# *Vagues scélérates :*

## *D'extrêmes et incertaines oscillations entre aléa et déterminisme*

**Michel Olagnon**

*Ifremer, Brest*

Bound for the Skerries in a force 8

**Janette Kerr, PRWA –** *Royal West of England Academy, Bristol*

# Outline

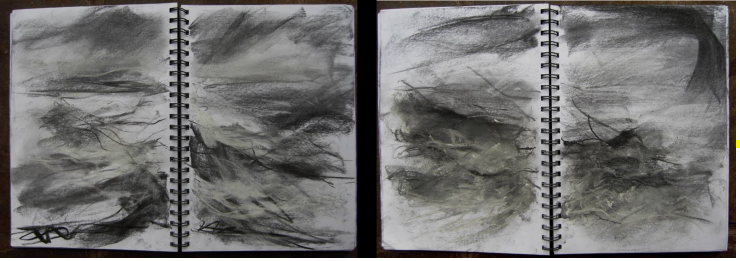
**What is a rogue wave ?**

- What is a wave ?
- What sort of extremes does theory predict for it ?
- True rogue waves or extreme waves of other kinds ?
- The reality of rogue waves

**From the scientist's point of view**

- A more difficult definition
- The constructive approach
- The observational approach

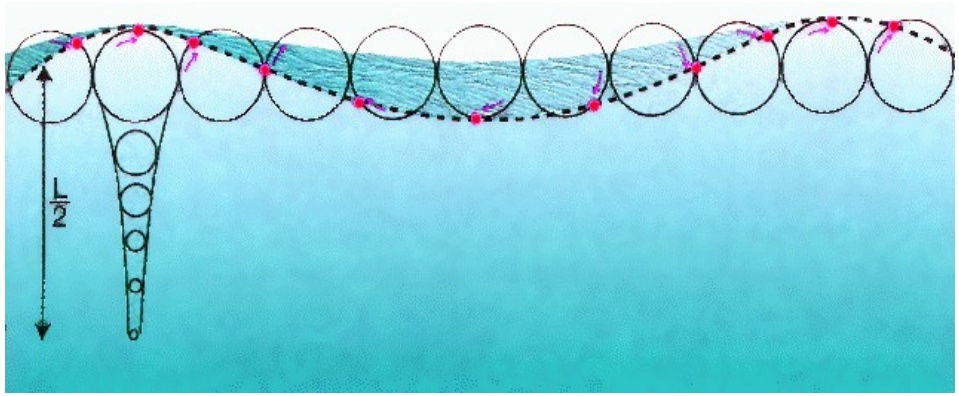
**Conclusions as of now**



# Gravity waves

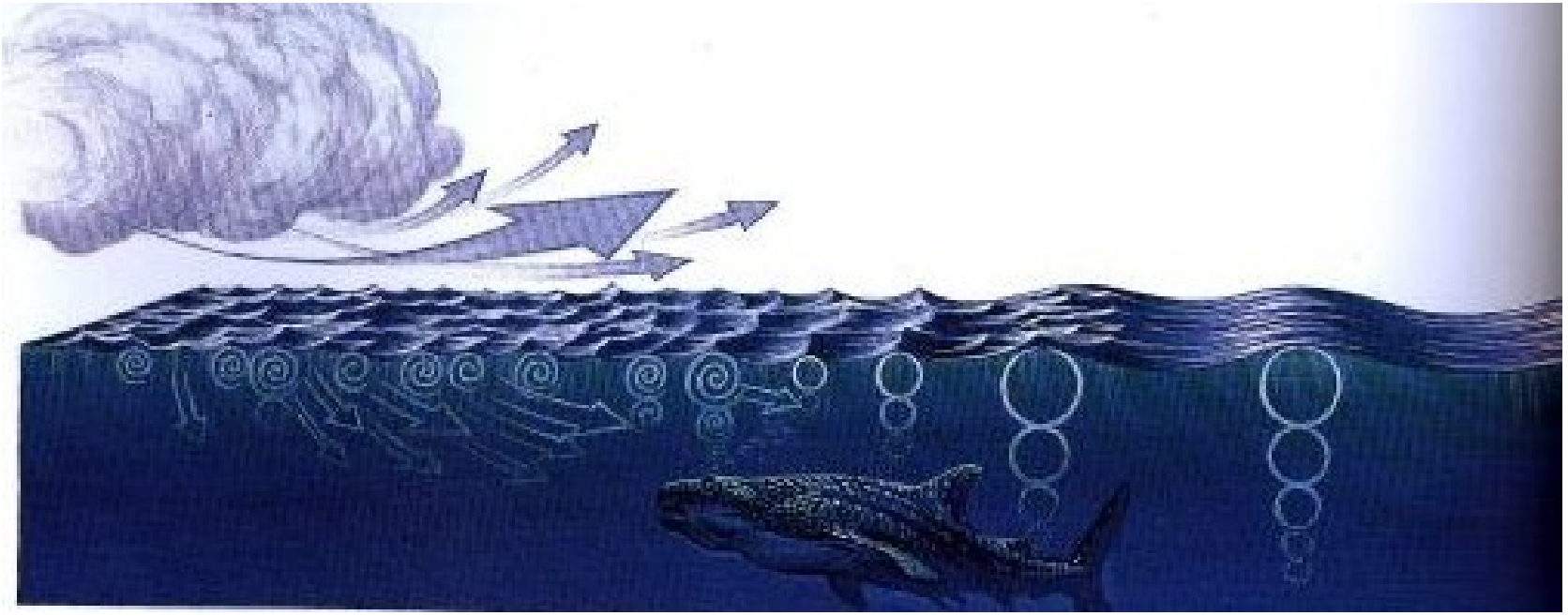
Starting from horizontal equilibrium, perturbations can be brought to the surface of oceans by accidents (landslides, earthquakes affecting the seafloor, etc.) or routine actions of winds. Since there is almost no damping, the oscillation propagates as dispersive waves until it reaches a coast and/or is dissipated by turbulence – whitecapping, breaking – or becomes unnoticeable through dispersion.

The differential equations have simple solutions, among which sine waves decreasing exponentially with depth, and provide a pretty good model of observed ocean waves.



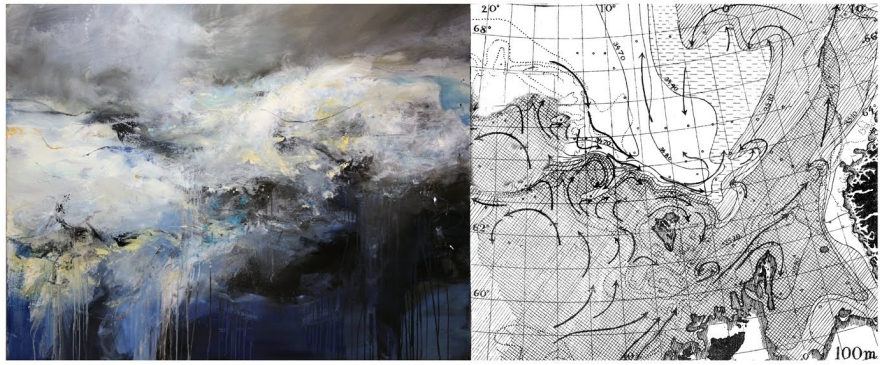
In the storm ...

and far away...

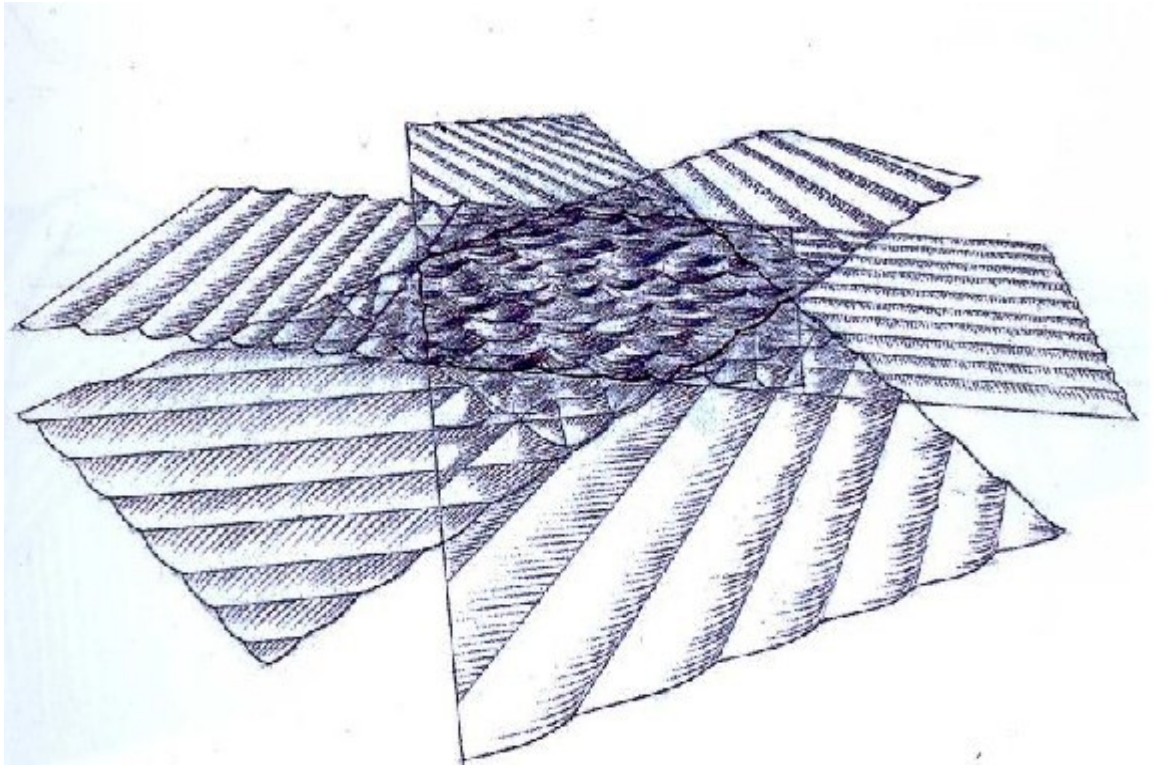


...[wind] sea

… swell.

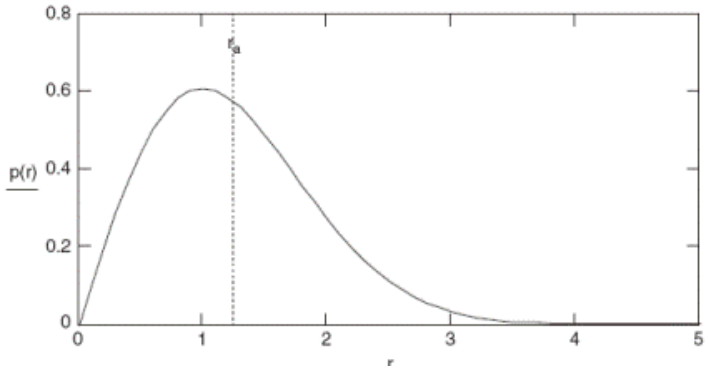


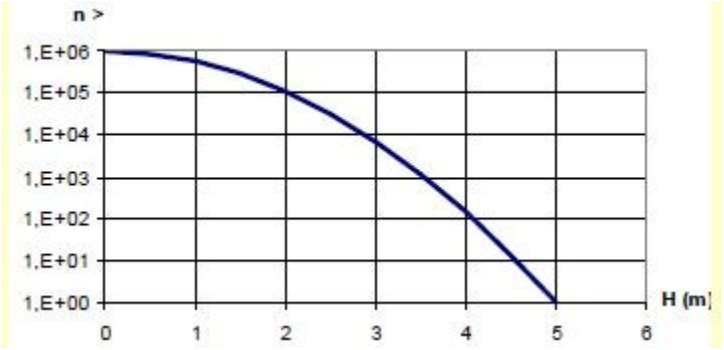

Close enough to the generating area, the waves that one can see are linear combinations of solutions of the differential equations.



… with some perturbations due to interactions between waves – an elementary wave would be supposed to occur on a perfectly flat surface – and to the fact that they are not infinitely small.

