. J. 1969. Wave Instabilities. Stud. Appl. Math., 48, 377-385.

BIRKNES, J. & BITNER-GREGERSEN, E. M. Non-Linearity of the Second-Order Wave Model for Directional Two-Peak Spectra. Proc. ISOPE, 2003 Honolulu, Hawai.

BITNER-GREGERSEN, E. M. Sea State Duration and Probability of Occurrence of a Freak Crest. Proc. OMAE, 2003 Cancun, Mexico.

BITNER-GREGERSEN, E. M. Reliability Assessment of Tlp Air-Gap in Nonlinear Waves. Proc. OMAE, June 19–24 2011 Rotterdam, The Netherlands.

BITNER-GREGERSEN, E. M. 2015. Exwacli. Research Review. Høvik, Norway: DNV GL.

BITNER-GREGERSEN, E. M., CRAMER, E. H. & KORBIJN, F. Environmental Description for Long-Term Load Response of Ship Structures. Proceedings of ISOPE-95 Conference, 11-16 June 1995 The Hague, The Netherlands.

BITNER-GREGERSEN, E. M., EIDE, L. I., HØRTE, T. & VANEM, E. Impact of Climate Change and Extreme Waves on Tanker Design. Proceedings of the SNAME Conference, 23-25 October 2014a Houston, USA. .

BITNER-GREGERSEN, E. M., FERNANDEZ, L., LEFEVRE, J.-M. & TOFFOLI, A. 2014b. The North Sea Andrea Storm and Numerical Simulations. Nat. Haz. Earth Sys., 14

BITNER-GREGERSEN, E. M. & HAGEN, Ø. 1990. Uncertainties in Data for the Offshore Environment. Struct. Safety, 7, 11-34.

BITNER-GREGERSEN, E. M. & HAGEN, Ø. Freak Wave Events within the 2nd Order Wave Model. Proc. OMAE, June 20-25 2004 Vancouver, Canada.

BITNER-GREGERSEN, E. M., HOVEM, L. & HØRTE, T. Impact of Freak Waves on Ship Design Practice. WMO Proceedings of the MAXWAVE project, 8-10 October 2003 2003 Geneva.

BITNER-GREGERSEN, E. M. & HØRTE, T. 2013. Simplified Approaches for Extreme Response Calculations in Extreme and Extraordinarily Large Waves. ES D6.3 Part C-DNV.

BITNER-GREGERSEN, E. M. & MAGNUSSON, A. K. Extreme Events in Field Data and in a Second Order Wave Model. Proc. of the Rogue Waves 2004 Workshop, October 20-32 2004 Brest, France.

BITNER-GREGERSEN, E. M. & MAGNUSSON, A. K. 2014. Effect of Intrinsic an Sampling Varaibility on Wave Parameters and Wave Statistics. Ocean Dynamics, 64(11), 1643-1655.

BITNER-GREGERSEN, E. M. & TOFFOLI, A. 2012a. On the Probability of Occurrence of Rogue Waves. Nat. Hazards Earth Syst. Sci., 12, 751-762.

BITNER-GREGERSEN, E. M. & TOFFOLI, A. A Semi-Empirical Wave Crest Distribution of Random Directional Wave Fields. Proc. OMAE, 1-6 July 2012b Rio de Janeiro, Brazil.

BITNER-GREGERSEN, E. M. & TOFFOLI, A. 2014. Occurrence of Rogue Sea States and Consequences for Marine Structures. Ocean Dyn., 64, 1457-1468.

BITNER-GREGERSEN, E. M. & TOFFOLI, A. Wave Steepness and Rogue Waves in the Changing Climate in the North Atlantic. Proc. OMAE, May 31 - June 5 2015 St. John's, Newfoundland, Canada.

BITNER-GREGERSEN, E. M., TOFFOLI, A., MONBALIU, J. & ONORATO, M. Implications of Non-Linear Waves for Marine Safety. Proc. of the Rogue Waves 2008 Workshop, October 20–31 2008 Brest, France.

BMT 1986. British Maritime Technology (Primary Contributors: Hogben N., Da Cunha L.F., Oliver H.N.) Global Wave Statistics. Atlas. London, England: Unwin Brothers Limited.

