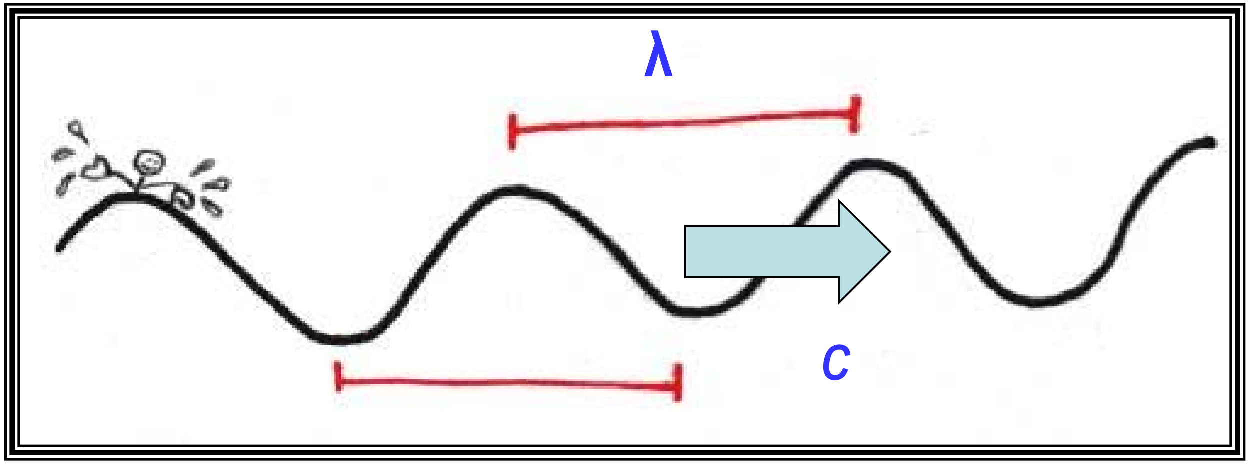
EXTREME WAVES: THEIR OBSERVATION AND THEIR GENERATION

Frédéric DIAS, University College Dublin

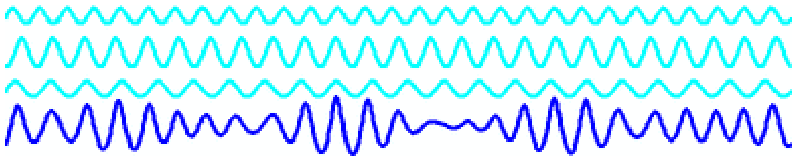
John Dudley, Claudio Viotti, Denys Dutykh, Roxana Tiron, Sarah Gallagher and others

WATER WAVES ARE DISPERSIVE

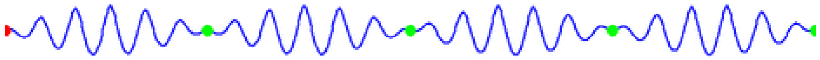


Their speed of propagation c depends on the wavelength λ. The longer the waves, the faster they travel! When the waves are very long (with respect to the water depth for example), their speed only depends on the water depth h.

WATER WAVES ARE DISPERSIVE



Superposition of three sine waves, with respectively 22, 25 and 29 wavelengths fitting in a horizontal domain of 2 km length.
The wave amplitudes of the components are respectively 1, 2 and 1 metre.
The differences in wavelength and phase speed of the components result in a changing pattern of wave groups.



The red dot moves with the phase velocity, and the green dots propagate with the group velocity. In this deep-water case, the phase velocity is twice the group velocity. The red dot overtakes two green dots, when moving from the left to the right of the figure.

CATEGORIES OF OCEAN WAVES

- STORM WAVES : wind surface waves that reach unusually large amplitude due to forcing by strong winds. For example, gale to hurricane force winds ranging from 8 to 12 on the Beaufort scale can produce maximum wave heights from 7.5 m to > 16 m (periods smaller than a minute)

- TSUNAMIS : generated from a sudden impact on the ocean caused by earthquakes, landslides or volcanoes displacing large volumes of water (linear shallow water wave during the propagation phase)

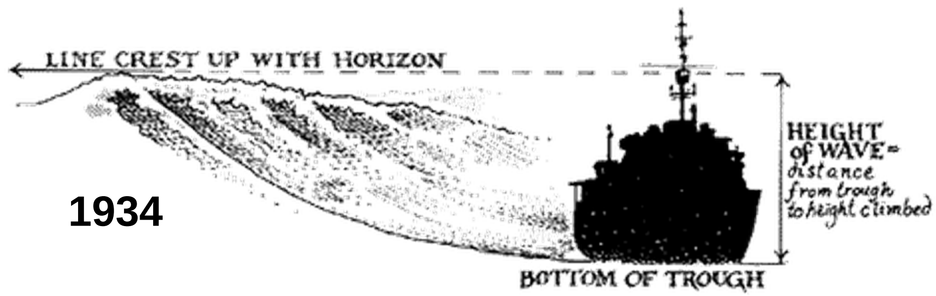
  Storm surges : increase in the level of sea surface associated with low atmospheric pressure – long-period wave (several minutes up to several days)

  Meteo-tsunami : also a long-period wave that possesses tsunami like properties but is meteorological in origin (maximum period does not exceed several hours)

... AND ROGUE WAVES

- Rogue Waves are large oceanic surface waves that represent statistically-rare wave height outliers

1934



Foremast

February 1986 - It was a nice day with light breezes and no significant sea. Only the long swell, about 5 m high and 200 to 300 m long. We were on the wing of the bridge, with a height of eye of 17 m, and this wave broke over our heads. Shot taken while diving down off the face of the second of a set of three waves. Foremast was bent back about 20 degrees (*Captain A. Chase*)

- Damage and fatalities when wave height is outside design criteria

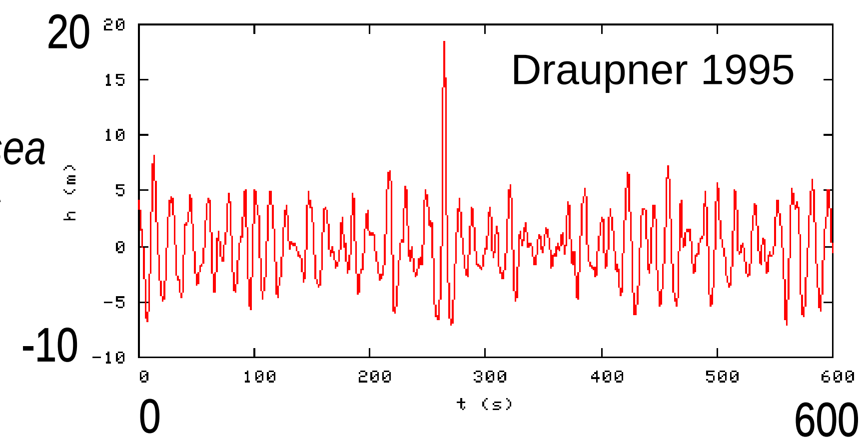
EXTREME OCEAN WAVES

- Definition of a Rogue Wave: $H / H_s > 2$ where H is the wave height (trough to crest) and H_s the significant wave height (average wave height of the one-third largest waves)

- Rogue waves are localised in space (order of 1 km) and in time (order of 1 minute)

- Existence confirmed in 1990's through long term wave height measurements and specific events (oil platform measurements)

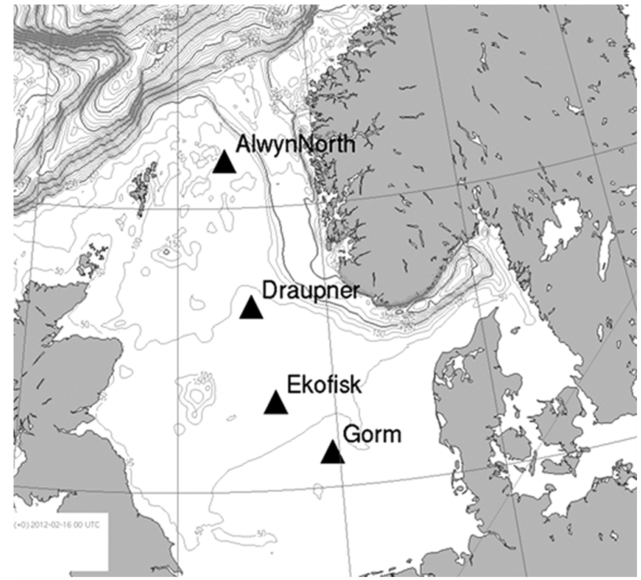
Elevation of the sea surface in metres

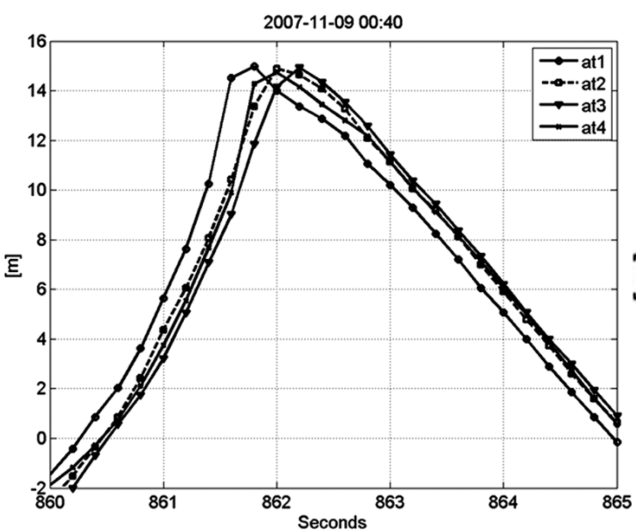


Time in seconds

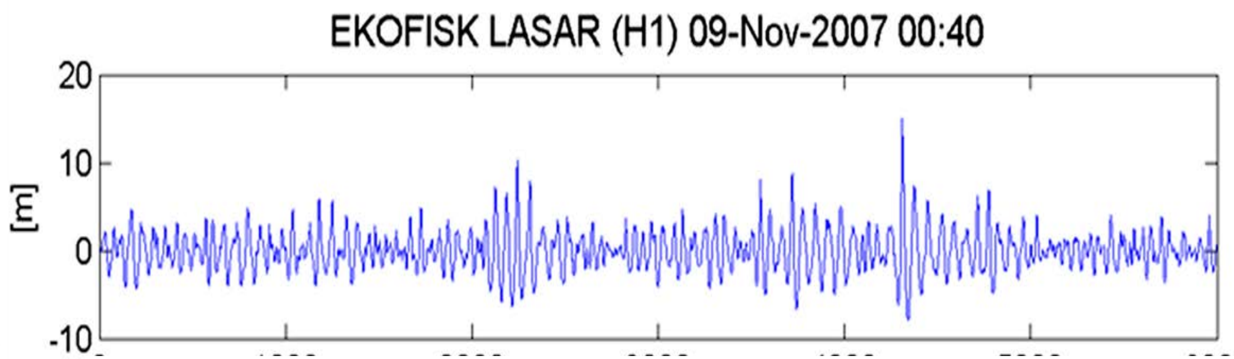
A NEW WELL DOCUMENTED ROGUE WAVE : THE ANDREA WAVE

Wave profiles have been measured with a system of 4 lasers mounted on a bridge at the oil production site Ekofisk in the central North Sea since 2003. A rogue wave was measured on Nov. 9, 2007 in a storm crossing the North Sea and named Andrea – Magnusson & Donelan (2013) “*The Andrea Wave Characteristics of a Measured North Sea Rogue Wave*”





