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Regular Article

Rogue waves – towards a unifying concept?: Discussions and debates

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Abstract. This paper contains the discussion inputs by the contributors of the special issue on the subject of rogue waves.

Victor Ruban

I shall attempt to answer the questions posed by the editors of this special issue about the nature and definition of the phenomenon called 'rogue waves'.

My opinion is based mainly on my own theoretical studies of water waves, and can be confirmed by the examples presented in my paper.

1. Is the phenomenon of 'rogue waves' linear or nonlinear?

I believe, in most cases, the linear mechanisms just 'prepare' a sea state, and then rogue waves are produced by nonlinear mechanisms. Without nonlinearity, big waves could not have arisen as often as they actually do. Also, the profiles of rogue waves and their behavior in the developed stage are determined by nonlinear interactions.

2. What is the onset of appearance of 'rogue waves'? Is it the phenomenon related to modulation instability?

No doubt, modulation instability is the decisive factor in producing rogue waves.

3. What is the spectral content of 'rogue waves'?

I think there is no uniformly valid answer to this question. Depending on the details of an initial sea state, the arising rogue waves can have different spatial structure, and thus different spectral content. The corresponding examples are the two different kinds of rogue waves in weakly crossing sea states described in the recent paper [53]: V. P. Ruban, Phys. Rev. E **79**, 065304(R) (2009).

4. How important is the distribution of wave amplitudes in registering rogue waves? For example, observations in optics pay special attention to the function of distribution.

Can this function be the first point to be taken into account in the definition?

This is a difficult question. On the one hand, the presence of rogue waves is naturally reflected in a 'tail' of the distribution function for wave amplitudes. On the other hand, an important part of information about rogue waves as a localized object is lost if we deal with the distribution of wave amplitudes only.

Moreover, the situation seems somewhat different for oceanic rogue waves and optical rogue waves. Usually, with a given typical wavelength λ, a peak-to-trough amplitude of oceanic waves is limited by a value $h_{\rm lim} \approx (0.10 \ldots 0.14)\lambda$ (close to the limiting Stokes wave), and higher-order nonlinearities contribute very significantly in the distribution of such wave amplitudes. It is important that the maximal steepness of water waves grows faster than their amplitude, and for extreme waves it becomes infinite. **Therefore, oceanic rogue waves are actually extreme and thus very steep individual waves with $h_{\mathbf{max}} \geq\approx 0.10\lambda$ among surrounding moderate waves having peak-to-trough amplitudes about $h_0 \leq\approx 0.05\lambda$ and small steepness**.

In my opinion, the above sentence is an almost exhaustive definition of oceanic rogue waves. Note that it is slightly different from the previous widely used definition, where no scale for the wave amplitude was mentioned. In terms of the distribution function for wave amplitudes, the above suggested definition means the presence of a pronounced 'tail' stretching sufficiently far from a core of the distribution.

The above definition also implies that there is no point in speaking about the phenomenon of 'rogue waves' if the typical amplitude h_0 is too high, say $h_0 \geq 0.07\lambda$, since in that case almost every individual wave is nearly extreme. At the same time, for optical rogue waves a universal value for the limiting amplitude does not exist, and a similar definition cannot be used. However, a 'heavy tail' in the distribution function should be considered as a necessary element indicating the presence of rogue waves.

5. Do I consider some other questions to be more important than those listed above?

I believe that there are some other questions equally important as those listed above. For example, in many cases rogue waves at a two-dimensional (2D) free water surface look like fragments of some idealized coherent structures (oblique solitons and giant breathers can be mentioned, as in [53]: V. P. Ruban, Phys. Rev. E 79, 065304(R) (2009)).

What other structures could be relevant? In particular, are there some 2D analogs of the 1D rational solutions of the nonlinear Schrodinger (NLS) equation? In general, the problem of establishing relations between realistic rogue waves and (partly) localized solutions of simplified equations is very important.

Yuji Kodama

I think the problem of 'rogue waves' itself is not well defined and focused. I can see so many different kinds of papers in this issue, and most of them have just their own closed discussions.

Your opinion, critique on other contributions of this issue:

Although there is almost no internal connection among papers, most of the papers do represent their own ideas and results. Just making a large-amplitude wave may not be difficult, but this depends on how you generate it, using instability, inelastic collisions or resonance (nonlinear interaction), particularly important in the 2D problem. These are clearly discussed in this issue. So the issue is not so bad.

