Probability of occurrence of rogue sea states and consequences for design

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Banff, 29 October 2013

MANAGING RISK

EXTREME SEAS
Design for Ship Safety in Extreme Seas

- **Work Programme:**

 2008, Cooperation Theme 7, Transport,

 7.2 Sustainable Surface Transport (SST), FP7- SST – 2007- RTD-1

- **Activity:** 7.2.4 Improving Safety and Security

- **11 Partners from six European countries**.
- **Starting Date:**

 1st Sept. 2009 – 30 April 2013

- **Coordinated by DNV; with the overall objectives:**
- To develop **technology and methodology that need to be a part of design for ship safety in extreme seas**.
- To develop **warning criteria for extreme sea states** for marine structures **.**
- To help shipping industry **to adapt to climate change.**
- **Budget: 4.1 million Euro**

ExWaCli

Extreme waves and climate change: Accounting for uncertainties in design of marine structures

Forskningsrådet

- **The Research Council of Norway (RCN) project**
- **Funded**: 40% by RCN, 60% by the Partners
- **Partners**
  - DNV
  - The Norwegian Meteorological Institute
  - The University of Oslo
  - Expected external participants
- **Starting Date:**

1st January 2013 – 30 December 2015

- **Managing by DNV; with the overall objectives:**
  - To understand how **climate change** will impact **wave conditions** in the northern areas **the 21st century** and specifying **uncertaintie**s associated with the predicted changes;
  - To suggest **an integrated approach** that handles the uncertainties associated in climate change projections of and take this **into account in current design and operation** of marine structures.
  - **Recommendations f**or design and operations of marine structures.
- **Budget: ca. 1.3 million Euro**

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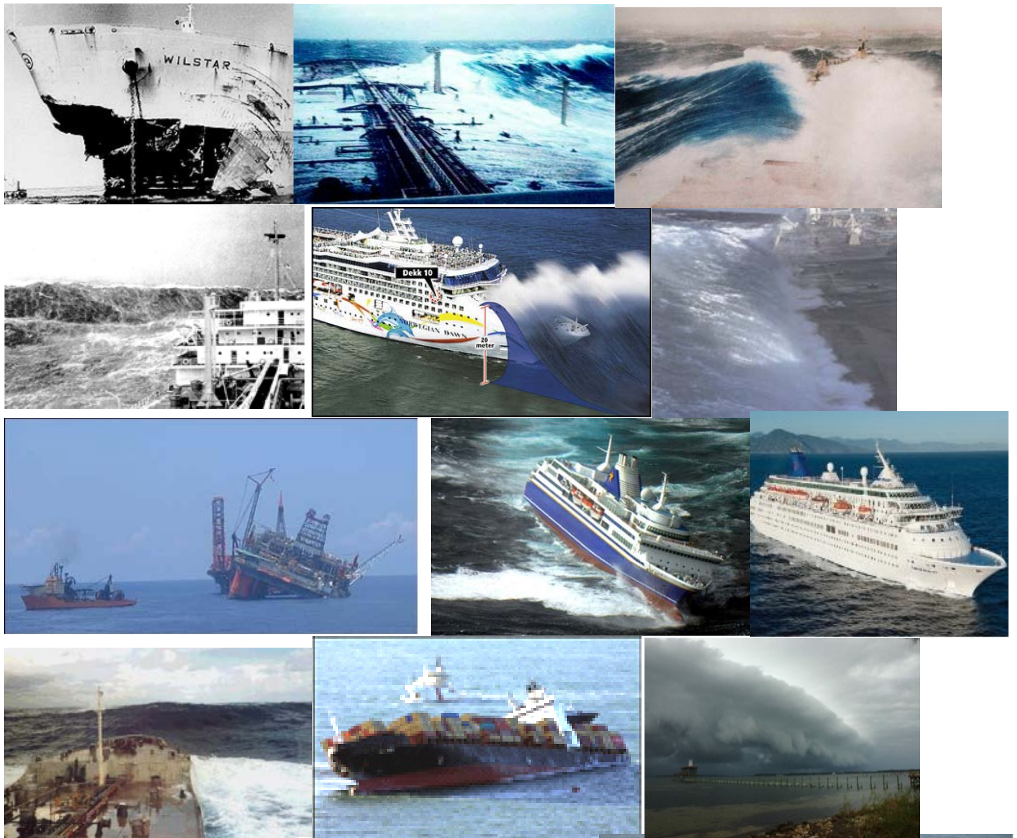
Background for the study