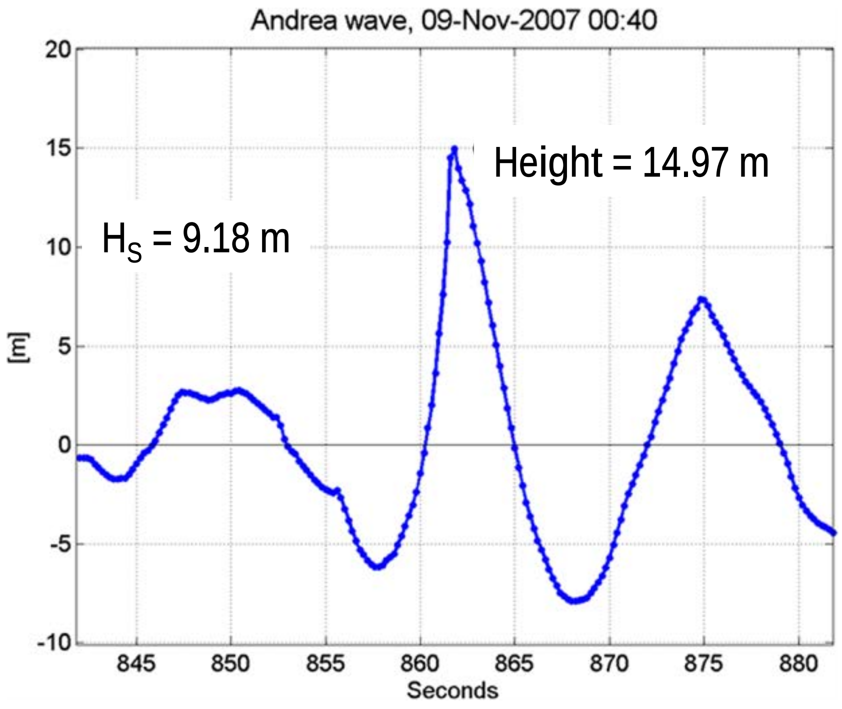
Time in seconds



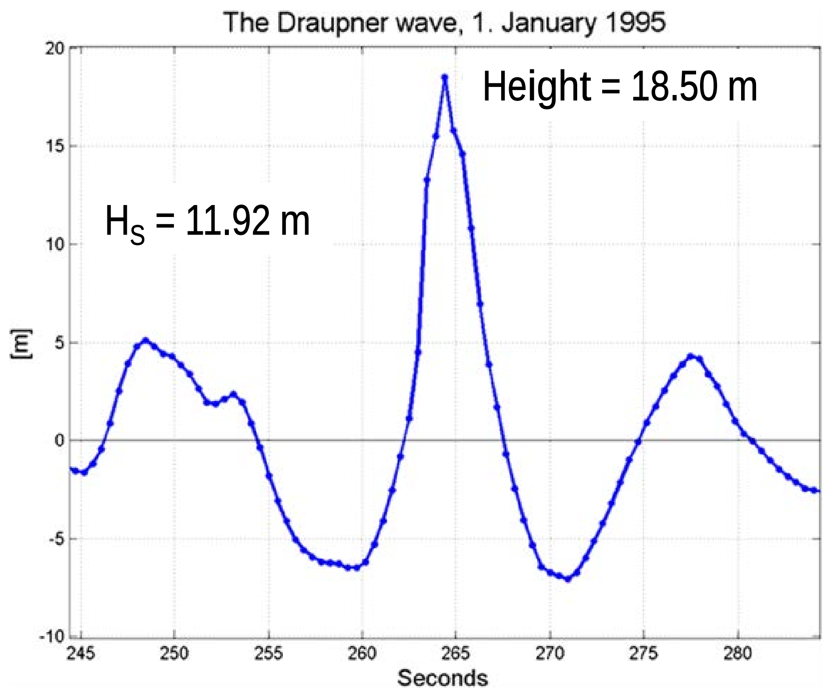
Wave profile time series during 20 min with 5 Hz sampling frequency

THE ANDREA WAVE VS THE DRAUPNER WAVE

The Andrea wave is comparable in height and characteristics to the well known 1995 Draupner wave. Front steepness is higher – Magnusson & Donelan (2013) "*The Andrea Wave Characteristics of a Measured North Sea Rogue Wave*"



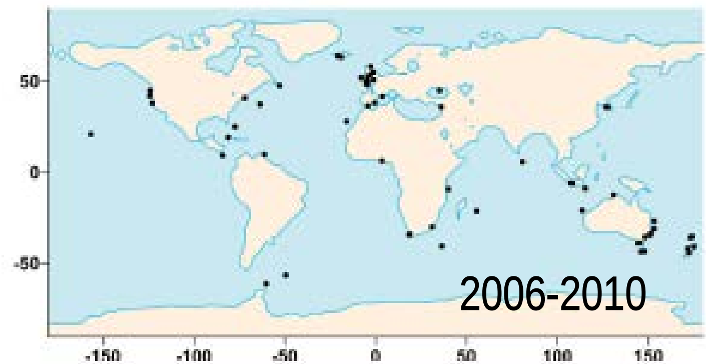
Time in seconds



Time in seconds

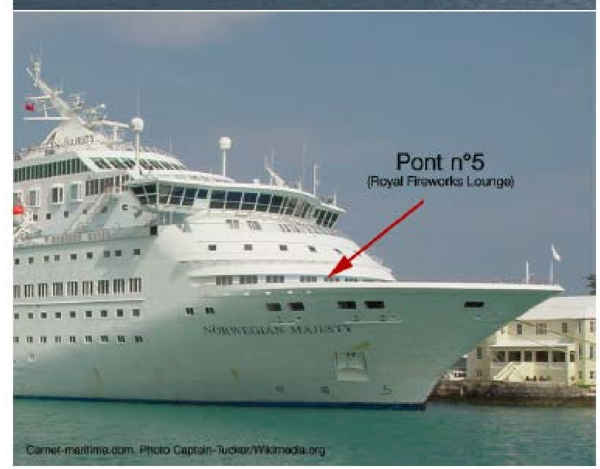
OCCURRENCE OF EXTREME OCEAN WAVES

Nikolkina & Didenkulova (2011)



MS Louis Majesty
3 March 2010
Spain
(2 casualties)

LÉ Róisín
5 October 2004
Ireland
(considerable damage)



EXTREME OCEAN WAVES

- The papers by Nikolkina & Didenkulova (2011) “*Rogue waves in 2006-2010*” and by O’Brien, Dudley & Dias (2013) “*Extreme wave events in Ireland: 14 680 BP–2012*” suggest that rogue waves occur not only in deep water but also in shallow water and along the coast.

- The $H / H_s > 2$ definition can still be used in shallow water. What about characterising rogue waves along the coast? One possibility is to compare the runup of rogue waves with significant runup. Unfortunately not much data.

$$\Downarrow$$

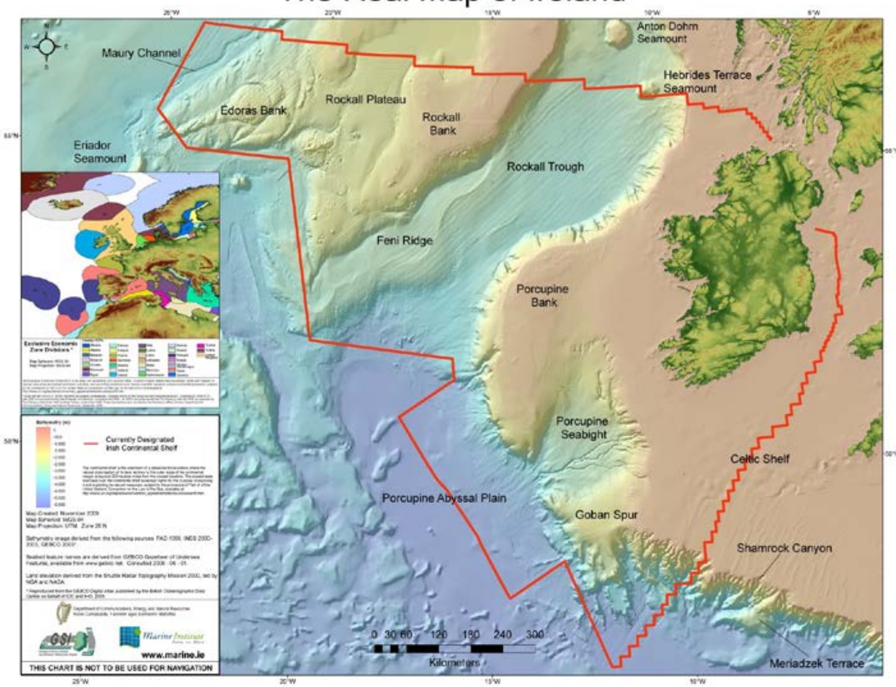
- A rogue wave along the coast is a wave that is either unexpectedly high or causes substantial damage (human fatalities and injuries, damage to coastal engineering structures, etc)

ROGUE WAVES IN IRELAND

- *Remark*: the phenomenon of rogue waves is probably much more frequent than generally thought.
- In the 2006-2010 count, there was a single rogue wave mentioned in northern Ireland.
- So our team decided to collect evidence for Ireland (Laura O'Brien, PhD student).
- What did we discover?

Ireland's current designated Irish Continental Shelf (November 2009) is one of the largest seabed territories in Europe !
(*Source = Marine Institute*)

The Real Map of Ireland



The Extreme Waves Map of Ireland

Ireland is battered by waves from all sides and has suffered many extreme oceanic events. From one of the largest known underwater landslides in the world at Storegga to the tragedy of the Fastnet Yacht race; from tsunamis in Kinsale to the navy vessel Róisín battered by rogue waves, it is clear that Ireland has experienced a wide variety of ocean extremes. This map presents the first catalogue of such events, dating as far back as the turn of the last ice age. Detailed studies of this kind are important both to understand the science of the ocean wave environment of Ireland, and also for applications such as improving the safety of shipping and coastal structures, and generating renewable energy from the sea. They can also provide new insights into myths and legends, and the origin of many unexplained features of our natural environment.

Extreme wave events in Ireland: 14680 BP–2012
L. O'Brien, J. M. Dudley and F. Dias. *Nat. Hazards Earth Syst. Sci.*, **13**, 1-24, 2013

Legend

Storm Waves

- S1 1837, 1861, 1894, 1935, 1987, 1988 and 1989 The Mullet Peninsula, Co. Mayo
- S2 1869 and 1881: Calf Rock, Co. Cork
- S4 1864: Valentia, Co. Kerry
- S5 1877: Railway Lines, Co. Dublin and Co. Wicklow
- S6 1899: Greenore, Carlingford Lough, Co. Louth
- S7 1941: Inisheer Lighthouse, the Aran Islands
- S8 1945: Rosslare, Co. Wexford
- S9 1951: Kilkee, Co. Clare
- S10 1953: the Aran Islands
- S11 1962: Co. Cork
- S12 1974: Kilmore, Co. Wexford
- S13 1979: Fastnet Race
- S14 1982: Ventry, Co. Kerry
- S15 1985: Fastnet Rock Lighthouse

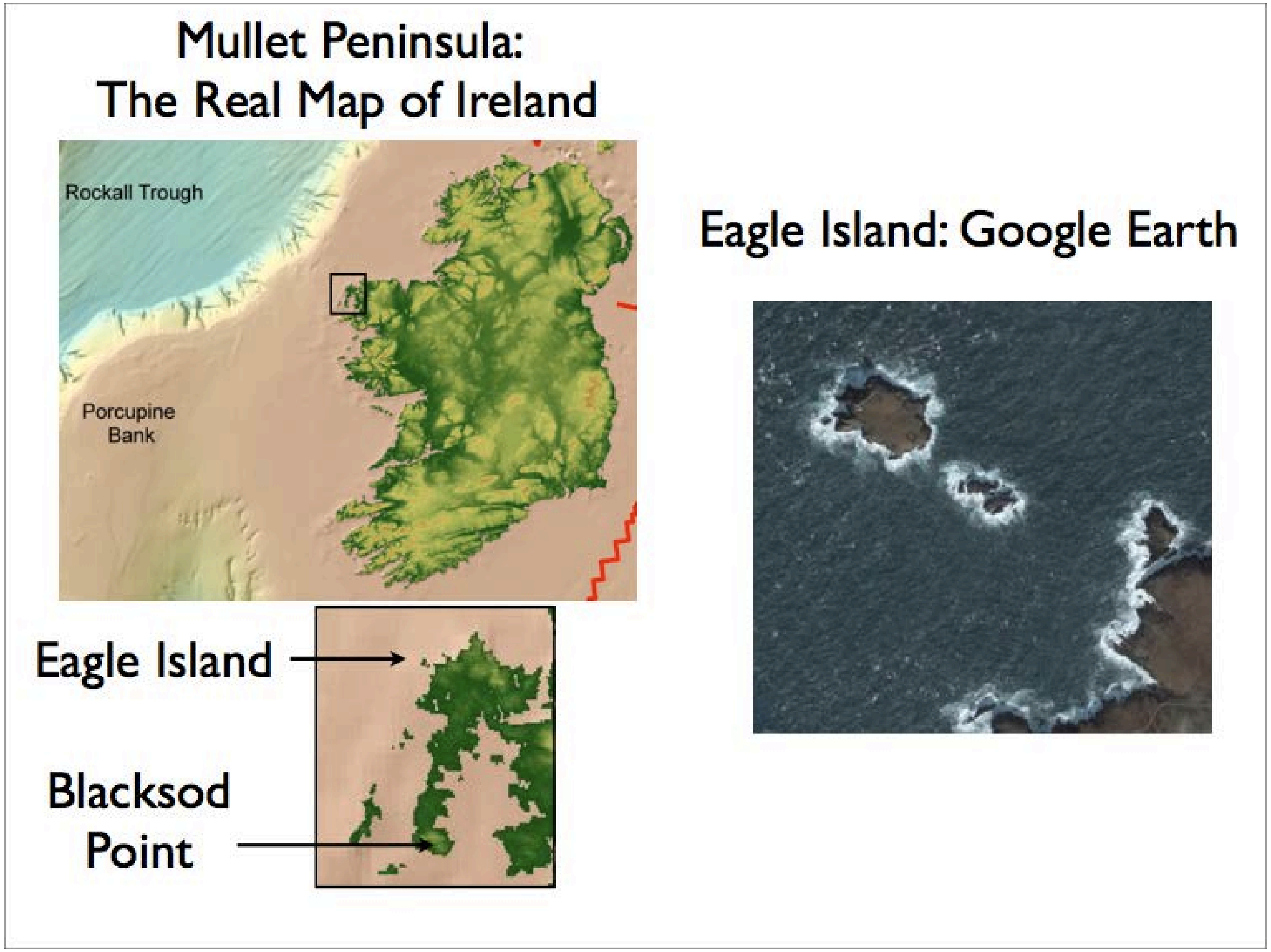
Tsunamis

- T1 14,680 BP: the Barra Fan, Peach Slide
- T2 8200 BP: Storegga slide
- T3 1755, 1761, 1941 and 1975: The Lisbon, Portugal tsunamis
- T4 1767: The River Liffey, Dublin
- T5 1841: Kilmore, Co. Wexford
- T6 1854: Kilmore, Co. Wexford
- T7 1894: Galway Bay and The Atlantic (*Festina Lente* and *Manhattan*)
- T8 1922: Ballycotton, Co. Cork
- T9 1909: Westport Quay, Co. Mayo
- T10 1910: Cork, Waterford, Southampton, Jersey, Dublin and Ilfracombe
- T11 1912: Bray, Co. Wicklow
- T12 1932: Inishowen, Co. Donegal

Rogue Waves

- R1 1852: Inis Mór, The Aran Islands
- R2 1883: Youghal , Co. Cork
- R3 1899: Kilkee, Co. Clare
- R4 1914: Iniskeeragh, off Donegal
- R5 1936: Dundalk, Co. Louth
- R6 1972: Mullaghderg, Donegal
- R7 2004: L.E. Róisín, off Donegal coast
- R8 2006: off Portrush, Co. Antrim
- R9 2006: Ardglass, Co. Down
- R10 2007: Doonbeg, Co. Clare
- R11 2007: Valentia Island, Co. Kerry
- R12 2011: Swanland, off Bardsey Island, Irish Sea
- R13 2011: Largest wave recorded in Ireland

SOME EXAMPLES : (1) MULLET PENINSULA



MULLET PENINSULA

Eagle Island Lighthouse

67 m above sea level
Tower height = 11 m

Close to the continental shelf

Originally : two towers, only one left today

MULLET PENINSULA

- During the construction of the west tower a great sea swept the partly built tower and much of the building materials into the sea. The towers were then completed with a massive storm wall on the sea side of the towers.