BUCHNER, B. & FORRISTAL, G. Are Basin Wave Different from Field Waves? (First Investigations During 'Crest' Jip). Proc. OMAE, 1-6 July 2012 2012 Rio de Janeiro, Brasil. .

CAVALERI, L., BERTOTTI, L., TORRISI, L., BITNER-GREGERSEN, E., SERIO, M. & ONORATO, M. 2012. Rogue Waves in Crossing Seas: The Louis Majesty Accident. J. Geophys. Res., 117.

CHABCHOUB, A., HOFFMANN, N. P. & AKHMEDIEV, N. 2011. Rogue Wave Observation in a Water Wave Tank. Phys. Rev. Lett., 106, 204502---204502.

CHRISTOU, M. & EWANS, K. 2014. Field Measurements of Rogue Water Waves. J. Phys. Oceanogr., 44, 2317-2335.

CLAUSS, G., KLEIN, M., DUDEK, M. & ONORATO, M. Application of Breather Solutions for the Investigation of Wave/Structure Interaction in High Steep Waves. Proc. OMAE, 1-6 July 2012 Rio de Janeiro, Brazil.

CLAUSS, G., SCHMITTNER, C., HENNIG, J., GUEDES SOARES, C., FONSECA, N. & PASCOAL, R. Bending Moments of an Fpso in Rogue Waves. Proc. OMAE, 2004.

CRAWFORD, D. R., SAFFMAN, P. G. & YUEN, H. C. 1980. Evolution of a Random Inhomogeneous Field of Non-Linear Deep-Water Gravity-Waves. Wave Motion, 2, 1-16.

CREST. 2009. Available: http://www.marin.nl/web/show/id=67808.

DANKERT, H. & ROSENTHAL, W. 2004. Ocean Surface Determination from X-Band Radar-Image Sequences. J. Geophys. Res., 109, C04016.

DAVEY, A. & STEWARTSON, K. 1974. On Three-Dimensional Packets of Surface Waves. Proc. R. Soc. Lond. A, 338, 101-110.

DNV 2014. Environmental Conditions and Environmental Loads. In: DNV (ed.). Høvik, Norway.

DOMMERMUTH, D. G. & YUE, D. K. P. 1987. A High-Order Spectral Method for the Study of Nonlinear Gravity Waves. J. Fluid Mech., 184, 267-288.

DRAPER, L. 1964. 'Freak' Ocean Waves. Oceanus, 10, 13-15.

DYSTHE, K. B. 1979. Note on a Modification to the Nonlinear Schrödinger Equation for Application to Deep Water Waves. Proc. R. Soc. Lond. A, 369, 105-114.

DYSTHE, K. B., KROGSTAD, H. E. & MÜLLER, P. 2008. Oceanic Rogue Waves. Annu. Rev. Fluid Mech., 40, 287-310.

DYSTHE, K. B., TRULSEN, K., KROGSTAD, H. E. & SOCQUET-JUGLARD, H. 2003. Evolution of a Narrow-Band Spectrum of Random Surface Gravity Waves. J. Fluid Mech., 478, 1-10.

EWANS, K. C. 1998. Observations of Directional Spectrum of Fetch-Limited Waves. J. Phys. Oceanogr., 28, 495-512.

EXTREME SEAS. 2013. Design for Ship Safety in Extreme Seas (Extreme Seas) [Online]. Contact person: Bitner-Gregersen, E. M. Available: http://cordis.europa.eu/result/rcn/55382_en.html.

FENTON, J. D. 1985. A 5th-Order Stokes Theory for Steady Waves. J. Waterw. Port Coast. Ocean Eng., 111, 216-234.

FERNANDEZ, L., ONORATO, M., MONBALIU, J. & TOFFOLI, A. 2014. Modulational Instability and Wave Amplification in Finite Water Depth. Nat. Hazards Earth Syst. Sci., 14, 705-711.

FONSECA, N., GUEDES SOARES, C. & PASCOAL, R. Prediction of Ship Dynamic Loads in Heavy Weather. Proc. of Design and Operation for Abnormal Conditions II, 2001 London. Royal Institution of Naval Architects (RINA).