- **Abnormal waves,** called also **rogue** or **freak**
- **The risk for ships** and **offshore structures** to encountering **dangerous sea states** has been emphasized by **news-media** within the last years with increasing frequency.
- Especially **accidents** with subsequent **pollution of large coastal areas** (Erika, Prestige, MSC Napoli), **ship damage** (Caledonia Star, Bremen, Schiehallion, Explorer, Voyager, Norwegian Dawn) and **human injuries** (e.g. Norwegian Dawn, Louis Majesty) have highlighted that improvements are needed to reduce the risk of these types of accidents.
- The **recent hurricanes** in the **Gulf of Mexico** have confirmed that extreme sea states can be dangerous for marine structures.

- **Questions arisen**

Are design and operation changes due to rogue waves needed?

EXTREME SEAS

How to design and operate in extreme seas?

Will we see more of these waves in the changing climate?

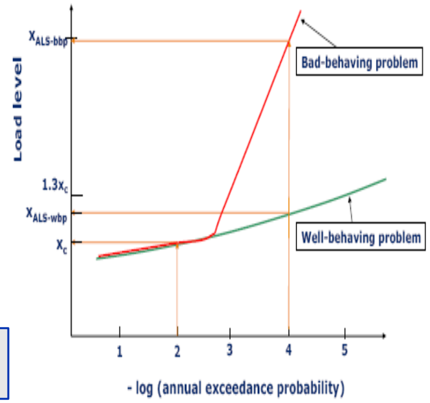
ExWaCli

Mars after Hurricane Katrina August 05

Background for the study
Design practice for marine structures

Offshore structures

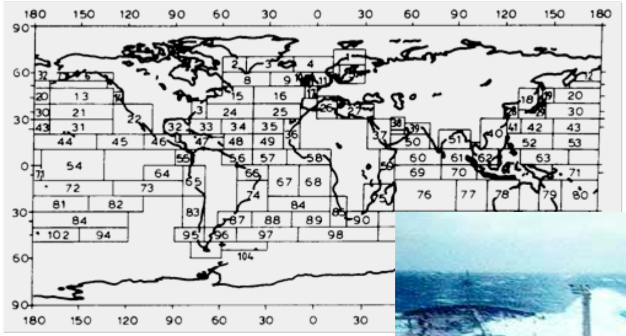
- **ULS** - for **a specific location,** a structure has to sustain the **100 year load level without damage**.
- **ALS - Norwegian Standard NORSOK** (2007) requires that there must be enough room for the **wave crest to pass beneath the deck** to ensure that **a 10 000-year wave load does** not endanger **the structure integrity**.



Ilustration of ULS control, Haver (2004

Ship structures

- **ULS** - for the **North Atlantic wave climate** (8, 9,15 &16) **, a** ship has to sustain the **20 year (25 year) load level without damage**.
- **ALS** - **grounding, collision** and **fire** and **explosion**



- **What is probability of occurrence of rogue waves?**

Background for the study
Mechanism generating rogue waves

- **Probability of occurrence of rogue waves is mandatory for any revision of Classification Societies' Rules and Offshore Standards.**
- **Probability of occurrence of rogue waves is related to mechanisms responsible for generation of these abnormal waves.**
- **A definition of extreme sea states and a rogue wave required.**

- **Recognized mechanisms for the formation of extreme & rogue waves:**

  - linear Fourier superposition (frequency or angular linear focussing)
  - **wave–current interaction**
  - **crossing seas**
  - **nonlinear interactions & modulational instability**
  - **shallow water effects**
  - **wind**

- **Rogue Sea State** (**due to Miguel Onorato**) **characterized by large steepness** and a **narrow wave spectrum**, **both in frequency and direction**.
  - The **Benjamin Feir Index** (BFI) - a measure of the relative importance of nonlinearity and dispersion, BFI=$(k_p H_s/2)/(\Delta\omega/\omega_p)$
  - **High wave steepness, directional spreading-** ca. **30 degrees, Waseda et al. (2011)**

