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Rogue waves in crossing seas: The Louis Majesty accident

L. Cavaleri,[1] L. Bertotti,[1] L. Torrisi,[2] E. Bitner-Gregersen,[3] M. Serio,[4] and M. Onorato[4,5]

[1] We analyze the sea state conditions during which the accident of the cruise ship Louis Majesty took place. The ship was hit by a large wave that destroyed some windows at deck number five and caused two fatalities. Using the wave model (WAM), driven by the Consortium for Small-Scale Modelling (COSMO-ME) winds, we perform a detailed hindcast of the local wave conditions. The results reveal the presence of two comparable wave systems characterized almost by the same frequency. We discuss such sea state conditions in the framework of a system of two coupled Nonlinear Schrödinger (CNLS) equations, each of which describe the dynamics of a single spectral peak. For some specific parameters, we discuss the breather solutions of the CNLS equations and estimate the maximum wave amplitude. Even though, due to the lack of measurements, it is impossible to establish the nature of the wave that caused the accident, we show that the angle between the two wave systems during the accident was close to the condition for which the maximum amplitude of the breather solution is observed.

C

1. Introduction

[2] Reports about very large waves, often reported as freak or rogue waves, have become more frequent in the last one or two decades, possibly because of the increased attention and the ever larger number of vessels on the sea. *Nikolkina and Didenkulova* [2011] provide an extensive list of events. Analysis of long-term records provides contradictory results. *Liu et al.* [2010], among others, suggest that freak waves, however defined, are more common than people thought. On the other hand, *Casas-Prat and Holthuijsen* [2010] report that a wave statistics from 10 million waves in deep water is well represented for wave crests, but overestimated for wave heights, by the conventional Rayleigh distribution. Even though the scientific community has not come to a definite answer on the problem of formation of rogue waves, there are a number of possible mechanisms that are well documented for being candidates in deep water (see *Kharif et al.* [2009] for a recent review): (i) the linear superposition of waves, (ii) the interaction of waves with current, and (iii) the modulational instability. In the latter case, it can happen that statistically the probability of finding an extreme wave is well beyond the statistics derived from linear theory or even the *Tayfun* [1980] second-order one [see, e.g., *Onorato et al.*, 2006a]). However, theory and experiments showed that, while the instability is possible in a narrow spectrum unidirectional sea [*Onorato et al.*, 2004], the related statistics shifts back toward the Rayleigh one when the directional spread is increased [*Onorato et al.*, 2009a, 2009b].

[3] In 2006, *Onorato et al.* [2006b] proposed a new mechanism of formation of rogue waves based on the study of a system of coupled Nonlinear Schrödinger equations. The authors speculated that the modulational instability of two wave trains with similar frequencies traveling at an angle could be responsible for the formation of rogue waves. Such results have been confirmed through recent numerical simulations of the Euler equations and experimental work performed at the Ocean basin in the Marintek Laboratories [*Toffoli et al.*, 2011]. Results showed that the kurtosis, a measure of the probability of occurrence of extreme waves, depends on the angle between the crossing systems. Its maximum value is achieved for $40° < \beta < 60°$, where β is the angle between the two wave systems. An explanation of this result can be found in *Onorato et al.* [2010] and will be discussed furthermore in section 4.

[4] As we will show in section 3, the accident of the Louis Majesty ship happened in crossing sea conditions: from the analysis of the wave spectra obtained from the hindcast of the storm it appears clear that, at the time of the accident, two wave systems of similar frequencies coexisted. The fact that crossing seas have the potential to create hazardous conditions for mariners is not new. Indeed, *Greenslade* [2001] analyzed the Sydney to Hobart yacht race that took place in 1998. According to the author "it was the most disastrous event in any offshore race held in Australian waters". During the race, a severe storm off the coast of southern New South

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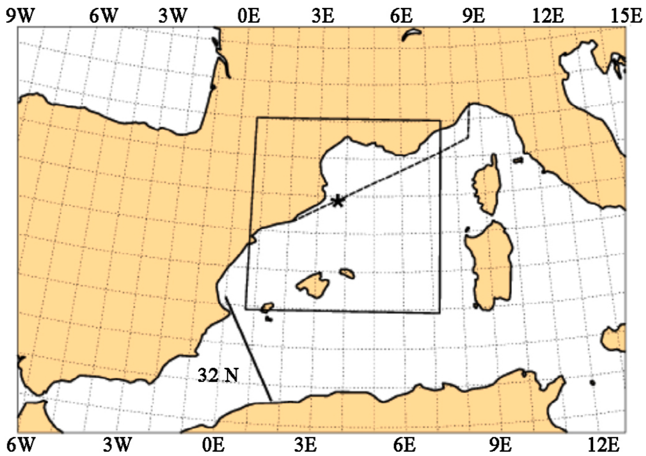

Figure 1. Western Mediterranean Sea: The area enclosed in the box corresponds to the one considered in Figure 2. The line in the lower left shows the only satellite pass at a time close to the accident. Accident (star) position is also shown. The dashed line is an indication of the expected route of the ship (toward ENE).

