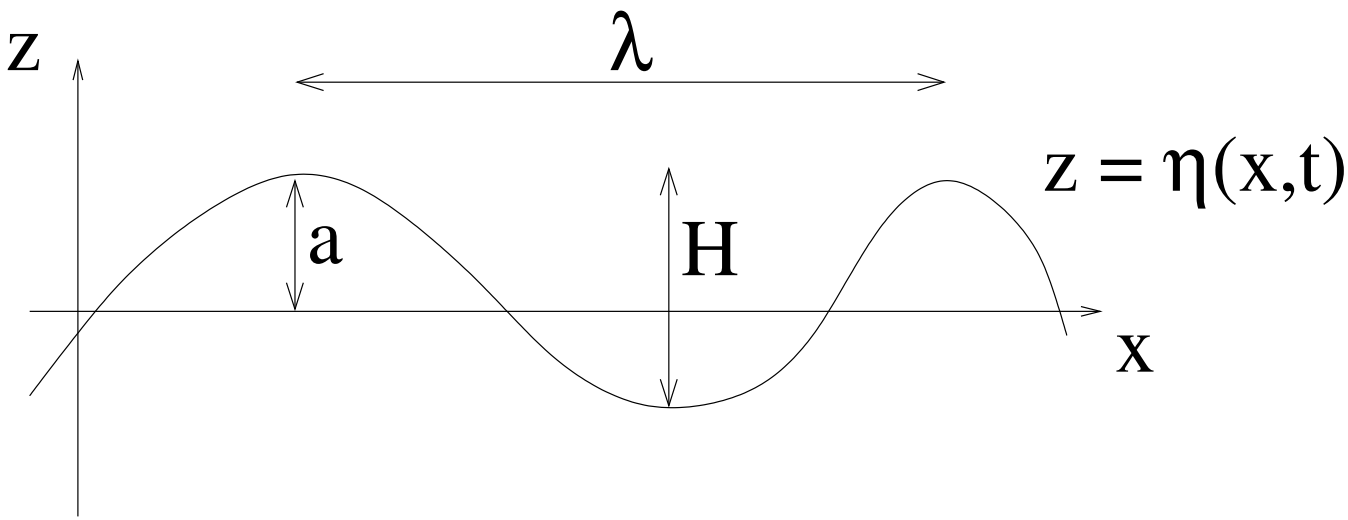
Olas extremas o freak en el mar - ¿que son, como se manifiestan, y que importancia tienen?

Karsten Trulsen

Sección de Mecánica, Departamento de Matemáticas, Universidad de Oslo

UAH 5 Julio 2022

Freak, rogue or extreme waves — olas gigantes, vagabundas o monstruosas



- Surface elevation $\eta(x, t)$
- Crest height $a = \eta_c$
- Wave height H
- Wave length λ

Freak = Rogue ≠ Extreme ≠ Tsunami

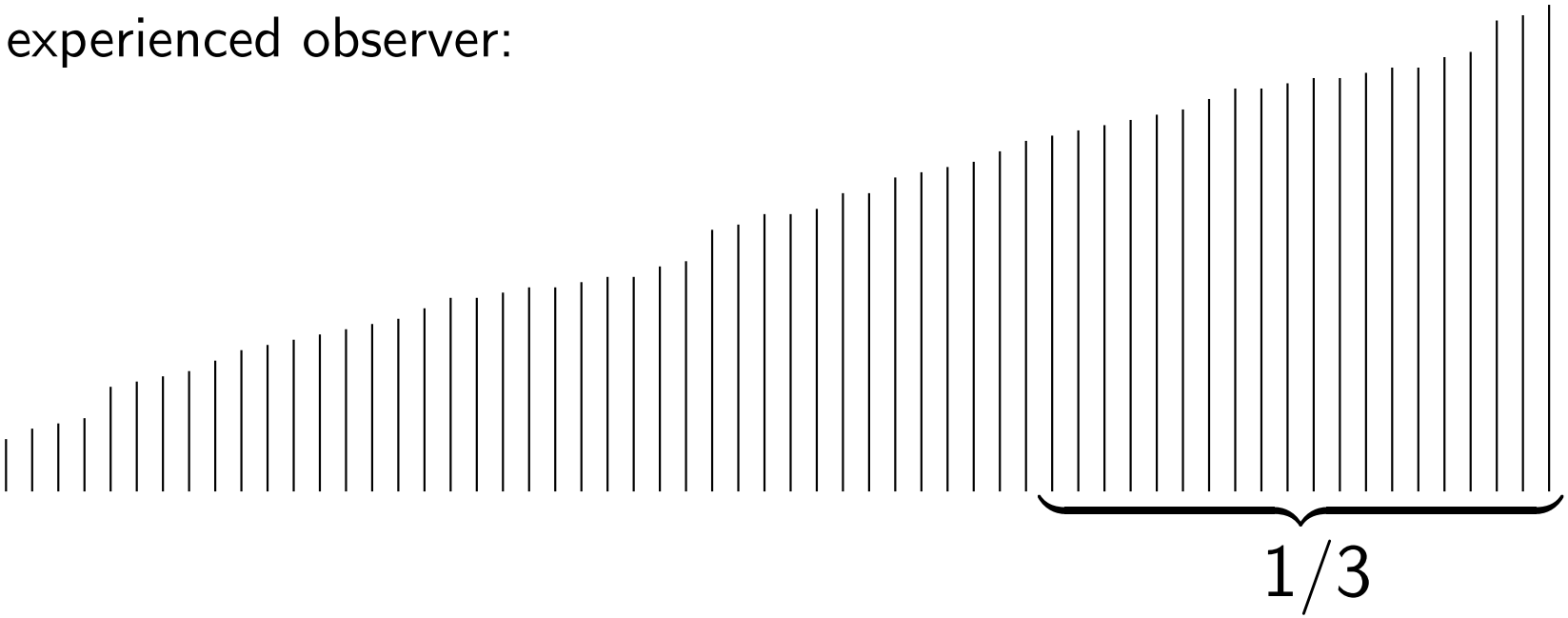
- Freak or rogue wave
  - *exceptionally large and surprising* compared to *ordinary* waves
- Extreme waves
  - large physical dimensions
  - does not have to be *exceptionally large* or *surprising*
- Tsunami
  - a small group of *long* waves generated by a local event, e.g. earthquake or avalanche (natural catastrophes)

I will talk about extreme waves that are freak.

