OCEAN FREAK WAVES

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My research focuses on few-body quantum mechanics, scattering theory, mesoscopic physics and quantum chaos, and now freak waves at sea. A recurrent theme in my work involves various aspects of the Correspondence Principle and semiclassical approximations in a variety of physical problems, including nonlinear dynamics and chaos theory. At the other end of the spectrum, the extreme quantum limit (e. g. ultracold collisions, proximity resonances and related effects such as Dicke super- and sub-radiance) is also an ongoing interest.

My earlier work in quantum chaos theory, combined with the opportunities created by the protected and productive environment at Wiko, created a chance for me to work on something new. I saw an opportunity to apply what I had learned from wave chaos theory to ocean freak waves. This was rewarded with many new results and some recognition, including a chapter in a book ("Freak ocean waves and refraction of Gaussian seas". In *Extreme Events in Nature and Society*. Springer, 2005) and a forthcoming feature in *Europhysics News*.

The following is a summary of my work at Wiko and its motivations.

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 on January 27, 2005 with 600 students aboard, the Voyager on February 14, 2005 in the Mediterranean, and the Norwegian Dawn off the coast of Florida on April 16, 2005. 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 shutdown.

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-meter 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, 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 and often sinking it in a few minutes. No radio for help (the electronics is the 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. One estimate from this data suggest that 50 or more freak waves are stalking the seas right now as you read this.

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?

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 much rarer than present estimates.

The crucial idea may be the known association between current eddies and freak waves. Ocean eddies are ubiquitous but 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 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 a paper by White and Fornberg[1] 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 the water waves in eddies on a scale 10^8 times larger. The reason for the similarity is a universal pattern seen in ray trajectories when passing through a random weakly deflecting medium.

The White and Fornberg work came under criticism 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

1 White, Benjamin S. and Bengt Fornberg. "On the chance of freak waves at sea." *J. Fluid Mech.* 355 (1998): 113–138.

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 non-Gaussian 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 variations greater than 20 percent in direction and wavelength. (This shows up strongly in very high moments, like the 20th or 24th.)

As one might expect, there is a figure of merit that 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 are 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 seem 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.

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[2] is suspended between Longuett-Higgins on the one hand, and White and Fornberg on the other. Like Longuett-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 that are not part of Longuett-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 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 extending 100 km south of a line from latitude 31, longitude –127, to the probability of a ship encountering a dangerous freak wave is 2% and that region should be avoided".

The bottom line 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.

2 Eric J. Heller. "Freak ocean waves and refraction of Gaussian seas." In *Extreme Events in Nature and Society*, edited by Sergio Albeverio, Volker Jentsch and Holger Kantz. Berlin: Springer, 2005.