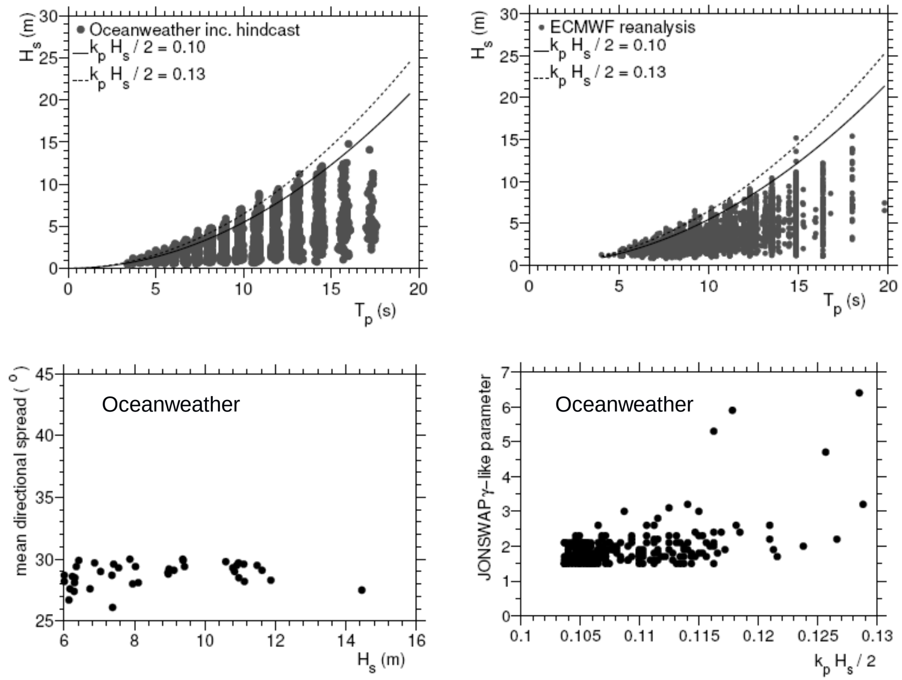
Probability of occurrence of rogue waves

The study refers to:

- Modulational instability due to quasi-nonlinear interactions
- Deep water wave trains propagating outside the influence of ocean currents (thus, effects related to wave-current interaction and bottom topography are excluded).
- Total sea, hindcast data

- **Bitner-Gregersen, E. M. and Toffoli, A. (2012**). On probability of occurrence of rogue waves. *Natural Hazards and Earth System Sciences*, 12, 751–762, 2012, doi:10.5194/nhess-12-751-2012.
- **Directional spreading-** ca. **30 degrees, Waseda et al. (2011)**
- The investigations carried out by **Bascheck and Imai (2011)** support the conclusions of the study.

- **Total sea: Oceanweather data (10-yr data) & ECMWF data (ca.10-yr data)**



The directional spreading was below **30 degrees** for approximately **17%** of the records with **Hs > 6m** and **kpHs/2 > 0.10. The largest sea state (Hs>15m); kpHs/2~0.13**

IACS - kpHs/2 = 0.11–0.13 and **Hs =16.5 m**

Probability of occurrence of rogue waves
Crossing seas

- The set of **Coupled Nonlinear Schrödinger** (CNLS) equations, Onorato et al., (2006, 2010)

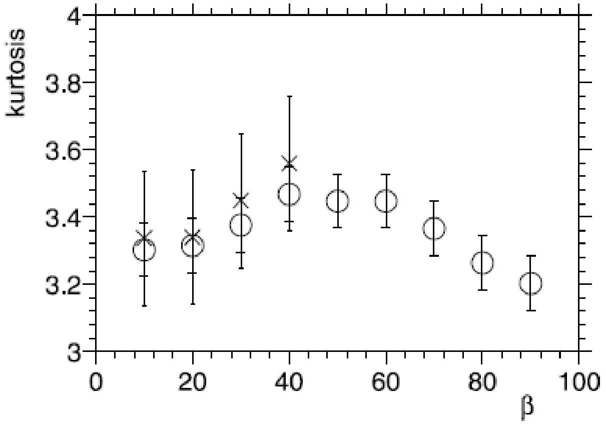
$$\frac{\partial A}{\partial t} - i\alpha\frac{\partial^2 A}{\partial x^2} + i(\xi|A|^2 + 2\varsigma|B|^2)A = 0$$

$$\frac{\partial B}{\partial t} - i\alpha\frac{\partial^2 B}{\partial x^2} + i(\xi|B|^2 + 2\varsigma|A|^2)B = 0$$

where *A* and *B* denote complex wave envelopes, α, ξ and ζ are coefficients.