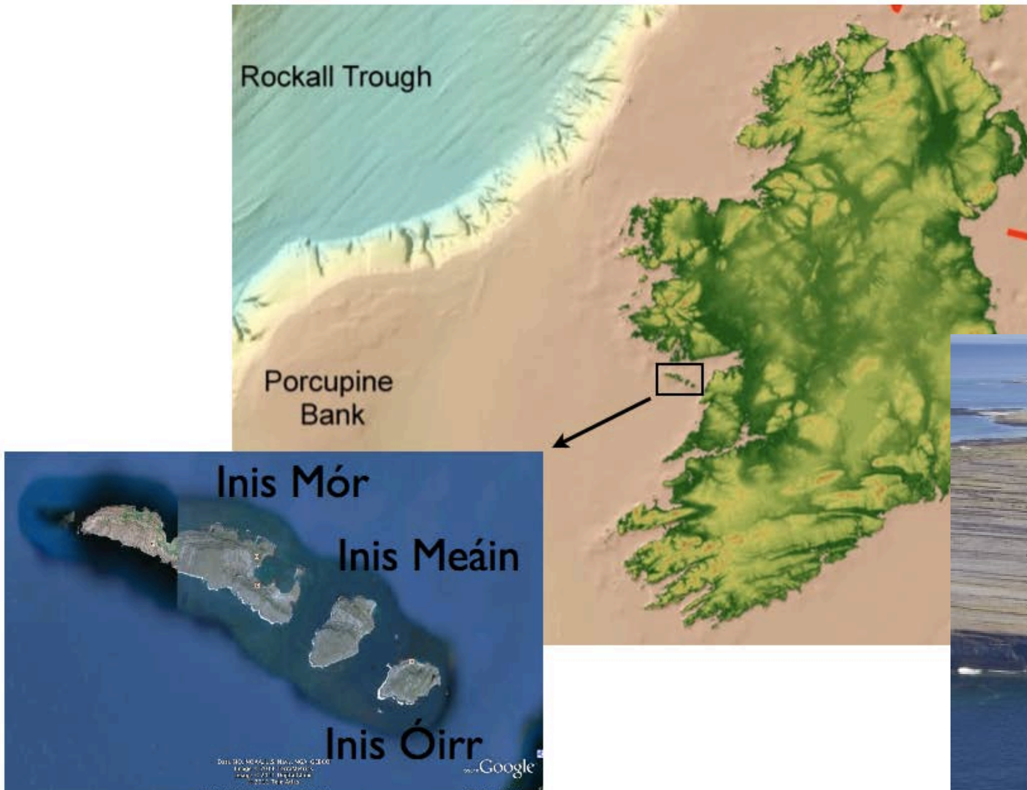
- 1837 – Wave swept over island and took off the roofs of the dwelling homes “there being no hurricane at the time”. The sea “must have risen 350 feet” (~106m) (The Irish Times)

- 11 March 1861 – A monster wave broke over the east light shattering 23 panes, damaging reflectors and flooding the tower. Rock thrown up by a severe storm ?

- 29 December 1894 – A storm damaged the dwellings and the east light beyond repair, broke the lantern glass, put out the light and damaged the protecting wall

- January 1987 and February 1988 – Substantial damage done by storm

SOME EXAMPLES : (2) THE ARAN ISLANDS



Friday 4 November 2011

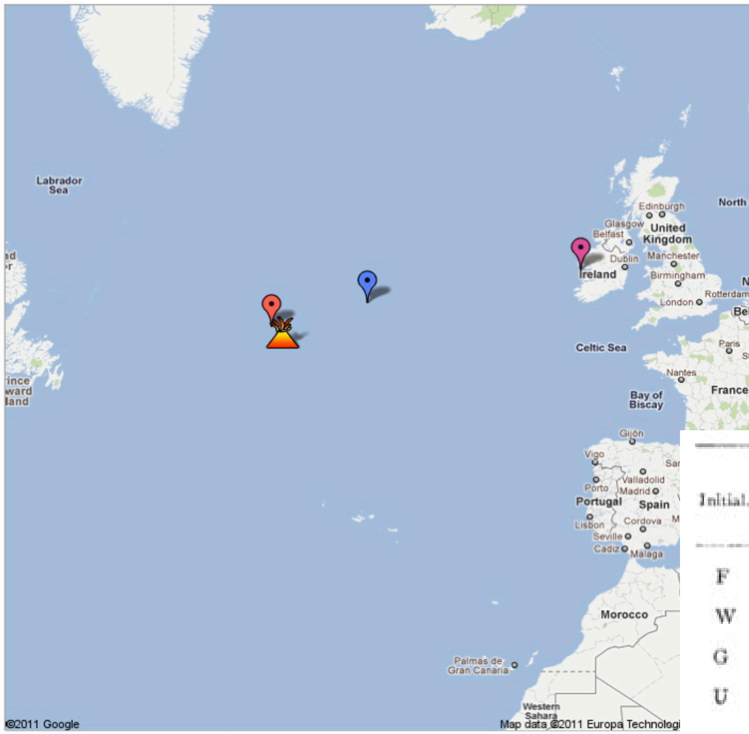
THE ARAN ISLANDS
1839 – 1852 – 1914 - 1953

- 1839 – Boulders thrown up during the Night of the Big Wind

- 1852 – Story that 15 people were swept to their deaths by a wave on Inis Mór

- Williams and Hall (2004) *Cliff-top megaclast deposits of Ireland, a record of extreme waves in the North Atlantic — storms or tsunamis?* Evidence of megaclast deposits on the top of vertical cliffs up to 50m above sea level weighing 2.9 tonnes (117 tonnes at 12m, 250 tonnes at sea level)

SOME EXAMPLES : (3) THE ATLANTIC OCEAN 1894



Ships- Freak waves 1894

L: Festina Lente (50 12 00N, 35 23 00W)
M: Manhattan (51 26 00N, 27 31 00W)
D: Diamond (53 09 00N, 09 52 00W)

Public · 0 views
Created on Feb 28 · By Loli · Updated < 1 minute ago

L: Festina Lente (50 12 00N, 35 23 00W)

M: Manhattan (51 26 00N, 27 31 00W)

D: Diamond (53 09 00N, 09 52 00W)
+53° 9' 0.00", -9° 52' 0.12"

Vicinity of Volcanic Activity 49 N, 34.5 W

Three incidents

- 12:00 16 November Festina Lente
- 02:00 17 November Manhattan
- 22:00 21 November Diamond

Nature, 7th March 1895, `Abnormal Atlantic Waves', C.E. Stromeyer

Initial.	Ship's name.	Local time.	Date.	Latitude. North.		Longitude. West.		Speed.	Ship's course.	Wave's course.
								Knots.		
F	*Faraday*	6 45 a.m.	14/2/84	46	11	27	53	6	N. 72° E.	Port beam.
W	*Westernland* ...	2.45 a.m.	27/11/86	47	59	43	57	7	S. 60° W.	Bow.
G	*Germanic*	9.40 a.m.	5/5/87	50	36	22	8	4	N. 68° W.	Bow.
U	*Umbria*	4.40 a.m.	26/7/87	50	50	27	8	16	S. nearly W.	3 points on starboard bow.
	H.M.S. *[illegible]utes*..	5 p.m.	18/2/91	36	12	32	50	9	?	Bow.
L	*Festina Lente* ..	noon.	16/11/94	50	12	35	23	?	S.E. by S.	?
M	*Manhattan* ...	2 a.m.	17/11/94	51	26	27	31	?	S. 86° W.	N.W.
D	*Diamond* ...	10 p.m.	21/11/94	53	9	9	52	Lying to	W.N.W.	W.N.W.

NO. [illegible], VOL. 51]

THE ATLANTIC OCEAN
1894

- ❑ NOAA Tsunami Events Database 21/11/1894: Probable tsunami from volcano in the middle of the North Atlantic with max water height 12.2 m from eyewitness accounts in Galway Bay

- ❑ "... the ship `S.S. Diamond' awaiting daylight to enter port, reported that the wave was heard some time before it was seen and then seemed to be about 40 feet high. The vessel was literally submerged for a time." (Berninghausen, 1968)

- ❑ *The Irish Times, 24/11/1894* : ''During a gale on the Western coast last night the SS Diamond was attacked by a tremendous sea, which smashed the lower bridge and carried away the mizzen mast. One of the sea men was washed overboard, but was thrown back on deck by a wave ... The Diamond arrived here this afternoon. Another steamer that was coming in at the same time is missing. She was seen by the crew of the Diamond before the wave struck the latter, but not afterwards. It is feared she has gone down."

- ❑The Festina Lente wave : ``A steep sea fell on board from both sides.". The Manhattan wave : ``The sea was high, but fairly true until a mountainous wave broke on board from N. W." (Stromeyer, 1895)

THE ATLANTIC OCEAN
1894

If we assume that The ‘Festina Lente’ and the ‘Manhattan’ encountered the same system of waves within 14 hours of each other, we can estimate the wave period to be 14 s : a big swell !

SOME EXAMPLES : (4) IRISH NAVAL SHIP
05 October 2004

- ❑ On Canadian submarine, HMS Chicoutimi, a fire broke out onboard after a significant ingress of water during repairs
- ❑ LE Róisín had taken shelter in Donegal Bay due to bad weather when it responded to a pan-pan broadcast
- ❑ Strong gale, heavy swell with waves approximately 3 – 4 m
- ❑ Sustained damage just off Rathlin O'Birne island by two unusually large waves

IRISH NAVAL SHIP 2004
Captain Lt Cdr. Terry Ward, eyewitness account

- ❑ 2 very large waves ~10-12 m with short period
- ❑ The ship pivoted on the crest of the first wave and fell down the other side.
- ❑ The bow plunged into a second large wave, about one third of the ship was submerged
- ❑ The front of the ship filled with water until the buoyancy of the ship pushed it back up through the wave
- ❑ On the port side of the forecastle the flare cracked and a piece (~A4 size) of the deck broke away and water was getting in.
- ❑The window wipers were all removed
- ❑The flare was moving and could have peeled back if the ship was to continue

OCEAN WAVE MEASUREMENT TECHNIQUES

- Current ocean wave measurement uses spectral approaches developed in the 1950s.
- Surface waves are recorded with a fixed length time series (usually 20 minutes) from which are derived nominal wave spectra.
- Hardware is based on wave staffs, wire gauges, buoys or underwater acoustic sensors, but device cost means that measurements are made at a single point.
- Deficiencies of these techniques:

(i) many of the most dangerous wave classes on the ocean either cannot be measured at all or are inaccurately recorded because of sampling deficiencies

(ii) existing wave buoys cannot reliably measure processes such as wave breaking or rogue waves which are all better characterized as instantaneous phenomena and which do not appear in average wave spectra

(iii) sensor cost precludes wide area deployment and inhibits measurement of full spatio-temporal wave evolution dynamics