What is then an "*ordinary*" wave?

Significant wave height ≈ ordinary

Classical definition corresponds to visual impression of an experienced observer:



$H_{1/3}$ = average of the 1/3 largest wave heights
Modern definition:

$$H_s = 4\sigma$$

where σ is the standard deviation of the surface elevation.

For an ordinary sea

$$H_s \approx H_{1/3}$$

Freak wave — definition

For a 20 minute time series measured at a fixed point in the North Sea a wave is regarded as a freak wave if:

$$H > 2H_s = 8\sigma$$

or

$$\eta_c > 1.25H_s = 5\sigma$$

Some examples of freak waves

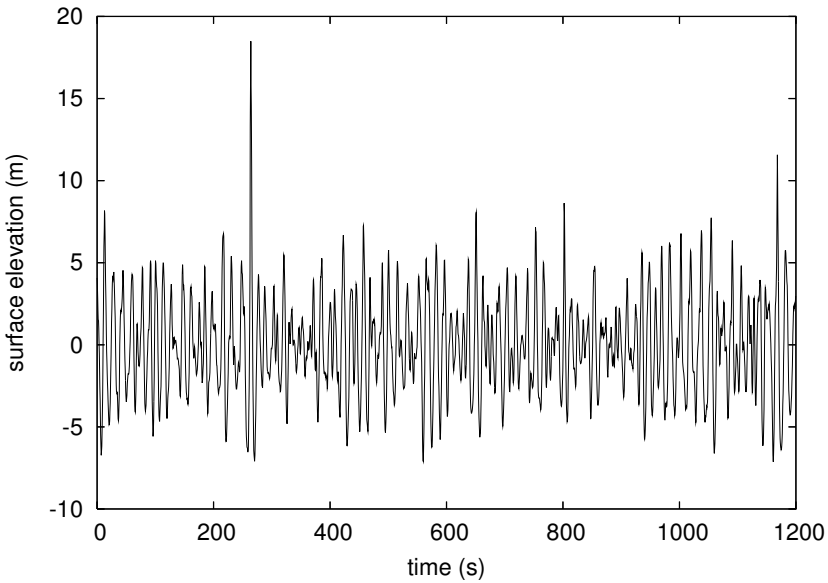
Definitively freak waves:

- New Year Wave at Draupner 1/1–1995
- Andrea wave at Ekofisk 9/11–2007
- The wave that hit COSL Innovator at Troll 30/12–2015

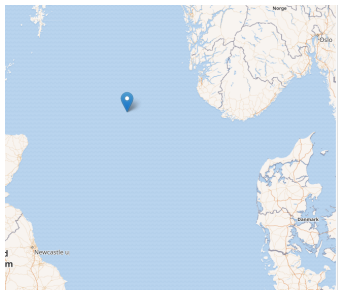
Probably not a freak wave

- Prestige accident outside Spain 13/11–2002

New Year Wave 1/1–1995 at Draupner







Data from Statoil. Map from Wikimedia map CC BY-SA 4.0

$$\eta_c/H_s = 1.56 > 1.25 \qquad H/H_s = 2.15 > 2$$

(criteria for time series of 20 minute duration for conditions similar to the North Sea)

Satisfies both criteria for being a freak wave

Andrea wave 9/11–2007 at Ekofisk



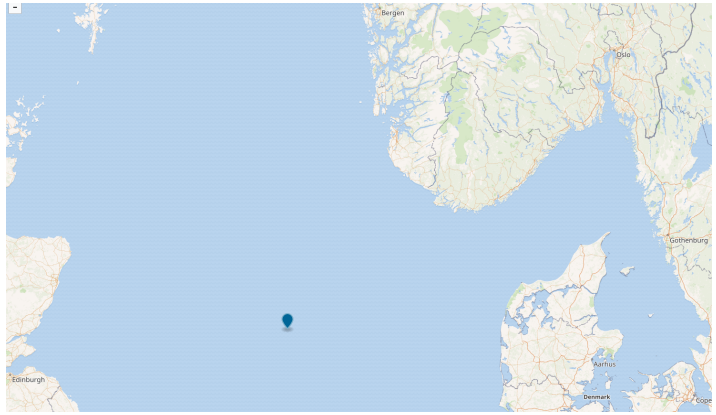
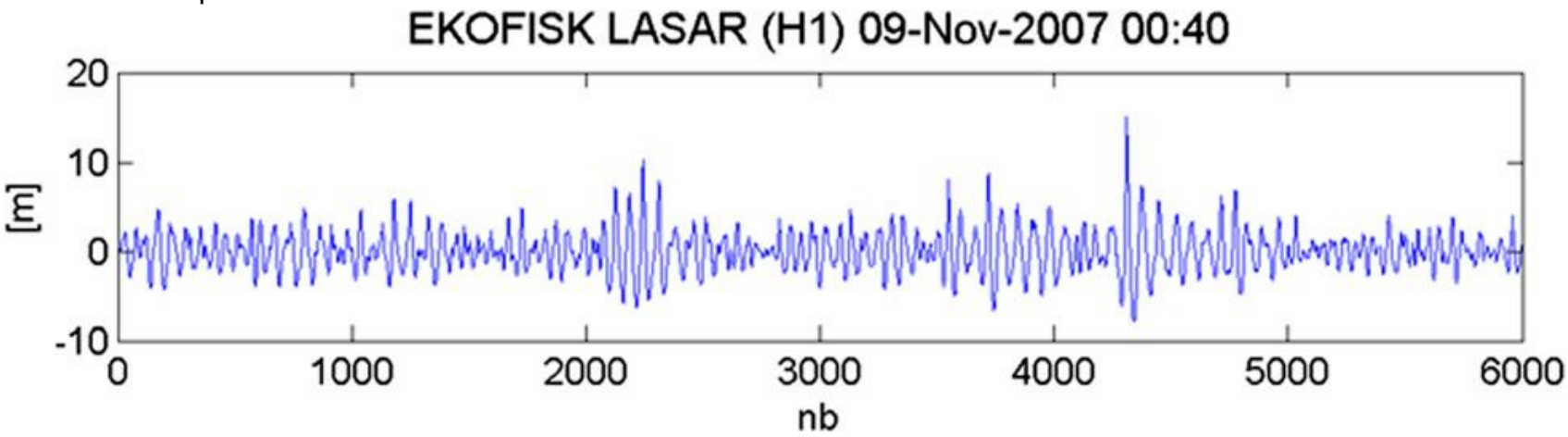


