

Freak waves: just bad luck, or avoidable?

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Coast Guard sends help to stalled 'Semester at Sea' ship

A 50-foot wave smashed through the bridge windows of the 591-foot MV Explorer around 2:30 p.m., pouring saltwater over electrical components on board and disabling all four of its engines, officials said.

FEBRUARY 14, 2005

Giant wave hits cruise ship

A rescue operation has been carried out in the Mediterranean after a cruise liner issued distress signals off the coast of Minorca. The ship was hit by ferocious waves that smashed windows on the bridge as the ship was sailing from Tunis to Barcelona. The spokesman said water poured in, knocking out electric power, stopping the engine and leaving the ship adrift with no communications. (www.itv.com)

APRIL 16, 2005

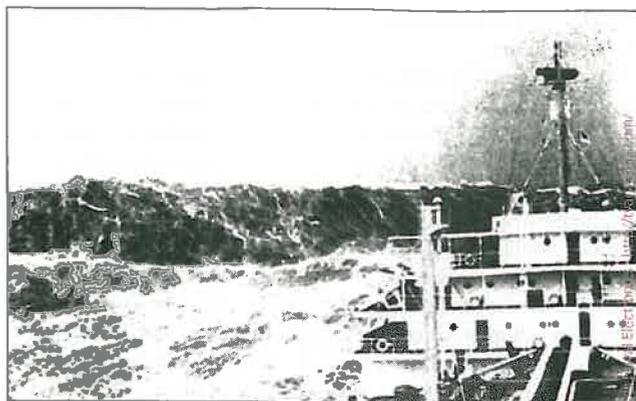
'Freak' wave rocks cruise

'Norwegian Dawn, an opulent ocean liner almost 1,000 feet long, limped into Charleston, S.C., yesterday afternoon after it hit vicious seas in an overnight storm off Florida - then was creamed by the rogue wave after dawn.' (NY Daily News)

Since the first of the year, three large cruise ships have been disabled by freak waves. All were sailing in moderate to heavy seas when the big one hit: the MV Explorer in the Pacific January 27 with 600 students aboard, the Voyager February 14 in the Mediterranean, and the Norwegian Dawn off the coast of Florida April 16. Windows as high as 100 feet above the waterline were damaged, and in some cases the bridge was compromised by seawater, leading to electronics problems and engine shut down.

Is this an unusual spate of freak waves? Probably not! The tragedy of the 2004 Tsunami has sensitized the press and the public to unusual events in the sea. These events would have received much less attention if they had happened before the Tsunami. For example, during a three week period when satellites were measuring sea surface heights, between February and March 2001, two stout cruise boats, the Bremen and the Caledonian Star, had their bridge windows demolished by 30-metre freak waves in the South Atlantic, with apparently less media attention. The Bremen was left helplessly drifting without navigation or power for two hours. In February 1995 the cruiser liner Queen Elizabeth II met a 29-meter high freak wave in the north Atlantic.

Freak waves are ultimately wind generated and have nothing to do with Tsunamis, claiming "only" perhaps one or two hundred souls per year. Weaker boats than cruise ships and military vessels, e.g. tankers and container vessels, often break in two when they meet a freak wave (Figure 1a), often described by surviving witnesses as "a hole in the sea followed by a wall of water". The bow buries itself in the wall, the wave breaks over the unsupported midships, snapping the vessel in two (Figure 1b) and often sinking it in a few minutes. No radio for help (the electronics is the



▲ **Fig. 1a:** A rare photograph showing the "wall of water" approaching a ship. The "hole in the sea" is presumably out of sight just in front of the "wall".

first to go), no debris, no black box. The news media are not triggered during the slow realization that a cargo ship with 10 or 20 seamen is missing. It's been happening for thousands of years, and it happens now at an estimated one ship every month or two.

Well before the 2004 Tsunami hit, scientific interest in freak waves picked up as photographic, ocean buoy, and satellite evidence mounted, finally giving credence to five or more thousand years of surviving sailor's yarns. The most convincing call to action however was the European Union MaxWave project [1], which used synthetic aperture radar (SAR) data to analyze 30,000 sea-surface images of five by 10 kilometers each. The data, taken over three weeks in 2001, revealed more than 10 freak waves - far more than expected. One estimate from this data suggest that 50 or more freak waves are stalking the seas right now as you read this. This work is spurring a much larger inventory of the sea surface called WaveAtlas.