Wales caused the abandonment of five yachts and forced a further 66 boats to retire from the race. During the peak of the storm, two wave systems were present in the wave spectra. The yachts that experienced problems reported that exceptional waves were responsible for causing damages.

[5] *Tamura et al.* [2009] analyzed the Suwa-Maru accident which happened in 2008 in the Kuroshio Extension region east of Japan. The authors report bimodal spectra some hours before the accident. Their interpretation of the accident is the following: under the influence of rising wind speed, the swell system grows at the expense of the wind sea energy, and the bimodal crossing sea state is transformed into an energetic unimodal sea characterized by a narrow spectrum. This last condition is called in *Tamura et al.* [2009] a *freakish* sea state because, due to the modulational instability, the probability of encountering a freak wave is large. It should be mentioned also that according to *Gramstad et al.* [2011] the sinking of the Tanker Prestige in 2002 has happened in crossing seas conditions.

[6] On 3 March 2010, the cruise ship Louis Majesty (207 m long, 41,000 gross tonnage) was en route from Barcelona to Genoa, in the Mediterranean Sea, see Figure 1, in stormy conditions when a large wave hit deck 5, 16.70 m above the mean floating line, smashing some windows of a living room. Two persons were killed and several injured. The ship reversed its course and aimed back to Barcelona.

[7] In the present paper we will perform a detailed hindcast of the meteorological conditions during which the accident of the Louis Majesty has happened. The model and the sea state conditions are reported in sections 2 and 3, respectively, while the discussion in terms of Coupled Nonlinear Schrödinger equations is reported in section 4. Conclusions are in section 5.

2. Modeling

[8] The accident happened in the western part of the Mediterranean Sea, close to the coast of Spain (see Figure 1). Therefore, we focus on modeling and results in this area. Several centers provide wind and wave forecasts in the Mediterranean, see, e.g., *Bertotti et al.* [2012] for a seven model intercomparison concerning an exceptionally strong event (Klaus storm, 2009). However, spectra are commonly not stored. As this was a key piece of information for the subsequent analysis, a devoted run has been performed. Below a short description of the wind and wave models is provided (more details can be found in the references below).

2.1. The Wind

[9] The Consortium for Small-Scale Modelling (COSMO-ME) meteorological model is a consortium product [*Steppeler et al.*, 2003] that CNMCA (the Italian Meteorological Service) runs with 7 km resolution on an enlarged Mediterranean area. It is a nonhydrostatic regional model that in the used setup is initialized by a 3D-VAR (three-dimensional Variational) assimilation system [*Bonavita and Torrisi*, 2005]) and driven by boundary conditions derived from the operational system of the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, U. K., http://www.ecmwf.int/research/ifsdocs/). The surface wind fields have been saved at 1 h interval from the day before till the one after the storm. Each field has been bilinearly interpolated to the wave model grid.

2.2. The Waves

[10] The wave model (WAM) [*Komen et al.*, 1994; *Janssen*, 2008], driven by the COSMO-ME winds, has been used for the hindcast of the wave conditions in the Mediterranean during the period of interest. Given the dimensions of the interested area and the kind of storm, 36 h (the accident happened at 14:20 UTC) are more than enough to ensure that the model results are fully representative of the situation. Indeed, the storm had a relatively local origin, without any far coming waves. A direct inspection of the wind and wave conditions 36 h before the accident (00:00 UTC, 2 March 2010) reveals an almost calm sea in the western Mediterranean, with a light wind and low waves directed to ENE. The waves began to grow only in the early hours of the following day. The resolution is 0.05° (5.5 km $\times$ 4 km in the area of interest). Wavefields (significant wave height, H_s, and all the other relevant integrated parameters) plus the 2D spectra have been saved at hourly intervals, providing a full picture of the marine situation at the time of the accident.

3. Sea State Conditions During the Accident

[11] We have hourly maps, so we focus our attention on the two fields of 14:00 and 15:00 UTC, 3 March 2010. Figure 2 provides a map of the wave conditions in the area at 14:00 and 15:00 UTC (Figures 2 (left) and 2 (right), respectively), longitude 1°E–7°E, latitude 39°N–44°N (see Figure 1 for its location in the Mediterranean Sea). The star in Figure 2 indicates the ship location at the time of the accident. Two wave systems were converging on the area of the ship, one from SE and another one from ENE. The ENE one was an active sea, with its typical directional spreading. The SE coming system, being just out of its generation area, has an only slightly narrower spectrum, both in frequency and direction. Their respective overall energy was very