FORRISTALL, G. Z. 1978. On the Statistical Distribution of Wave Heights in a Storm. J. Geophys. Res., 83, 2353-2358.

FORRISTALL, G. Z. 2000. Wave Crest Distributions: Observations and Second-Order Theory. J. Phys. Oceanogr., 30, 1931-1943.

GRAMSTAD, O., AGNON, Y. & STIASSNIE, M. 2011. The Localized Zakharov Equation: Derivation and Validation. Eur. J. Mech. B, 30, 137-146.

GRAMSTAD, O. & TRULSEN, K. 2007. Influence of Crest and Group Length on the Occurrence of Freak Waves. J. Fluid Mech., 582, 463-472.

GRAMSTAD, O. & TRULSEN, K. 2010. Can Swell Increase the Number of Freak Waves in a Wind Sea? J. Fluid Mech., 650, 57-79.

GRAMSTAD, O., ZENG, H., TRULSEN, K. & PEDERSEN, G. K. 2013. Freak Waves in Weakly Nonlinear Unidirectional Wave Trains over a Sloping Bottom in Shallow Water. Phys. Fluids, 25.

GUEDES SOARES, C., BITNER-GREGERSEN, E. M. & ANTAO, P. Analysis of the Frequency of Ship Accidents under Severe North Atlantic Weather Conditions. Proc. of design and operation for abnormal conditions II, 2001 London. Royal Institution of Naval Architects (RINA).

GUEDES SOARES, C., CHERNEVA, Z. & ANTÃO, E. M. 2004. Abnormal Waves During Hurricane Camille. J. Geophys. Res., 109, 1-7.

GUO, B. J., BITNER-GREGERSEN, E. M., SUN, H. & HELMERS, J. B. Prediction of Ship Response Statistics in Extreme Seas Using Model Test Data and Numerical Simulation Based on the Rankine Panel Method. Proc. OMAE, June 9-14 2013 Nantes, France.

HAGEN, Ø. Reliability Assessment for Tlp Tether Overload in Nonlinear Waves. Proc. OMAE, June 19–24 2011 Rotterdam, The Netherlands.

HAVER, S. Evidences of the Existence of Freak Waves. Proc. Rogue Waves, 2000. Ifremer, 129-140.

HAVER, S. & ANDERSON, O. J. Freak Waves: Rare Realizations of a Typical Population or Typical Realizations of a Rare Population. Proceedings of the 10th International Offshore and Polar Engineering (ISOPE) Conference, 28 May- 2 June 2000 Seattle, USA.

HEMER, M. A., FAN, Y., MORI, N., SEMEDO, A. & WANG, X. L. 2013. Projected Changes in Wave Climate from a Multi-Model Ensemble. Nature Climate Change, 3, 471-476.

HENNIG, J., SCHARNKE, J., SWAN, C., HAGEN, Ø., EWANS, K., TROMANS, P. & FORRISTALL, G. Z. Effects of Short-Crestedness on Extreme Wave Impact – a Summary of Findings from the Joint Industry Project Shortcrest. Proc. OMAE, 31 May – 5 June 2015 St. John's, Newfoundland, Canada.

HJELMERVIK, K. B. & TRULSEN, K. 2009. Freak Wave Statistics on Collinear Currents. J. Fluid Mech., 637, 267-284.

IACS 2000. Standard Wave Data for Direct Wave Load Analysis. In: IACS (ed.) Recommended Practice.

IACS 2010. Common Structural Rules for Double Hull Oil Tankers with Length 150 Metres and Above. In: IACS (ed.) Rules for Classification of Ships.

IMO 1997. Interim Guidelines for the Application of Formal Safety Assessment (Fsa) to the Imo Rule Making Process. Maritime Safety Committee, 68th session June 1997; and Marine Environment Protection Committee, 40th session, September 1997.

IMO 2001. Guidelines for Formal Safety Assessment for the Imo Rule Making Process. IMO/Marine Safety Committee 74/WP.19.

IPPC 2013. The Fifth Assessment Report: Climate Change (Ar5): The Ar5 Synthesis Report.