Much theoretical and experimental progress has been made, especially on the issues of nonlinear evolution of waves, which can amplify wave heights and alter their shape to more menacing, breaking walls of water. The biggest question remains, however: how often and under what conditions should freak waves be expected?

Freak waves have a technical definition, beginning with the significant wave height (SWH), which is the average height of the highest 1/3rd of the waves in a long sample. Freak waves are defined as waves bigger than 2.2 times the SWH.

For anyone familiar with wave behavior, the first thing that comes to mind as an explanation for freak waves is an unlucky constructive interference of independent wavesets moving in slightly different directions, with somewhat different wavelengths, etc. Indeed such bad luck is certainly possible and this idea led to the first and most predictive of all freak wave theories, the venerable Gaussian seas model of M.S. Longuet-Higgins[2]. A storm does not produce a single plane wave, but the idealization of a random superposition of many plane waves with a mean direction of travel and some dispersion in angle, wavelength, and amplitude was introduced. The Central Limit Theorem applies; the distribution of amplitudes is Gaussian.

The danger a wave poses is not merely a matter of its height. A 40 foot wave in a sea with SWH of 40 feet is likely to be far less dangerous than a 40 foot wave with SWH 16 feet. The reason is the steepness. A SWH = 40 foot sea is likely to have a much longer wavelength than a SWH = 16 foot sea, so that the sudden appearance of a 40 foot wave among the 16 footers means a very steep wave. Steep waves tend to break, which makes them more dangerous to any ship or boat.

There is no widely accepted theory of how freak waves form in the open ocean.

Three categories of models predominate: (1) Gaussian statistical (the “unlucky” constructive addition mentioned above) (2) refraction leading to focusing of wave energy, and (3) nonlinear growth and steepening of waves. The trouble with the Gaussian model is that freak events it predicts are too rare compared to present estimates.

The natural place to turn to generate more freak events is through nonlinear growth of waves. There is no doubt whatsoever that nonlinear processes are important to water wave physics. Any breaking wave is exhibiting nonlinear behavior. The slow evolution from short chop produced by wind to long ocean swell (which can sometimes travel faster than the wind that originally provided their energy) is caused by the Benjamin-Feir instability [3], a well established nonlinear wave process. Much work has gone into water wave evolution, governed by a variant of the nonlinear Schroedinger equation of quantum physics (recently playing a big role in Bose-Einstein condensed matter [4,5]). Presumably these nonlinear events are relevant for the minutes or moments just prior to a wave becoming dangerous. It seems likely that this sort of nonlinear evolution, in which a wave can grow at the expense of its neighbors, can contribute to some freak wave events. One difficulty with this theory however is a lack of predictive power: what triggers the mechanism of nonlinear growth? If always operative, it seems nonlinear growth would put freak waves everywhere in all kinds of seas.

The crucial link may be the known association between current eddies and freak waves. Ocean eddies are ubiquitous but the most well known strong eddy regions, like the Agulhas current off the coast of South Africa, and near the Gulf stream, are also famous sites for freak waves. The mechanism must have something to do with refraction of the waves. Waves of any sort refract when they propagate in a medium moving at different velocities in different regions. The refraction was worked out for water waves in general by Peregrine [6], but more recently White and Fornberg [7] pioneered a model that specifically involves waves traveling through random fields of current eddies. The generic result is a pattern of caustics where wave energy concentrates; these caustics are infinitely sharp and strong if ray tracing of the waves is carried for a single incident direction. The compelling images given in the White and Fornberg paper were a shock to this author, because they looked exactly like the ray tracing patterns for electron waves in a special class of semiconductor called a two dimensional electron gas (2DEG), computed in our group. Electrons in these micron-sized devices must negotiate random potential fields filled with hills and valleys, whose height is small compared to the electron energy, deflecting them just a little this way and that, just like



▲ Fig. 1b: A ship broken up by a freak wave with another large wave approaching.

the water waves in eddies on a scale 10^8 times larger (Fig. 2). The reason for the similarity is a universal pattern seen in ray trajectories when passing through a random weakly deflecting medium. The universal structure is called a cusp caustic, (Fig. 3); many generations of these cusps form downstream, of even more correlation lengths of the random interaction leads to the universal branching pattern which was the subject of Refs.[8] and [9].