# Rayleigh distribution

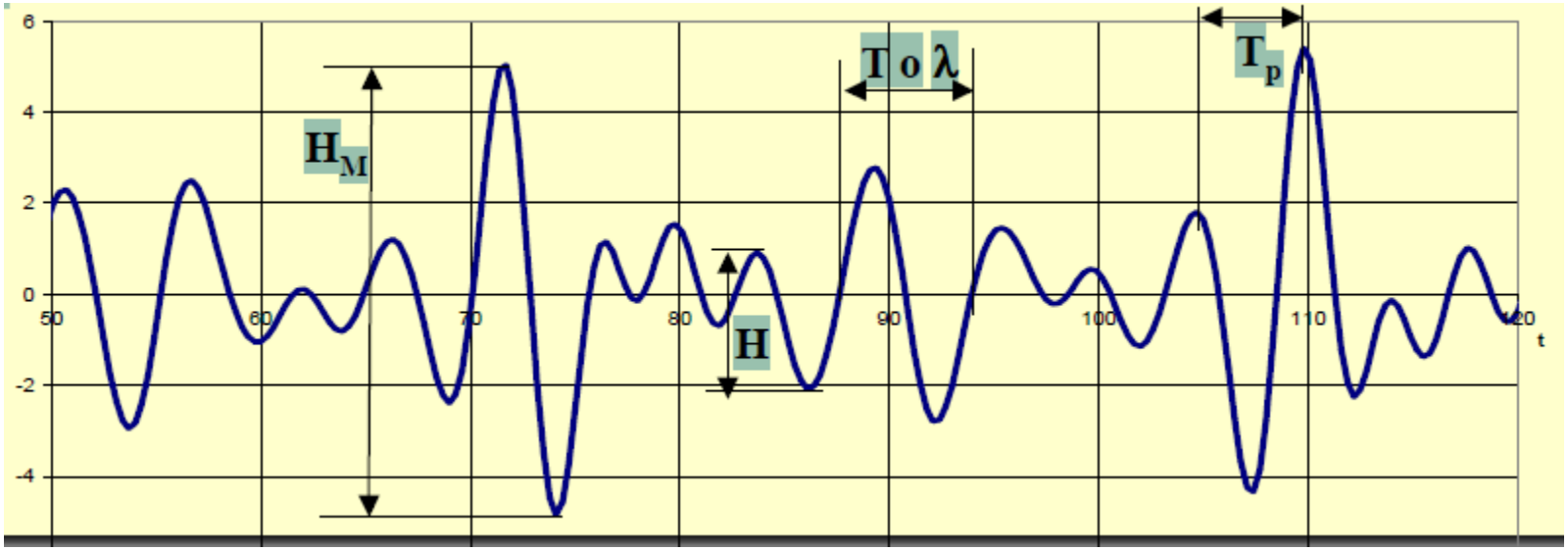


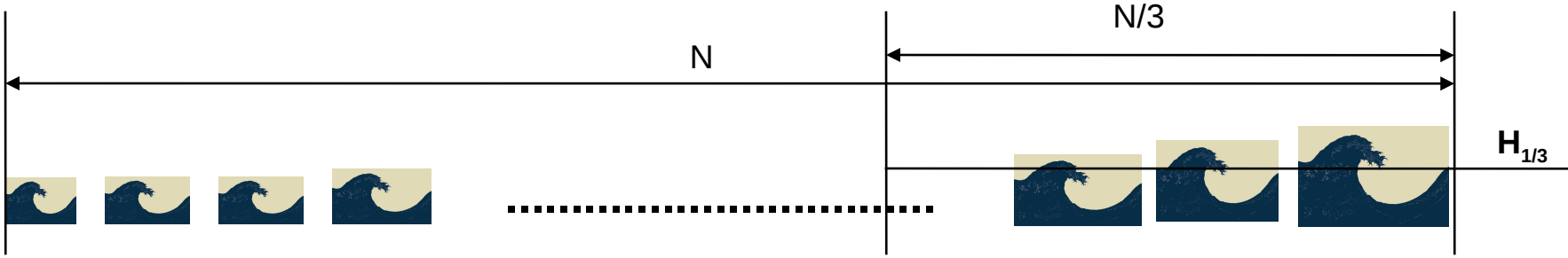

The phase of a sine wavelet when it reaches the observation point is random uniformly distributed (distance to generation point modulo wavelength), thus heights of the linear combinations of all wavelets follow a Rayleigh distribution.

That distribution may be modified to account for non-linearities (interactions). They have limited influence in the case of crest-trough heights – non-linearities in the crests and troughs mostly cancel each other.

# Hs




**Significant wave height**, Hs or $H_{1/3}$, is the mean of the highest one-third of the set of waves. In the case of narrow-band linear combination of waves and thus Rayleigh distribution of heights, it is equal to 4 (4.004 actually) times the sea water surface elevation standard deviation.



# So, extremes should be:

Assuming a significant wave height of 10 m (overpassed once every 9 waves in average), waves would be met in average at:

- 18.5 m every 3 hours
- 21.5 m every day
- 25.0 m every month
- 27.5 m every year
- 30.0 m every 20 years
- 31.5 m every 100 years
- 33.1 m every 1000 years
- 34.8 m every 10000 years

# So, extremes should be:

Assuming a significant wave height of 10 m (overpassed once every 9 waves in average), waves would be met at:

- 18.5 m every 3 hours
- 21.5 m every day
- 25.0 m every month
- 27.5 m every year
- 30.0 m every 20 years
- 31.5 m every 100 years
- 33.1 m every 1000 years
- 34.8 m every 10000 years

Commonly, people forget about longer periods than they spend watching waves → a wave more than twice Hs is “abnormal, a freak, a rogue, a killer, ...”.

# Extremes might thus be...

**… just the largest waves in a rather homogeneous family**

Photo Iván Morán Garcia-Rendueles

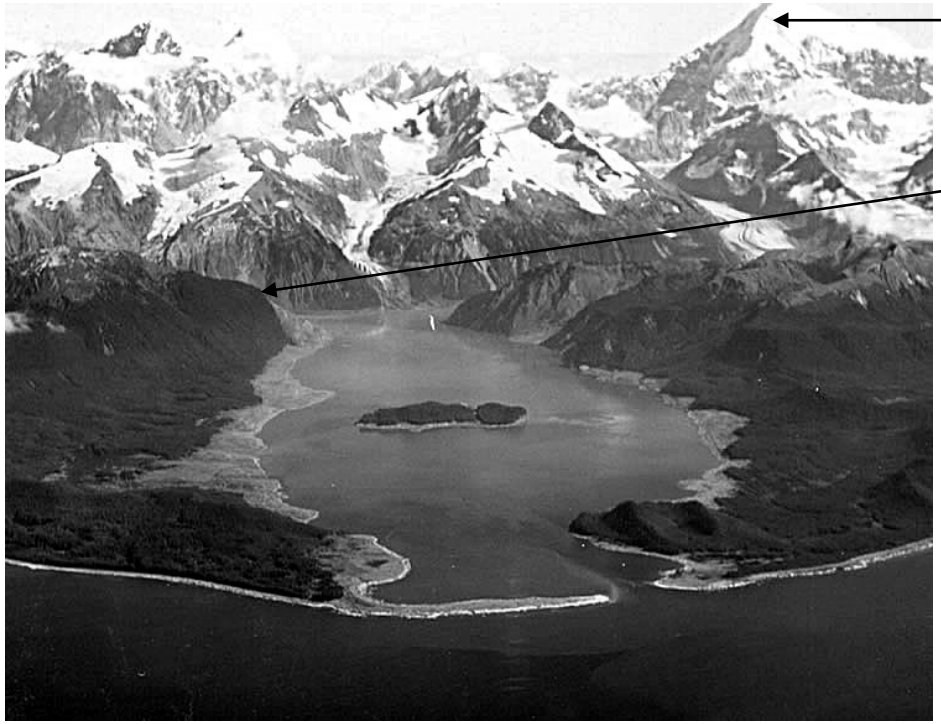
LISBONNE, 1755 La catastrophe avait suscité un âpre débat Rousseau-Voltaire.

# Extreme waves might be ...

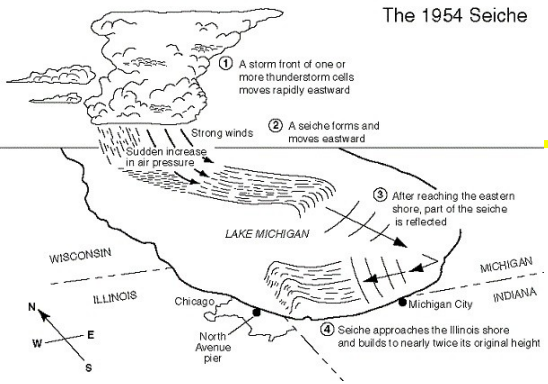
**“Harbour waves” (tsunami), i.e. solitary waves, in good accordance with math. theory yet no combination of wave trains.**

# Extreme waves might be ...

… “splashes”, unrelated to any wind waves prevailing at the time they occurred.




Lituya Bay, named Port-des-Français by Lapérouse, where trees were swept away as high as 524 m on July 9th 1958.




# Extreme waves might be ...

**A “seiche”, also named marrobbio, abiki, rissaga, seebär, milghuba, šćiga, meteotsunami, or tidal wave, raised by remote squalls.**

## BIG TIDAL WAVE HERE!

### *Many Swept Into Lake; Fear 10 Killed*

**Three Bodies Already Found**

***Mother of 11 Among Victims***

***3 Divers, Boats Hunt Others***

Three persons were drowned and several more were feared lost Saturday when a 25-mile-wide tidal wave smashed the Lake Michigan shore here.
The freak wave, estimated from 3 to 10 feet high, struck at about 9 a.m. from Jackson Park north to Wilmette. An undetermined number of persons were swept into the lake.

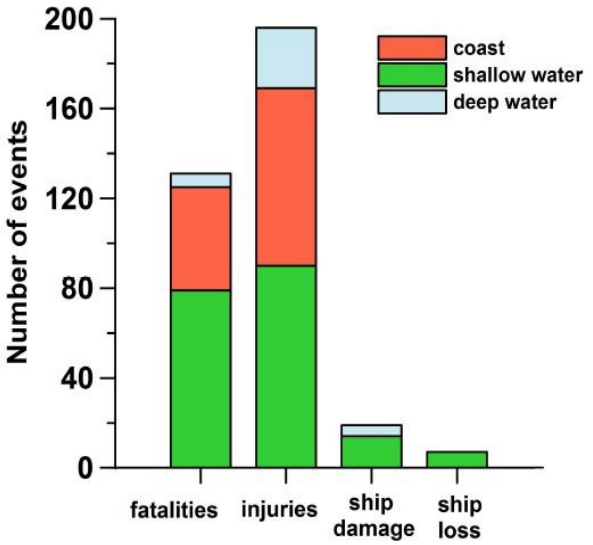
**Estimates of the death toll ran as high as 10, possibly including some children.**
One of the victims was a mother of 11 children. Her husband also was feared drowned.
The wind-whipped water did its worst damage at Montrose Harbor, where about 15 or 20 fishermen were swept off a narrow, 175-foot pier.

Several of these struggled to safety or were rescued and at least two were known to be dead.

**RESCUE BOATS dragged for bodies of others feared dead in still churning waters.**
**Three divers went down. But the current was so strong 3**4 hours after the wave hit that they could not see more than 6 inches ahead.
The dead were listed as:
—**Theodore Stempinski,** 40, of 1129 N. Winches-ter, a jewelry polisher.
—**John Jaworski** 52, of 1757 N. Honore, a car-penter.
—**Mrs. Mae Gabriel,** 48, of 3035 N. Hamlin, mother of 11 children.
Her husband Edward, 49, was missing and pre-sumed drowned.
Both Stempinski and Jaworski were fishing with their sons when the wave hit.
An anxious crowd of about 500 watched the rescue operations at Montrose Harbor, conducted by the Coast Guard, police and fire departments.
Relatives of missing persons waited tensely for news.

# Extreme waves might be ...

Most rogue waves are observed at or near the shore




## Shoreline rogue waves.

Maverick's 2010 surf contest

Photos Scott Anderson

# However,

**Some ocean wind-generated rogue waves exceed common expectations.**

The master of the *Selkirk Settler*, sailing from Tampa to Ghent, enjoys a kiss of the sea on Valentine's Day Eve 1987

Bulk carrier 34000t, length 222m, width 23m

Photos George Ianiev

Hence another definition:

*a rogue wave, occurring among wind waves, ...*

*... is a wave of unexpected severity, even for an experienced observer, when compared with the other prevailing waves in the same sea-state*.

It may seem a less scientific definition than 2xHs, yet it is more open and suited to scientific research.


# Urban myth ?

(email 19.juni 2006)
Lars, (Lars Golmen, NIVA)

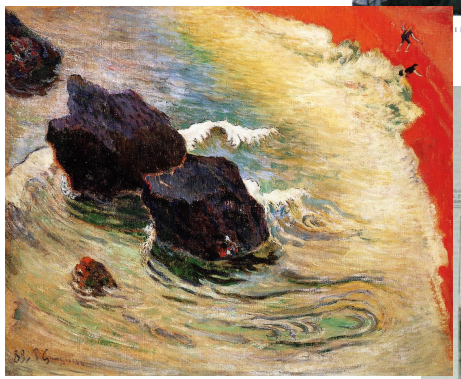
Sorry to say but we are not surprised that you cannot find anybody at the Norne field who knows about this photo - It's a FAKE.

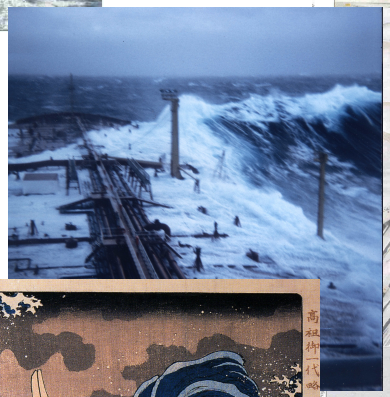
The original photo of the vessel was taken offshore Newfoundland - copy attached.

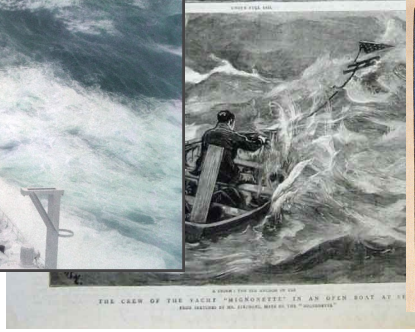
Regards
Niels F Hansen

Niels F Hansen
Chartering and Operations - Canada, Far East, Cable
Maersk Supply Service
Copenhagen - Denmark
Tel: +45 33633355 - Fax: +45 33633353
http://www.maersksupplyservice.com

# Rogue waves do happen !





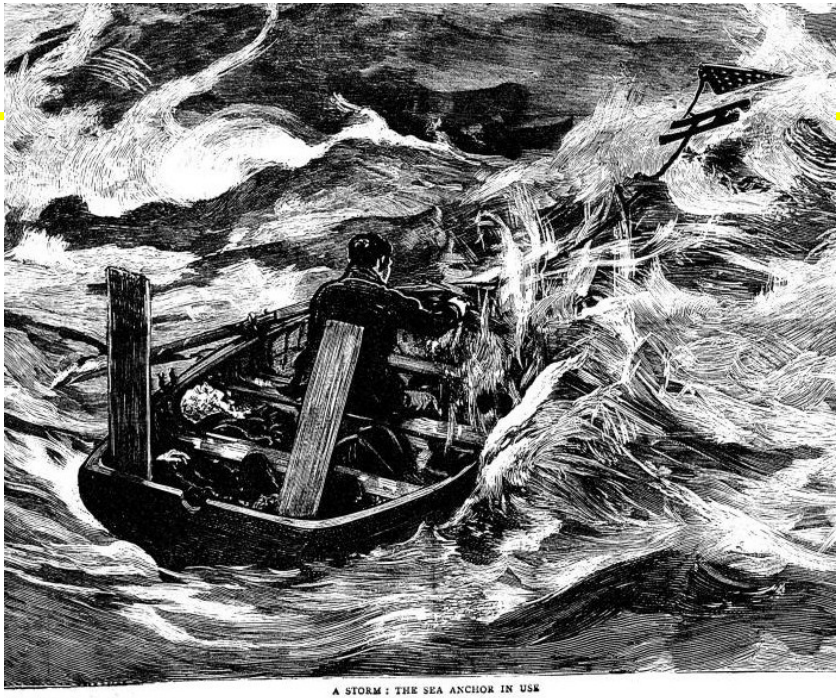


## Unquestioned existence:

# The *Mignonette*

July 5th, 1884 :

The *Mignonette*, a 16m-yacht sailing to Sydney, tries to avoid a strong gale 1600 nm NW of Capetown. Dudley, the master, asks to hove to so as to let the crew take some rest, and sends the boy Richard Parker down to prepare some tea. A giant wave suddenly smashes against the stern of the ship and springs loose its timbers, and the 4 of the crew have barely time to jump into the lifeboat with two tins of turnips and their water is washed away !