Your opinion on other papers published in journals:

I do not know many papers on the subject, and in my limited knowledge, rogue waves are only treated as modulation instability, i.e. by the NLS equation. I want to see something very new (well, so far I see just small modifications of modulation instability).

Your views on the present state of the art:

I am currently interested in 2D solutions, where resonance phenomena are so common and very important. I cannot say much about the present state of the art for rogue wave research.

Your views on future directions:

I think multi-dimensional analysis (resonances), an experimental study (recurrence of rogue waves) and then of course modeling the wave phenomenon. Maybe a statistical model should be developed, and a coherent structure (if there is one) or some global quantities (?) should be found.

Your views on unsolved problems:

I am interested in answering how energy is concentrated locally (in space and/or in time) for a 2D problem (just like the soliton in 1D). What is the mechanism to make a high-amplitude wave when the wave collides (should be a fundamental process?)?

Relation between rogue waves in the ocean and other fields of science:

If you believe that the rogue wave is generated by modulation instability, then the answer is obvious (NLS-related science). But I like to see them in multi-dimensional situations, maybe outer space (gravity collapse, plasma instability, etc.).

Anything you think that is important to the topic of 'rogue waves':

It is hard to answer this, but maybe we still need a definite term to describe a 'rogue wave'.

Your opinion on the last paper in the issue 'Rogue waves as a weapon':

The last paper in this issue demonstrates an example of making a large-amplitude wave, but it is, I think, common for a near-integrable system (i.e. including higher-order terms). But this is just a $0.1 \times 10 = 100\%$ type coherent process, and may not be the way to describe a rogue wave (I am not so sure, of course).

Michael Ruderman

Since I have only studied rogue waves in plasmas, I do not feel that I am in a position to comment on the whole subject of rogue waves. Hence, I restrict my comments to plasma waves.

First of all, it is not surprising that there are rogue waves in plasmas because, very often, they are described by the same model equations as waves in fluids, e.g. KdV, mKdV, NLS, KP and so on. The main problem is how important rogue waves in plasmas are. In contrast to rogue waves in the ocean, this question does not have a clear answer, and, at the moment, I am discussing it with people familiar with the observation of space plasmas.

I was very impressed by the last paper about soliton amplification. It even made me quite philosophical and slightly sad. It seems that this is a universal law of both nature and society: a stronger one almost always gains at the expense of a weaker one: stronger solitons are amplified and weaker ones decay, rich people get richer and poor people get poorer, etc.

John Dudley

1. Your opinion, critique on other contributions of this issue:

The papers in the issue highlight both the progress and remaining problems in the field. From my perspective, the most interesting result seems to be the realization that collisions play an absolutely central role in the generation of large-amplitude waves. Our own paper revisiting the statistics in fact indicates that maybe the only real waves with the statistics that can be classed as 'rogue' with genuine long tails may only arise from collisions. Getting the history right here may be important — collisions within NLS systems were proposed as ocean rogue wave generators previously and so the idea is not new. Also, as other commentators to this issue have remarked, perhaps NLS-related dynamics are obvious from a mathematical viewpoint, but actually linking these effects to experiments is not so clear it seems. For example, the fact that Akhmediev Breather theory and modulation instability were linked experimentally only recently is really quite surprising in my view. Moreover, although modulation instability dynamics might be well known, they can still seed a wide range of different behavior, because one is always in a perturbed NLS system. Trying to establish predictive signatures of rogue dynamics seems to be the most important goal.

2. Your opinion on other papers published in journals:

I think that the papers published elsewhere reflect a similar spread of ideas as this special issue.

3. Your views on the present state of the art:

I think that there is a developing consensus that the isolated single solitons in optics that were initially proposed as rogue waves may in the end turn out to have no real oceanic counterpart. However, even though the initial ideas of rogue events in optics may ultimately turn out to be irrelevant to the ocean case, the importance of these ideas and the impetus that they have given the field in general must not be underestimated and the Jalali group's insight must be fully appreciated and recognized. Also the ideas of Akhmediev in bringing the role of breather collisions to the attention of the optics community is very important to recognize.