Photo: By BoH - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=11223835. Map: Wikimedia map CC BY-SA 4.0



Data from ConocoPhillips, presented by Magnusson & Donelan (2013)

$\eta_c/H_s = 1.63 > 1.25 \qquad H/H_s = 2.49 > 2$

The Andrea wave is more freak than the Draupner wave

The wave that hit COSL Innovator 30/12–2015 at Troll





By L.C. Nøttaasen from Sandnes, Norway - Oil Rigs at Coast Center Base outside Bergen, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=53068057. Map: Wikimedia map CC BY-SA 4.0

"It was a completely ordinary day."

Henning Bruvik, captain on COSL Innovator

Suddenly the rig was hit by a wave. One employee died instantaneously when the wave broke the window of his cabin.

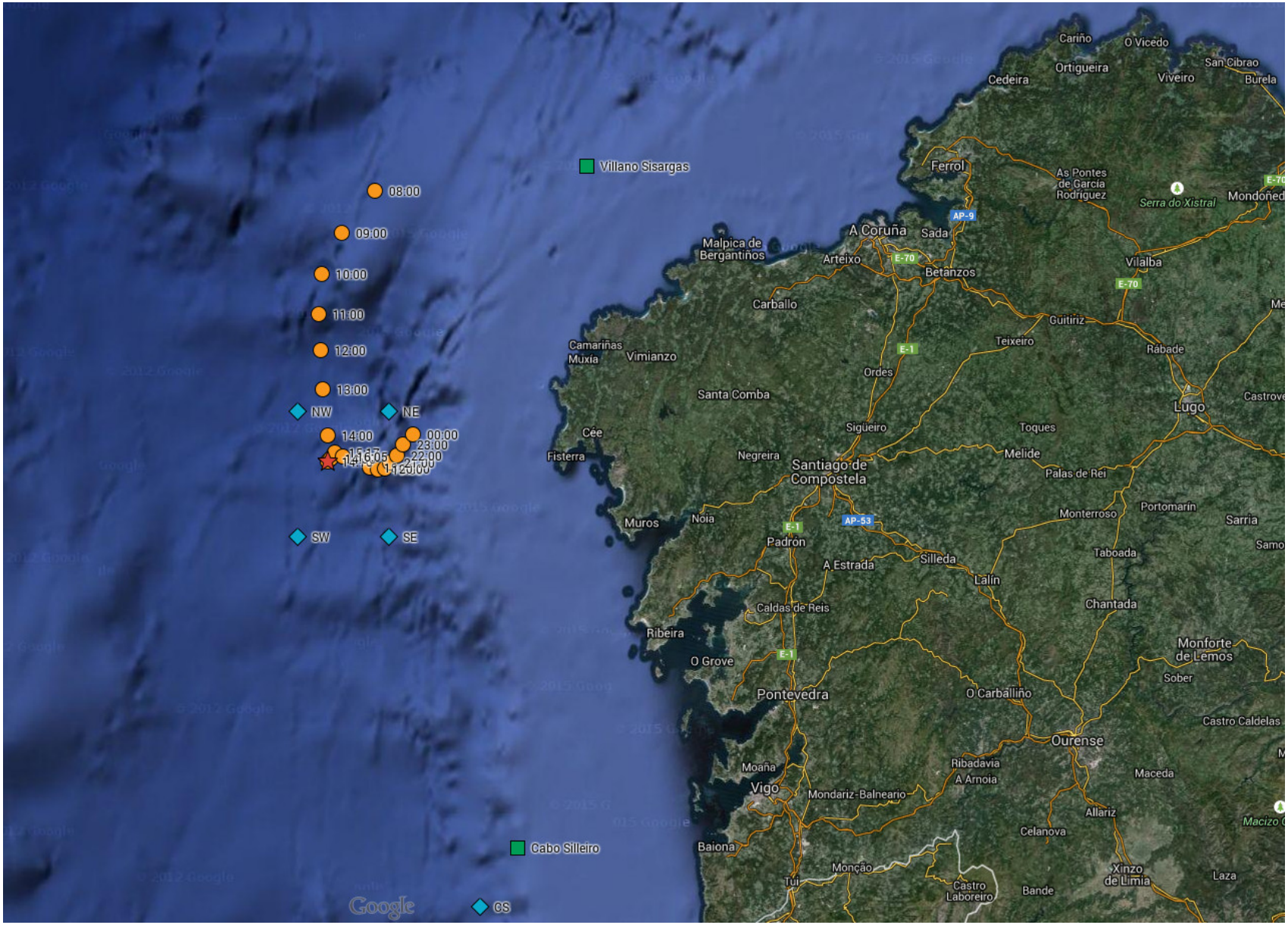
COSL Innovator

Several windows were broken



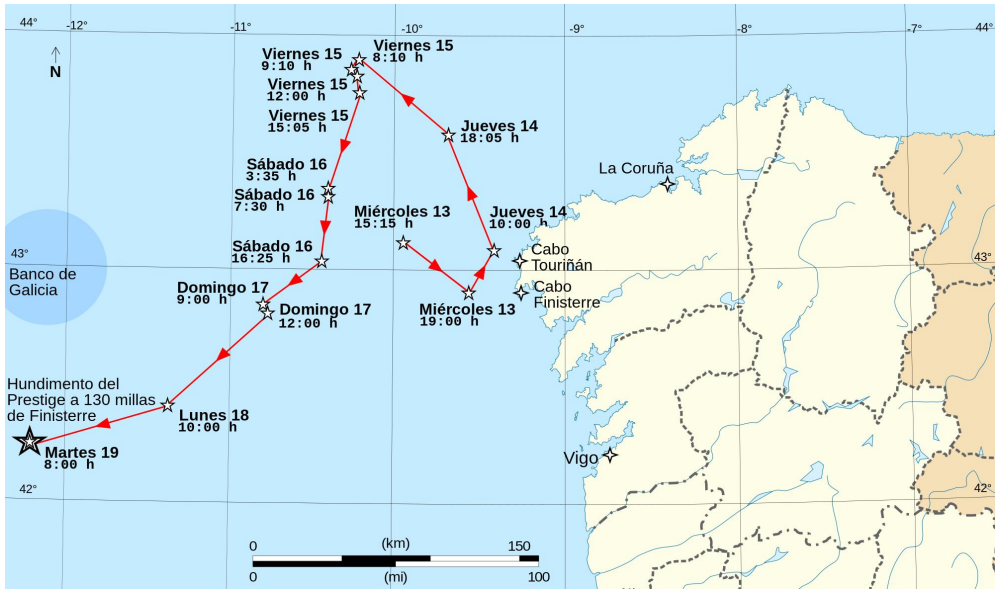
Prestige accident 13/11–2002 and the following catastrophe 19/11–2002 outside Spain

The accident: Prestige is damaged 13 November 2002



After the accident: Prestige is towed away from the coast



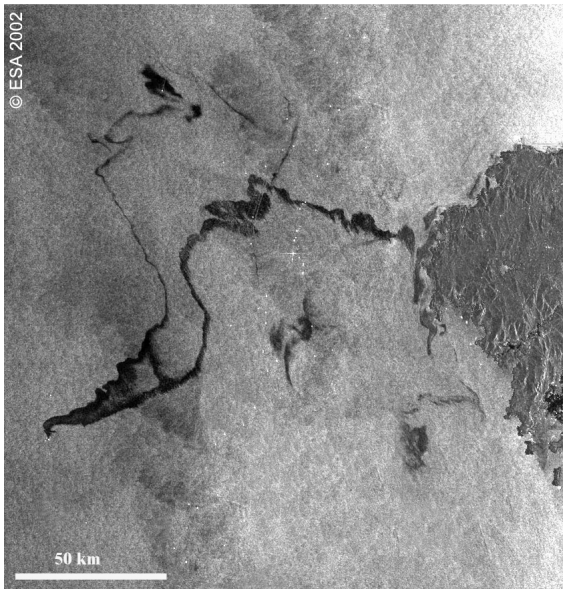


The catastrophe: Prestige breaks and sinks 19 November 2002





The catastrophe: After Prestige sunk 19 November 2002







How do we handle freak waves?