ISSC. Issc 2012 Committee I.1 Environment Reply to Discussers (Bitner-Gregersen, E.M. (Chairman), Bhattacharya S. K., Chatjigeorgiouc, I.K, Eames, I., Ellermann, K. Ewans, K. Hermanski, G., Johnson, M.C., Ma, N., Maisondieu, Ch, Nilva, A., Rychlik, I., Waseda, T). . Proceedings ISSC 2012 9-13 September 2013 Rostok, Germany.

ISSC. Committee I.1 Environment Report (Bitner-Gregersen, E.M. (Chair), Bhattacharya, S.K., Cherneva, Z., Dong, S., Fu, T., Kapsenberg, K., Ma, N., Maisondieu, Miyake, R., Murphy, M., Rychlik, I.). Proceedings of the ISSC 2015, 6-10 September 2015 Cascaise, Portugal.

JANSSEN, P. A. E. M. 2003. Nonlinear Four-Wave Interactions and Freak Waves. J. Phys. Oceanogr., 33, 863-884.

JANSSEN, T. T. & HERBERS, T. H. C. 2009. Nonlinear Wave Statistics in a Focal Zone. J. Phys. Oceanogr., 39, 1948-1964.

KHARIF, C., PELINOVSKY, E. & SLUNYAEV, A. 2009. Rogue Waves in the Ocean, Springer.

KINSMAN, B. 1965. Wind Waves, Their Generation and Propagation on the Ocean Surface, Prentice-Hall.

KROGSTAD, H. E., BARSTOW, S. F., MATHIESEN, L. P., LØNSETH, L., MAGNUSSON, A. K. & DONELAN, M. A. Extreme Waves in the Long-Term Wave Measurements at Ekofisk. Proc. Rogue Waves 2008 Workshop, 23 – 33 October 2008 Brest, France.

LAVRENOV, I. V. 1998. The Wave Energy Concentration at the Agulhas Current Off South Africa. Nat. Hazards, 17, 117-127.

LEY, J. 2013. Report with Validation of the New Time Domain Seakeeping Code by Systematic Comparisons with Experimental Data Obtained in the Project EXTREME SEAS report. University of Duisburg-Essen.

LONGUET-HIGGINS, M. S. 1952. On the Statistical Distribution of the Heights of Sea Waves. J. Mar. Res., 11, 245-266.

LONGUET-HIGGINS, M. S. 1963. The Effect of Non-Linearities on Statistical Distributions in the Theory of Sea Waves. J. Fluid Mech., 17, 459-480.

LONGUET-HIGGINS, M. S. 1976. On the Nonlinear Transfer of Energy in the Peak of a Gravity-Wave Spectrum: A Simplified Model. Proc. R. Soc. Lond. A, 347, 311–328.

LONGUET-HIGGINS, M. S. 1980. On the Distribution of the Heights of Sea Waves - Some Effects of Nonlinearity and Finite Band-Width. J. Geophys. Res., 85, 1519-1523.

MAGNUSSON, A. K. & DONELAN, M. A. 2013. The Andrea Wave. Characteristics of a Measured North Sea Rogue Wave. J. Offshore Mech. Arct. Eng., 135, 031108.

MALLORY, J. K. 1974. Abnormal Waves in the South-East Coast of South Africa. Int. Hydrog. Rev., 51, 89-129.

MIRANDA, A., BARROS, M. A. & ALVES, C. 2013. Impact on Cost and Ship Design Related to an Increase on Ship's Safety Level Due to a Higher Wave Bending Moments, Induced by a Rogue Wave. ES D7.2-ENVC.

MORI, N. & JANSSEN, P. A. E. M. 2006. On Kurtosis and Occurrence Probability of Freak Waves. J. Phys. Oceanogr., 36, 1471-1483.

MORI, N., ONORATO, M. & JANSSEN, P. A. E. M. 2011. On the Estimation of the Kurtosis in Directional Sea States for Freak Wave Forecasting. J. Phys. Oceanogr., 41, 1484-1497.