ALTERNATIVE OCEAN WAVE MEASUREMENT TECHNIQUES

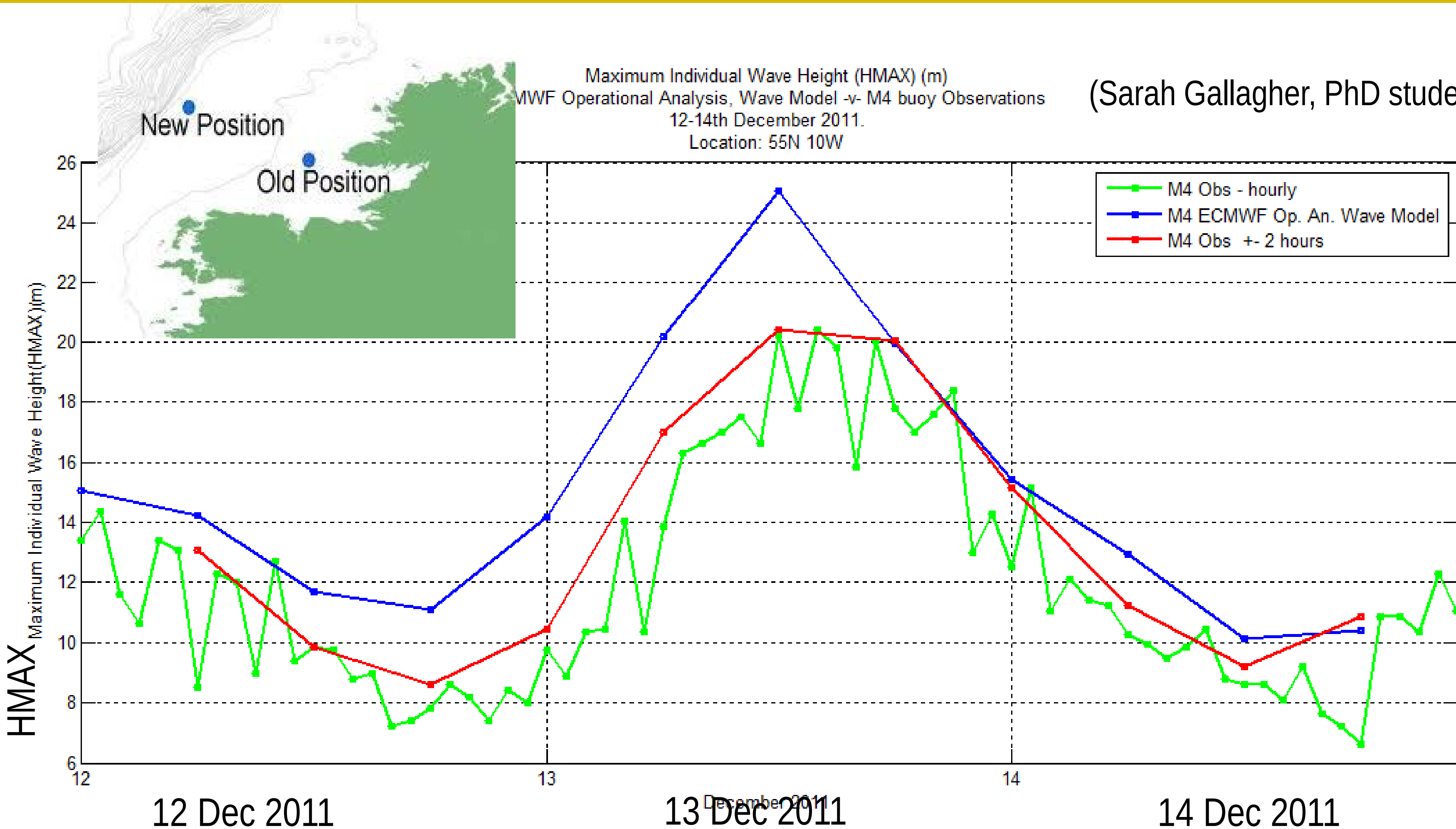
	Remote sensing	In situ	Optical methods
Spatial coverage	Extensive	Limited	Limited
Sea surface representation	Limited	High quality	High quality/ Problems in rough sea states
Accessibility	Available	High costs	High costs/ platforms required

Advantages (in green) and drawbacks (in red)

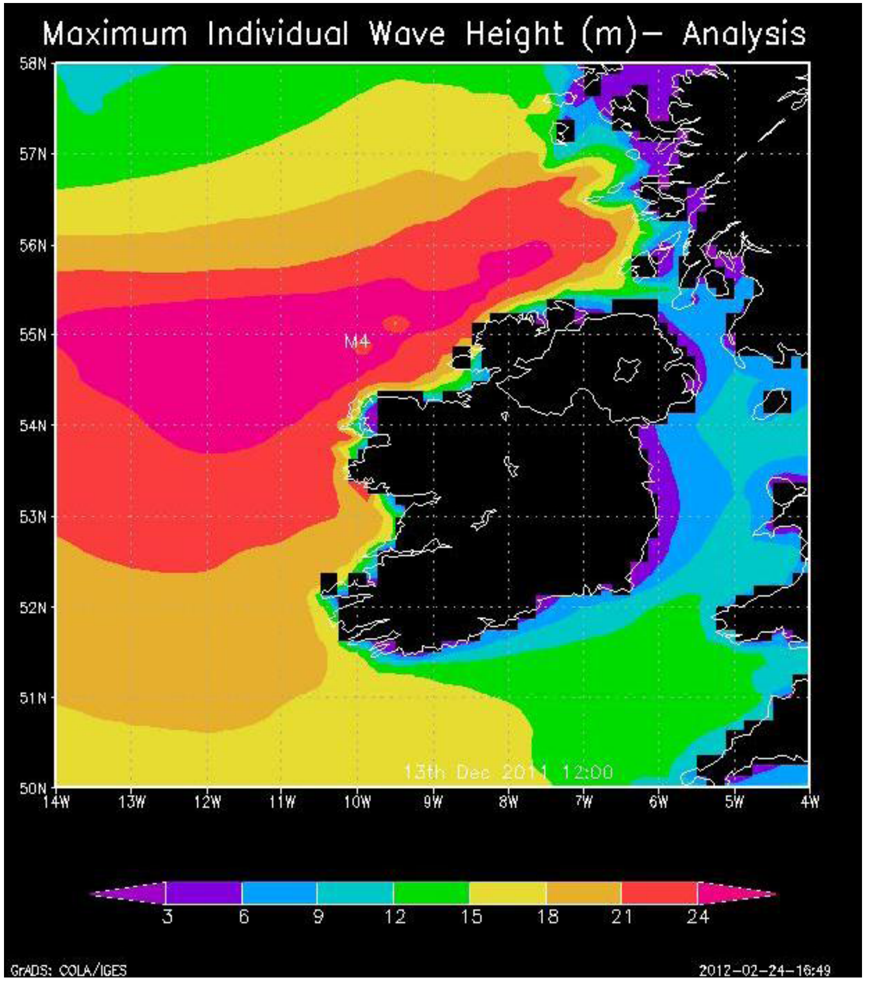
Irish M4 Weather Buoy

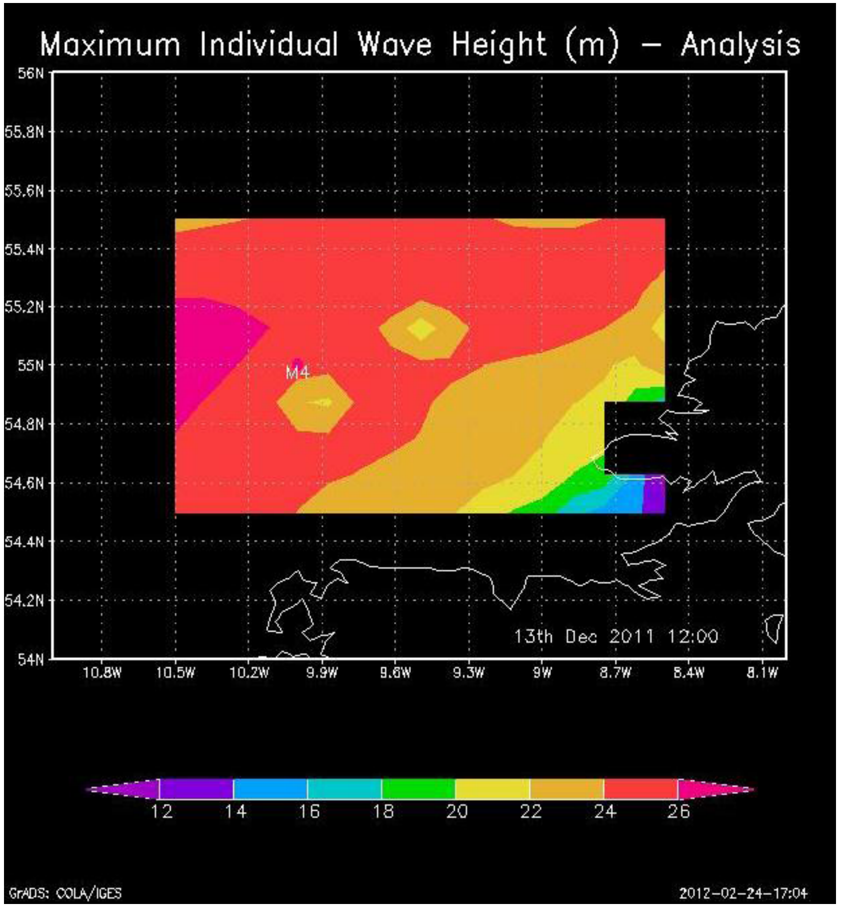
Irish M4 Buoy 12 – 14 December 2011
Several 20 m waves

(Sarah Gallagher, PhD student)



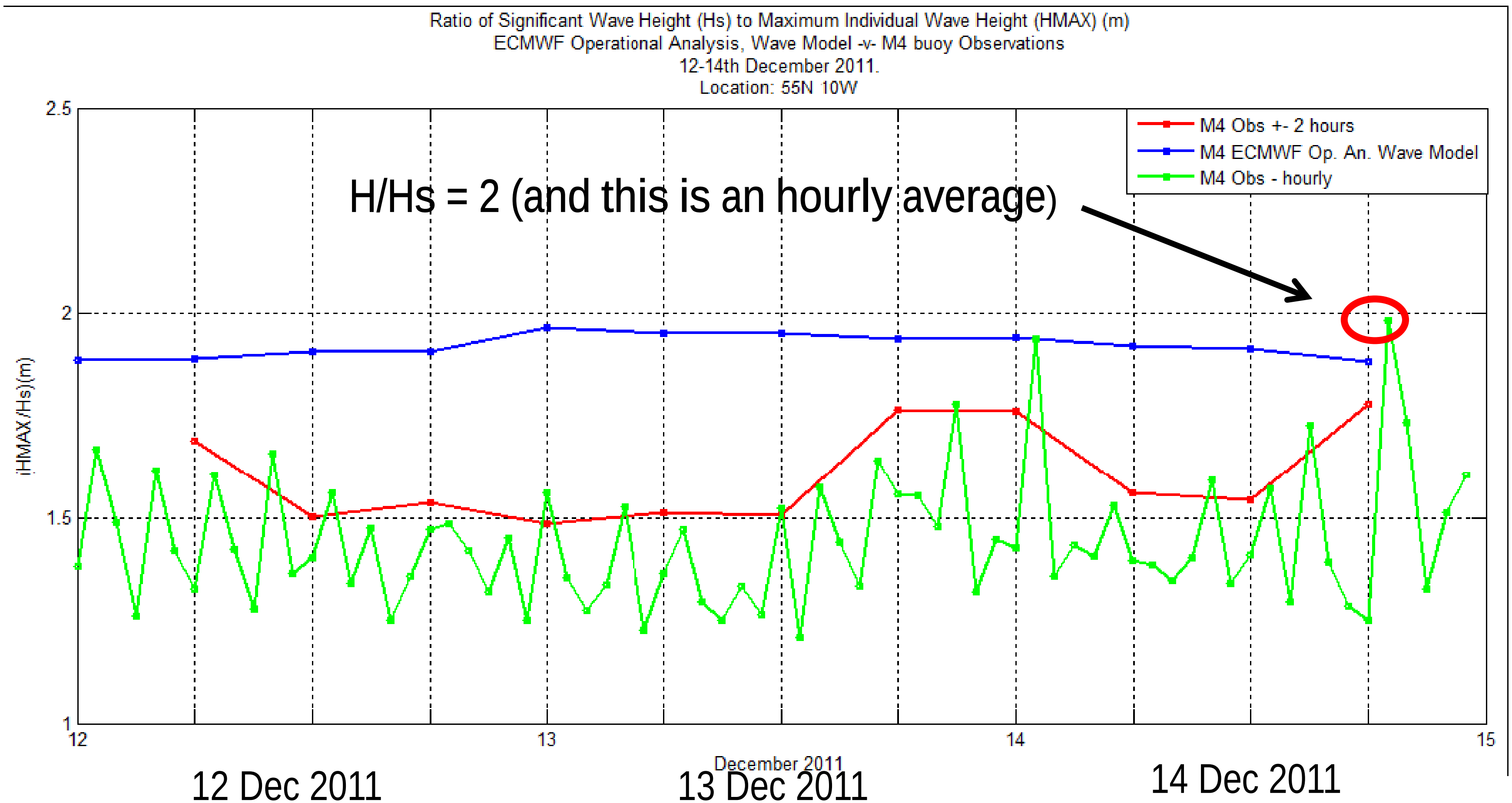
IRELAND 13 December 2011 at 12:00
Some even larger waves away from the buoy





Scale goes to more than 26 metres

IRELAND 12 – 14 December 2011
Ratio of significant wave height (Hs) to HMAX



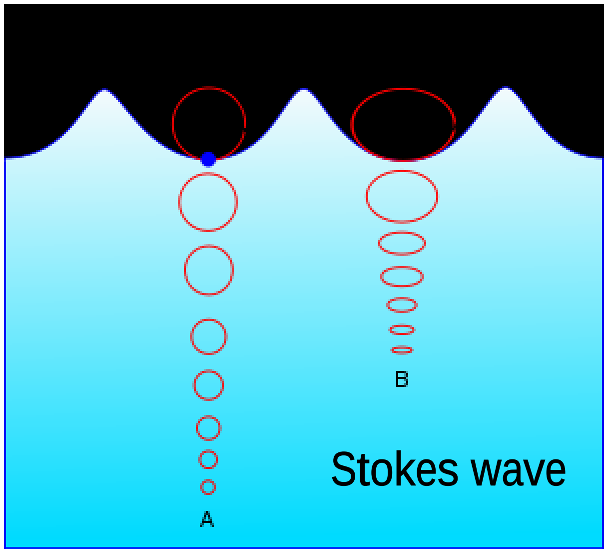
Physique des phénomènes extrêmes, Nice 2013

HOW ARE EXTREME OCEAN WAVES GENERATED ?