Two ways to attack the problem:

- Deterministic
- Stochastic

People tend to purify one or the other angle of attack.

Combining the two we end up with surprises — that is more fun.

Better understanding requires both angles of attack simultaneously.

Examples follow!

Deterministic description: Schrödinger equation. Modulational instability. Breathers.

Simple model for generation of a freak wave from "nothing"

Nonlinear Schrödinger (NLS) equation

$$\frac{\partial A}{\partial t} + \frac{1}{2}\frac{\partial A}{\partial x} + \frac{\mathrm{i}}{8}\frac{\partial^2 A}{\partial x^2} - \frac{\mathrm{i}}{4}\frac{\partial^2 A}{\partial y^2} + \frac{\mathrm{i}}{2}|A|^2 A = 0$$

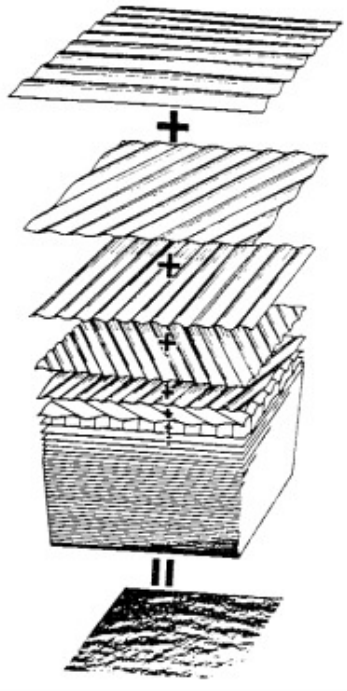
Modulational instability — small disturbances can grow and become large.

Breathers — an innocent sea surface can focus into a giant wave, and thereafter calm down to an innocent sea surface again.

Peregrine breather

Stochastic description: "ordinary" sea = Gaussian process

Superposition of statistically independent contributions



Pierson et al. (1958)

Central limit theorem says the ocean is Gaussian.

Can freak waves happen more often than this?

Nonlinearity causes central limit theorem to break down . . .