- As the angle between two wave trains *β* approaches ***β*$_c$ ≈ 70.53,** the **ratio between nonlinearity and dispersion**, a measure for the presence of extreme waves increases substantially (see Onorato et al., 2010).
- For ***β* > *β*$_c$**, however, the ratio changes sign and the CNLS equations change **from focusing to defocusing.**
- **Energy and frequency of two wave trains almost the same and crossing at the angle angle 40º < *β* < 60º**

- **Numerical simulations** of the Euler equations carried out by the **Higher Order Spectral Method** (HOSM) proposed by West et al. (1987) and experimental work performed out in the **MARINTEK Laboratories** (Toffoli et al. 2011)



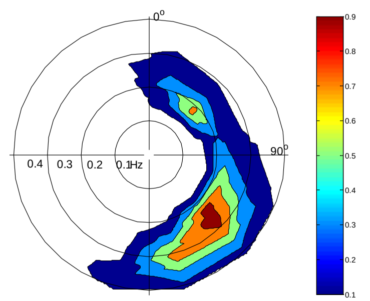
Maximum recorded kurtosis as a function of *β*:laboratory experiments (crosses); numerical simulations (circles).

- **Angle 40º < *β* < 60º**.

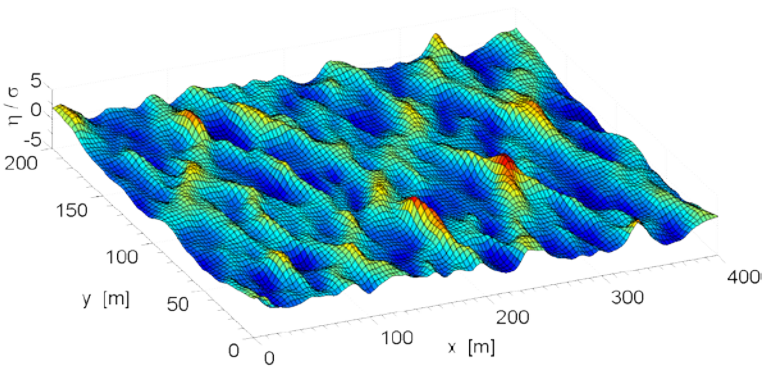
Toffoli, A. Bitner-Gregersen, E. M., Osborne, A. R. Serio, M., Monbaliu, J. and Onorato, M., (2011). Extreme Waves in Random Crossing Seas: Laboratory Experiments and Numerical Simulations. Geophysical Research Letters, Vol. 38, L06605, doi:10.1029/2011GL046827

Probability of occurrence of rogue-prone crossing seas

- **We can generate rogue-prone crossing seas in the laboratory and by the numerical models.**

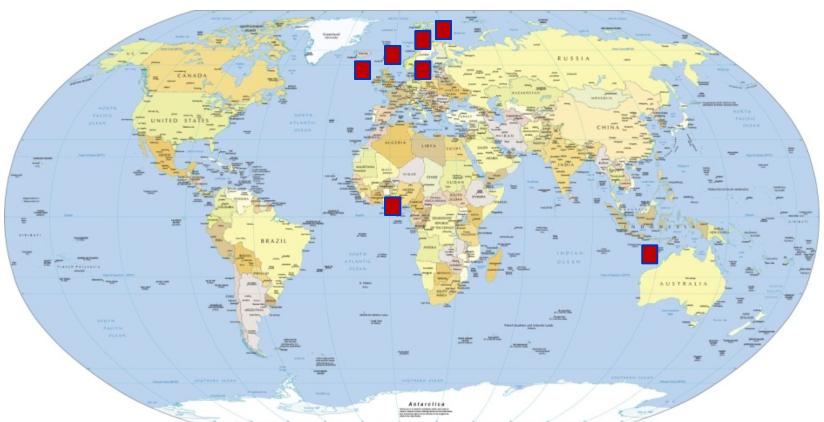


HOS simulations



- **Can combined wave systems with almost the same *Hs* and *Tp* and we observe them in the nature? How frequent they will occur?**