The physics of rogue wave formation is a subject of active debate.
Very few observations!

- **Linear Effects**
  - Focusing due to continental shelf topography
  - Directional focusing of wave trains
  - Dispersive focusing of wave trains
  - Waves + opposite current
- **Nonlinear Effects**
  - Exponential amplification of surface noise (instabilities)
  - Formation of quasi-localised surface states

THE FULL WATER WAVE EQUATIONS



Governing equation for the velocity potential φ

$$\nabla^2 \varphi(x, y, z, t) = 0$$

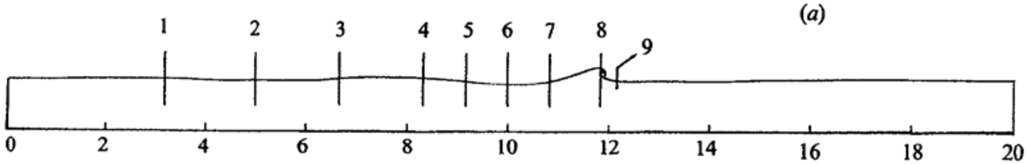
Sir George Gabriel Stokes
1819 – 1903
(born in Ireland)

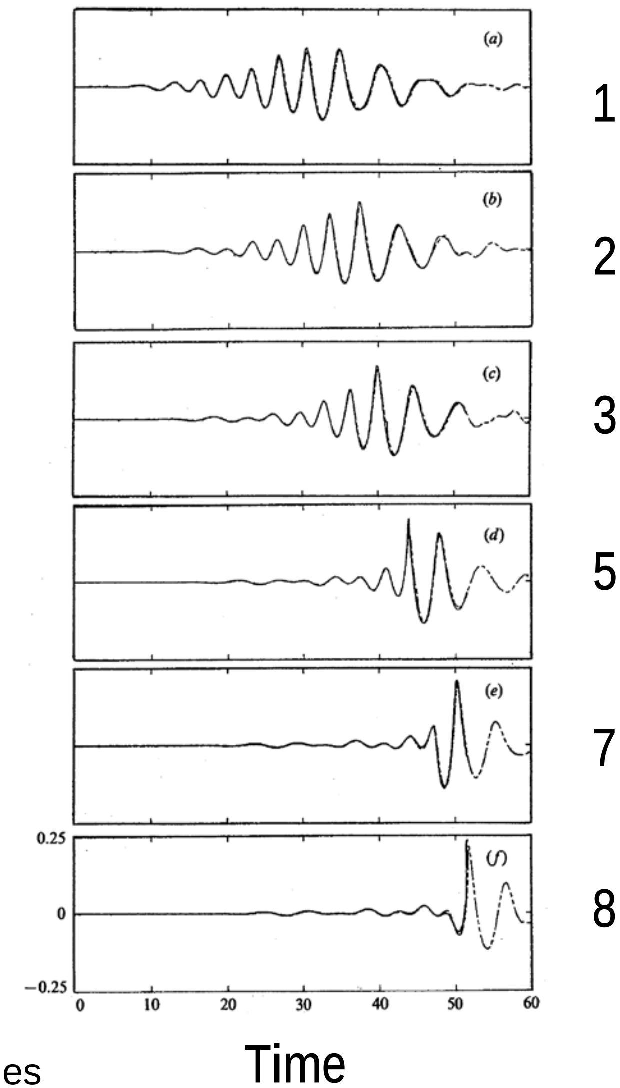
Bernoulli's equation $$\frac{\partial \varphi}{\partial t} + \frac{1}{2}|\nabla \varphi|^2 + gz + \frac{p - p_0}{\rho} = 0$$

At the bottom $z = -h(x, y)$ $$\frac{\partial \varphi}{\partial x}\frac{\partial h}{\partial x} + \frac{\partial \varphi}{\partial y}\frac{\partial h}{\partial y} + \frac{\partial \varphi}{\partial z} = 0$$

EXTREME OCEAN WAVES GENERATED BY DISPERSIVE FOCUSING

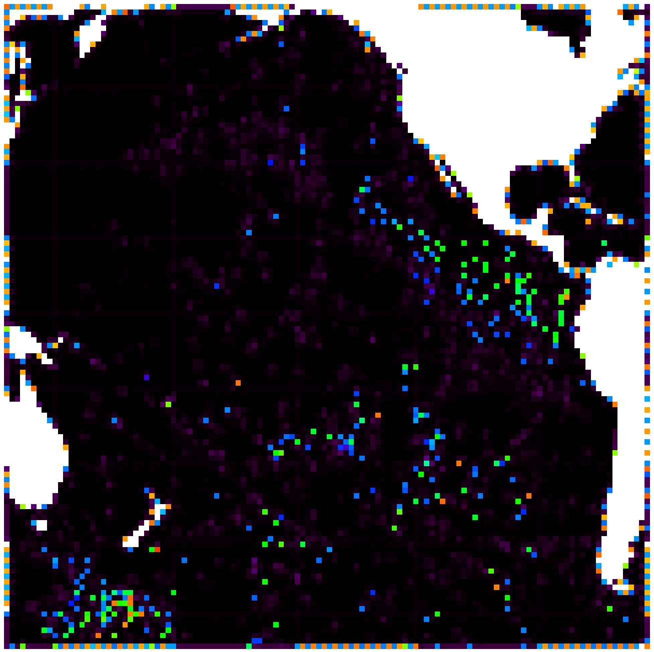
Comparisons between experiments in a wave tank and numerical simulations
Dommermuth, Yue, Lin, Rapp & Melville (1988)





Free-surface elevations as a function of time as one moves away from the wavemaker

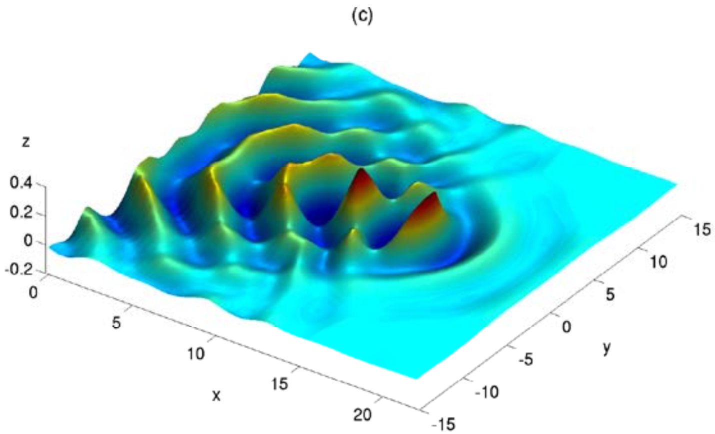
EXTREME OCEAN WAVES GENERATED BY DIRECTIONAL FOCUSING



Observation of swell propagation from satellite data – one can predict the time needed to cross the ocean (IFREMER, BOOst Technologies)

Evidence of directional wave focusing in a real wave tank (Ecole Centrale de Nantes) – see MOVIE

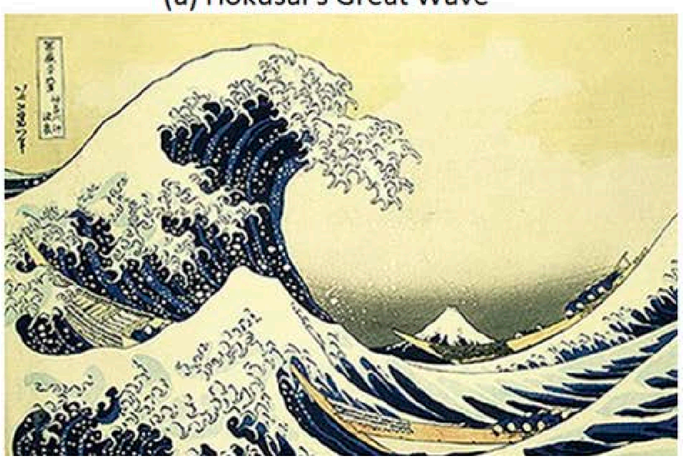
Evidence of in a « numerical » wave tank (our work)



EXTREME OCEAN WAVES GENERATED BY DIRECTIONAL FOCUSING

- By making reference to the Great Wave’s simultaneous transverse and longitudinal localisation, we have shown that the purely linear mechanism of directional focussing predicts characteristics consistent with those of the Great Wave.
- Collaboration with the photographer V. Sarano who has provided us with a truly remarkable photograph of a 6 m rogue wave observed on the Southern Ocean from the French icebreaker Astrolabe, which bears a quite spectacular resemblance to the Hokusai print

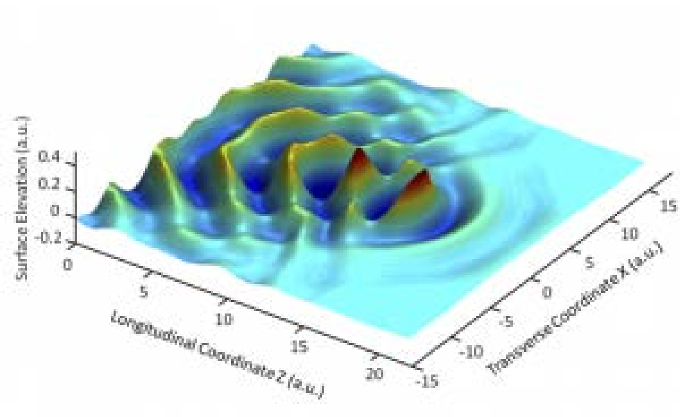
(a) Hokusai’s Great Wave



(b) Breaking Wave in the Southern Ocean

EXTREME OCEAN WAVES GENERATED BY DIRECTIONAL FOCUSING

Typical results of numerical modeling of the directional focusing process are shown. The modeling is based on propagation equations that include both linear and nonlinear effects, but the concentration of energy at the focus arises from linear convergence. Nonlinearity plays a role only as the wave approaches the linear focus where it increases the steepness to the point of breaking.



NOTES & RECORDS OF THE ROYAL SOCIETY

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Notes Rec. R. Soc. (2013) **67**, 159–164
doi:10.1098/rsnr.2012.0066
Published online 6 March 2013

ON HOKUSAI'S *GREAT WAVE OFF KANAGAWA*: LOCALIZATION, LINEARITY AND A ROGUE WAVE IN SUB-ANTARCTIC WATERS

by

J. M. Dudley[1,*], V. Sarano[2] and F. Dias[3]

books & arts

NATURE PHYSICS | VOL 9 | SEPTEMBER 2013 | www.nature.com/naturephysics

The great rogue wave

EXHIBITION

A red volcanic cone on a dark blue sky, a breaking wave in a stormy sea — Katsushika Hokusai's vivid depictions of Mount Fuji have become iconic for Japanese art. At seventy years of age, Hokusai began the work on Thirty-Six Views of Mount Fuji (*Fugaku sanjurokkei*), his masterpiece, in 1830. The woodblock print series actually consists of forty-six views of the mountain, the other scenes bearing Hokusai's new signature and being printed almost entirely in shades of Prussian blue. *The Great Wave off Kanagawa* (*Kangawa oki nami ura*) is the central piece of Hokusai's celebrated series, and of an exhibition at the Art Institute of Chicago (Beyond the Great Wave: Hokusai's Images of Mount Fuji, 20 July–6 October 2013).

Hokusai's *Great Wave* is very realistic and there is more to it than first meets the eye. It is not a tsunami as many might have thought. A recent study (J. M. Dudley, V. Sarano and F. Dias, *Notes Rec. R. Soc.* 67, 159–164; 2013) suggests that it is a rogue wave — a very rare phenomenon caused by the combined effect of winds and ocean currents. Rogue waves occur spontaneously and are much larger than any other wave close by. By contrast, tsunamis refer to a massive water displacement propagating as a linear wave, and are created by a sudden movement of the ocean floor.