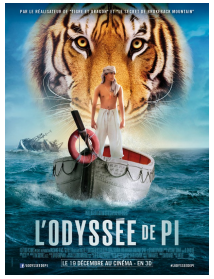
A STORM : THE SEA ANCHOR IN USE

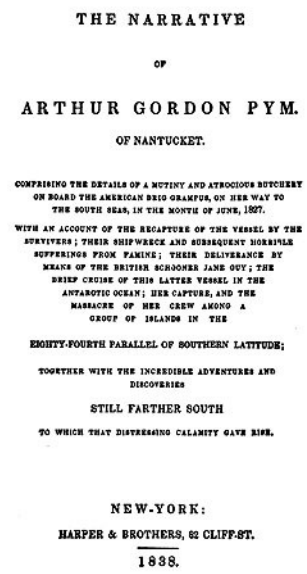
THE CREW OF THE YACHT "MIGNONETTE" IN AN OPEN BOAT AT SEA

FROM SKETCHES BY MR. STEPHENS, MATE OF THE "MIGNONETTE"

On July 23rd, the 3 others slay Parker and begin to eat him. They shall be saved on 29th by German *Montezuma,* and the case remains extensively studied, not for the wave, but in Law Schools.

Also in the book *The Narrative of Arthur Gordon Pym*, by Edgar Allan Poe, written 50 years earlier, 4 survivors after a storm and mutiny draw on the 18th day to kill and eat one of them, named ... Richard Parker!



THE NARRATIVE

OF

ARTHUR GORDON PYM.

OF NANTUCKET.

COMPRISING THE DETAILS OF A MUTINY AND ATROCIOUS BUTCHERY ON BOARD THE AMERICAN BRIG GRAMPUS, ON HER WAY TO THE SOUTH SEAS, IN THE MONTH OF JUNE, 1827.

WITH AN ACCOUNT OF THE RECAPTURE OF THE VESSEL BY THE SURVIVERS; THEIR SHIPWRECK AND SUBSEQUENT HORRIBLE SUFFERINGS FROM FAMINE; THEIR DELIVERANCE BY MEANS OF THE BRITISH SCHOONER JANE GUY; THE BRIEF CRUISE OF THIS LATTER VESSEL IN THE ANTARCTIC OCEAN; HER CAPTURE, AND THE MASSACRE OF HER CREW AMONG A GROUP OF ISLANDS IN THE

EIGHTY-FOURTH PARALLEL OF SOUTHERN LATITUDE;

TOGETHER WITH THE INCREDIBLE ADVENTURES AND DISCOVERIES

STILL FARTHER SOUTH

TO WHICH THAT DISTRESSING CALAMITY GAVE RISE.

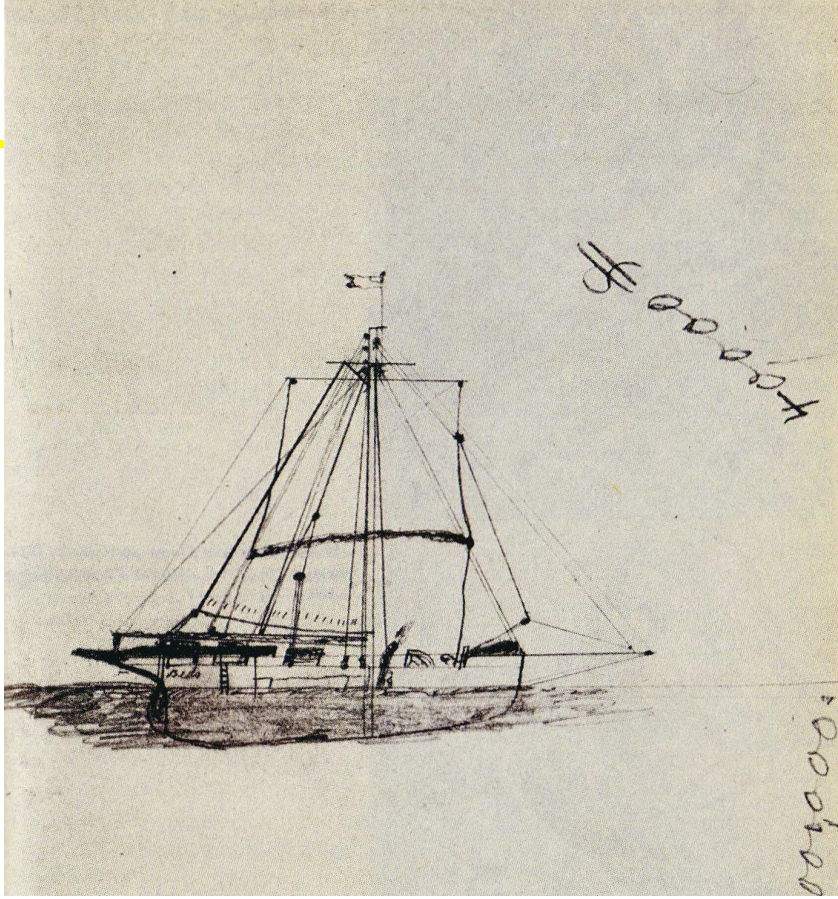
NEW-YORK:

HARPER & BROTHERS, 82 CLIFF-ST.

1838.

# Some inferences:

- Rogue waves also strike small boats.
- They occur at times when one feels somewhat secure.
- They are characterized by their consequences more than their heights.
- Their existence has long been admitted.
- They seem to challenge probabilities.



# The Glorious Three

Morning of Feb. 4th, 1963

The "*Jeanne d'Arc*" crosses North Pacific in order to go to Hong-Kong yards for a replacement propeller and avoid typhoons.

She sailed in a severe storm all trough the night, the Master sits at the bridge in his nightgown, yet patches of blue sky begin to appear.

Suddenly, a group of extreme waves is sighted straight ahead...

Photo Bernard Dujardin

The roll indicator hits the blocks at 30°, once, twice, three times !

# Inferences

5 abnormal points were
spotted out
by the Captain and Officers:

- Outstanding height and remarkable vertical front.
- Very short times between the successive waves.
- Direction shifted 20-30° from the main wave train.
- Very high propagation celerity.
- Very short crest lateral extension, very small extent of the wave group.

Is there a link between those features and the conditions and mechanism of occurrence?


## Are rogue waves a problem for structural design?

**Could be – but that depends very much what is meant by rogues waves.**

**At least two options:**

**a) ”Classical” extreme waves**

**i.e. rare members of a population of waves defined by modelling the surface process as a piecewise stationary and homogenous slightly non-Gaussian process.**

**This type of extreme waves are presently accounted properly for by the offshore industry provided some accidental wave load scenario is implemented.**
**Traditional shipping may have some room for improvements.**

**However, waves that are likely to cause structural failure do exist within this population, but their annual probability of occurrence should be lower than say $10^{-5}$.**

## Are rogue waves a problem for structural design?

**b) Freak (extreme) waves;**
**defined as typical members of a population being in agreement with physical mechanisms well beyond those under a).**

**This type of extreme waves are outside our design events. If such a population exists, it may challenge present design recipes if it affects the $10^{-3}$ – $10^{-5}$ annual probability of exceedance level at a given site.**

## Suggested definition of freak waves

(Sverre Haver)

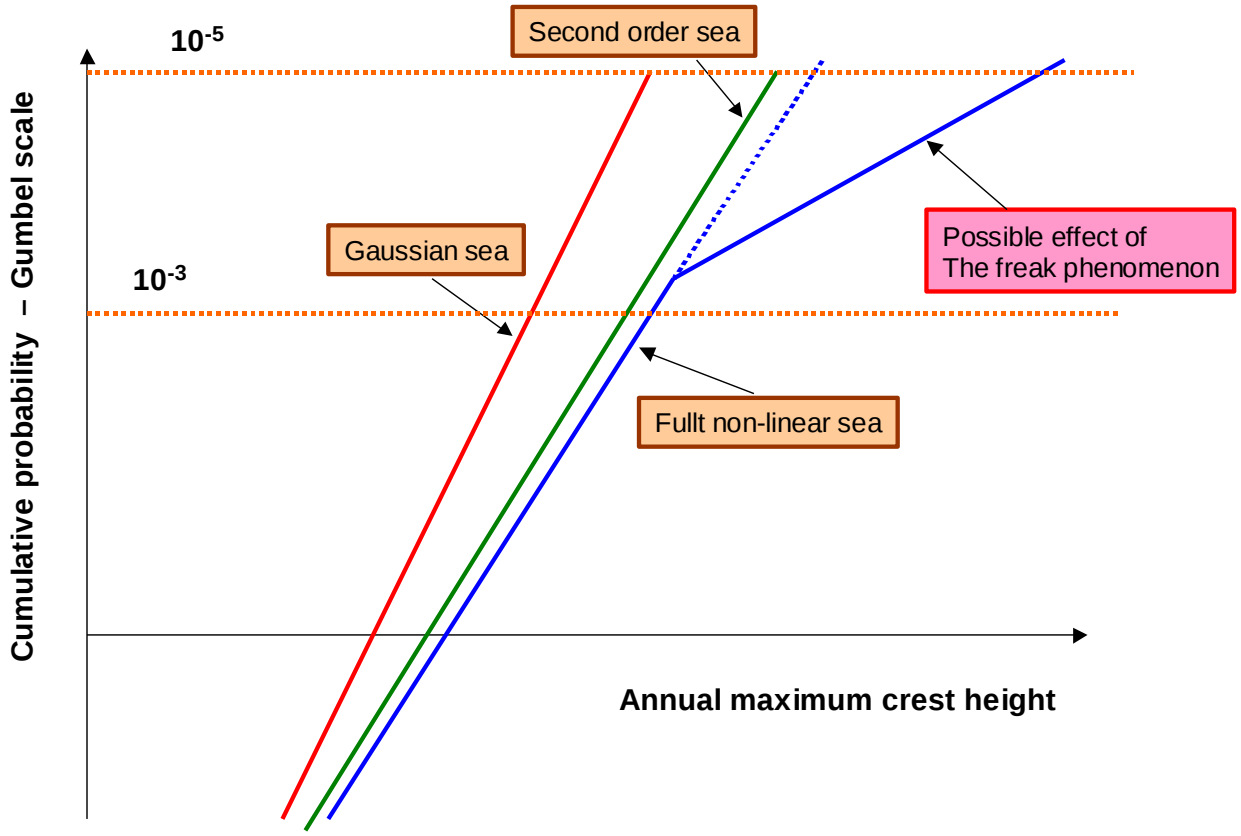
**A freak wave event is an event that is governed by mechanisms and/or phenomena well beyond those underlying the piecewise stationary and homogenous second order model of the sea surface.**

**A second order model is selected as a reference population for non-freak events because that is the most sophisticated model available for routine design.**

**A factor definition is not very useful since it may – with low probability – be exceeded even under Gaussian assumption for the sea surface elevation.**

# Can freak waves represent ”an ugly” mechanism?

**YES – IF THEY MAKE THE UPPER TAIL ($10^{-3}$ – $10^{-5}$) FOR THE ANNUAL EXTREME VALUE DISTRIBUTION AT A GIVEN SITE SIGNIFICANTLY FATTER**



# The Challenge!

**KNOWN THREAT**

**Major threat of safety – but can be accounted for.**

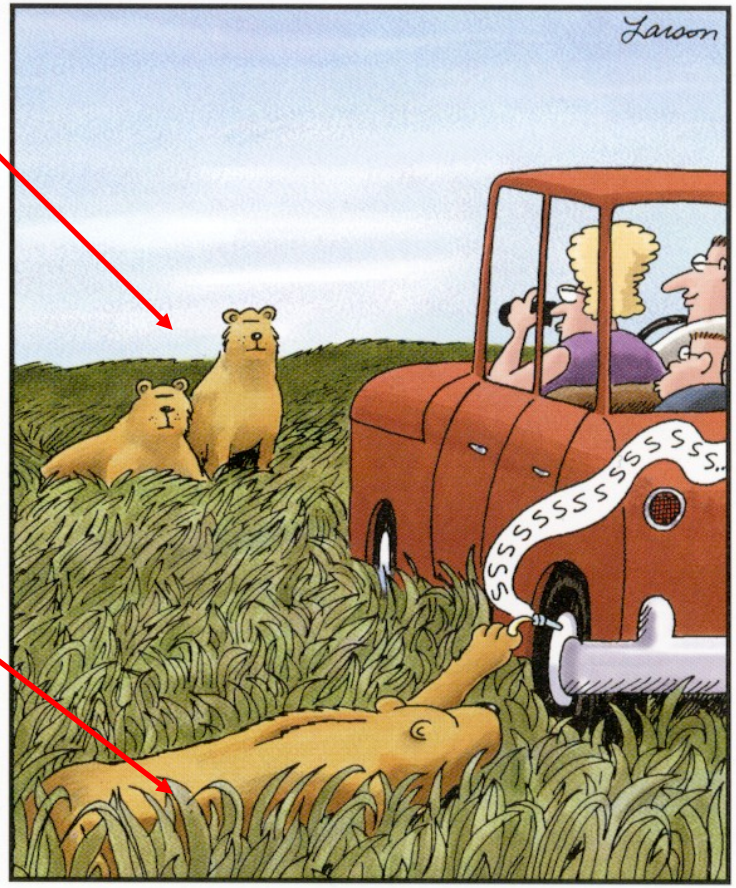
**Wave-parallel:**
**”Classical” extreme waves**