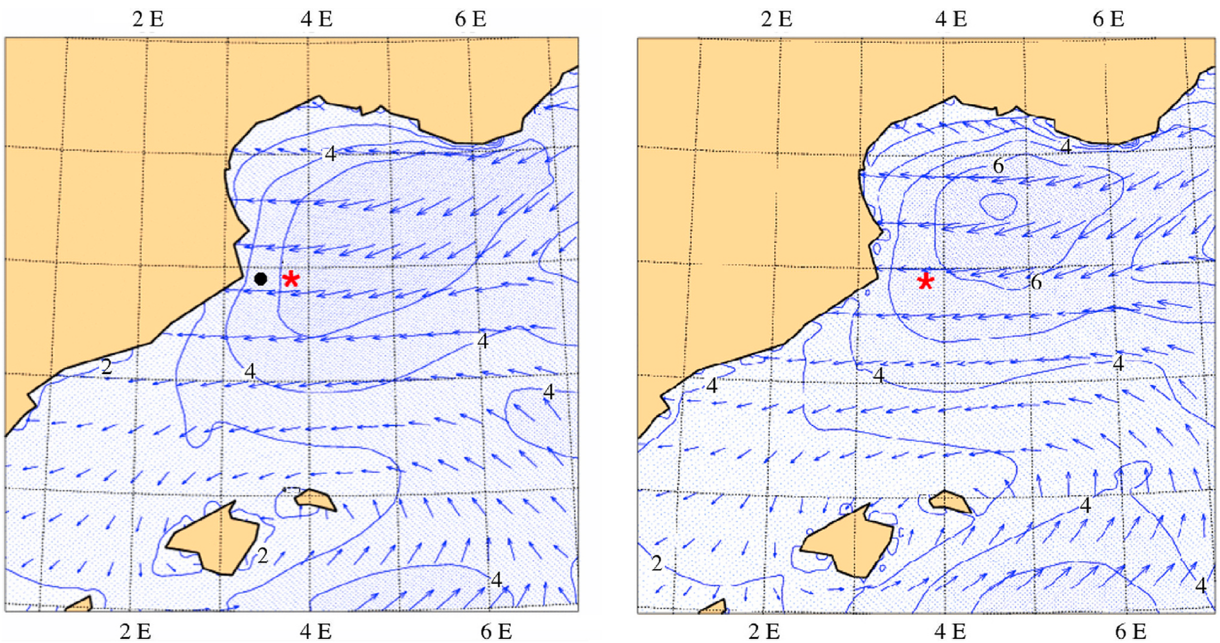

Figure 2. Significant wave height field at (left) 14:00 and (right) 15:00 UTC, 3 March 2010. Isolines at 1 m interval. The arrows indicate the mean wave direction, and their length is proportional to the significant wave height. The area, shown in Figure 1, spans 1°E–7°E, 39°N–44°N. The grid is shown at 1° intervals. The star points to the ship location at the time of the accident. The dot in Figure 2 (left) indicates the position of the Begur buoy.

similar. No altimeter data was available to verify the relevant model results. The only pass, 2 h after the accident, is shown in Figure 1, well off the area of interest. However, the Begur buoy of Puertos del Estado, its position marked in Figure 2 (left), is about 25 km off the accident location. In Figure 3 the H_s recorded at the buoy and the corresponding model values are provided. The peak values are similar, but the model seems to be lagging behind by about 1 h, with a consequent slight H_s underestimate at the time of the accident between 0.2 and 0.3 m. Figure 4 provides the time history of the estimated wave conditions encountered by the Louis Majesty on its way from and toward Barcelona. The

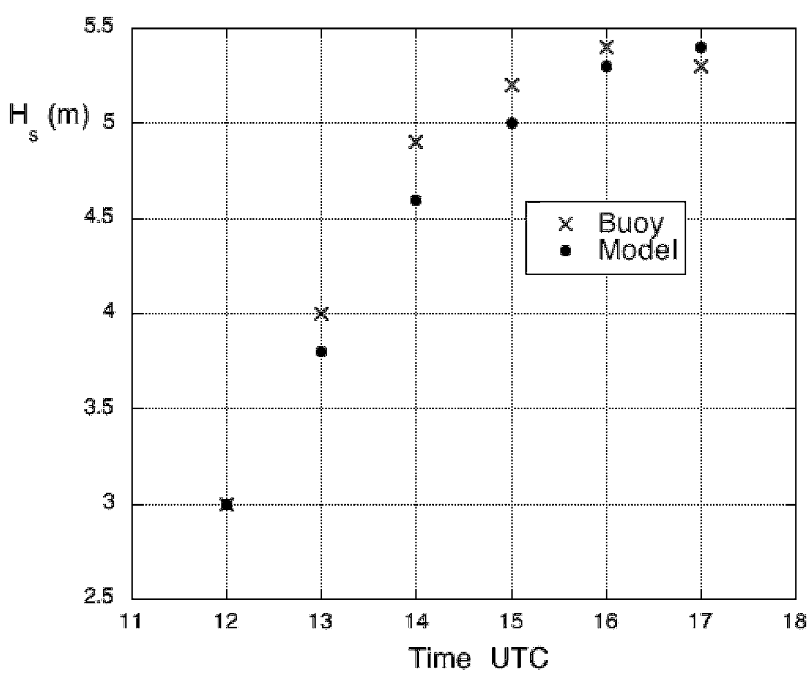

Figure 3. Significant wave heights measured on 3 March 2010 at the Begur buoy (crosses, see Figure 2) and corresponding model values (dots).