Both tsunamis and rogue waves are dangerous natural phenomena, but for ships far out at sea tsunamis do not represent a threat, whereas unpredictable rogue waves do. But, the *oshiokuri* boats in Hokusai's *Great Wave* may not be so vulnerable after all. This is because of the strong localization that could arise from linear propagation effects. Photographs of subantarctic waves show very similar localization and breaking dynamics. An alternative explanation for the characteristics of the *Great Wave* invokes solitons (J. H. E. Cartwright and H. Nakamura, *Notes Rec. R. Soc.* 63, 119–135; 2009), but the role of linear and nonlinear effects in the formation of rogue waves remains controversial. Perhaps the absence of a complete understanding of the underlying physics makes the art more mysterious and allows us to enjoy it even more. ❐

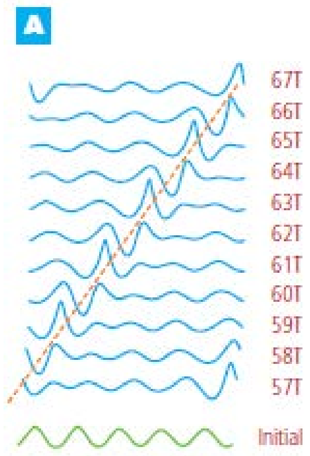
IULIA GEORGESCU

EXTREME WAVES GENERATED BY MODULATIONAL INSTABILITY

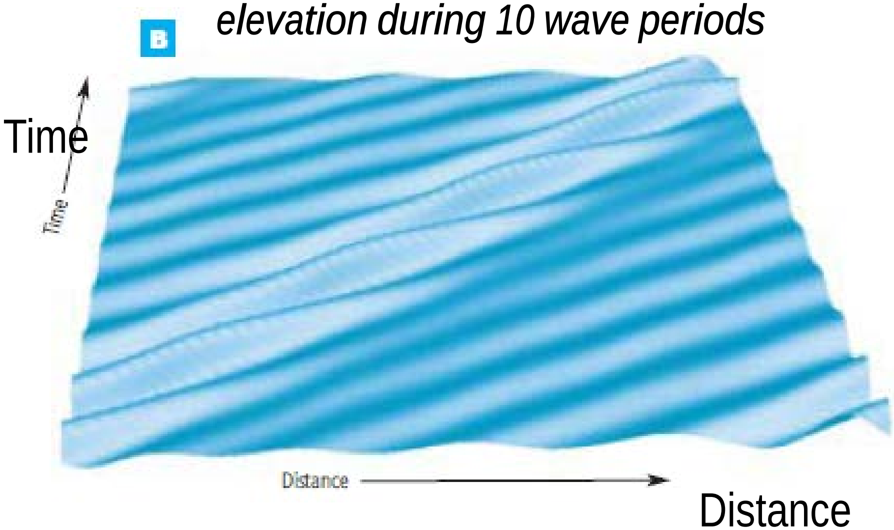
The initial wave condition is a monochromatic deep water wave with a small disturbance added (modulation with a wavelength much larger than the wavelength of the carrier).

After several wave periods instabilities develop and energy becomes concentrated at a single peak in the wave group.

Surface elevation in a time-space representation (during 10 wave periods)

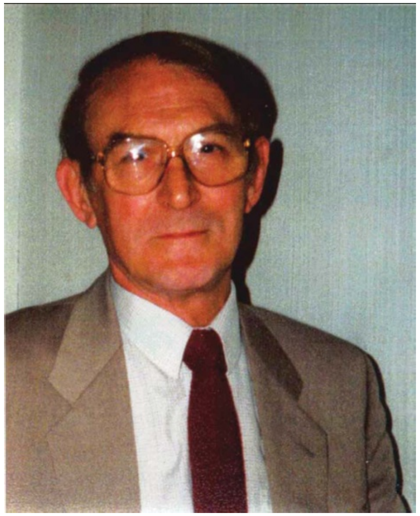


Snapshots of the surface elevation during 10 wave periods



BENJAMIN-FEIR INSTABILITY

In 1963 Benjamin's Canadian research student Jim Feir was measuring in detail the waves along a new 10-m tank in the Engineering Department in Cambridge. He and Benjamin observed how waves generated at the wave maker started as a regular train with constant frequency and wavelength, but then about 5 m down the tank began to form into groups of waves with varying frequencies and wavelengths. (I was a research student in an adjoining laboratory, watching their surprising phenomena, and shared in the excitement as the story unfolded. But this account of the events is largely due to Feir.)



I = Julian Hunt

Both of them believed that these first observations might be associated with serious imperfections in the construction and operation of the wave maker because by varying its frequency the curious evolution of the wave patterns could be generated deliberately. Benjamin worked out a simple control system to eliminate any measurable drift in frequency. Still, the wave breakdown observed earlier persisted, and Feir was able to measure wave profiles along the tank for various values of wave slope. These showed an exponentially growing amplitude modulation along the tank at one fifth the wave maker frequency, and in particular suggested that modulation growth ceased at certain cut-off values of wave slope.

BENJAMIN-FEIR INSTABILITY

Then Feir moved to the much larger wave tank equipped with a programmable wave maker in the National Physical Laboratory (NPL) at Feltham (near London). Several modulating frequencies and amplitudes were imposed on the wave maker. The results of these experiments confirmed what had been observed at Cambridge. The synthesis of a weak-amplitude modulation into a dominant carrier and two small side-bands led Benjamin to the idea of instability arising from wave propagation through a periodic medium. He derived a linear analysis of a deep-water Stokes wave perturbed by two sidebands, leading to predictions of sideband growth rate as the wave slope increased, provided it was greater than a critical value, defined by the ratio of wave height h to wavelength λ equal to $1.363/2\pi$. Both aspects of these results were in good agreement with the experimental measurements.

BENJAMIN-FEIR INDEX

BFI = wave steepness x characteristic wave number / spectral width

$$\mathrm{BFI} = \sqrt{2}\mathrm{s}\frac{\mathrm{k_w}}{\sigma_\mathrm{w}}, \qquad (3)$$

with spectral width and characteristic wavenumber respectively given by

$$\sigma_w = \frac{\int_0^{+\infty} (k - k_w)^2 P \mathrm{d}k}{\int_0^{+\infty} P \mathrm{d}k}, \quad k_w = \frac{\int_0^{+\infty} k P \mathrm{d}k}{\int_0^{+\infty} P \mathrm{d}k},$$

and wave steepness

$$s = k_w \eta_{\mathrm{rms}},$$

where

$$\eta_{\mathrm{rms}} \equiv \langle \eta^2 \rangle^{1/2} = 2 \left\langle \int_0^{+\infty} P \mathrm{d}k \right\rangle^{1/2}.$$

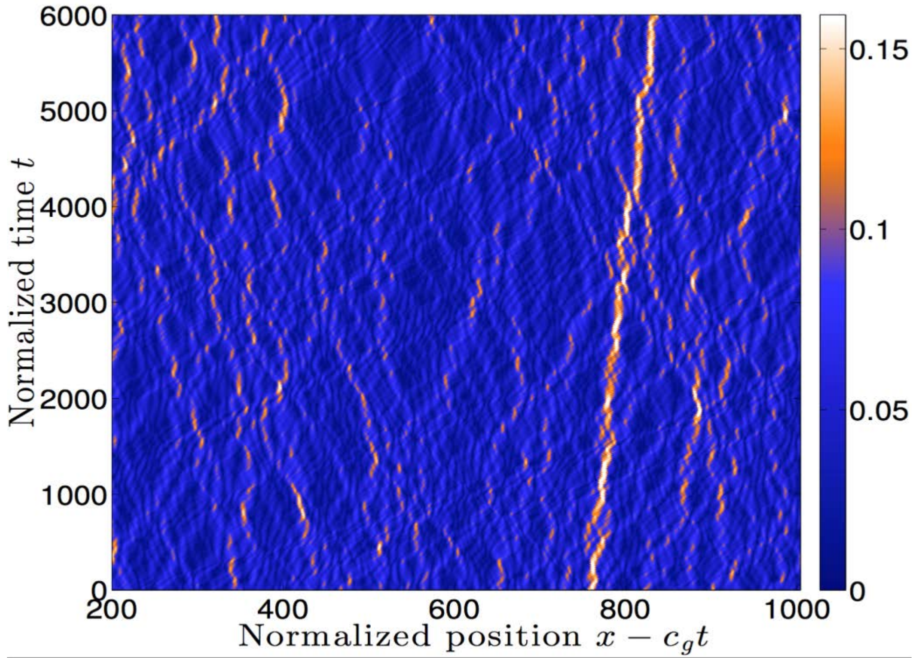
Observations of coherent structures in deep water waves from random initial conditions

- Euler equations
- Random initial data with prescribed power spectrum
- Spectral simulations based on conformal mapping

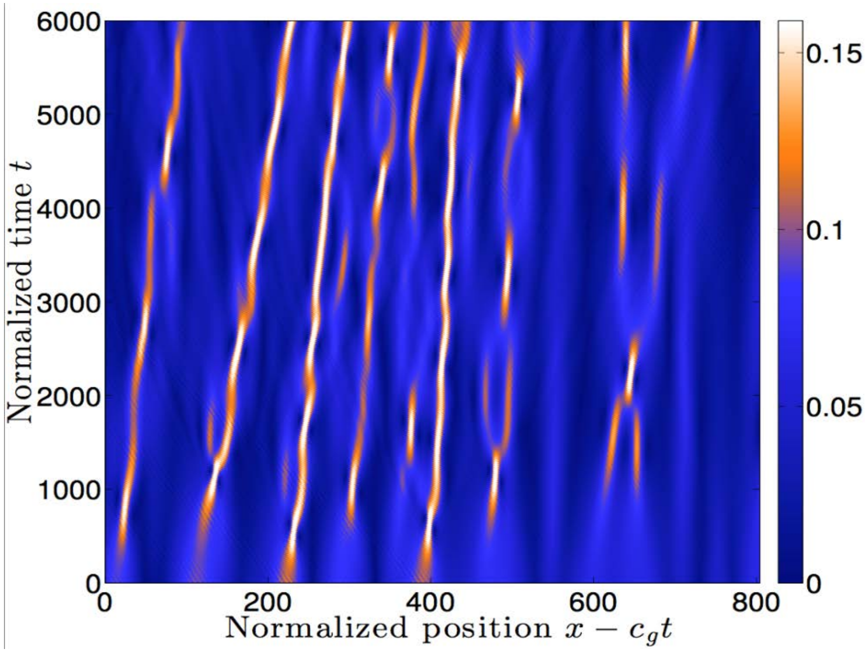
Viotti, Dutykh, Dudley, Dias (2013) Phys. Rev. E 87, 063001

Wave envelope

Wide-banded spectrum
(BFI=0.216)



Narrow-banded spectrum
(BFI=1.333)



SIMPLIFIED PARTIAL DIFFERENTIAL EQUATION

The Non Linear Schrödinger equation (NLS) equation is the simplest approximate equation that describes the modulations of weakly nonlinear, deep-water gravity Stokes waves, with basic wave number *k* and frequency $\omega(k)$

$$\varphi(x,z,t) = A(x,t)e^{kz}e^{-i(\omega t - kx)} + complex\ conjugate$$

A(x,t) is the slowly varying complex modulation amplitude.
It is governed by the NLS equation

$$2i\omega\left(A_t + c_g A_x\right) - {c_g}^2 A_{xx} = 4k^4|A|^2 A$$

In 1938 de Valera (then Taoiseach) was planning to establish an Institute for Advanced Studies in Dublin (like Princeton) – D.I.A.S.. He wanted en eminent physicist to head the School of Theoretical Physics $\Longrightarrow$ *Schrödinger*

THE BENJAMIN-FEIR INSTABILITY

The equation for *A(x,t)* can be transformed to the self-focussing NLS equation

$$iq_T + q_{XX} + 2|q|^2 q = 0$$

by the transformation

$$T = \frac{1}{2}\omega t \qquad X = kx - \frac{1}{2}\omega t \qquad q = \frac{\sqrt{2}k^2 A^*}{\omega}$$

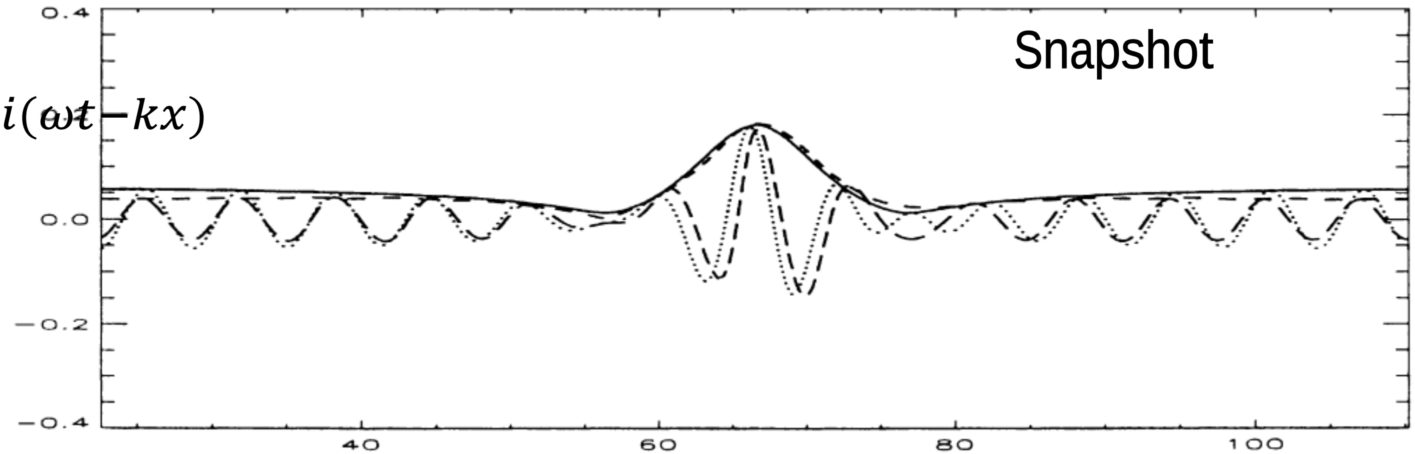
where * denotes complex conjugate.