Some statistics:

Let η be a stochastic variable

Mean value $\mu = E[\eta]$

Variance $\sigma^2 = E[(\eta - \mu)^2]$

Standard deviation $\sigma = \sqrt{\sigma^2}$

Skewness $\gamma = \frac{E[(\eta-\mu)^3]}{\sigma^3}$

Kurtosis $\kappa = \frac{E[(\eta-\mu)^4]}{\sigma^4}$

A Gaussian variable has skewness $\gamma = 0$ and kurtosis $\kappa = 3$

Simplest criterion for increased probability of freak waves:

$$\kappa > 3$$

The sea during Prestige accident was disappointingly "ordinary"

- Our efforts to model sea state when Prestige accident happened suggest kurtosis disappointingly near 3.
- We conclude there is no reason to speak about freak waves during any trial.
- However, it has never been spoken more about freak waves in any trial.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE
10.1002/2015JC011161

Crossing sea state and rogue wave probability during the Prestige accident

Karsten Trulsen[1], José Carlos Nieto Borge[2], Odin Gramstad[1,3,4], Lotfi Aouf[5], and Jean–Michel Lefèvre[5,6]

[1]Department of Mathematics, University of Oslo, Norway, [2]Department of Signal Theory and Communications, University of Alcalá, Spain, [3]Centre for Ocean Engineering Science and Technology, Swinburne University of Technology, Melbourne, Australia, [4]Now at DNV GL Strategic Research and Innovation, Høvik, Norway, [5]Météo-France, Département Marine et Océanographie, Toulouse, France, [6]Deceased April 5th, 2014

Key Point:
- Discuss the crossing sea state and rogue wave probability during the Prestige accident

Correspondence to:
K. Trulsen,
karstent@math.uio.no

Citation:
Trulsen, K., J. C. Nieto Borge,

Abstract We discuss the crossing sea state and the probability of rogue waves during the accident of the tanker Prestige on 13 November 2002. We present newly computed hindcast spectra for every hour dur-

“El Camino Atlantico” = Atlanterhavsveien





Waves in opposing current

Deterministic description: Waves in opposing current are slowed down and become larger

Stochastic description: The probability for freak waves in opposing jet current is less than in open ocean without current

Ph.D. research of Karina Hjelmervik

Movie from Atlanterhavsveien



Waves in opposing current — consequence

- Do ship captains like to sail in the middle of jet currents?
- Then waves heading toward the ship can be large.
- Among those there are fewer freak than in "ordinary" sea.
- Captain will be more guilty if something goes wrong?

J. Fluid Mech. (2009), *vol.* 637, *pp.* 267–284. © Cambridge University Press 2009
doi:10.1017/S0022112009990607

Freak wave statistics on collinear currents

KARINA B. HJELMERVIK AND KARSTEN TRULSEN†
Department of Mathematics, University of Oslo, P.O. Box 1053 Blindern, NO-0316 Oslo, Norway

(Received 23 March 2009; revised 12 May 2009; accepted 20 May 2009; first published online 17 September 2009)

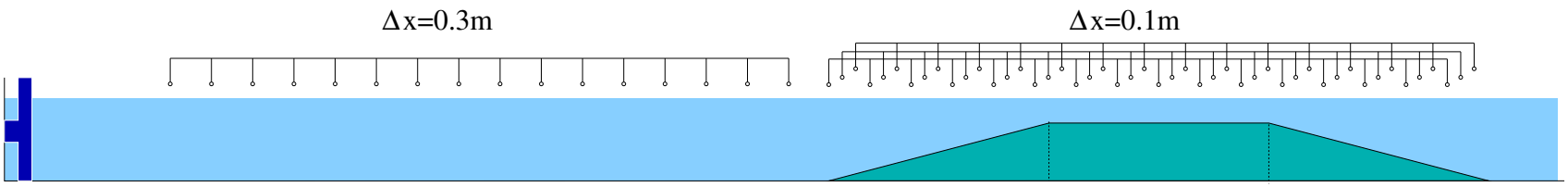
Linear refraction of waves on inhomogeneous current is known to provoke extreme waves. We investigate the effect of nonlinearity on this phenomenon, with respect to the variation of significant wave height, kurtosis and occurrence of freak waves. Monte Carlo simulations are performed employing a modified nonlinear Schrödinger equation that includes the effects of a prescribed non-potential current. We recommend that freak waves should be defined by a local criterion according to the wave distribution at each location of constant current, not by a global criterion that is either averaged over, or insensitive to, inhomogeneities of the current. Nonlinearity can reduce the modulation of significant wave height. Depending on the configuration of current and waves, the kurtosis and probability of freak waves can either grow or decrease when the wave height increases due to linear refraction. At the centre of