- **Hindcast data from several locations**
  - **North Atlantic**: NORA10 (1958-2009), ECMWF ERA-Interim data (1989-2008).
  - **Northern North Sea** and the **Norwegian Sea**: Statfjord (1955-2000) , Halten ((1955-2000) and Væring (1955-2000)
  - **NWS Australia** (1994-2005) , **off coast of Nigeria (1985-1999)** and **the Southern North Sea** (1964-1995)



The locations characterised by different wave climate

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Probability of occurrence of rogue-prone crossing seas

- **Scatter diagrams** of (Hs, Tp) have been established and fitted by the **joint model** (see for review Bitner-Gregersen, 2012)

$$f_{H_S}(h_s)=\frac{\beta}{\alpha}\left(\frac{h_s-\gamma}{\alpha}\right)^{\beta-1}\exp\left\{-\left(\frac{h_s-\gamma}{\alpha}\right)^{\beta}\right\}$$

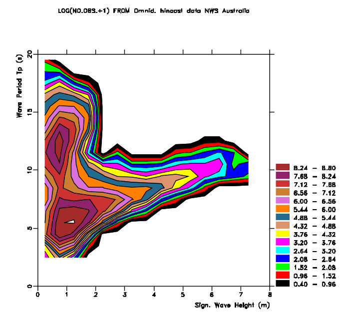
$$f_{T_p|H_{m0}}(t_p\,|\,h_s)=\frac{1}{\sigma(h_{m0})t_p\sqrt{2\pi}}\exp\left\{-\frac{(\ln t_p-\mu(h_{m0}))^2}{2\sigma(h_{m0})^2}\right\}$$

$$\mu=\mathrm{E}(\ln T_p)=a_1+a_2h_{m0}$$

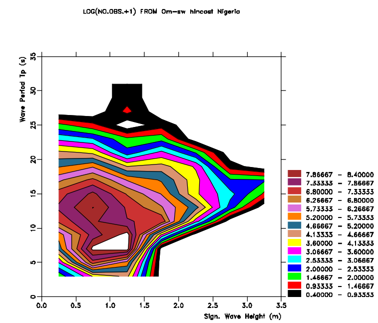
$$\sigma=\mathrm{Std}(\ln T_p)=b_1+b_2e^{b_3h_{m0}}$$

where α is a scale parameter, β a shape parameter and γ a location parameter, the coefficients a_i, b_i, $i=1,2,3$ are estimated from data for the actual location.