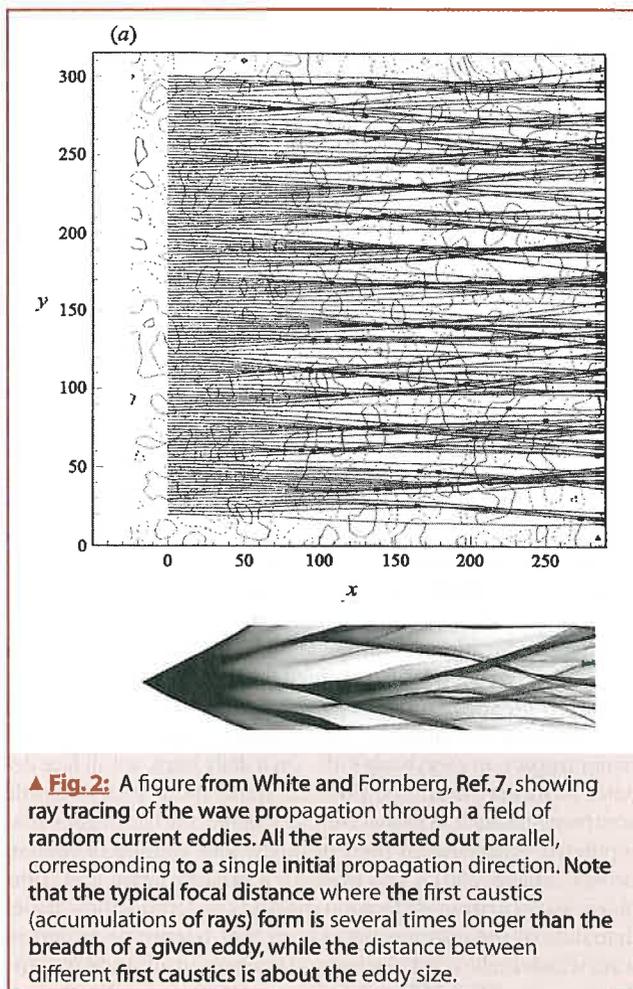
The White and Fornberg work came under criticism [10] since, unrealistically, they used only a single incident plane wave in their studies. A good analogy is a magnifying glass outdoors. On a sunny day, with strongly directional rays, the focal point is very bright. So much energy is concentrated there that waves are constantly being produced with high amplitudes. Try the same on a cloudy day, with rays coming from all over the sky, and the focal region is ill defined and hardly any brighter. The critics assumed correctly that the caustics would wash out and the huge waves that were predicted to occur at the caustics would not materialize.

Or would they? It occurred to this author that, while the caustics would indeed wash away, what would remain would not be a uniform energy density. It is not widely appreciated that truly Gaussian seas must have a *uniform* underlying energy density, even though this is a simple point. What would happen to the statistics when there is, say, a factor of 2 or 3 variation of energy density giving rise to hot spots of suddenly higher density where wave energy is concentrating?

The answer is: almost nothing happens to the statistics, unless you are interested in *rare events!* The SWH is almost unchanged, averaging over the hot spots, and on a linear scale the Gaussian statistics looks almost unchanged. Even the fourth moment of the Gaussian versus the fourth moment of the nonGaussian patchy hot spot density (the so-called Kurtosis) is almost unaffected. However, very large wave event probabilities can be several orders of magnitude larger than the Gaussian sea model, just the sort of effect we are looking for, even after averaging over 20 percent variations in direction and wavelength. (This shows up strongly in very high moments, like the 20^{th} or 24^{th}).

Figure 4 shows ray tracing and wave propagation on a random velocity field, using the linear Schroedinger equation. (Indeed although the underlying ray tracing is “nonlinear dynamics” in the sense of classical physics, the wave propagation, done independent of any ray tracing, is perfectly linear, meaning that the equations used depend only on the wave ψ and its derivatives, not on ψ^2 , etc.) The caustics are indeed smoothed out, but the remaining high energy hot spots have become loci for extreme events, recorded in color for a long run passing many waves over the whole region, with again 20 percent variations in direction and wavelength for realism. The high energy hot spots are clearly visible in either the ray tracing over many ray paths (so many that they form a smooth density) or time averages of wave energy density.