**UNKNOWN THREAT**

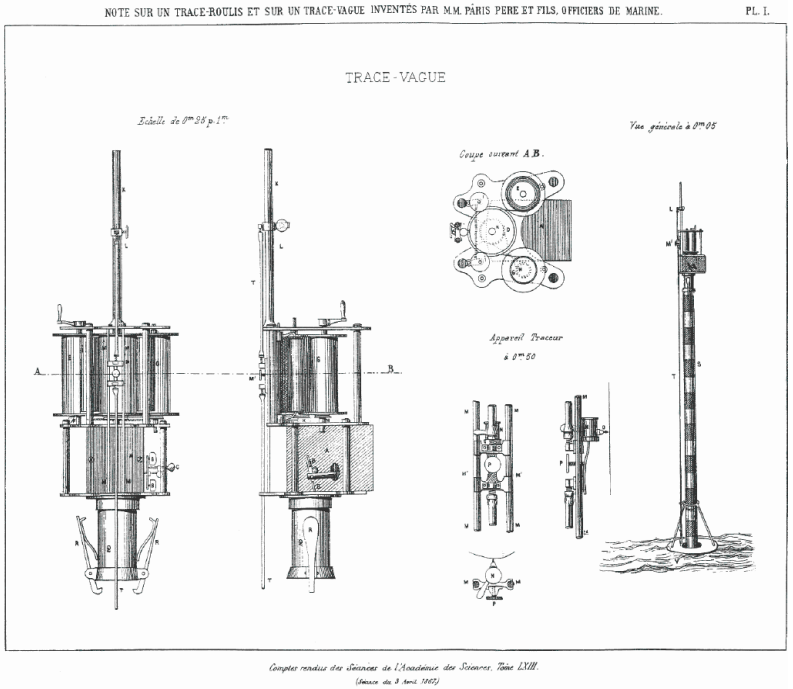
**Difficult to approach in a rational way – but can be crucial regarding safety.**

**Wave-parallel:**
**Freak extreme waves**

**Does a separate freak wave population exist????**



# Two lines of attack:




- **The statistical observer**

- **The mathematical constructor**

# Design expectations are not so bad

Platforms and ships are designed according to 10000-year waves specifications (often less for ships), the world merchant fleet is about 90000 ships, we might loose 9 ships per year because of waves. There are about 1100 platforms, one might loose one per 9 years.
Do we loose that many ? Not because of waves.

Conclusion : Design specifications do not currently underestimate the occurrence probabilities of extreme waves. That is for reliability targets of a few billion waves. Note that in the 80's, experience and feedback were far from as favourable...

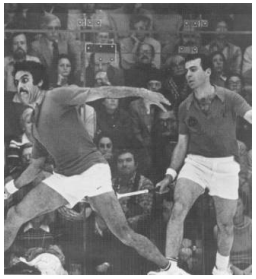
**Yet...**


# Statistical conclusion would require reliable measurements of many hundred million waves...

**We are close to those numbers, but they are far from reliable, neither sufficiently free from other effects (shallow water, run-up on structure, etc.). So let's try to speculate rather than remain within the bounds of statistics :**

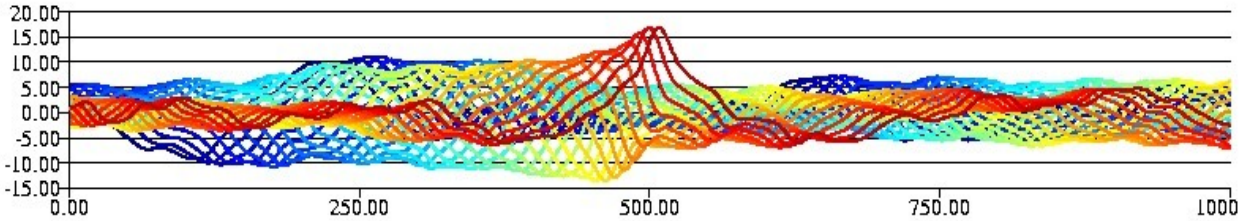
**“ When a woman at a party asks me what I do, I invariably say «*I ’m just a speculator.*» The encounter ’s over. The only worse conversation stopper is «*I ’m just a statistician.*» ”**

*Victor Niederhoffer, The Education of a Speculator, Wiley, 1997*

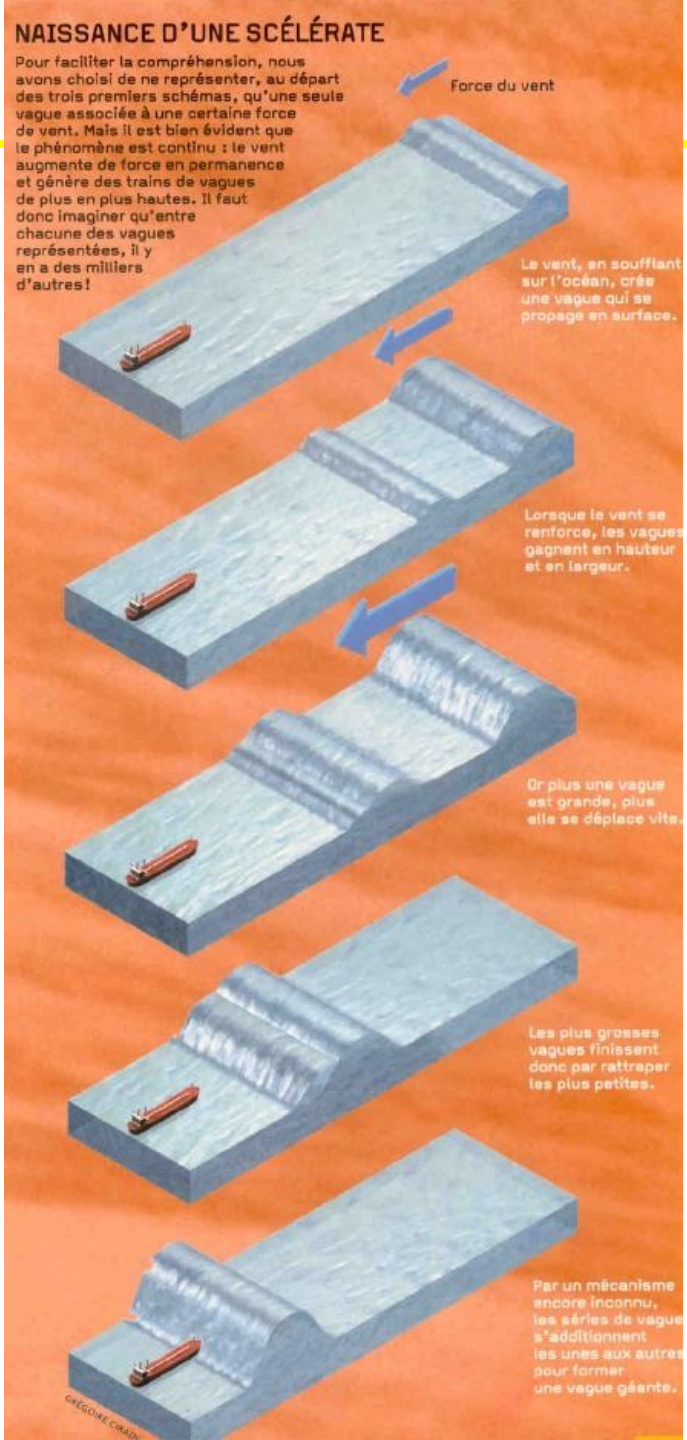


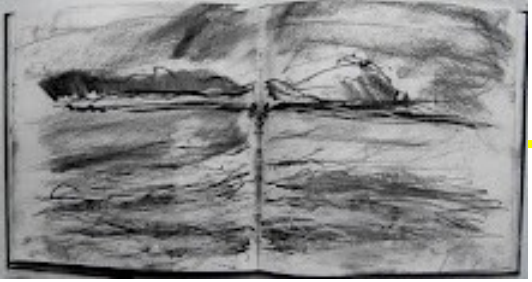
# We have three proposals:

- **Miguel and Al (Onorato & Osborne, 2005) : a special mechanism triggered by some factor.**
- **Sverre (Haver, 2000) : a typical wave of a different statistical population, no special prior assumption about that population.**
- **Georg (Lindgren, 1970) : an extreme extreme in the normal statistical population.**



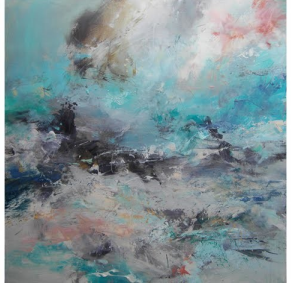
Just like in some horse races where groups start from several starting lines, the fastest the farthest, at some point all run together and interactions may occur to remain in a single bunch.





# Reconstruction

Or the wave trains may come from different directions.



# Benjamin-Feir instability

**Waves are like cyclists : they run with different speeds, and when one overcomes another, they stay together for some duration and interactions occur. Those interactions may follow, as expected, natural rules, or some other less transparent ones. Natural rules says that the group should disband pretty quickly, yet if the waves merge, they gain speed, overcome more waves, merge with them, gain more speed, …**

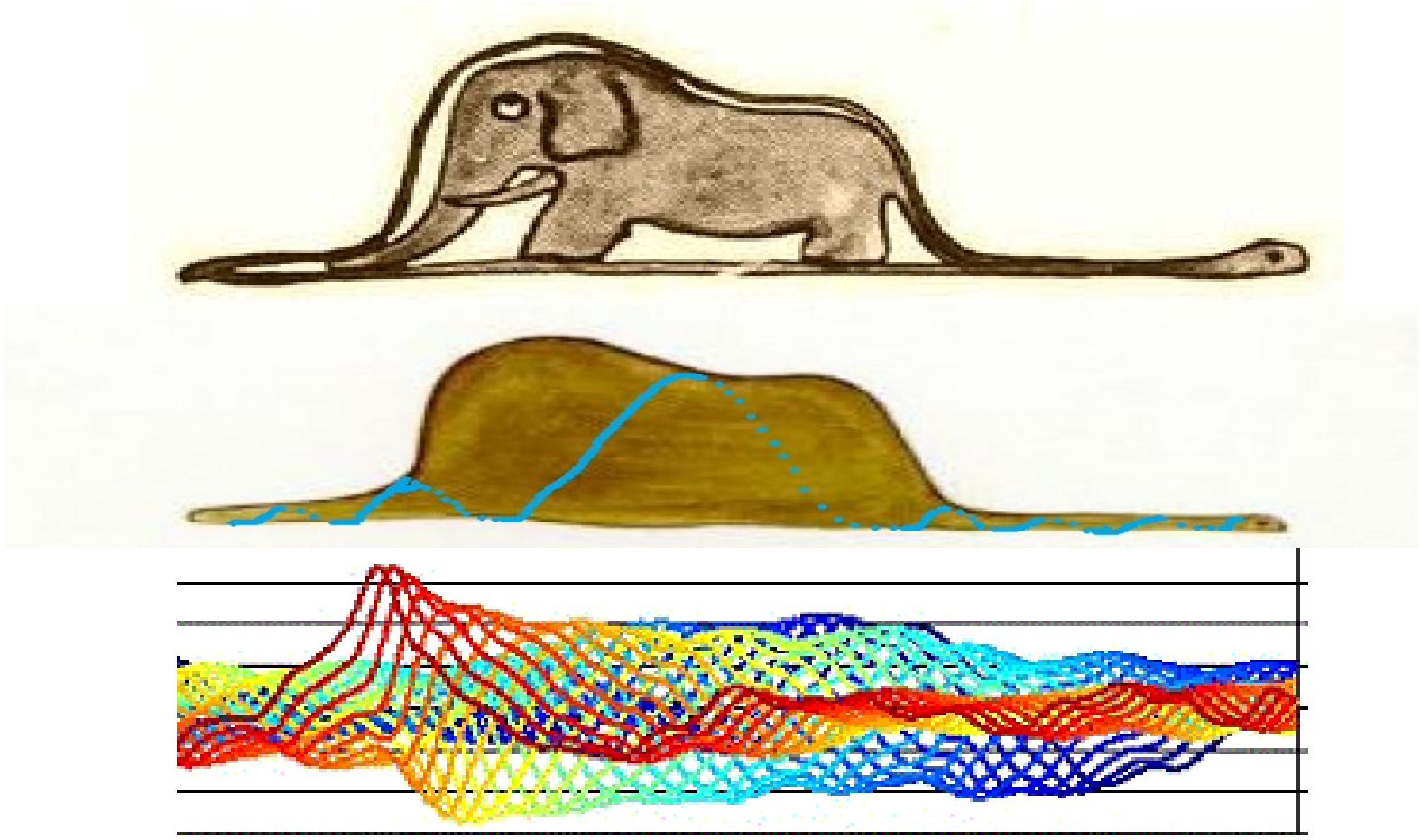
**In practice, two behaviours are possible : Navier-Stokes non-linearities or Schrödinger equation model of « breathing » wave groups. Benjamin-Feir Instability parameter (BFI) would in the second case govern the breathing of the group envelope. Group velocity and energy velocity are the same, thus breathing means that at some times the group contains six or seven waves, and at others only one or two.**