MORI, N., SHIMURA, T., NAKAJO, S., YSUJIO, D., YASUDA, T., MASE, H. & SUH, K. D. Projection of Future Wave Climate Change and Application to Coastal Structure Design. Proceedings of Breakwater Conference, 2013 Edinburgh, UK.

NIETO BORGE, J. C., REICHERT, K. & DITTMER, J. 1999. Use of Nautical Radar as a Wave Monitoring Instrument. Coastal Eng., 37, 331-342.

NIKOLKINA, I. & DIDENKULOVA, I. 2011. Rogue Waves in 2006–2010. Nat. Haz. Earth Sys., 11, 2913-2924.

NIKOLKINA, I. & DIDENKULOVA, I. 2012. Catalogue of Rogue Waves Reported in Media in 2006–2010. Nat. Hazards Earth Syst. Sci., 61.

NORSOK 2007. Action and Action Effects. In: DIRECTORATE, T. N. O. (ed.). Norway.

ONORATO, M., CAVALERI, L., FOUQUES, S., GRAMSTAD, O., JANSSEN, P. A. E. M., MONBALIU, J., OSBORNE, A. R., PAKOZDI, C., SERIO, M., STANSBERG, C. T., TOFFOLI, A. & TRULSEN, K. 2009a. Statistical Properties of Mechanically Generated Surface Gravity Waves: A Laboratory Experiment in a Three-Dimensional Wave Basin. J. Fluid Mech., 627, 235-257.

ONORATO, M., OSBORNE, A. R. & SERIO, M. 2002. Extreme Wave Events in Directional, Random Oceanic Sea States. Phys. Fluids, 14, L25-L28.

ONORATO, M., OSBORNE, A. R. & SERIO, M. 2006. Modulational Instability in Crossing Sea States: A Possible Mechanism for the Formation of Freak Waves. Phys. Rev. Lett., 96, 014503.

ONORATO, M., OSBORNE, A. R., SERIO, M. & BERTONE, S. 2001. Freak Waves in Random Oceanic Sea States. Phys. Rev. Lett., 86, 5831-5834.

ONORATO, M., OSBORNE, A. R., SERIO, M., CAVALERI, L., BRANDINI, C. & STANSBERG, C. T. 2004. Observation of Strongly Non-Gaussian Statistics for Random Sea Surface Gravity Waves in Wave Flume Experiments. Phys. Rev. E, 70, 067302-067302.

ONORATO, M., PROMENT, D. & TOFFOLI, A. 2010. Freak Waves in Crossing Seas. Eur. Phys. J. Special Topics, 185, 45-55.

ONORATO, M., PROMENT, D. & TOFFOLI, A. 2011. Triggering Rogue Waves in Opposing Currents. Phys. Rev. Lett., 107, 184502-184502.

ONORATO, M., WASEDA, T., TOFFOLI, A., CAVALERI, L., GRAMSTAD, O., JANSSEN, P. A. E. M., KINOSHITA, T., MONBALIU, J., MORI, N., OSBORNE, A. R., SERIO, M., STANSBERG, C. T., TAMURA, H. & TRULSEN, K. 2009b. Statistical Properties of Directional Ocean Waves: The Role of the Modulational Instability in the Formation of Extreme Events. Phys. Rev. Lett., 102, 114502-114502.

PASTOOR, W., HELMERS, J. B. & BITNER-GREGERSEN, E. M. Time Simulation of Ocean-Going Structures in Extreme Waves.  Proc. OMAE, 2003 Cancun, Mexico.

PEREGRINE, D. H. 1983. Water-Waves, Non-Linear Schrödinger-Equations and Their Solutions. J. Austral. Math. Soc. Ser. B, 25, 16-43.

PETERSON, P., SOOMERE, T., ENGELBRECHT, J. & VAN GROESEN, E. 2003. Soliton Interaction as a Possible Model for Extreme Waves in Shallow Water. Nonlin. Processes Geophys., 10, 503-510.

RIENECKER, M. M. & FENTON, J. D. 1981. A Fourier Approximation Method for Steady Water Waves. J. Fluid Mech., 104, 119-137.

ROSENTHAL, W. 2004. Maxwave, Final Report. GKSS, Geesthacht.