A monochromatic wave perturbed by a modulation with *n* waves in it will grow !

EXPLICIT SOLUTIONS

- A periodic growth and decay of an isolated steep wave event is described by the Kuznetsov-Ma soliton

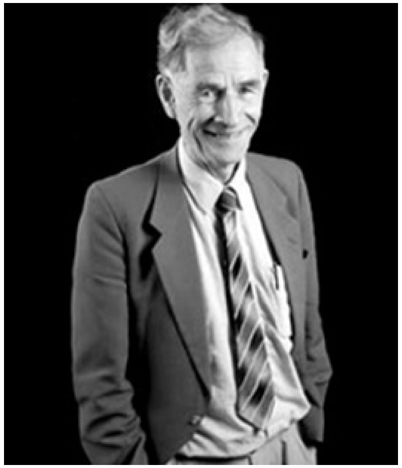
$$A(x,t)e^{-i(\omega t-kx)}$$



Distance x

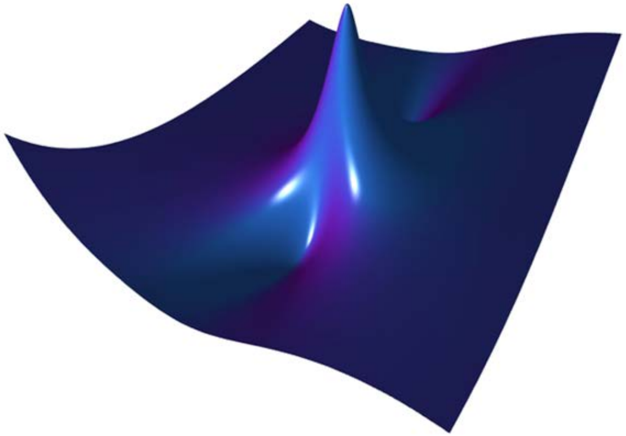
Henderson, Peregrine & Dold, 1999

ANOTHER EXPLICIT SOLUTION : THE PEREGRINE SOLITON

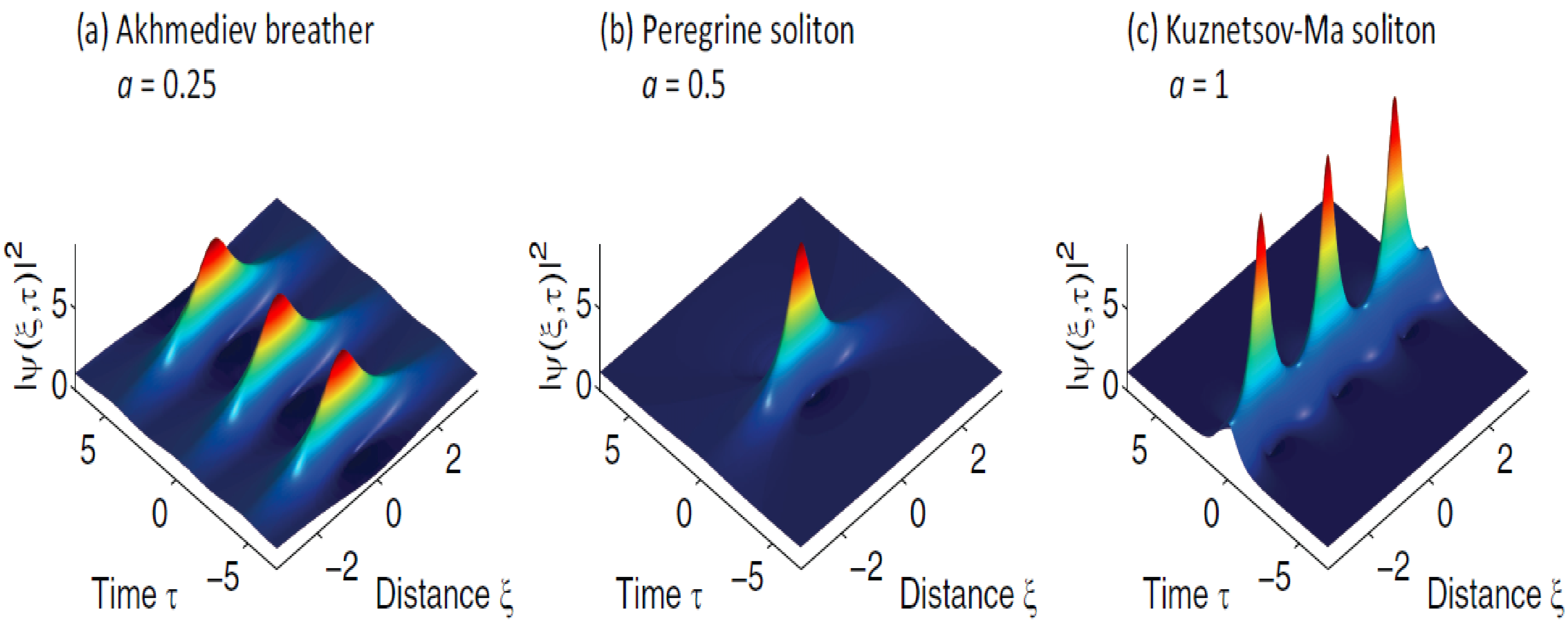


- Emergence "from nowhere" of a steep wave spike
- Polynomial form (*H. Peregrine – 1938-2007*)
- Maximum contrast between peak and background

$$q = q_0 e^{2iq_0{}^2T}\left(1 - \frac{4(1+4iq_0{}^2T)}{1+4q_0{}^2X^2+16q_0{}^4T^2}\right)$$



EXPLICIT SOLUTIONS : SUMMARY



OBSERVING AN UNOBSERVABLE SOLITON

Sir James Lighthill
(1924–1998)

"… as Sir Cyril Hinshelwood has observed … fluid dynamicists were divided into hydraulic engineers who observed things that could not be explained and mathematicians who explained things that could not be observed."

James Lighthill

COLLABORATION WITH SCIENTISTS IN OPTICS

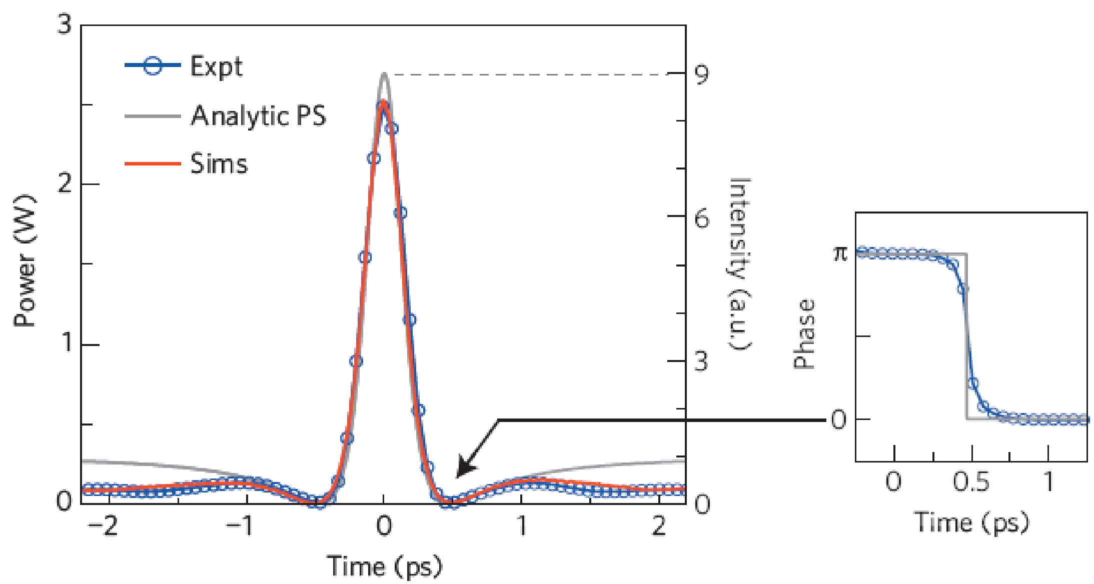
nature physics

LETTERS

PUBLISHED ONLINE: 22 AUGUST 2010 | DOI: 10.1038/NPHYS1740

The Peregrine soliton in nonlinear fibre optics

B. Kibler[1], J. Fatome[1], C. Finot[1], G. Millot[1], F. Dias[2,3], G. Genty[4], N. Akhmediev[5] and J. M. Dudley[6]*



THIS ROGUE WAVE SOLUTION IN A WAVE TANK ?

PRL **106,** 204502 (2011) PHYSICAL REVIEW LETTERS week ending 20 MAY 2011

Rogue Wave Observation in a Water Wave Tank

A. Chabchoub,[1,*] N. P. Hoffmann,[1] and N. Akhmediev[2]

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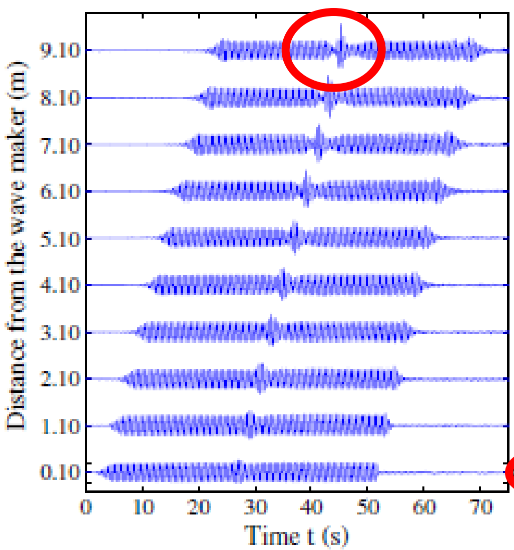
(Received 28 February 2011; published 16 May 2011)



Guess the wave amplitude !

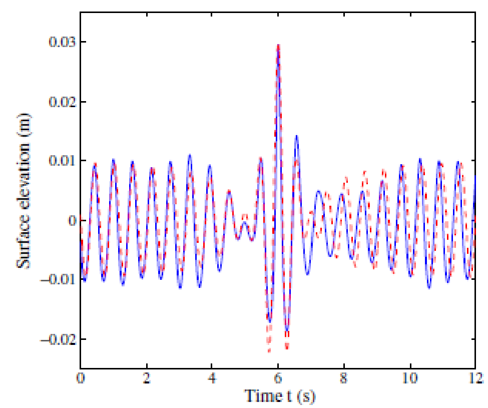


FIG. 5 (color online). Comparison of measured surface height at the position of maximum rogue wave amplitude (solid line) with the theoretical Peregrine solution (dashed line) evaluated at $X = 0$.