Waves over a shoal

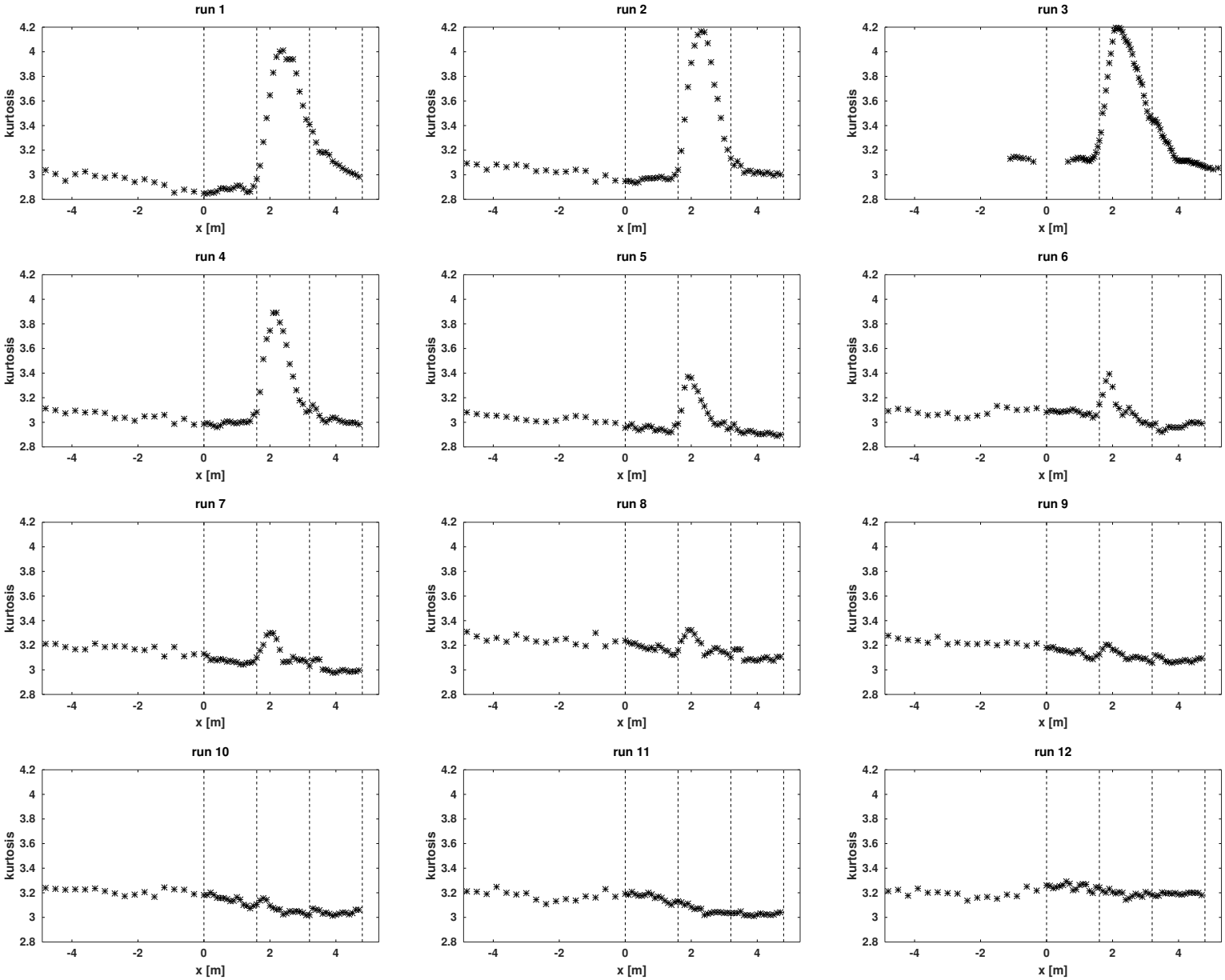
Deterministic description: Waves approaching shallower water are slowed down and grow in size. Modulational instability becomes significantly weaker.

Stochastic description: The probability for freak waves over a shoal can be significantly larger than on flat bottom.

Master thesis of Anne Raustøl



Waves over a shoal — kurtosis (Master thesis of Anne Raustøl)



Waves over a shoal — consequence

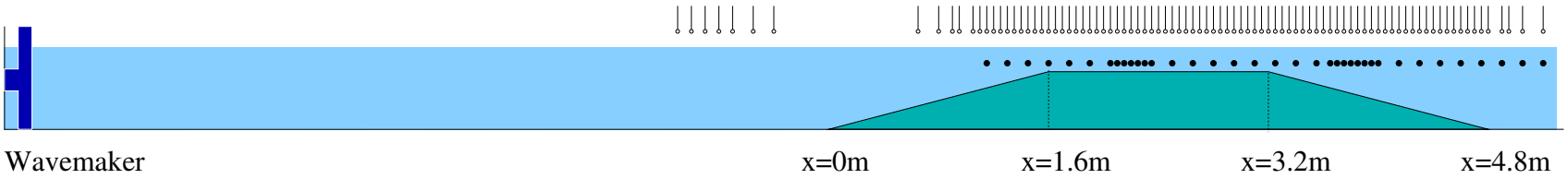
- If a shoal is sufficiently shallow it can provoke significantly increased occurrence of freak waves.
- Fishing banks are shoals ...
- Coastal regions have many shoals ...

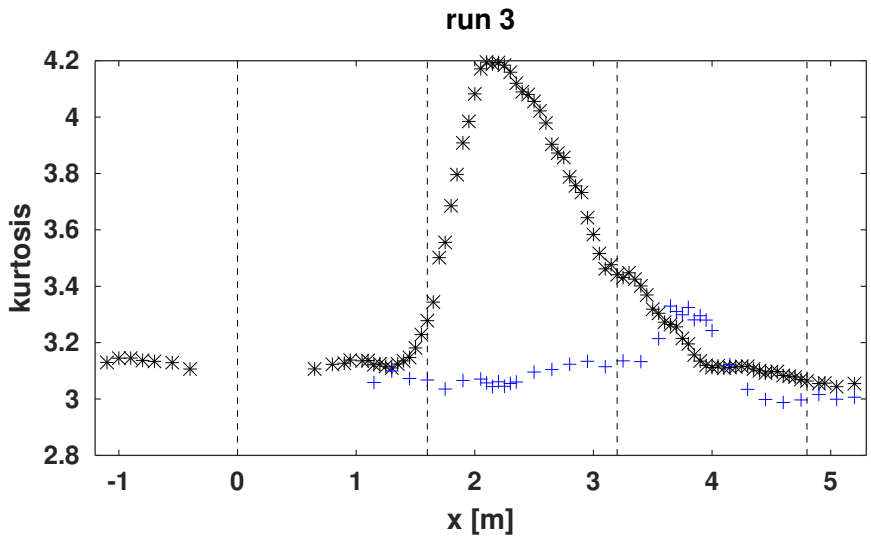
Surface elevation and velocity field — over a shoal

Deterministic description: Surface elevation and velocity field of waves are locked to each other.

Stochastic description: Freak surface waves and freak velocity waves happen at different locations over a shoal.