As one might expect, there is a figure of merit which tells us how close to the “cloudy day” limit we are, using the focusing lens analogy given above. The more spread out the wave directions to begin with, the safer we are from freak waves. This might go against intuition, in that confused seas (seas with a wide range of directions of propagation) are already unruly and seeming ready to spring a surprise. But the lens effect will be small and the washout of the caustics very strong in already confused seas. The statistics of the wave heights is actually independent of the mix of wave directions in a purely Gaussian context. So the most dangerous situation is a fairly collimated sea impinging on an eddy field. Although the caustics may still be washed out, the high energy hot spots remain statistically very dangerous. Even averaging over the low energy and high energy hot spots gives large enhancements of freak wave formation.



▲ **Fig. 2:** A figure from White and Fornberg, Ref. 7, showing ray tracing of the wave propagation through a field of random current eddies. All the rays started out parallel, corresponding to a single initial propagation direction. Note that the typical focal distance where the first caustics (accumulations of rays) form is several times longer than the breadth of a given eddy, while the distance between different first caustics is about the eddy size.

The figure of merit is measure of danger, called the “freak wave index” γ . The defining equation is

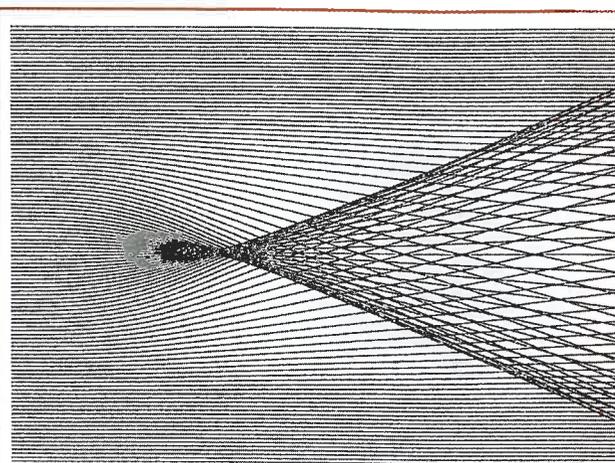
$$\gamma = \delta\theta/\Delta\theta,$$

where $\Delta\theta$ is the initial spread of angles of the waves incident on the eddies, and $\delta\theta$ is the angle of deflection of the rays when they reach their first focal point. This latter is a property of the wave velocity and the eddy field. For typical parameters used by White and Fornberg, this index lies between 1.5 and 3, with 3 being very dangerous and 1.5 less dangerous.

The idea of our new work [11] is suspended between Longuet-Higgins on the one hand, and White and Fornberg on the other. Like Longuet-Higgins’s original work, the appearance of a rogue wave is a statistical event, not a certainty as with White and Fornberg’s caustics. Indeed we assume *locally* Gaussian statistics, but averaging over the high hot spots strongly enhances the wings of the resulting overall distribution. On the other hand White and Fornberg’s statistical refraction through current eddies, with the additional directional averaging, give energy hot spots which are not part of Longuet-Higgins’s model.

The nonlinear mechanisms surely play an important role, since once a freak wave starts to form in the way we have suggested (“bad luck at hot spots”, essentially) nonlinear processes will surely come to play a more critical role with the large waves thus generated. Perhaps the “hot spot + bad luck” mechanism is the trigger necessary to initiate important nonlinear events.

By combining aspects of both the refraction model and



▲ **Fig. 3:** The ray trace pattern (a cusp caustic) as initially parallel rays pass through a focusing region. The focal distance varies with the distance of approach from the center, i.e. as in a “bad” lens with spherical aberration. By averaging over incident directions, the cusp singularity will be softened but not washed away completely.

Gaussian random addition it appears that we have an effect that is either a major cause of rogue waves, confirming their association with current eddies for example, or it has to be debunked in some way involving new physics. Either way it is going to be an interesting ride.

One can envision the day when, by studying currents eddies (say with Doppler satellite radar) and wave propagation and height data, the marine forecast could say “the freak index is 2.3 today in a region 100 km south of a line...; the probability of a ship encountering a dangerous freak wave is 2 % and that region should be avoided”.