MORE RESULTS IN OPTICS

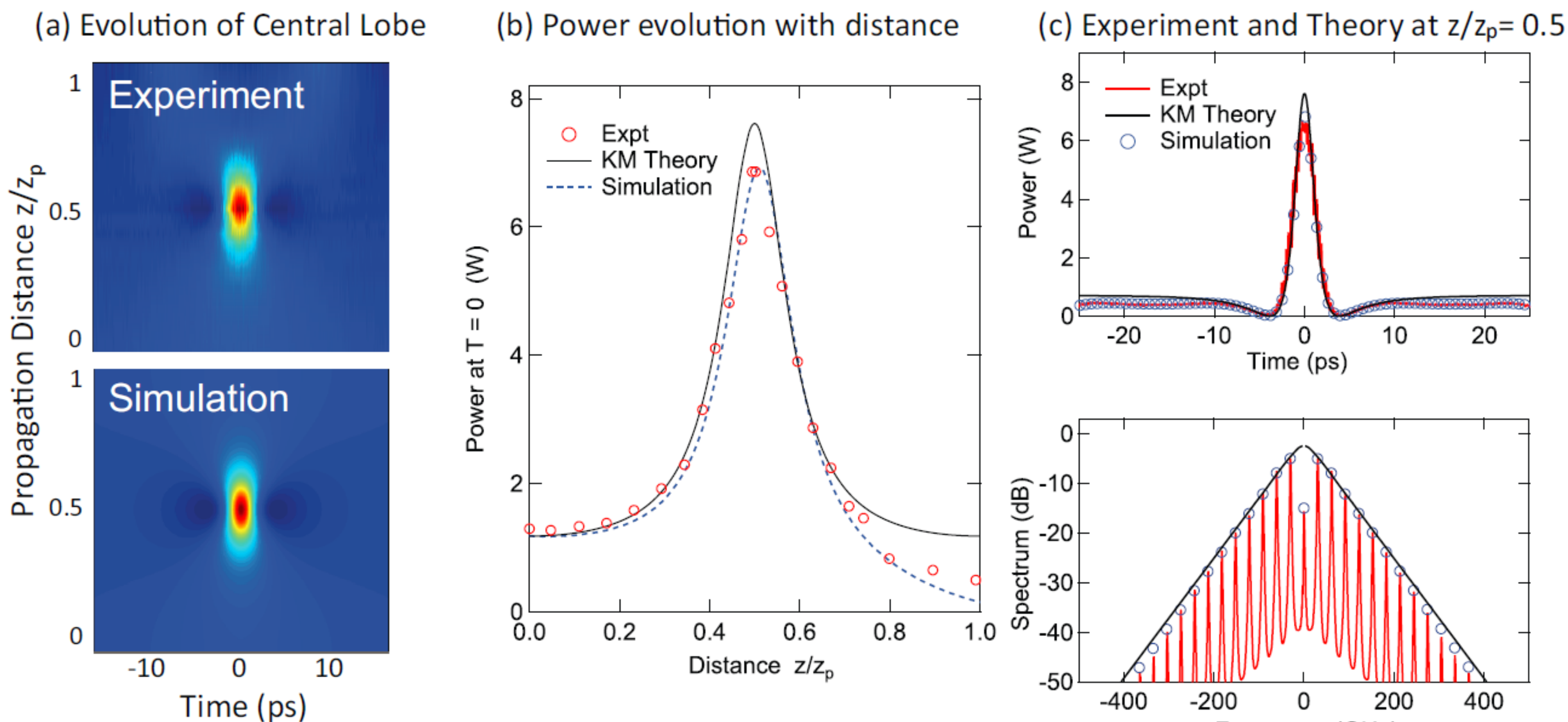
SCIENTIFIC REPORTS

OPEN

Observation of Kuznetsov-Ma soliton dynamics in optical fibre

SUBJECT AREAS:
PHYSICS

B. Kibler[1], J. Fatome[1], C. Finot[1], G. Millot[1], G. Genty[2], B. Wetzel[3], N. Akhmediev[4], F. Dias[5] & J. M. Dudley[3]



MOTIVATING NEW EXPERIMENTS IN HYDRODYNAMICS

OPEN ACCESS Freely available online
PLOS ONE

Rogue Waves: From Nonlinear Schrödinger Breather Solutions to Sea-Keeping Test

Miguel Onorato[1,2], Davide Proment[3]*, Günther Clauss[4], Marco Klein[4]

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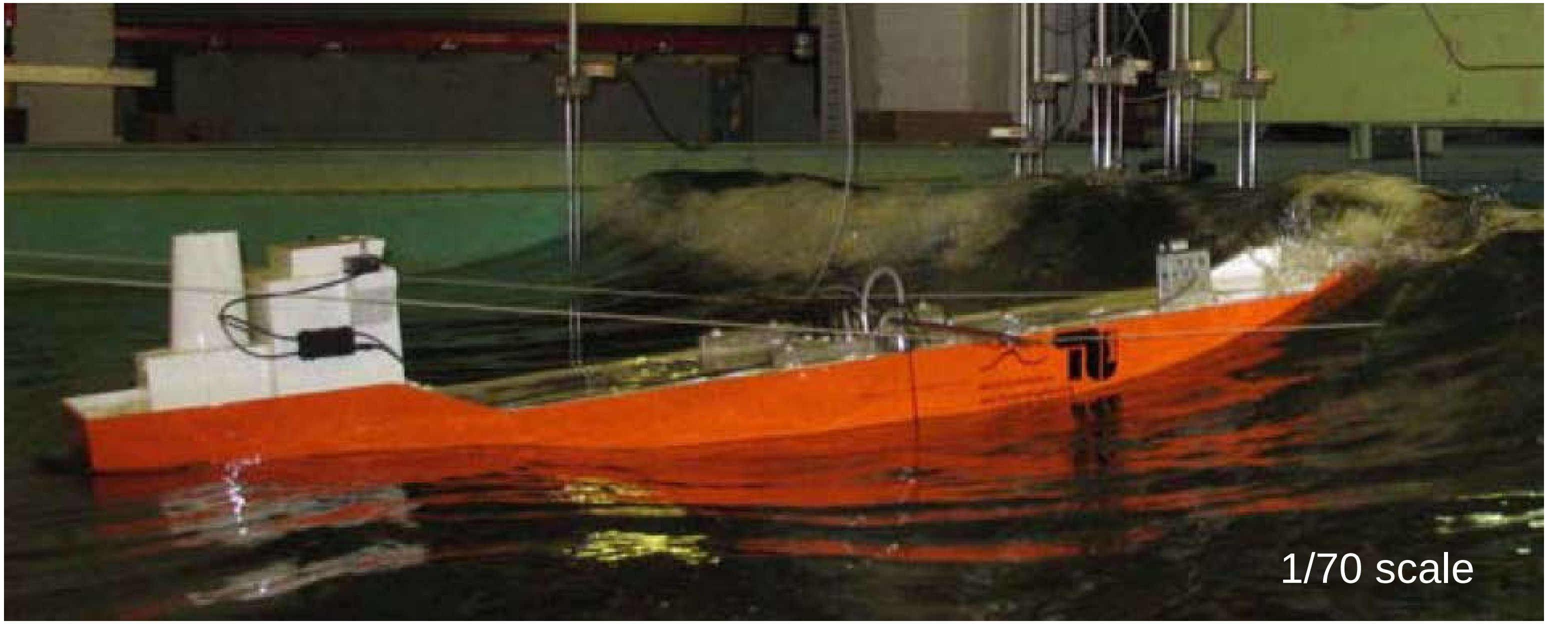


BACK TO OCEAN WAVES – AND WHAT ABOUT CLIMATE CHANGE ?

Our team in collaboration with Met Éireann looked at the future of wave climate and of extreme waves (Roxana Tiron, Sarah Gallagher, Ray McGrath, Emily Gleeson)

- A unified framework for global climate models testing: the Coupled Model Inter-comparison Project (**CMIP5**)
  - defines a series of experiments: multi-century and decadal with set spatial resolutions and initializations
  - under defined emission scenarios: **Representative Concentration Pathways** (RCP)

Moss et al. (2010) "The next generation of scenarios for climate change research and assessment"

Table 1 | The four RCPs

Name	Radiative forcing	Concentration (p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 W m^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE	55,56
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	57,58
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	48,59
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	60,61

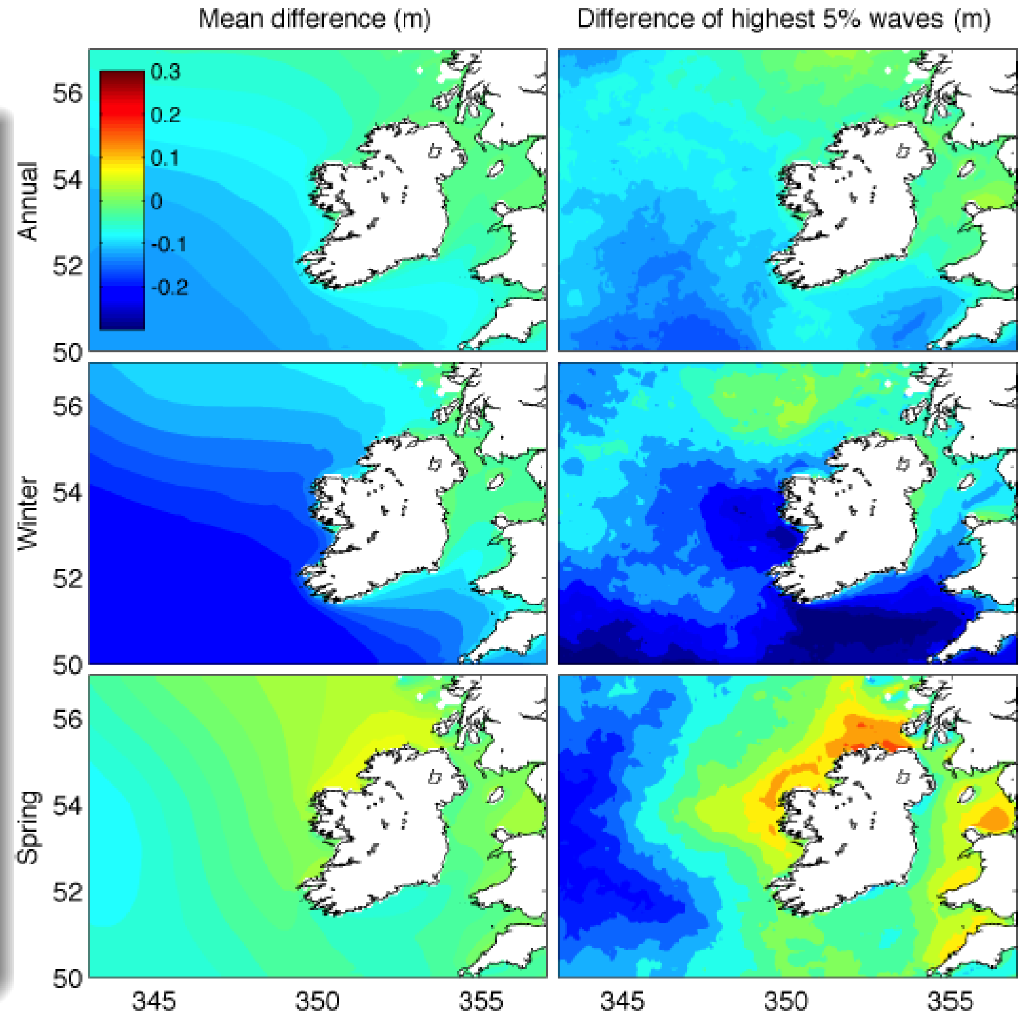
* MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

ESTIMATING THE FUTURE WAVE CLIMATE OF IRELAND

- We examine a likely future wave climate projection for Ireland using the **RCP 4.5** climate scenario as defined by CMIP5 experiment design for the years **2031-2060**.
- The **RCP 4.5** climate scenario predicts that the radiative forcing stabilizes at approximately **4.5 W/m^2 by 2100**, compared to pre-industrial concentrations.
- **Global EC-Earth** 10m winds (Met Éireann) are used to drive a nested grid wave model zooming in on Ireland.
- **Past wave climate of Ireland for: 1981-2009** with wind forcing from the **ERA-Interim** re-analysis provided by **ECMWF**.
- We perform a **29 years historical climate run** for the same period, forced with historical EC-Earth winds: "parallel Universe" where day to day values do not match observations, however, long term trends and averages should follow the real climate.

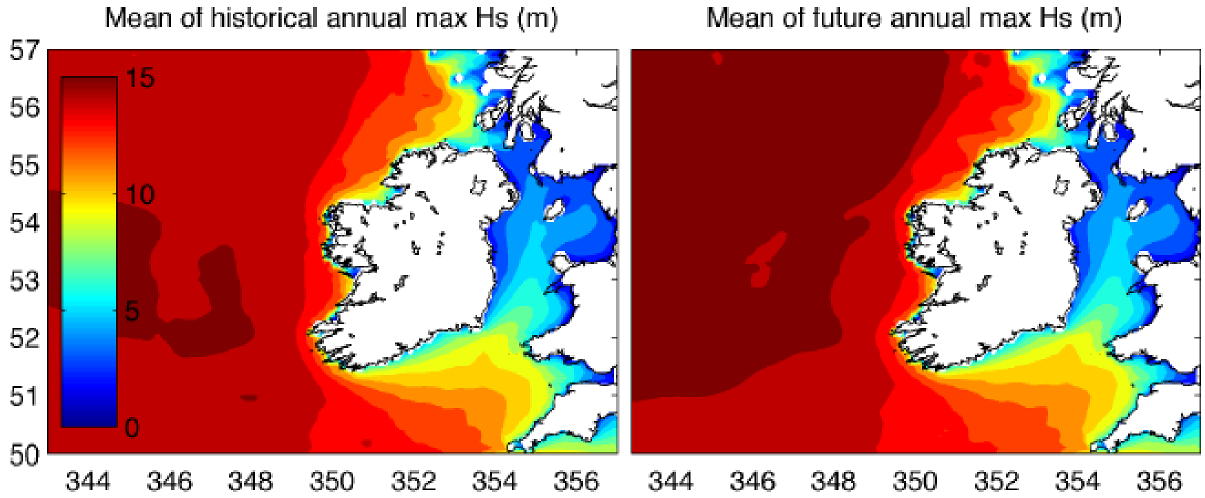
ESTIMATING THE FUTURE WAVE CLIMATE OF IRELAND

- A decrease of 20cm can be seen off the southwest coast in winter.
- For storm wave heights (highest 5% of Hs), annual values show a small decrease around Ireland:
    - spring becomes stormier in the north and northwest, with increases of over 20cm
    - large decreases can be seen off the southwest coast
    - a small increase in the north can also be seen in the winter



WHAT ABOUT EXTREMES ?

A look at the average of the annual maxima of significant wave height offers an interesting counterpoint to the overall decreases in the means. Remarkably, this average is higher for the future than the past, in contrast with the mean of the highest 5% of sea-states. Annual maxima, being associated with individual storm events, are not as accurate a characterization of extreme sea-state occurrence!



THANK YOU FOR YOUR ATTENTION

Howth, Ireland