# Schrödinger equation and Saint-Exupéry

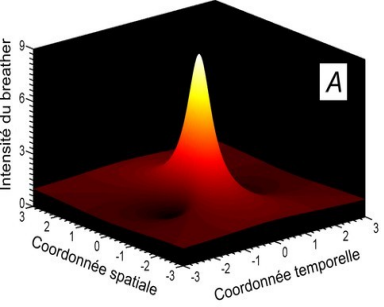
***Does my drawing frighten you?***

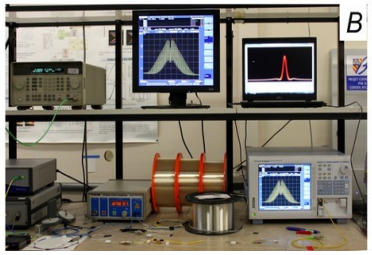
## It should :

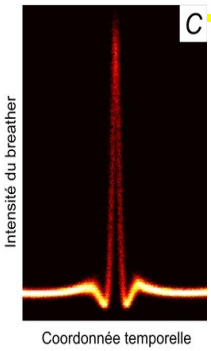
**NLS equation models the complex envelope (the boa's skin), the real part of which (the sectional view) shows the time-space evolution of the waves shape (digesting an elephant in the case of a rogue wave).**

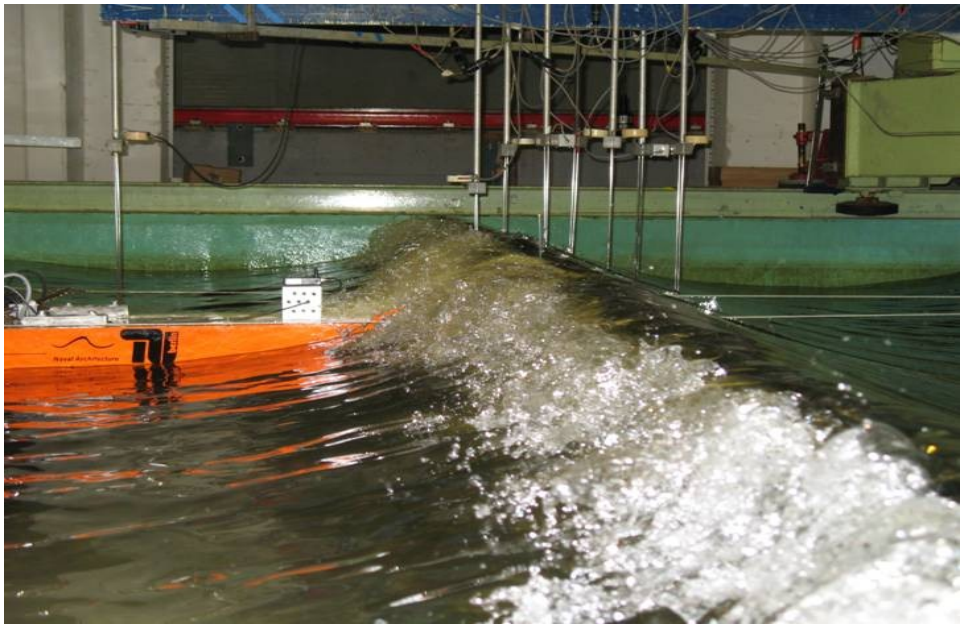


# NLS does enable to construct freak waves



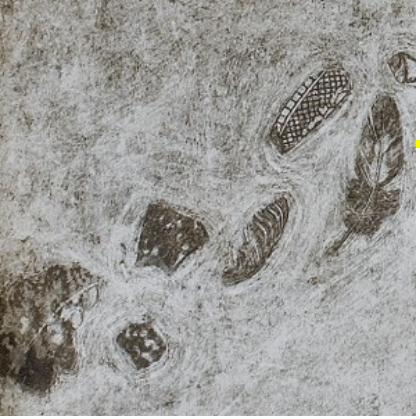



Parameters for the Peregrine soliton were set to make a rogue wave in an optical fiber, and it worked. Using the parameters defined for that soliton, researchers were then able to reproduce it in a wave tank !

However in the ocean, we cannot measure all the simultaneous parameters that would be needed to check whether Navier-Stokes or Schrödinger applies. NLS is a postulate that can neither be theoretically proven nor disproven. Yet, we would make progress if we could answer the questions :

- Are there more extreme waves than common (design) expectations ?
- If there are, are there any characteristic features in the sea-states in which they occur ?



# Kurtosis and Benjamin-Feir instability

**“When a similarity connection is achieved between two objects to 20 decimal places, the greater will move to the lesser”**

*A.E. Van Vogt, The World of Null-A, 1945*

One may imagine that in some neighbourhood of the extreme wave, modulational (Benjamin-Feir) instability would govern the evolution in such a way that it would not appear in mid- or long-term statistics.

Mori & Janssen 2005 showed a relationship between Benjamin-Feir Instability index and water surface elevation kurtosis … however, does that mean causality ?

I.e, does Benjamin-Feir Instability index (BFI) predict or just detect extreme waves ?

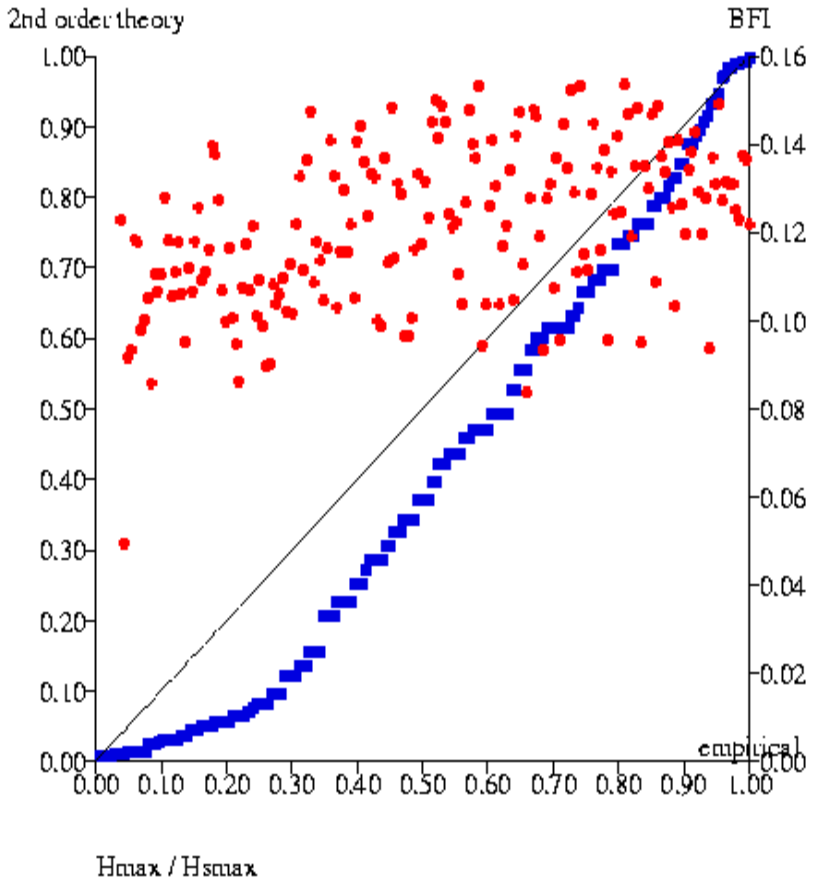
# BFI at the scale of the storms

## QQ-plot of Hmax/ $H_{1/3}$max

## Average BFI over the storm

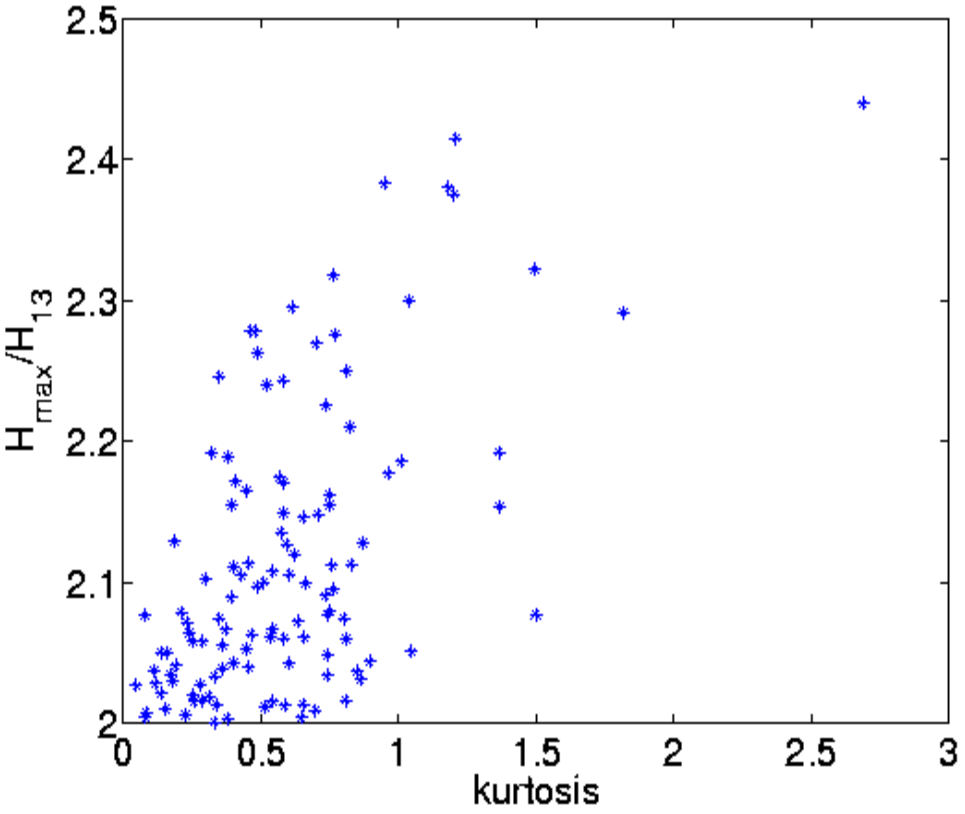
**1000 simulated theoretical clones for each storm.**

**The same storm ranks lower in freakness as observed than its simulated clones : observations are not as severe as theory !**



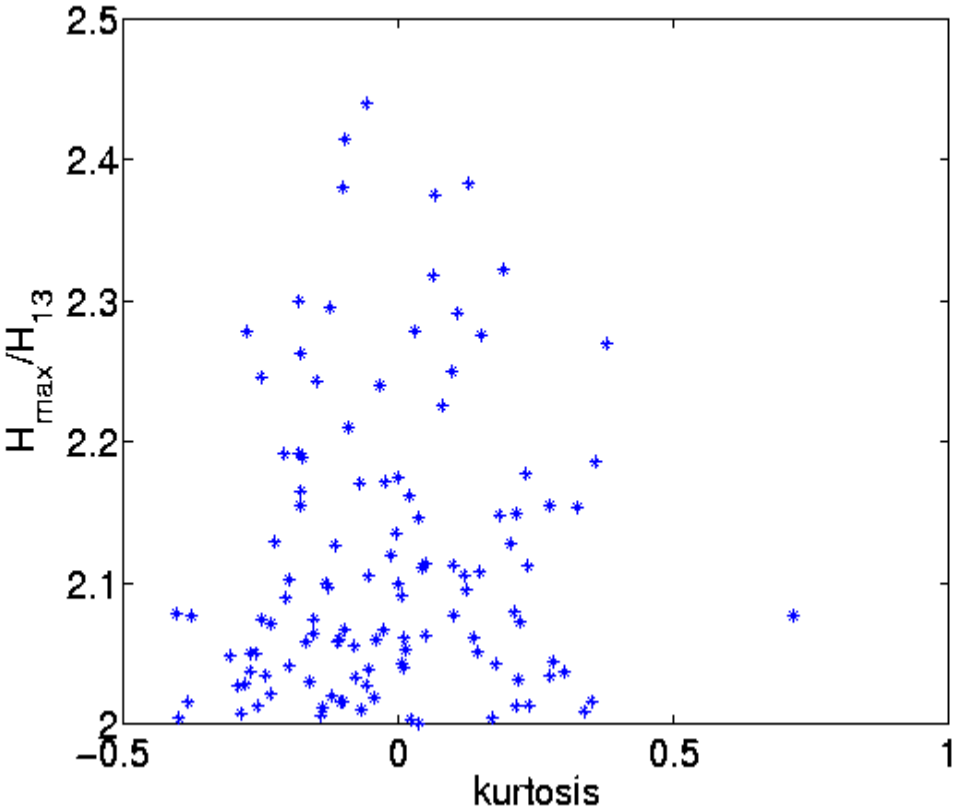
# Kurtosis and Hmax at the sea-state time scale

**Hmax/ $H_{1/3}$ shows a strong experimental correlation with kurtosis (and thus BFI) ...**



# Kurtosis and Hmax at the sea-state time scale

**…yet computing kurtosis over the sea-state with a window removed at the maximum waves also removes the correlation.**



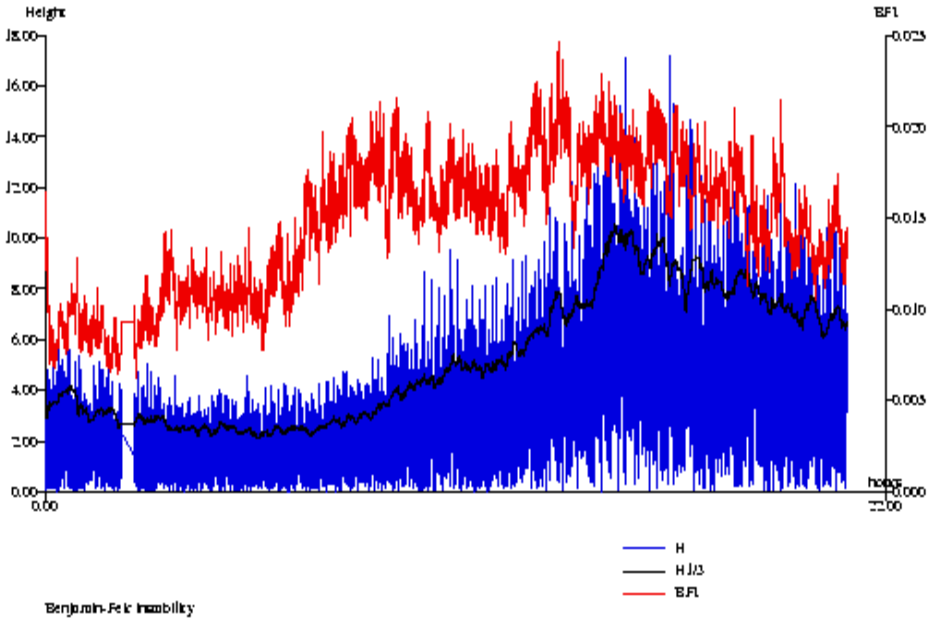

2015 results by *Birkholz et al.* confirm that the “deterministic duration” of an ocean rogue wave is of the order of magnitude of the dominant wave period.