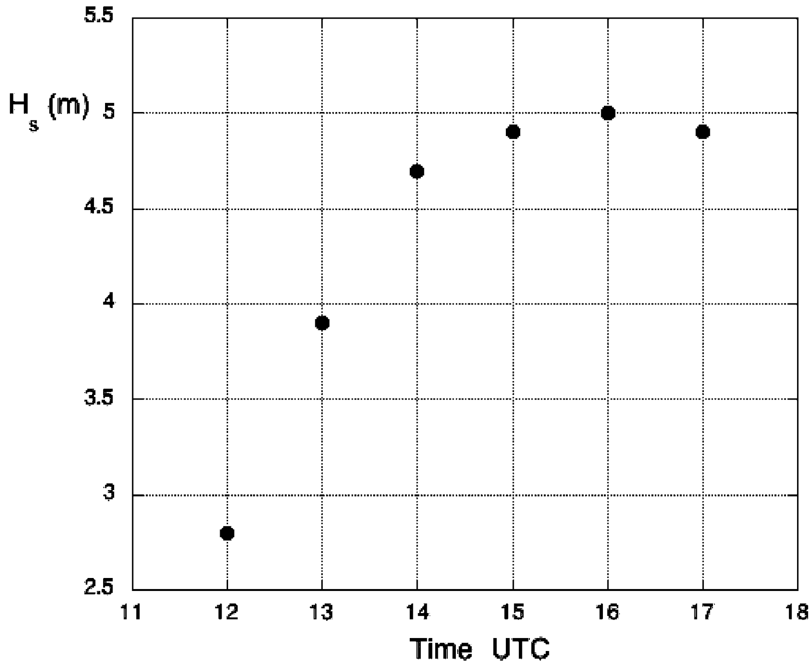

Figure 4. Significant wave heights, according to model hindcast, encountered on 3 March 2010 by the Louis Majesty on its estimated route from and toward Barcelona, respectively, before and after the accident (14:20 UTC).

model estimate at the time of the accident is close to 5 m, possibly slightly underestimated given the results at Begur. A better view of the previously mentioned two wave systems is provided by the 2D spectra in Figure 5, respectively at 14:00 and 15:00 UTC, at the grid point coincident with the official ship position (41°51′N, 3°0.45′E) at the time of the accident. Each spectrum is normalized with respect to its peak value. At 14:00 and 15:00 UTC the presence of two wave systems is very clear, both having almost the same peak frequency between 0.10 and 0.11 Hz. The two wave systems were separated by an angle β of 40°–60°. The wind, at about 20 m/s, was from ENE. The SE wave systems had been generated slightly to the south, and it was still characterized by steep waves.

4. The Coupled Nonlinear Schrödinger Equations

[12] The wave condition during which the accident of the Louis Majesty happened seems to be suitably described by a set of two Nonlinear Schrödinger equations each describing the dynamics of a peak in the spectrum. Such system has been recently discussed in a number of papers [*Onorato et al.*, 2006b; *Shukla et al.*, 2006; *Hammack et al.*, 2005; *Gronlund et al.*, 2009] (also see *Gramstad and Trulsen* [2011] for a Hamiltonian formulation of higher-order coupled Nonlinear Schrödinger equations). The modulational instability in crossing seas has been studied using such system. A linear stability analysis of a plane wave solution of the system indicates that the introduction of a second noncollinear wave system can result in an increase of the growth rates of the perturbation and in an enlargement of the instability region. It has been found in *Onorato et al.* [2006b] that the growth rates depend not only on the wavelength of the perturbation and on the steepness of the initial waves, but also on the angle between the two wave systems. An experimental and numerical investigation on the statistical properties of the surface elevation in crossing sea conditions has been performed by *Toffoli et al.* [2011]. Experiments have been performed in a very large wave basin (70 m × 50 m × 3 m) and numerical results are obtained using a higher-order method for solving the Euler equations. Both experimental and numerical results indicate that the number of extreme events depends on the angle between the two interacting systems. In what follows the coupled