Master thesis of Stian Jorde





Waves over a shoal

Thesis research of three master students of which two lektor-students:

J. Fluid Mech. (2020), *vol.* 882, R2, doi:10.1017/jfm.2019.861



JFM RAPIDS
journals.cambridge.org/rapids

Extreme wave statistics of long-crested irregular waves over a shoal

Karsten Trulsen[1,†], Anne Raustøl[1], Stian Jorde[1] and Lisa Bæverfjord Rye[1]

[1]Department of Mathematics, University of Oslo, 0371 Oslo, Norway

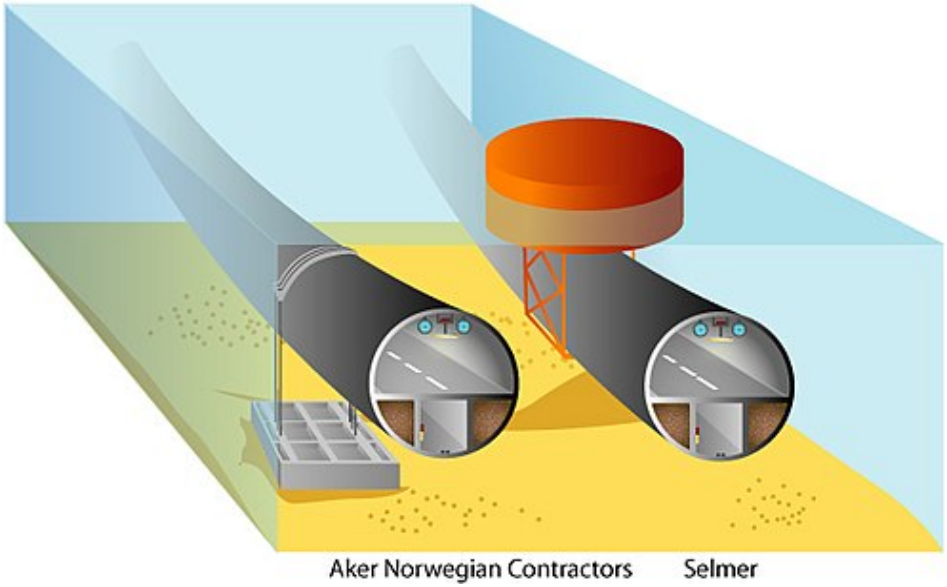
(Received 14 August 2019; revised 23 September 2019; accepted 14 October 2019)

We report laboratory experiments of long-crested irregular water surface waves propagating over a shoal. For a sufficiently shallow shoal we find that the surface elevation can have a local maximum of skewness and kurtosis above the shallower part of the shoal close to the edge on the incoming side, and a local minimum of

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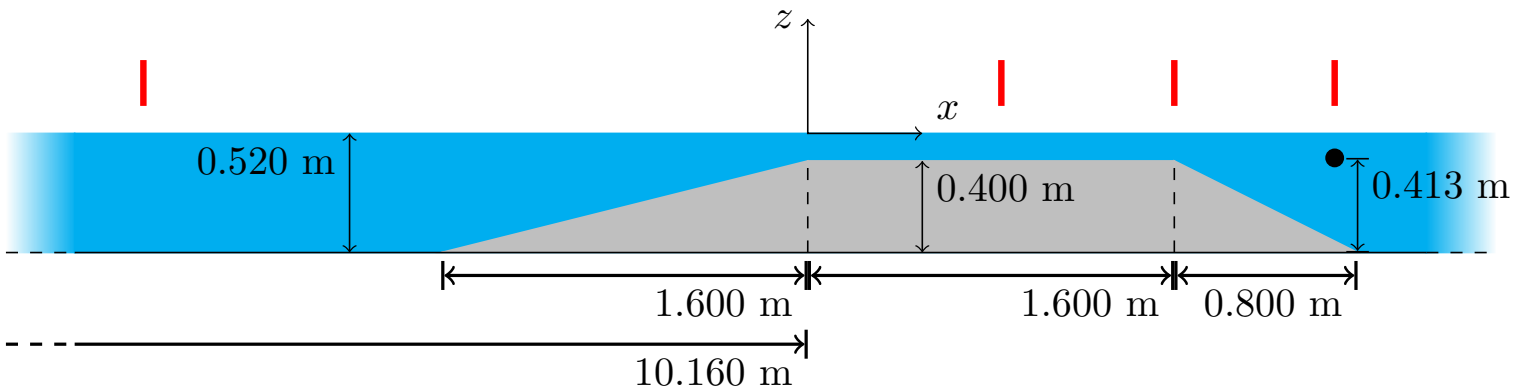
Submerged floating tunnel bridge — Archimedes bridge