# Can something be detected at the time scale of a few waves ?

**Moving window BFI index :**

**nothing either.**

**H**
**H1/3**
**BFI Index**



## Conclusion as to Schrödinger non-linear equation :

## it is a detector, a posterior explanation, not a predictor

**“We have a wonderful mathematical theory, that allows us to construct rogue waves that cannot be distinguished from the ones we can observe in nature. Yet I fear that we can never know if this is indeed what happens in nature.”**

***Kristian Dysthe*****,** *developer of the Schrödinger equation variant that is used for ocean waves.*

# Yes indeed !


**Boas**

**Elephants**

**It is easy to identify the dwelling areas of boas and elephants. Only artificially arranged meetings can occur, and it might well be the same for NLS freak waves.**

# Conclusions as of today

- **Extreme waves do not occur more frequently than conventional models predict.**
- **When they can be observed, none of the parameters that we could think of shows any predictive power.**
- **There is no reason to believe that commonly used theories fail to model their occurrences.**
- **… Still nothing could be found that would invalidate specially developed theories such as NLS (modulational instability).**

# Any risk to meet one ?

That might still happen !

# Merci !

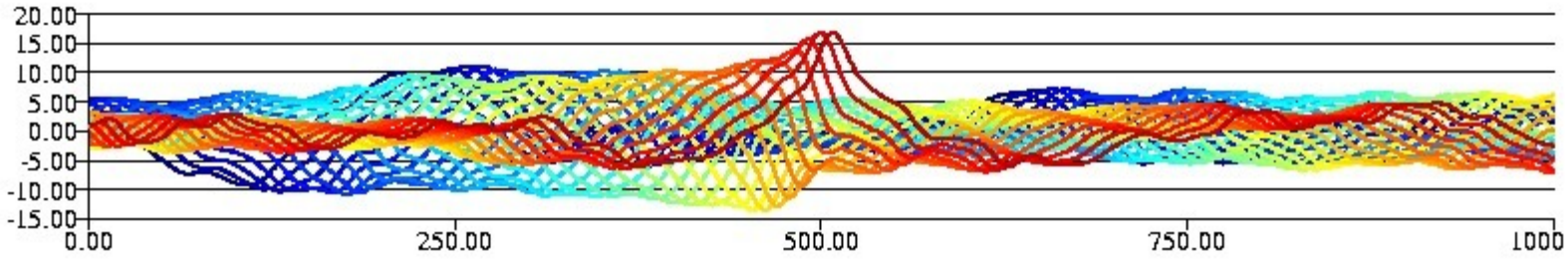
Et merci à Janette pour l'intérêt exceptionnel d'une artiste envers le sujet.

http://extremewavetheory.blogspot.fr/

http://www.janettekerr.co.uk/

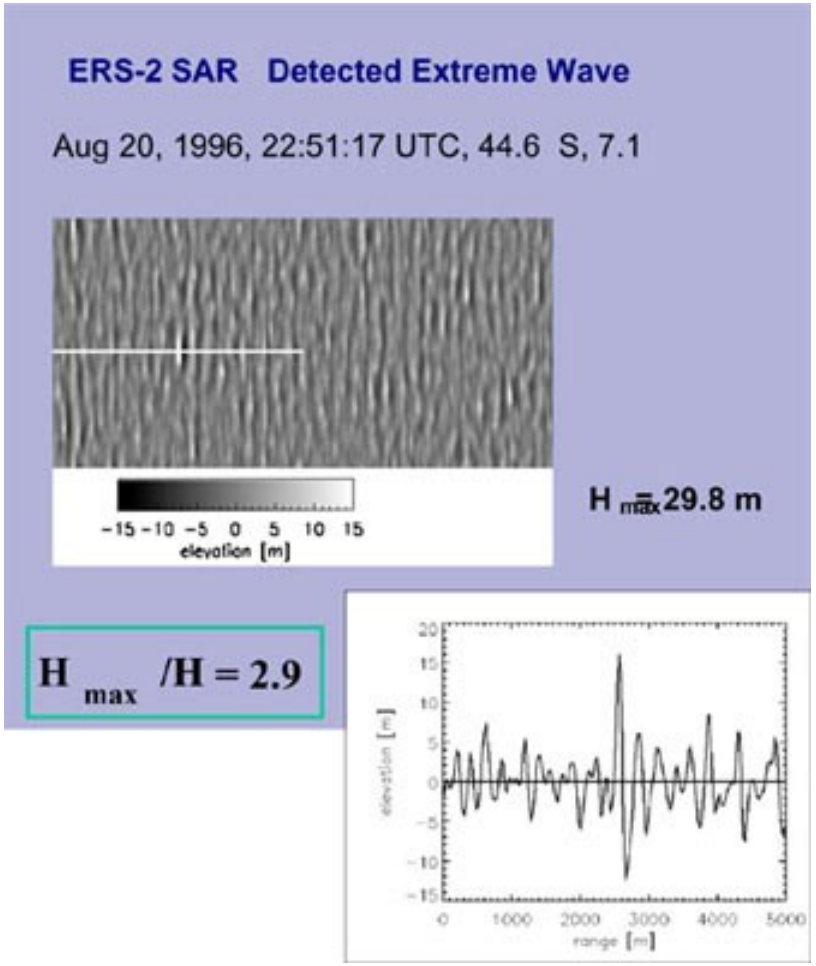
“ Yet the Draupner wave was nearly 30 m. with a 18 m. crest height above sea level”.

As time passes, it is more and more likely that it was the bad place at the bad time. Design is not questionned.



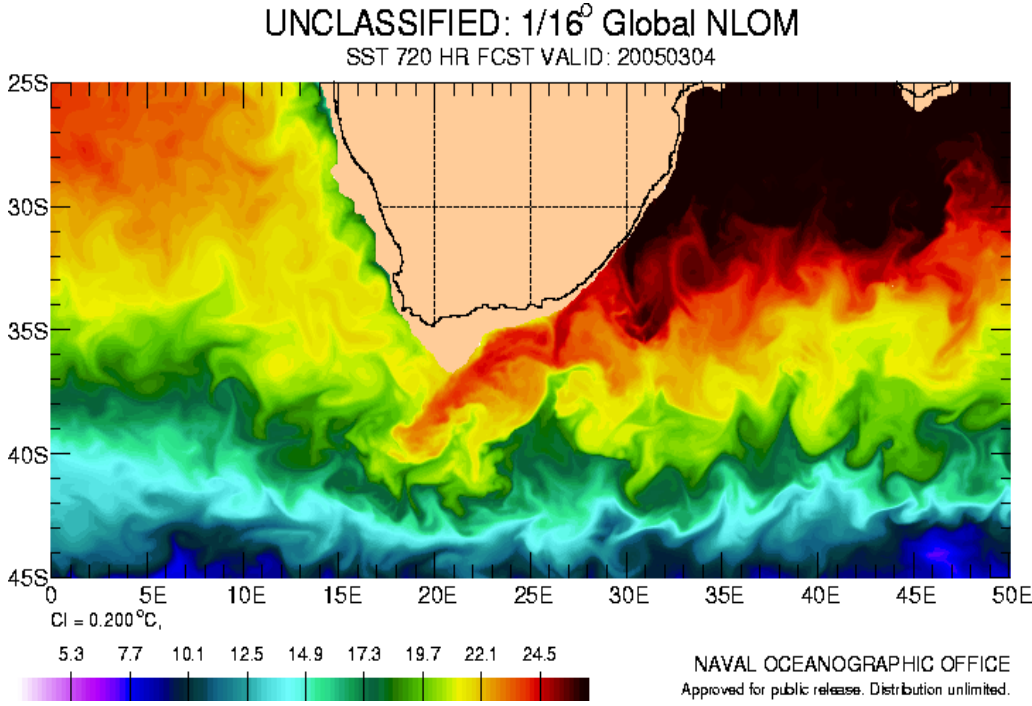
“ Satellites are said to detect lots of rogue waves.”

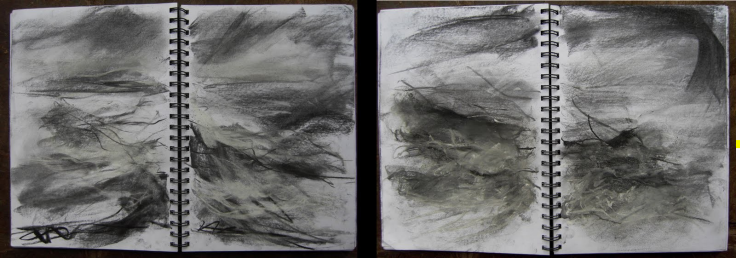
Uncertainties are such that waves that are just “big” may be qualified as “rogue”. In addition, ratios over a surface rather than along a line are theoretically larger.



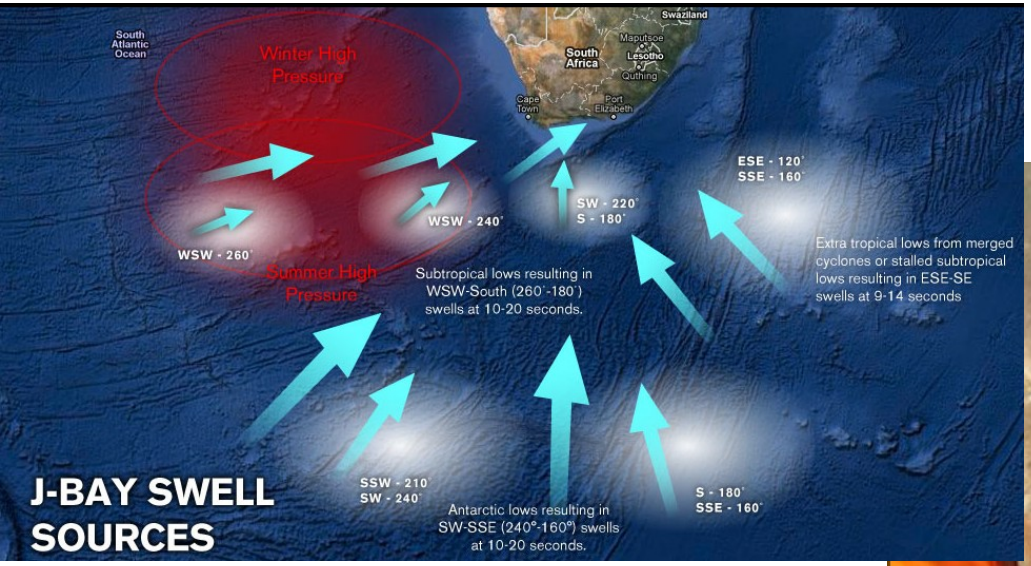
“ Rogue waves are said to be very frequent in the Agulhas current”.

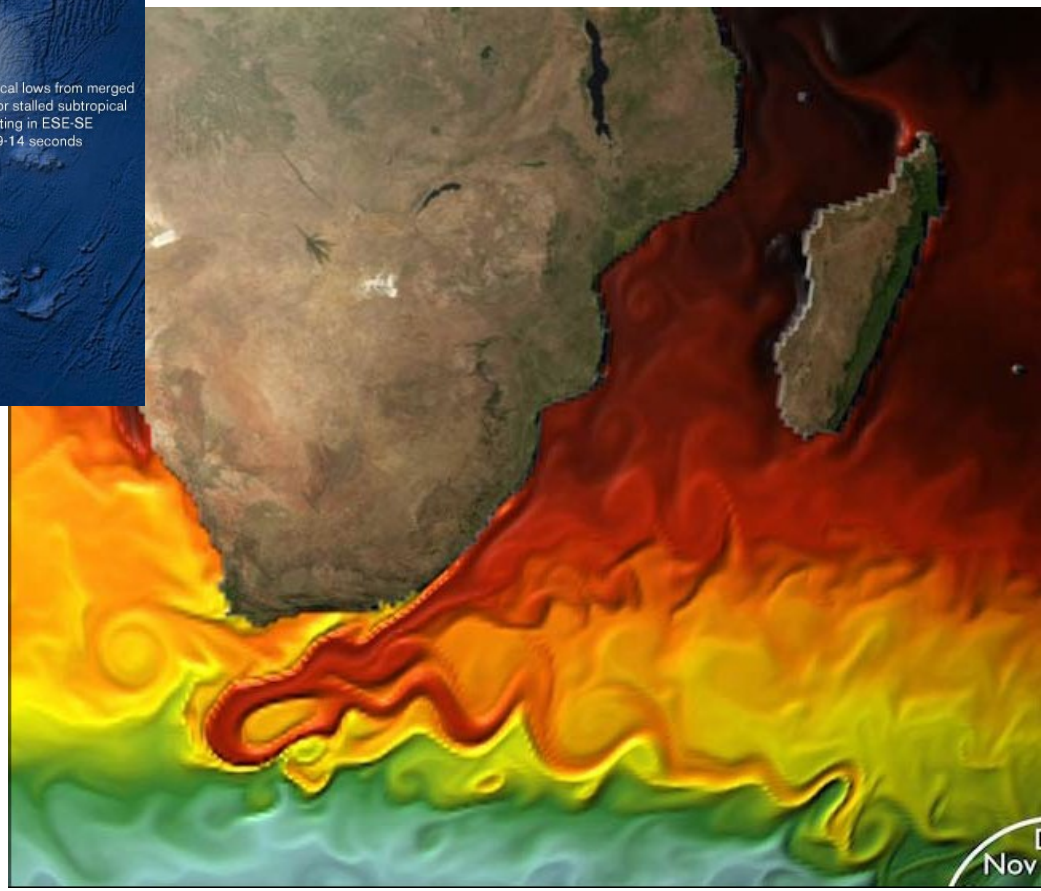
Favorable conditions were identified in the '70ies, and accidents have almost disappeared as seafarers have learnt to watch out for them.