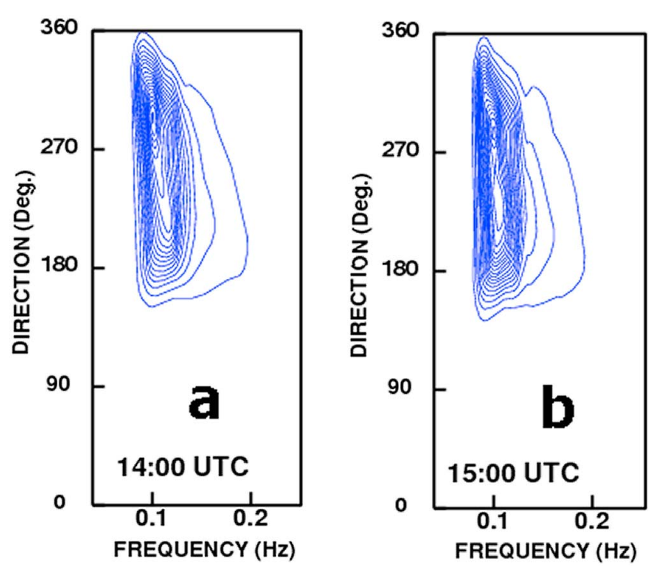

Figure 5. Two-dimensional spectra, at (a) 14:00 and (b) 15:00 UTC, at the official position of the accident. Each spectrum is normalized with respect to its peak value.

Nonlinear Schrödinger (CNLS) equations will be introduced and their breather solutions will be discussed. The starting point for the derivation of the model is the Zakharov equation in 2D + 1

$$\frac{\partial a_1}{\partial t} + i\omega_1 a_1 = -i \int T_{1,2,3,4} a_2^* a_3 a_4 \delta_{1,2}^{3,4} d\mathbf{k}_{2,3,4}. \quad (1)$$

Here $a_i = a(\mathbf{k}_i, t)$ is the complex variable defined for example in *Krasitskii* [1994], $\delta_{1,2}^{3,4} = \delta(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_3 - \mathbf{k}_4)$ and $\omega = \sqrt{g\kappa}$, where κ is the modulus of the vector $\mathbf{k}$. $T_{1,2,3,4}$ is the coupling coefficient whose analytical form can be found in *Krasitskii* [1994].

[13] We work under the hypothesis that the energy is concentrated mainly around two carrier waves, therefore it is natural to consider the following decomposition:

$$a(\mathbf{k}) = A\left(\mathbf{k} - \mathbf{k}^{(a)}\right) e^{-i\omega^{(a)} t} + B\left(\mathbf{k} - \mathbf{k}^{(b)}\right) e^{-i\omega^{(b)} t} \quad (2)$$

$$a(\mathbf{k}) = \left[\frac{\omega(\kappa)}{2\kappa}\right]^{1/2} A e^{-i\omega^{(a)} t} + \left[\frac{\omega(\kappa)}{2\kappa}\right]^{1/2} B e^{-i\omega^{(b)} t}, \quad (3)$$

with $\omega^{(a)} = \sqrt{g\left|\mathbf{k}^{(a)}\right|}$ and $\omega^{(b)} = \sqrt{g\left|\mathbf{k}^{(b)}\right|}$. $\mathbf{k}^{(a)} = (k^{(a)}, l^{(a)})$, $\mathbf{k}^{(b)} = (k^{(b)}, l^{(b)})$ are the wave numbers corresponding to the two peaks in the directional spectrum. Inserting (2) into (1), assuming that $\mathbf{k}^{(a)} = (k, l)$ and $\mathbf{k}^{(b)} = (k, -l)$ with $l \neq 0$ (this assumption implies that the frequencies of both wave systems are the same) and considering each wave system as quasi-monochromatic, two coupled equations can be obtained (see *Onorato et al.* [2010] for details). In order to deal with equations that are correct in an asymptotic sense, the system is projected along the direction at which the group velocities are the same. Finally, the system of CNLS takes the following form:

$$\begin{aligned} &\frac{\partial A}{\partial t} - i\alpha\frac{\partial^2 A}{\partial x^2} + i(\xi|A|^2 + 2\zeta|B|^2)A = 0 \\ &\frac{\partial B}{\partial t} - i\alpha\frac{\partial^2 B}{\partial x^2} + i(\xi|B|^2 + 2\zeta|A|^2)B = 0, \end{aligned} \quad (4)$$

where

$$\begin{aligned} \alpha &= \frac{\omega(\kappa)}{8\kappa^4}\left(2l^2 - k^2\right) \\ \xi &= \frac{1}{2}\omega(\kappa)\kappa^2 \\ \zeta &= \frac{\omega(\kappa)}{2\kappa}\left(\frac{k^5 - k^3 l^2 - 3kl^4 - 2k^4\kappa + 2k^2 l^2\kappa + 2l^4\kappa}{-2k^2 - 2l^2 + k\kappa}\right). \end{aligned} \quad (5)$$

The surface elevation $\eta = \eta(x, y, t)$ is related to the wave envelope to the leading order in the following way:

$$\eta = \frac{1}{2}\left(A e^{i(kx+ly-\omega t)} + B e^{i(kx-ly-\omega t)}\right) + c.c., \quad (6)$$

where c.c. stands for complex conjugate. An analysis of the coefficients performed in *Onorato et al.* [2010] has revealed the following: (i) for $\beta < 70.52°$, dispersive and nonlinear terms have the same sign; this means that the system is focusing (β is the angle between the two wave systems); (ii) the ratio between nonlinearity and dispersion becomes larger as β approaches 70.52° (this is valid for both self-interaction and cross-interaction nonlinearity); and (iii) the cross-interaction nonlinearity is stronger than the self interaction one for angles between 0 and 53.46°. A linear stability analysis shows that the growth rate is maximum for small angles. In *Onorato et al.* [2010] it was speculated that the appearance of rogue waves is the result of a compromise between strong nonlinearity and large growth rate and it has been estimated that this happens for angles between 40° and 60°. This range of angles includes the one in which the Louis Majesty accident took place.