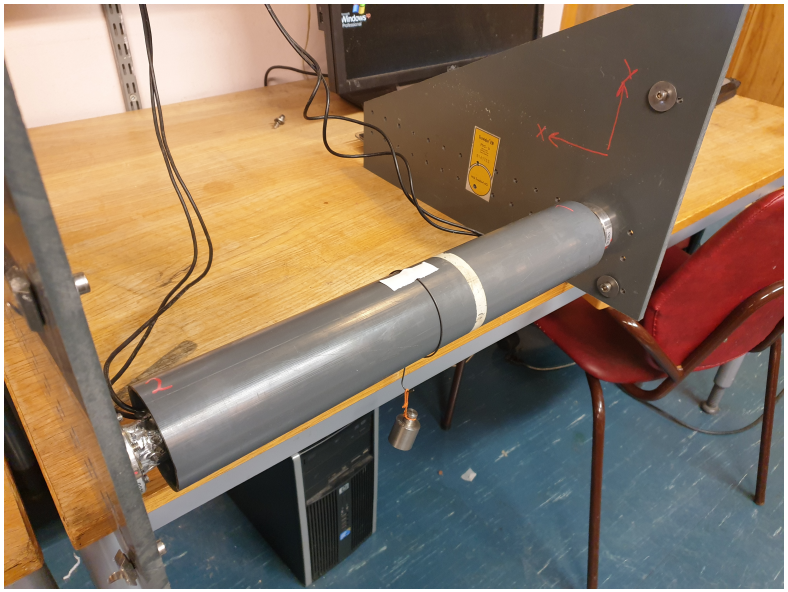


Force on submerged horizontal cylinder — behind a shoal

Master thesis of Karen Samseth

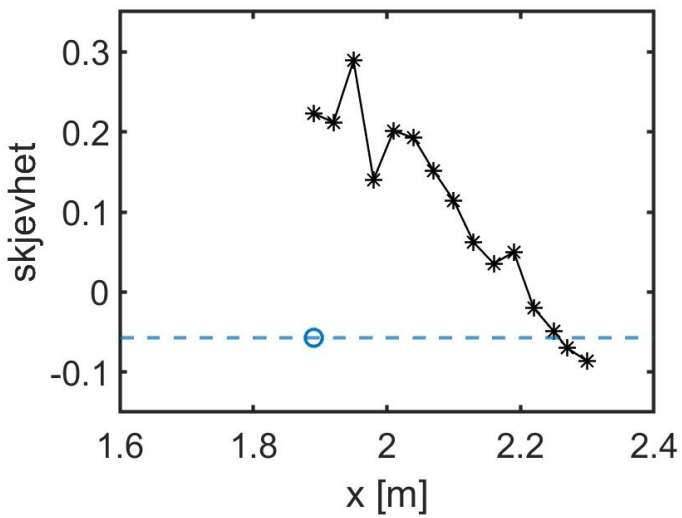


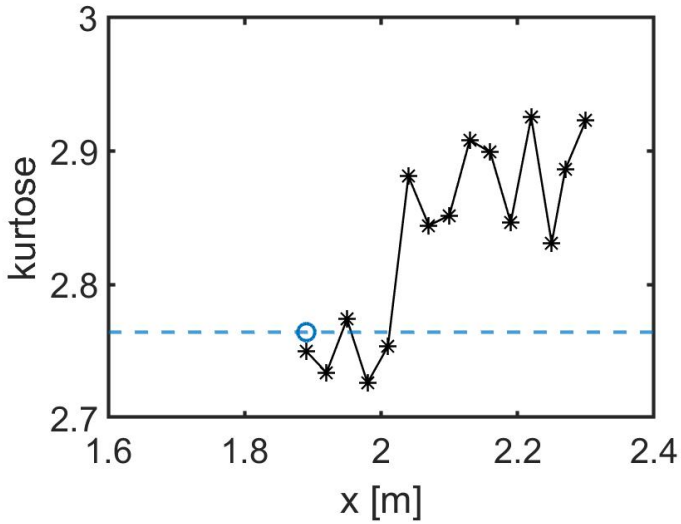
The horizontal cylinder





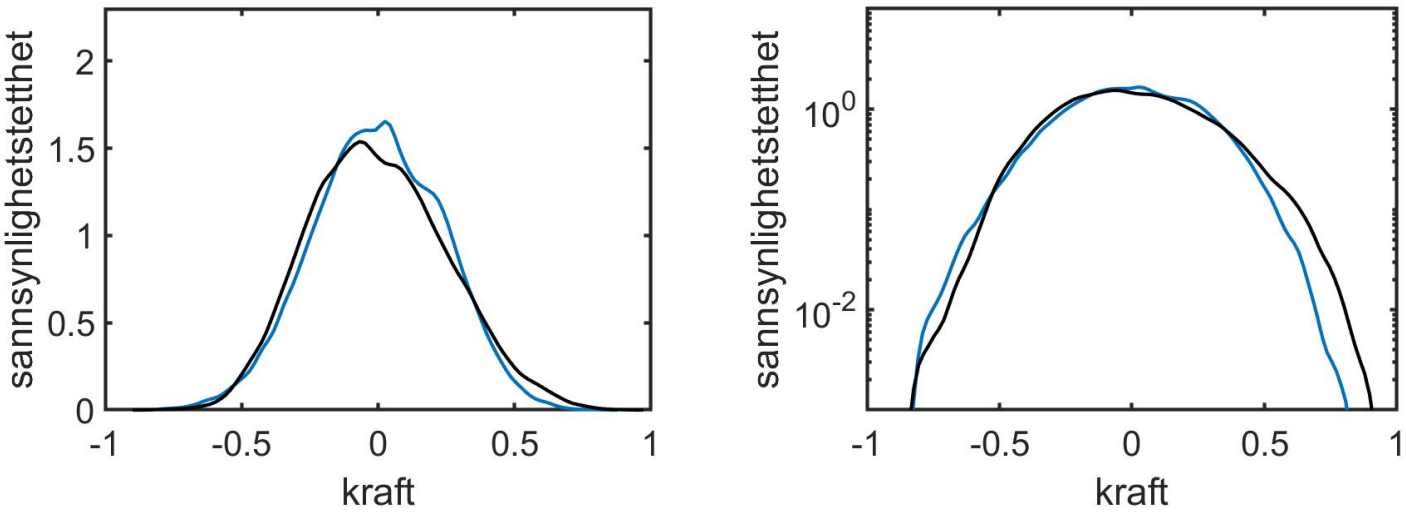
Statistics depends on position relative to shoal





- Blue reference value without shoal
- Black value with shoal — different positions relative to shoal

Distribution of forces can become more extreme due to the presence of a shoal



- Blue reference value without shoal
- Black value with shoal — one position relative to shoal

Look how happy my students are!



Conclusion

- Mechanics is fun and Statistics is fun
- Their combination is **more than twice as fun**
- Deterministic and stochastic approach alone appear to give opposite conclusions, better to combine both

As a master student you can come very near the research front, especially with experimental thesis. Contributions from:

- Karen Samseth — Lektor-student
- Eva Charlotte Berner — Master student
- Anne Raustøl — Lektor-student
- Stian Jorde — Lektor-student
- Karina B. Hjelmervik — Ph.D. student
- Odin Gramstad — Master and Ph.D. student and Postdoc