ROSENTHAL, W. & LEHNER, S. 2008. Rogue Waves: Results of the Maxwave Project. J. Offshore Mech. Arct. Eng., 130, 021006.

SAVINA, H., LEFEVRE, J.-M., JOSSE, P. & DANDIN, P. Definition of Warning Criteria.  Proc. of the MaxWave Final Meeting, Oct. 8-10 2003 Geneva, Switzerland.

SCHULZ-STELLENFLETH, J. & LEHNER, S. 2004. Measurement of 2-D Sea Surface Elevation Fields Using Complex Synthetic Aperture Radar Data. IEEE TGARS, 42, 1149-1160.

SEAMOCS. 2009. Http://Www.Maths.Lth.Se/Seamocs/ [Online].

SERGEEVA, A., PELINOVSKY, E. & TALIPOVA, T. 2011. Nonlinear Random Wave Field in Shallow Water: Variable Korteweg-De Vries Framework. Nat. Hazards Earth Syst. Sci., 11, 323-330.

SHARMA, J. N. & DEAN, R. G. 1979. Development and Evaluation of a Procedure for Simulating a Random Directional Second Order Sea Surface and Associated Wave Forces.

SKJELBREIA, L. & HENDRICKSON, J. Fifth Order Gravity Wave Theory.  Proceedings of 7th Conference on Coastal Engineering, 1960. 184-196.

SOCQUET-JUGLARD, H., DYSTHE, K., TRULSEN, K., KROGSTAD, H. E. & LIU, J. D. 2005. Probability Distributions of Surface Gravity Waves During Spectral Changes. J. Fluid Mech., 542, 195-216.

STANSBERG, C. T. Effects from Directionality and Spectral Bandwidth on Non-Linear Spatial Modulations of Deep-Water Surface Gravity Wave Trains.  Proceedings 24th Int. Conference on Coastal Engineering, 1994. 579-593.

STOKES, G. G. 1847. On the Theory of Oscillatory Waves. Trans. Camb. Philos. Soc., 8, 441-455.

TAYFUN, M. A. 1980. Narrow-Band Nonlinear Sea Waves. J. Geophys. Res., 85, 1548-1552.

TOFFOLI, A. & BITNER-GREGERSEN, E. M. 2011. Extreme and Rogue Waves in Directional Wave Field. The Open Ocean Engineering Journal, 4, 24-33.

TOFFOLI, A., BITNER-GREGERSEN, E. M., ONORATO, M. & BABANIN, A. V. 2008a. Wave Crest and Trough Distributions in a Broad-Banded Directional Wave Field. Ocean Eng., 35, 1784-1792.

TOFFOLI, A., BITNER-GREGERSEN, E. M., OSBORNE, A. R., SERIO, M., MONBALIU, J. & ONORATO, M. 2011a. Extreme Waves in Random Crossing Seas: Laboratory Experiments and Numerical Simulations. Geophys. Res. Lett., 38.

TOFFOLI, A., CAVALERI, L., BABANIN, A. V., BENOIT, M., BITNER-GREGERSEN, E. M., MONBALIU, J., ONORATO, M., OSBORNE, A. R. & STANSBERG, C. T. 2011b. Occurrence of Extreme Waves in Three-Dimensional Mechanically Generated Wave Fields Propagating over an Oblique Current. Nat. Hazards Earth Syst. Sci., 11, 895-903.

TOFFOLI, A., CHAI, S., BITNER-GREGERSEN, E. M. & PISTANI, F. Probability of Occurrence of Extreme Waves in Three Dimensional Mechanically Generated Wave Fields: A Comparison with Numerical Simulations. Proc. OMAE, June 19-24 2011c Rotterdam, The Netherlands.

TOFFOLI, A., FERNANDEZ, L., MONBALIU, J., BENOIT, M., GAGNAIRE-RENOU, E., LEFÉVRE, J. M., CAVALERI, L., PROMENT, D., PAKOZDI, C., STANSBERG, C. T., WASEDA, T. & ONORATO, M. 2013a. Experimental Evidence of the Modulation of a Plane Wave to Oblique Perturbations and Generation of Rogue Waves in Finite Water Depth. Phys. Fluids, 25, 091701-091701.