- **Example of the scatter diagrams**

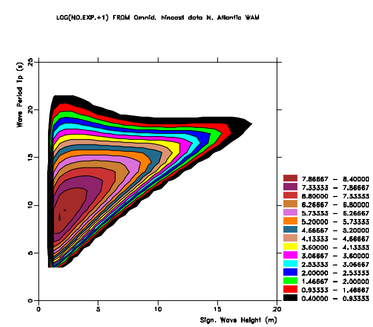


NWS Australia

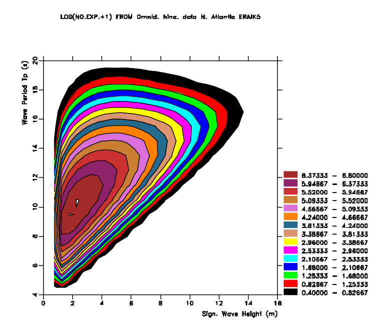


Nigeria

- **Examples of the fits, North Atlantic**



NORA10

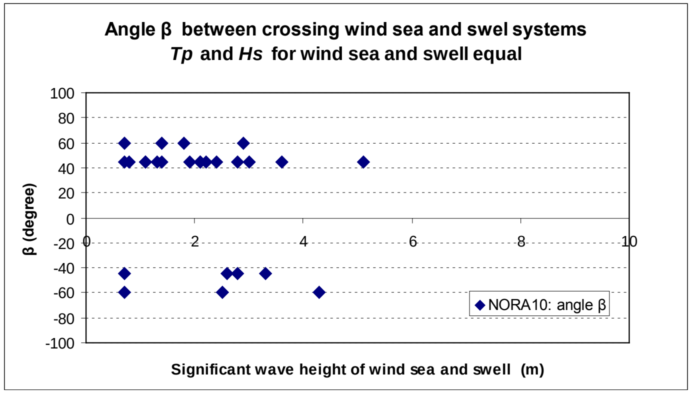


ERAIterim

Probability of occurrence of rogue waves
Crossing seas

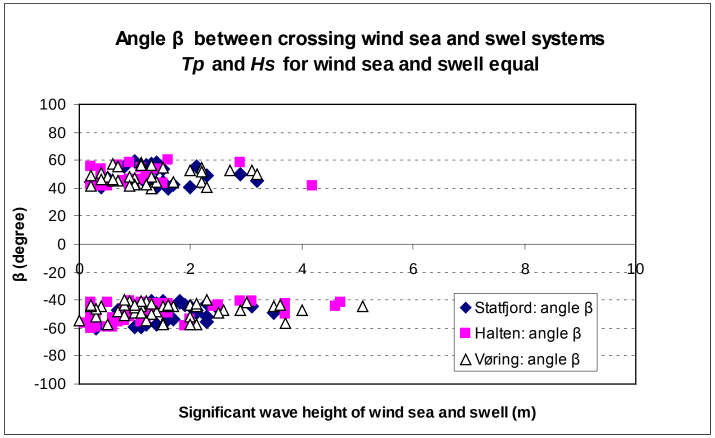
- Occurrence **of wind sea** and swell having almost **the same spectral period (Tp_{w}~Tp_{s})** and **significant wave height (H_{sw}~H_{ss})** and crossing at the **angle 40º < β < 60º**

- **The North Atlantic, NORA10 data**



- Observed only for **low** and **intermediate sea states** with the total Hm0 in the range **1.0-7.2 m** and there are more of them for significant wave height lower than 2.5 m. **Totally 27 crossing seas satisfying** the significant wave height, spectral period and the angle *β* **criteria** have been identified

- **The Northern North Sea and the Norwegian Seas**



- Wind sea and swell systems satisfying the criteria: **56 crossing seas for Statfjord, 74 for Halten and 81 for Vøring**; again majority of them are in **low sea states** and some in **the intermediate sea states** with the **total significant wave height** in the range **0.4-7.2 m.**

- **Not observed in NWS Australia, Nigeria and the Southern North Sea.**

Rogue-prone crossing seas- consequences for design

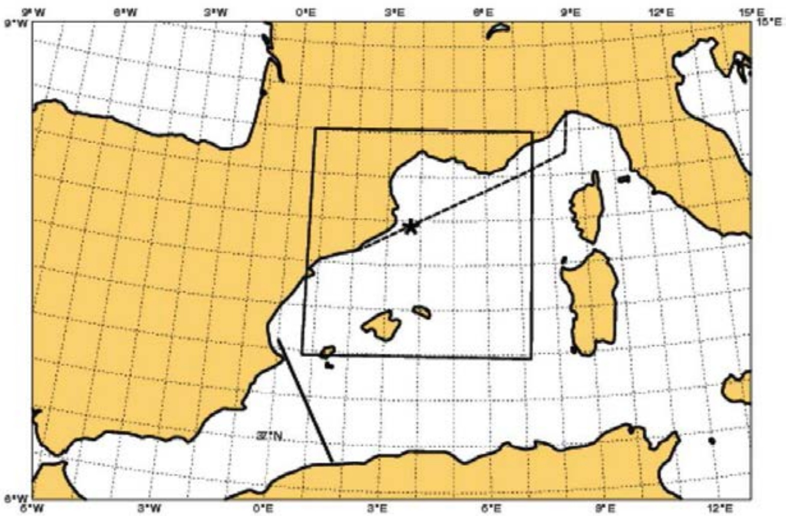
- Rogue-prone seas due to **quasi-resonant interactions** (modulational instability) can occur in **low, intermediate and high sea states**, Bitner-Gregersen and Toffoli (2012). This type of sea states can have **impact on design loads and responses of marine structures** depending on how frequent they can occur in the North Atlantic and in specific locations.