4. Your views on future directions:

I think it is easy to get lost in the mathematical complexity of this problem. The remaining focus on trying to provide some concrete insight into origin and prediction must be a priority.

5. Your views on unsolved problems:

See 4.

6. Relation between rogue waves in the ocean and other fields of science

The earlier work studying localization effects in discrete NLS lattices and DNA was cited in a recent paper by Genty et al. (Phys. Lett. A **374**, 989 (2010)) as a kind of precursor study to current rogue wave studies. This raises the question of whether the statistics of transcription errors in DNA replication are long tailed. Do such data exist?

Roger Grimshaw

I do not claim to have specific expertise on rogue waves, but here are some random comments based mainly on the literature, and on this special issue in particular:

1. I believe that there is still a problem with the definition of a rogue wave. In the water wave context, there is the commonly used statistical definition of a wave that is 2–3 times larger than the significant wave height, but this has no dynamical content. I would argue that a better definition is a large wave that is temporally and spatially localized, but this clearly needs refinement to say what 'large' means, and also needs a constraint about specifying the likelihood of occurrence.

2. Given that the breather solutions of the focusing NLS equation are commonly used to describe a rogue wave, in my view with some success, it is not surprising and indeed to be expected that rogue waves can be found in many physical contexts, and in that sense are generic.
3. While energy focusing of some kind is clearly involved, I am concerned about invoking linear focusing mechanisms such as currents and topography in the water wave context. I would support the view that while these certainly happen (e.g. the Agulhas current rogue waves), they should be regarded essentially as pre-conditioning for nonlinear focusing.
4. At present only 1D rogue waves have been well studied, using the NLS equation for instance, whereas in many physical contexts, notable for surface and internal waves, the spatial localization is often 2D.

Peter McClintock

In the light of our experiments and numerical simulations, and treating second-sound acoustic turbulence as a model of what may happen on the ocean surface, we suggest that rogue waves represent a *nonlinear phenomenon* that arises through modulation instability (analogous to the decay instability in superfluid helium). The present experiments reveal immediately the spectral content of a wave system that includes rogue waves (see Fig. 4(e) of our paper): we can of course select windows of different sizes in Fig. 4(a) to facilitate the extraction of whatever spectral information is needed. The distribution of wave amplitudes in our measurements away from the rogue waves would seemingly not tell us that a rogue wave was imminent: the rogue waves are quite distinct from neighboring waves and do not seem to have any precursors. Finally, regardless of the details of the production mechanism, rogue waves clearly have much in common with classical large fluctuations and this perception of rogue waves is likely to be worth pursuing.

Miguel Onorato

Your opinion, critique on other contributions of this issue:

I am happy that the physics of ocean waves has been contagious. Ten years ago rogue waves were discussed only in the surface gravity wave community and now I see a number of applications of the rogue wave concept in many different fields of physics. I also see some progress in the fully nonlinear computation of surface gravity waves in conformal variables (including weak 2D+1 effects) and some effort to include a realistic wind forcing in the simulations (see Christian Kharif and Julien Touboul).

Your views on the present state of the art:

In the field of ocean waves, most of the theoretical and numerical work has been performed for long-crested (unidirectional) waves, in the absence of forcing and dissipation. The leading-order equation is the NLS equation so that many analytical results are available. However, ocean waves are generated by the wind, they break and transverse instability destroys the long-crested condition. Strictly speaking, the Benjamin–Feir instability applies to a plane wave to which a small perturbation is superimposed. Ocean waves are characterized by a finite-width spectrum. In this case the concept of modulational instability has to be generalized. Rigorous results for a broad-band spectrum are not straightforward, unless some statistical hypotheses (usually a quasi-Gaussian approximation) are introduced. Numerical results and recent experiments show that the presence of a directional spreading in the spectrum seems to quench the formation of rogue waves. Predictions on rogue wave probability based on 1D+1 models represent an upper limit of what can happen in more realistic ocean wave conditions.

Your views on future directions:

A full 2D+1 numerical computation of the primitive equation of motion, including a realistic forcing and (some parametrization of) dissipation, is surely needed in order to establish with some accuracy the probability of formation of extreme waves in different sea state conditions. Dedicated laboratory experiments where the 2D surface is measured in time are lacking.