TOFFOLI, A., GRAMSTAD, O., TRULSEN, K., MONBALIU, J., BITNER-GREGERSEN, E. M. & ONORATO, M. 2010a. Evolution of Weakly Nonlinear Random Directional Waves: Laboratory Experiments and Numerical Simulations. J. Fluid Mech., 664, 313-336.

TOFFOLI, A., LEFÈVRE, J. M., BITNER-GREGERSEN, E. M. & MONBALIU, J. 2005. Towards the Identification of Warning Criteria: Analysis of a Ship Accident Database. Appl. Ocean Res., 27, 281-291.

TOFFOLI, A., ONORATO, M., BITNER-GREGERSEN, E. M. & MONBALIU, J. 2010b. Development of a Bimodal Structure in Ocean Wave Spectra. J. Geophys. Res., 115, C03006.

TOFFOLI, A., ONORATO, M., BITNER-GREGERSEN, E. M., OSBORNE, A. R. & BABAIN, A. V. 2008b. Surface Gravity Waves from Direct Numerical Simulations of the Euler Equations: A Comparison with Second Order Theory. Ocean Eng., 35, 367-379.

TOFFOLI, A., WASEDA, T., HOUTANI, H., CAVALERI, L., GREAVES, D. & ONORATO, M. 2015. Rogue Waves in Opposing Currents: An Experimental Study on Deterministic and Stochastic Wave Trains. J. Fluid Mech., 769, 277-297.

TOFFOLI, A., WASEDA, T., HOUTANI, H., KINOSHITA, T., COLLINS, K., PROMENT, D. & ONORATO, M. 2013b. Excitation of Rogue Waves in a Variable Medium: An Experimental Study on the Interaction of Water Waves and Currents. Phys. Rev. E, 87, 051201-051201.

TOMITA, H. & KAWAMURA, T. Statistical Analysis and Inference from the in-Situ Data of the Sea of Japan with Reference to Abnormal and/or Freak Waves. 10th ISOPE Conference, 2000 Seattle, USA. Int. Soc. of Offshore and Polar Eng., 116-122.

TRULSEN, K., NIETO BORGE, J. C., GRAMSTAD, O., AOUF, L. & LEFÈVRE, J. M. 2015. Crossing Sea State and Rogue Wave Probability During the Prestige Accident. Journal of Geophysical Research: Oceans, 120, 7113-7136.

TRULSEN, K., ZENG, H. & GRAMSTAD, O. 2012. Laboratory Evidence of Freak Waves Provoked by Non-Uniform Bathymetry. Phys. Fluids, 24, 097101-097101.

WASEDA, T., HALLERSTIG, M., OZAKI, K. & TOMITA, H. 2011. Enhanced Freak Wave Occurrence with Narrow Directional Spectrum in the North Sea. Geophys. Res. Lett., 38, L13605-L13605.

WASEDA, T., KINOSHITA, T. & TAMURA, H. 2009. Evolution of a Random Directional Wave and Freak Wave Occurrence. J. Phys. Oceanogr., 39, 621-639.

WASEDA, T., SINCHI, M., KIYOMATSU, K., NISHIDA, K., TAKAHASHI, S., ASAUMI, S., KAWAI, Y., TAMURA, H. & MIYAZAWA, Y. 2014. Deep Water Observations of Extreme Waves with Moored and Free Gps Buoys. Ocean Dynamics, 64, 1269–1280

WEST, B. J., BRUECKNER, K. A., JANDA, R. S., MILDER, D. M. & MILTON, R. L. 1987. A New Numerical Method for Surface Hydrodynamics. J. Geophys. Res., 92, 11803-11824.

XIAO, W., LIU, Y., WU, G. & YUE, D. K. P. 2013. Rogue Wave Occurrence and Dynamics by Direct Simulations of Nonlinear Wave-Field Evolution. J. Fluid Mech., 720, 357-392.

ZAKHAROV, V. E. 1968. Stability of Periodic Waves of Finite Amplitude on the Surface of a Deep Fluid. J. Appl. Mech. Tech. Phys., 9, 190-194.

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