- The present study indicates that **rogue-prone crossing seas** can be found only in **low and intermediate sea states**. Their **occurrence depends on local wave climate features** typical for a specific location. These rogue-prone sea states can be expected to **impact operational conditions of marine structures but may also influence weather restricted design as well as design of local loads.**

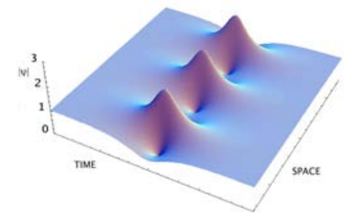
Louis Majesty accident

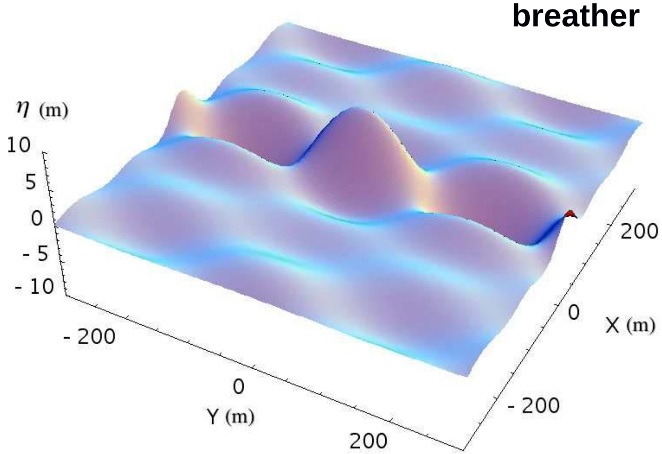
- **Louis Majesty, 3 March 2010** – **WAM** and the Coupled Nonlinear Schrödinger equations, **CNLS**

L. Cavaleri, L. Bertotti, L. Torrisi, E. Bitner-Gregersen, M. Serio, and M. Onorato (2011). Rogue waves in crossing seas: the Louis Majesty accident. JGR.

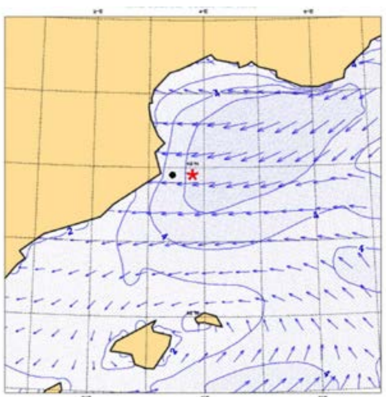


Akhmediev breather

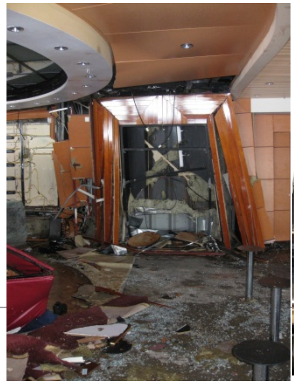




The surface elevation corresponding to the breather solution with β= 50º



Two wave systems from ENE and SE of **similar frequencies and energy** coexisted. 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**.
Hws=1=Hss ≃ 3:5 m, Hs=5 m
Tp ≃ 10 s, steepness=0.07, Amax=8.8 m



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Louis Majesty Cruise accident

http://www.youtube.com/watch?feature=player_detailpage&v=lvOceI6egg0

Owner: **Majesty Cruise Line (1992–1997)**
Norwegian Cruise Line (1997–2004)
Star Cruises (2004–2008)
Louis Cruise Lines (2008–present)

Operator: Majesty Cruise Line (1992–1997)
Norwegian Cruise Line (1997–2009)
Louis Cruise Line (2009–2012)
Thomson Cruises (2012–present)

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Conclusions

- The study points out that **rogue-prone crossing** wave systems responsible for generation of abnormal waves **can occur** primarily in **low and intermediate sea states**.
- **Their occurrence is location specific**, depending strongly on local features of wave climate. They are not expected to be present in the locations where wind sea and swell components, or several swell components, are well separated characterised by significantly different spectral peak periods.
- **These wave systems can be dangerous for marine structures** depending on a type and size of a structure, as demonstrated by Cavaleri et al. (2012) for the cruise ship.
- They are expected to have **most impact on operations of ships and offshore structures**, but may also influence weather restricted design as well as design of local loads.
- **Uncertainties** of the data used in the study affect the presented results.
- Development of **warning criteria for rogue-prone sea states** is called for.
- **Change of storm tracks in some ocean regions**, due to changing climate, may lead to secondary effects such as **increase the frequency of occurrence of combined wave systems** leading consequently to more frequent rogue events.

Probability of occurrence of rogue sea states and consequences for design

THANK YOU FOR YOUR ATTENTION

ACKNOWLEDGEMENTS

The authors are indebted to **met.no** and **Shell** for providing the wave data.

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