[14] In the present paper, motivated by the accident, we find in some specific conditions, analytical breather solutions of equation (4) which are prototypes of rogue waves [see *Osborne et al.*, 2000; *Dysthe and Trulsen*, 1999]. Therefore, we look for solutions of the form

$$A(x,t) = c_1\psi(x,t) \; B(x,t) = c_2\psi(x,t)\exp(i\delta). \quad (7)$$

δ is a constant phase mismatch between the two wave groups; c_1 and c_2 are two real constants. From the two-dimensional wave spectra in Figure 5 we observe that the amplitudes of the two wave systems are comparable, therefore $c_1 \simeq c_2$; in the following analysis we set the two constants equal to 1. Then, $\psi(x, t)$ satisfies the following NLS equation:

$$\frac{\partial\psi}{\partial t} - i\alpha\frac{\partial^2\psi}{\partial x^2} + i(\xi + 2\zeta)|\psi|^2\psi = 0. \quad (8)$$

[15] The surface elevation takes the following form:

$$\eta = |\psi|[\cos(kx + ly - \omega t) + \cos(kx - ly - \omega t + \delta)], \quad (9)$$

from which the envelope of η can be computed by considering the analytical signal and it results in

$$\eta_{env} = |\psi|\sqrt{2}\sqrt{1 + \cos(2ly - \delta)}. \quad (10)$$

For any value of the phase mismatch δ, it is possible to find a coordinate y for which the argument of the cos function is zero, so that the $\eta_{env} = 2|\psi|$. Equation (8) is the standard NLS equation and admits exact breather solutions [*Akhmediev et al.*, 1987; *Kuznetsov*, 1977; *Ma*, 1979]. Here we will concentrate our analysis on the so-called *Akhmediev breather* which describes the modulational instability also in its nonlinear stages. The solution is periodic in space and, depending on the choice of the parameters, the maximum amplification factor can range from 1 to 3 (the latter case corresponds to the Peregrine solution [*Peregrine*, 1983]). The breather has the following analytical form:

$$\psi(x,t) = \psi_0\left(\frac{\sqrt{2}\tilde{\nu}^2\cosh[\Omega t] - i\sqrt{2}\tilde{\sigma}\sinh[\Omega t]}{\sqrt{2}\cosh[\Omega t] - \sqrt{2 - \tilde{\nu}^2}\cos[Kx]} - 1\right)e^{i(\xi+2\zeta)|\psi_0|^2 t}, \quad (11)$$

with

$$\tilde{\nu} = \frac{K}{\psi_0}\sqrt{\frac{-\alpha}{(\xi + 2\zeta)}}, \quad \tilde{\sigma} = \tilde{\nu}\sqrt{2 - \tilde{\nu}^2}, \quad \Omega = -(\xi + 2\zeta)\,|\psi_0|^2\tilde{\sigma}. \quad (12)$$

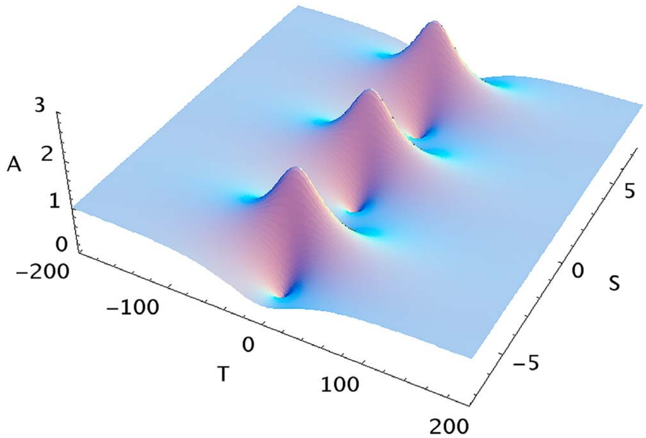

Figure 6. The Akhmediev solution: normalized wave envelope as a function of nondimensional time T and space S.

K is the wave number of the perturbation. The solution is periodic in space. It is straightforward to show that for large negative times, the solution corresponds to $\psi_0 \exp(i\phi)(1 + \delta \cos(Kx))$; Ω is the exponential growth rate of the perturbation. In Figure 6 we show an example of such solution with $|\psi|_{max}/|\psi_0| = 2.4142$.