# Prof. Mallory explained in 1974:

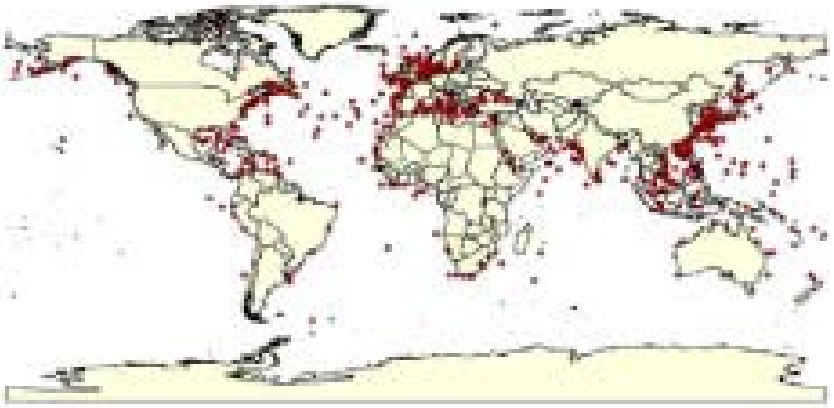


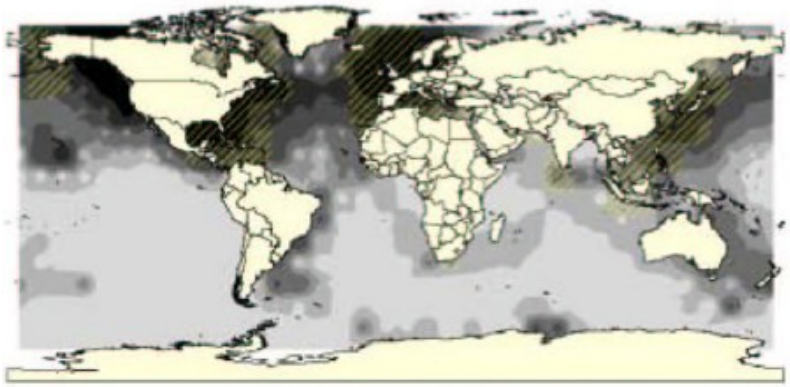




Swell going against the current.

# Are there some regions in the world more prone to rogue waves than others ?

**The actual question meant in-between the words: “Are there regions where one is safe from rogue waves ?”**






**There are just places where nobody is watching...**

# A Black Swan

For Nassim Nicholas Taleb, a black swan is an extreme unexpected event, the causes of which can yet easily be determined but only after it occurred.

In that respect, a rogue wave is indeed a *black swan*. Still, the layman has mainly heard *extreme* and *unexpected*, and saw there arguments towards some pessimistic fatalism. On the one hand,Taleb never said that *unexpected* would mean that the occurrence probability could not be determined, on the other hand he stressed in his later book *Antifragile* that in many cases the consequences could be beneficial. A rogue wave is thus a black swan *stricto sensu,* and departs from the popular representation of it.

# In case of global warming

A rogue wave is defined with respect to the other waves => Everything that is global affects all waves, thus an increase in the average wave height does not lead to an increase in rogue waves numbers.

There are physical limits to wind waves heights => The closer one comes to those limits, the less the extreme wave heights will depart from the mean.

The effect of climate change is not to make new phenomena appear, but to redistribute existing conditions among regions => No reason to forecast that severity should increase rather than decrease.

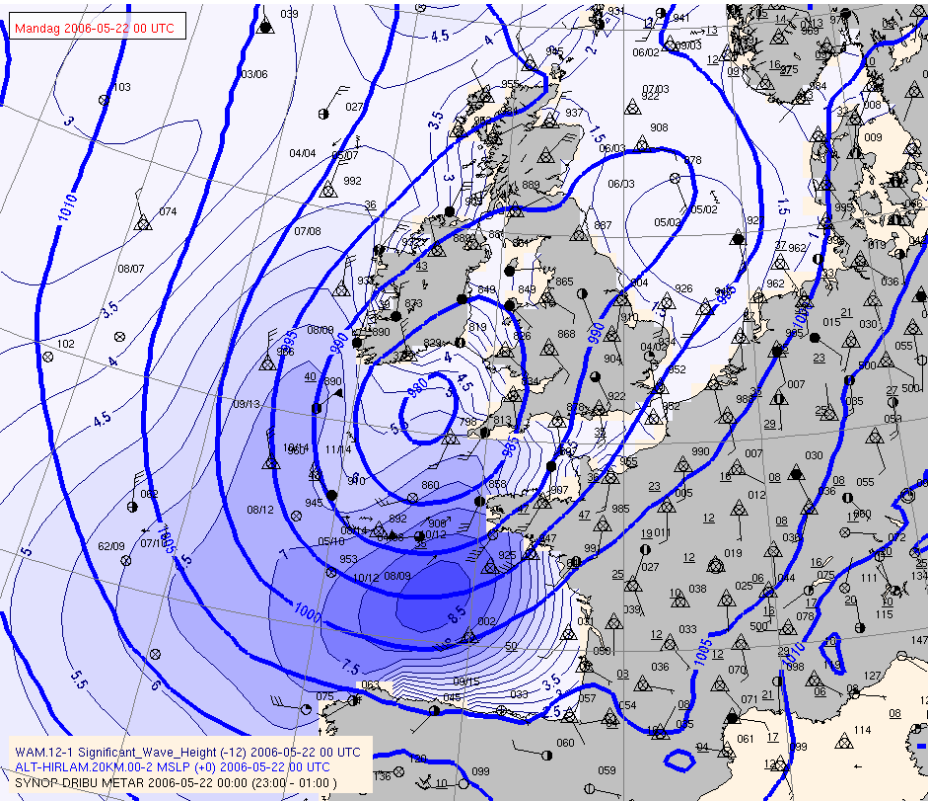
*The oceans will become more and more populated and measured => More rogue waves will be reported, yet* ***their actual number in the oceans will not have increased****.*

# Sailing into the “hot spot”

## The *Pont-Aven*

During the night of Whitsunday to Whit Monday 2006, the *Pont-Aven* ferry was hit by a 15 to 18 metres wave when approaching Ushant.

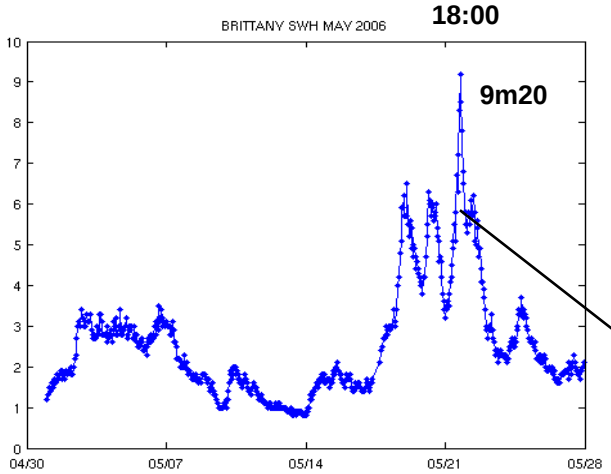

# **The** *Pont-Aven*



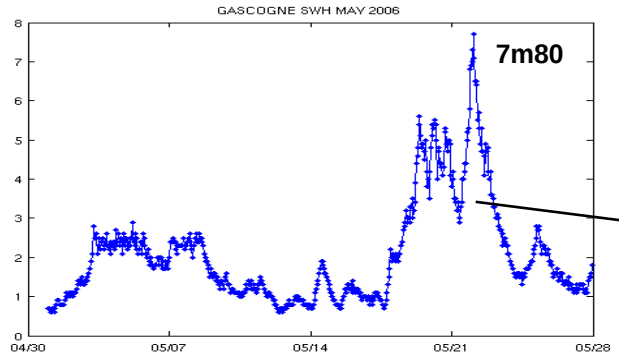

The crew intented to sail behind the area of 8 metres waves that was moving to the East of the Bay of Biscaye.

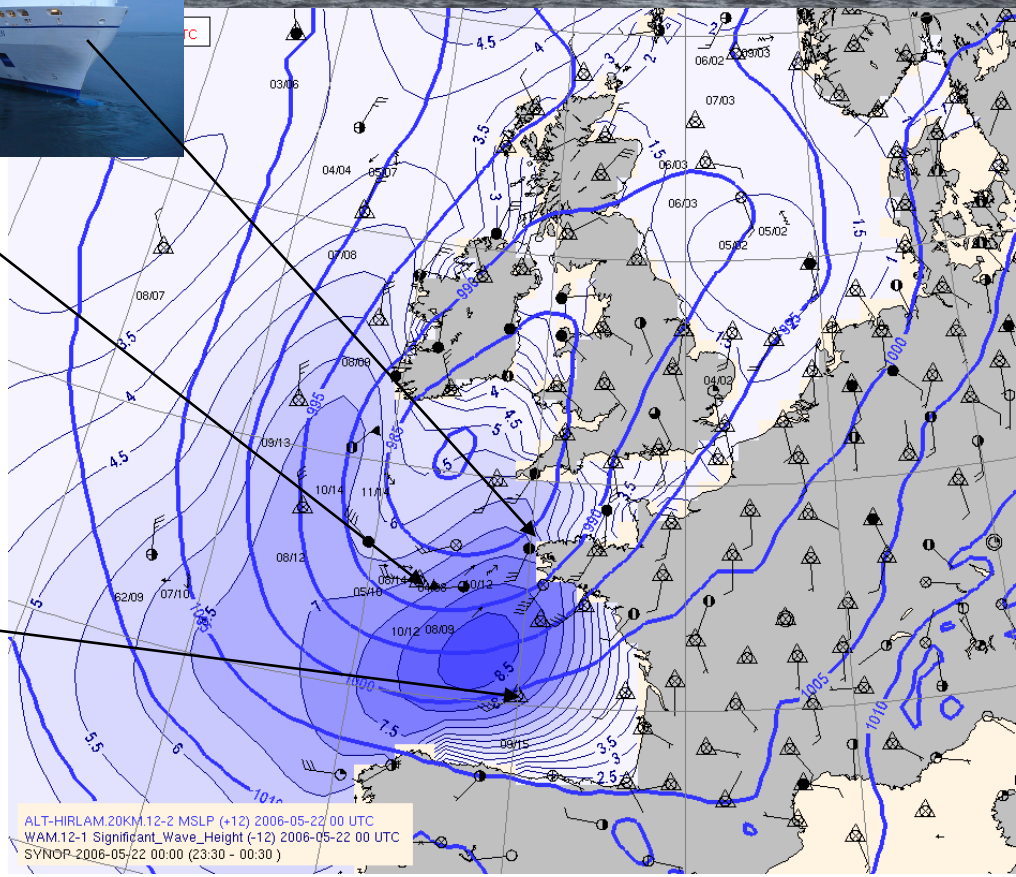
A secondary storm of small extent yet even stronger appeared North of the first, and the ferry sailed straight into it.

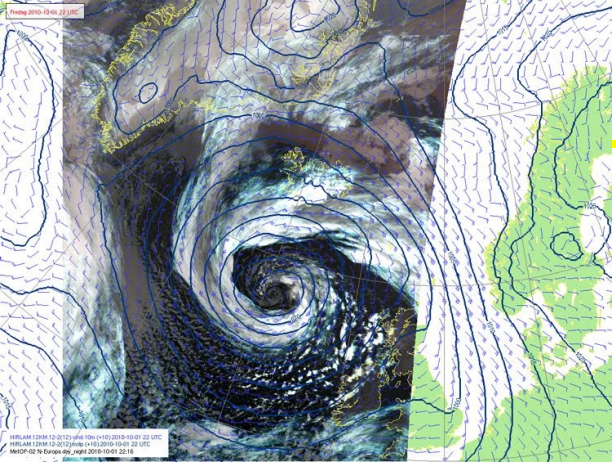
# Hs !


BRITTANY SWH MAY 2006
18:00
9m20
04/30
05/07
05/14
05/21
05/28


24:00


GASCOGNE SWH MAY 2006
7m80
04/30
05/07
05/14
05/21
05/28


ALT-HIRLAM.20KM.12-2 MSLP (+12) 2006-05-22 00 UTC
WAM.12-1 Significant_Wave_Height (-12) 2006-05-22 00 UTC
SYNOP 2006-05-22 00:00 (23:30 - 00:30 )

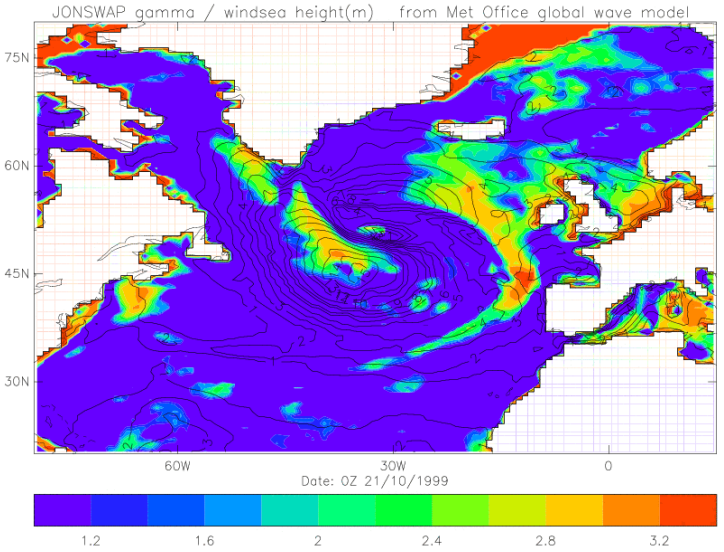


# So, can we expect to become able to predict areas of increased risk ?

**NO**

Relevance of parameters cannot be theoretically assessed

Experimental validation fails by lack of volunteers to carry it out

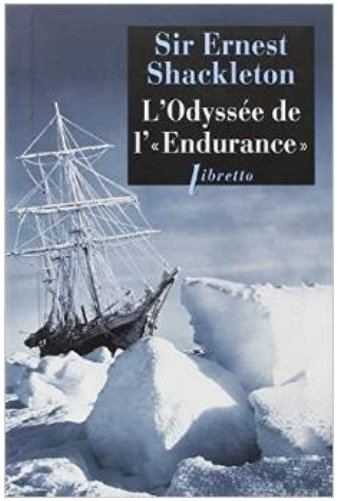



**Above all, random extremes remain the majority.**

# Shackleton


April 1916 :

*Endurance*, blocked for 9 months by ice, then crunched, the group makes it 6 months later to Elephant Island. Winter is approaching, one must go and seek help, Shackleton sails out on the *James Caird* to Georgia.