The bottom line, at least in the author’s opinion, is that the original explanation of an “unlucky addition of waves” is partly true, but that the odds get much worse when there are energy hot spots around, a trend that seems to agree with the prevailing notion that something out there is responsible for a lot more freak waves than were thought to exist only a few years ago. ■

About the Author

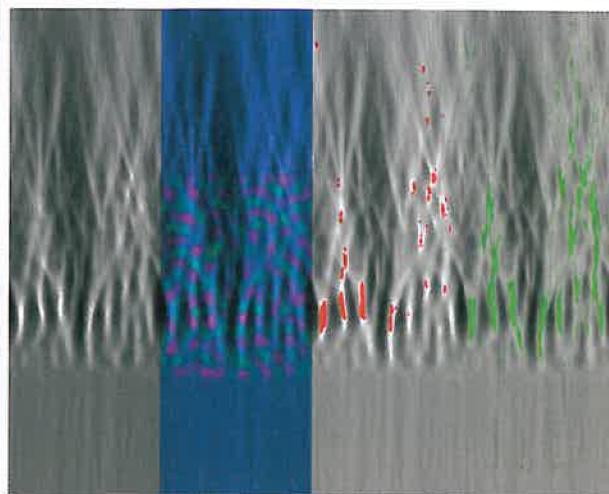
After receiving a Ph.D. in Chemical Physics at Harvard in 1973, Heller took positions at UCLA, Los Alamos, University of Washington, and since 1993, Harvard University, where he is Professor of Physics and Professor of Chemistry. Heller’s research focuses on few body quantum mechanics, scattering theory, mesoscopic physics and quantum chaos, ultracold matter, and now freak waves at sea. Heller enjoys sailing off the British Columbia coast aboard his sailboat “Resonance”, but thankfully he has never seen a freak wave.

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▲ Fig. 4: This figure collects data from a long run with “Languet-Higgins” Gaussian seas impinging from below on an eddy field, here represented as a potential force field. In the left panel, the average energy density of the waves is plotted in grayscale, with lighter regions having higher energy density. The potential field (deflecting the rays) is shown as hills (green) and valleys (purple) in the next panel. Severe freak wave events (waves six or more standard deviations computed from the mean Gaussian) were recorded as red in the next panel; note that there are no events before the refraction starts and some after it has ended. Finally the 4.4σ events are shown in green in the right panel; there are a few of these before the refraction but many more after it starts and beyond.

Is Science Education Relevant?

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In this article a range of results from the ROSE-project (Schreiner & Sjøberg, 2004, 2005) are reported with particular focus on the question of whether science education is relevant to 15-year olds in three OECD countries: Japan, England and Denmark. Based on an analysis of the available data, four dimensions of science and science class relevance are investigated. These dimensions will be referred to as the *Everyday life dimension*, the *Future- and career dimension*, the *Science, technology and society dimension* and finally the *Science class content dimension*. Finally the results are discussed in a broader perspective.

Science education in Europe at all levels is facing significant challenges. Firstly; it is often argued that all citizens must be scientifically literate in order to participate competently in a modern knowledge-based society where science and technology have major impact on everybody's life. On a daily basis, we all face debates in media and in the political arena about socioscientific controversies such as global climate change, the use of gene manipulated organisms in food products and cloning of human beings (Kolstø, 2001). The need for a broadly based and competent participation in decision making concerning these issues demands of the educational system that science be taught in ways which make it interesting and relevant to all students (Andersen et al., 2003; Millar & Osborne, 1998). Secondly, there is concern that European countries will find it increasingly more difficult to meet the need for a knowledge- and technology-based society to produce a high proportion of trained citizens capable of conducting research, development and education within science and technology (The High Level Group on Increasing Humans Resources for Science and Technology in Europe, 2004).

In order for European educational systems to meet these challenges science educators and scientists need a qualitatively deeper and more solid evidence-based understanding of young peoples' attitudes towards science, technology and school science. Hence the ROSE-project and this article.

The ROSE-project

The ROSE-project is an international comparative study led by Professor Svein Sjøberg along with Ph.D.-student Camilla Schreiner from the University of Oslo in collaboration with science education researchers from 40 other countries representing all continents except North America. In each country a geographically and socio-economically representative sample of 15-year old students' has filled out the ROSE-questionnaire, which consists of 250 statements (items) to which the students were asked to respond on a four-point Likert scale (see below). The complete international data set is not yet fully released, but for the purpose of the present article permission has been granted to publish some international results.

1 Cf. (Schreiner & Sjøberg, 2004) for the sampling procedures.

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