[16] We now turn our attention to the Louis Majesty case and apply our NLS tool and its solutions to the sea state condition during which the accident has happened. The goal is to verify if rogue waves (breathers) are eventually consistent with the sea state conditions. We have mentioned since the beginning that the model we use should be considered as a prototype whose goal is to highlight some physical behavior rather than furnishing quantitative results. Indeed, the CNLS model requires a number of hypotheses in its derivation and just the leading order physics (which includes nonlinearity and dispersion) is contained. Note that such approach has been very successful in the case of a single NLS: it has been found that the breather solutions of NLS exist also in real water (this was not obvious *a priori*): they have been successfully generated in wave tank facilities [*Clauss et al.*, 2011; *Chabchoub et al.*, 2011; *Karjanto and Van Groesen*, 2010].

[17] The significant wave height, H_s, at the time of the accident was estimated around 5 m. The sea state condition was characterized by two wave systems with more or less the same amplitudes traveling at an angle. Approximately, each wave system had a significant wave height of $H_{sA} = H_{sB} = H_s/\sqrt{2} \simeq 3.5$ m. Excluding the Stokes contribution which, for moderate steepness, brings some small asymmetries in deep water, wave packets in each wave system are characterized by an amplitude $\psi_0 = 1.7$ m. The frequency of both systems is around 0.1 Hz, therefore $\kappa = \omega^2/g = \simeq 0.04\ \mathrm{m}^{-1}$. The estimated steepness, estimated as $H_{sA}\kappa/2 = \psi_0\kappa$ for each wave system is 0.07. In the presence of a single wave system, the modulational instability would hardly manifest itself. However, as we have discussed, the presence of a second wave system may cause an instability and the formation of a rogue wave. In order to depict the solution for the crossing sea condition the parameter K (see equation (12)) must be selected. From a physical point of view such parameter corresponds to the wave number of the perturbation of the plane wave, which, given κ, is related to the number of waves under the wave packets. Ocean wind wave packets, depending on the spectral shape, are characterized by an average of $N = 3$–5 waves under each wave packet corresponding to 6 to 10 waves in a time series [see *Onorato et al.*, 2000]. For our analysis we choose $N = 4$ as a reference number; therefore, $K = \kappa/N = 0.01\ \mathrm{m}^{-1}$. We are ready to build the breather solution and study the dependence of its maximum as a function of the angle between the two sea states. In Figure 7 we show the maximum amplitude reached by the breather for the parameters selected before as a function of the angle β between the two wave systems. The figure shows that the maximum crest (the Stokes contribution is excluded) achievable within the Akhmediev solution oscillates between about 8 to 10.1 m (note that one should include the Stokes correction to establish the crest amplitude). The amplitude increases for angles approaching 70.52°. For larger angles the

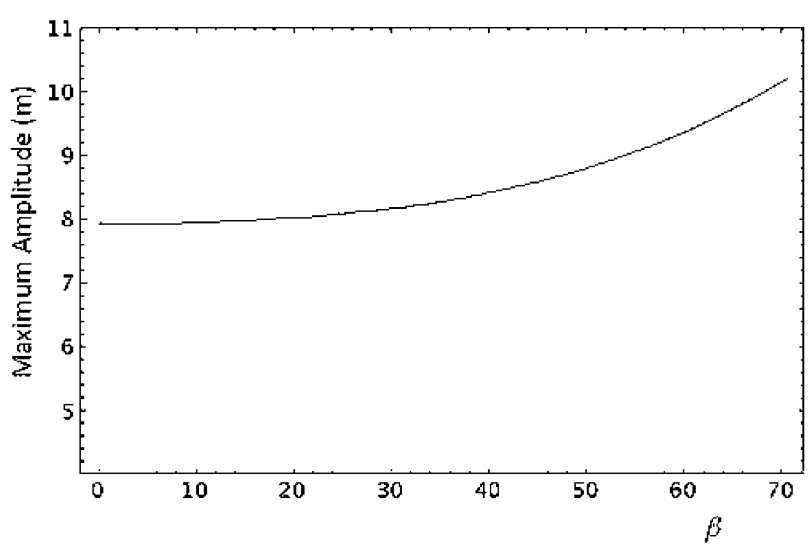

Figure 7. The maximum crest amplitude of the Akhmediev breather for the Louis Majesty sea state conditions as a function of the angle between the two wave systems.