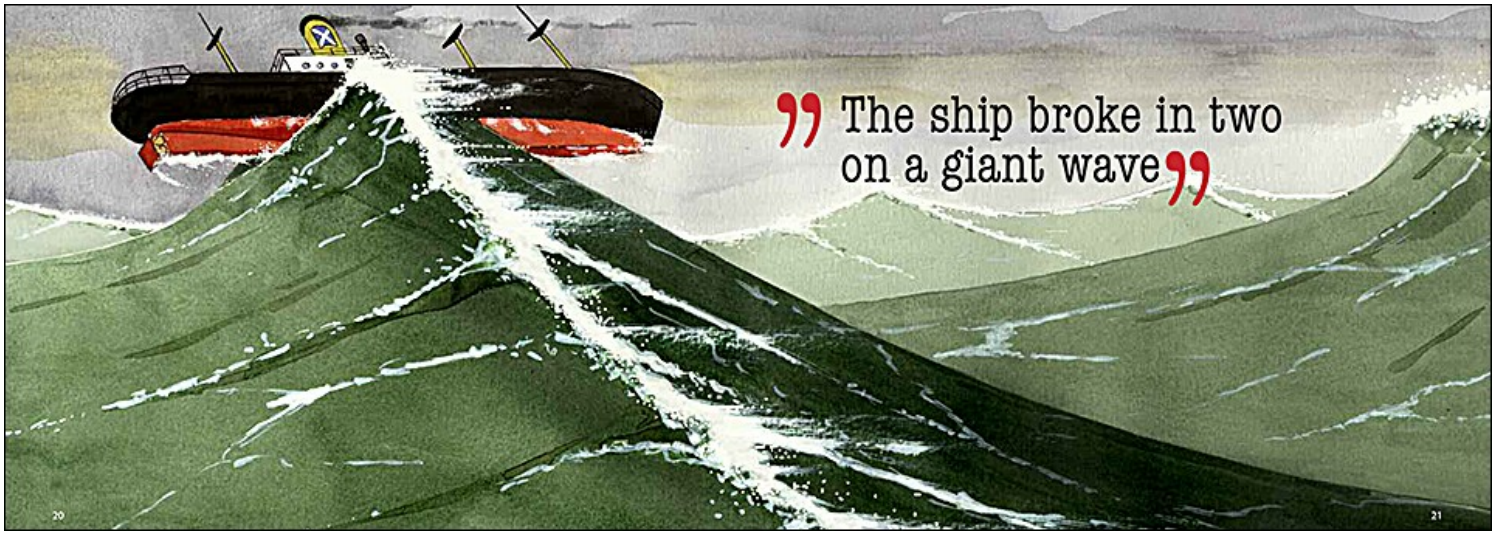



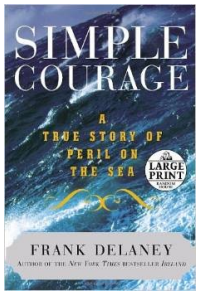

On the eleventh day, during the night, Shackleton shouts to his mates that the sky is clearing up... then “Hold on !” The light he saw was the white foam of a giant wave falling over the boat.

# The *Flying Enterprise*

A first rogue wave on boxing day 26/12/1951, a crack but watertight, a second one on 28th, and 45° list.

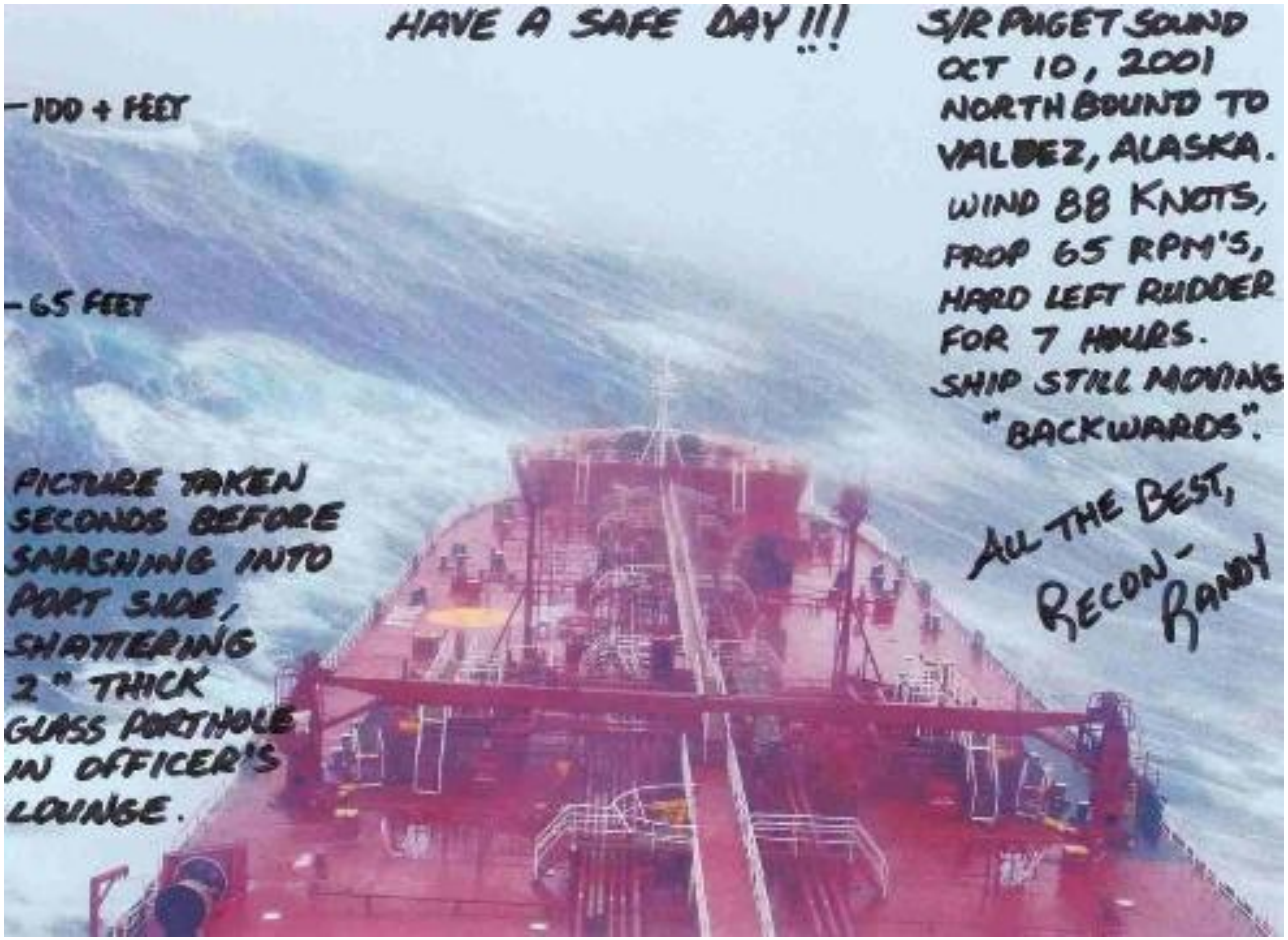
The waves were secondary in the story, mostly famous because Captain Kurt Carlsen refused to abandon ship until it sank on 10th January.



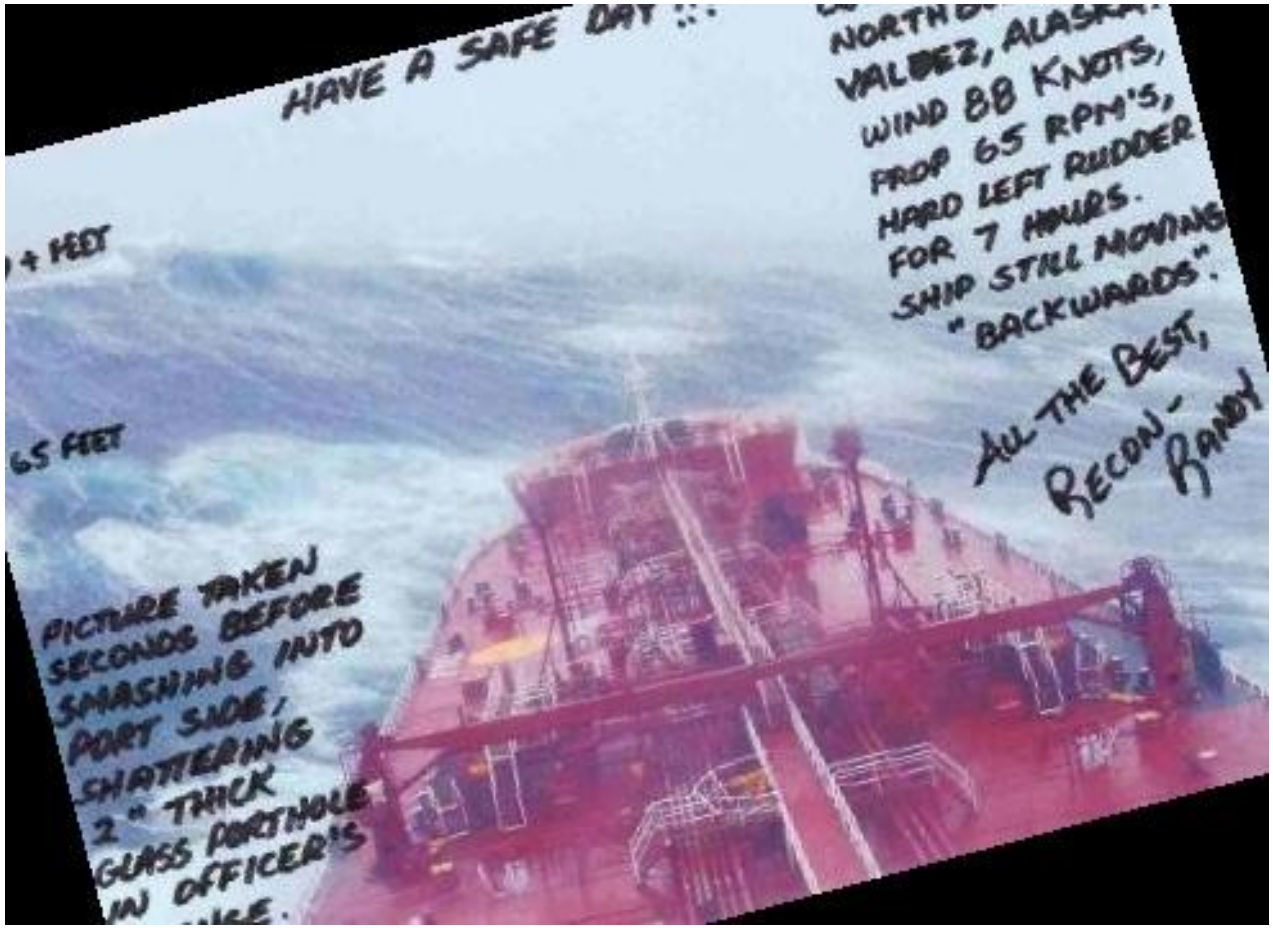



# An image never rejects Photoshop

Of course, the sea was not flat, yet...



…the camera might have rolled 15° too !



rd, en mer, le 6 Février 1963.

Croiseur "JEANNE D'ARC"

-=-=-=-=-=-=-=-=-=-=-

## C O M M U N I C A T I O N

La matinée du 4 Février a été marquée par un "événement de mer" de courte durée (moins de trente secondes au total...) mais qui mérite cependant de faire l'objet de quelques commentaires à l'intention, notamment, de tous ceux qui en constatèrent les effets sans être en bonne position pour en observer la cause.

Dans ce but, je diffuse la Fiche jointe qui expose sommairement le déroulement de l'événement tel qu'il a été observé depuis la Passerelle.

*

Certains d'entre vous se sont peut-être demandé : est-ce que cela aurait pu mal finir ?

A cette question on peut répondre :

- la "JEANNE D'ARC" doit pouvoir étaler sans danger une gîte de 40° environ ; or elle s'est arrêté avant 35° ;
- pour rouler de 40°, il eut fallu se mesurer avec des vagues sensiblement plus hautes ; or la hauteur des "3 glorieuses" (de 15 à 20 mètres) était tout à fait exceptionnelle, puisque même au cours des cyclones, il est très rare que des lames atteignent 20 mètres ;
- enfin, il est certain que la manière la plus sûre d'éviter les "événements de mer" consiste à ne jamais quitter la terre ferme...

Le Capitaine de Frégate FREDERIC-MOREAU
Commandant en Second,

Diffusion : tous présents à bord.

***If you want to go at sea, and yet not capsize, don't buy a ship: buy an island !***
*Marcel Pagnol*

# Difficult to imagine that extreme waves could be **normal**


"For a while until they got it squared away, they launched them sailing backwards."