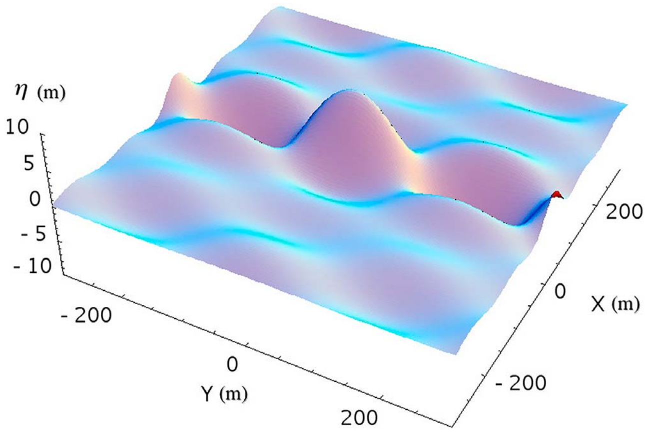

Figure 8. The surface elevation corresponding to the breather solution with the angle β between the two wave systems equal to 50°.

breather solution does not exist because the CNLS equations becomes of defocussing type. The angle between the two sea states during the Louis Majesty accident was $40° < \beta < 60°$, therefore the estimated maximum wave amplitude oscillates between 8.4 and 9.4 m. An example of the surface elevation reconstructed with equation (9) and computed for $\beta = 50°$ is shown in Figure 8 where it is highlighted the nature of the rogue wave as a short crested isolated structure close to which two deep holes are present. The maximum amplitude is 8.8 m.

5. Discussion and Conclusions

[18] The Louis Majesty accident is one of the many which have happened due to bad weather in the sea [see, e.g., *Toffoli et al.*, 2005]. A natural question which everybody wishes to answer is if the wave that caused the damage was a rogue wave. In our opinion such question cannot have a scientific answer. First of all, there is not a unique and accepted definition of rogue wave in the scientific and engineering community; second, we do not have any scientific measurements of the wave. The only unambiguous information is that the wave hit the windows at deck number 5, located at 16.70 m above the mean floating line. The impact of the wave on the ship was strong enough to break the windows, not just the tip of the wave bang into them. This means that the wave reached probably higher decks (even though no damage was reported). Moreover, a likely possibility is that the pitch due to the previous wave exposed the deck 5 to the subsequent large wave.

[19] Despite such considerations, modern numerical and mathematical instruments allow us to make some in depth analysis of the sea state conditions in which the accidents has happened and highlight some mechanism which can be responsible for the formation of rogue waves. In this context, we have performed a detailed hindcast of the region of the accident with WAM. The significant wave height from the model has been found to be consistent with the one from the Begur buoy, located 25 km off the position of the accident. Results indicate that the significant wave height was approximately 5 m. Such condition is surely not prohibitive for a ship like the Louis Majesty (207 m long and 41,000 gross tonnage). However, the directional spectra from the model show the coexistence of two systems traveling at an angle between 40° and 60°, characterized by similar peak frequencies (0.1 Hz) and similar amplitudes. In the limit that both systems are narrow banded (and this is probably the strongest assumption), a system of two coupled Nonlinear Schrödinger equations can be considered for modeling deterministically the wave conditions. Using the parameters from the hindcast we have considered the Akhmediev breather solutions of such system. The present approach, even if somehow naive, allows one to estimate the maximum wave height within a nonlinear theory. Results indicate that the maximum wave amplitude (10.1 m) is achieved for angles approaching 70°. For smaller angles, characteristic of the Louis Majesty situation, the maximum crest amplitude of the breather tends to approximately 8 m. Note that, assuming a linear dynamics, following the Rayleigh distribution, a crest larger than 8 m would have a probability of $1.27\ 10^{-9}$. One may also think that currents could have played a role in the formation of the rogue wave. However, as shown in *Bolanos-Sanchez et al.* [2009] the flow is locally toward SW, parallel to the coast; its speed is not significant for our purposes (less than 0.5 m/s), and in any case, given the similar propagation directions, it would have acted to lower the local wave height.

[20] While not essential for the analysis, we point out that the storm was forecast well in advance. Table 1 shows the ratio between the forecast H_s at the Louis Majesty time and position and the following analysis values of ECMWF. An analysis of the related 2D spectra (not reported here) shows clearly the presence of the two cross wave systems. We stress the reliability of the present forecast systems (statistics are available at http://www.ecmwf.int/products/forecasts/wavecharts/index.html) [see also *Janssen*, 2008]. Note that the forecasts include an estimate, at each time and position, of the probability of rogue waves, as a function of the local wave conditions.

[21] It should be stressed that our analysis does not represent a prove that the Louis Majesty has been hit by a rogue wave (surely the wave was large enough to reach the deck number 5 and create damages). Our aim is to devise a physical mechanism which could be suitable for explaining the presence of rogue waves in crossing seas. In this context the approach based on the CNLS equations has allowed an interesting analysis on the crossing sea conditions. Needless to say that the NLS type of equations are the simplest approximation possible which contain nonlinear and dispersive effects; despite their simplicity, in the past the single NLS equation has furnished very important results which have allowed a deep understanding of the physical

Table 1. Wave Forecasts of the European Centre for Medium-Range Weather Forecasts[a]

Forecast Range (days)	fc/an
1	0.98
2	0.97
3	1.01
4	1.00

[a]Here fc/an shows the average ratio between the H_s at different forecast range and the corresponding analysis. An area of $1° \times 0.5°$ around the location of the accident has been considered.

phenomena of rogue waves. We hope that the present results will stimulate further research in this direction.

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