Your views on unsolved problems:

It would be nice to have a 2D+1 integrable equation in deep water so that some analytical solution could help in understanding more realistic sea state conditions

Relation between rogue waves in the ocean and other fields of science:

From the present issue, I can see that the NLS equation is the common starting point for describing rogue waves in different fields. As previously mentioned, the 1D+1 assumption is only partially satisfied in ocean waves; moreover, ocean waves break. The breaking process is a strongly nonlinear one; however, it has the role of keeping the surface weakly nonlinear on average. I wonder whether in other fields of physics the 1D+1 assumption is reasonable and if there exists a limiting process such as wave breaking.

Christian Kharif and Efim Pelinovsky

From our point of view, the standard definition of rogue waves, i.e. $H = 2H_s$ or $2.2H_s$ where H is the wave height and H_s the significant wave height, is too restrictive to characterize the corresponding extreme wave events. This comment can be exemplified by the occurrence, in March 2010, of an extreme wave event in the Mediterranean, off the coast of Catalonia, which struck at 14h15 TU a 207 m long ferry, the Louis Majesty, and killed two tourists. To be more precise, it consisted of three large waves (the three sisters). Their heights were estimated to be 8 m, whereas the significant height was 5 m. From the classical definition, this event is not a rogue wave event. Nevertheless, the waves were killer waves. Instead of a geometric definition, a definition based on wave energy seems to be more relevant to include the large population of different rogue waves appearing in the ocean.

On future directions, we would like to cite the direct *effect of wind* on rogue wave dynamics. Most rogue waves occur under storm conditions where wind action must be taken into account. Until now, simple models have been used to consider wind input on rogue waves. It is time to use more sophisticated models that couple together a turbulent boundary layer in the atmosphere with strongly nonlinear water waves. It should be of interest to introduce a wind parameter in the occurrence probability of freak waves. The *3D aspect* is also of great importance within the framework of crossing seas (see the paper by Onorato et al.) and other 3D mechanisms such as geometrical focusing for instance. The observed occurrence probability of freak waves in deep and shallow waters is approximately the same. It is well known that in 2D, the Benjamin–Feir instability does not occur in shallow water. This means that modulational instability is not necessarily the dominant mechanism causing rogue waves at least in the coastal zone where wave focusing and blocking due to bathymetry and current effects are important. Nevertheless, it should be interesting to consider the evolution of a wave train perturbed by oblique unstable modulations in shallow water.

Tarmo Soomere

The science of rogue waves, although the phenomenon itself has been known in some environments such as ocean waves for centuries, is today in a stage of early formation. In this light, gathering together different (to a large extent controversial and partially even contradicting) views to this marvel is extremely important for understanding where we are and what are the central questions that need to be solved. Moreover, the problem of rogue waves is far from being purely theoretical and involves a multitude of serious practical consequences.

Similarly to soliton science where the simple original definitions given in the 1960s were substantially expanded when more knowledge was gathered, studies into rogue waves are apparently at the crossroads and the emergence of quite diverse subcultures in this field is likely. The plain reason behind this is the fact that substantially different physical mechanisms produce abnormal waves in different environments. For example, modulational instability is the main source of rogue waves in deep water and in many fields where the NLS equation governs the evolution whereas directional effects (including line soliton interactions) produce them in shallow water. In many applications (again, water waves serve here as a convenient framework), both linear and nonlinear mechanisms may lead to waves of similar appearance and present similar levels of danger. Examples from a shallow water environment even provide evidence that extremely high and steep waves need not be spatially or temporally localized.

A similar diversity of approaches is present in the analysis of the spectral content of rogue waves. While the use of the classical Fourier spectrum is common in such analysis, it is frequently convenient to apply more complex basis functions such as theta functions and/or cnoidal wave components like Al Osborne is doing in his studies.

The state of the art of rogue wave studies is the most mature in environments governed by NLS equations (or its analogues), where efforts of experts from a wide range of disciplines have mostly shaped the existing mechanisms and created a coherent picture about potential phenomena. This competence is currently being spread towards various applications and interpretations of how the rogue waves become evident in the reality in different physical systems. There has also been extensive progress in understanding how rogue waves may be created in systems described by the Gardner or Kadomtsev–Petviashvili equations.

Today it is customary to identify rogue waves based on certain height criteria. For some environments, other properties of waves such as wave steepness, orientation of the crest or even the possibility of oblique motion of the high hump along the crests of interacting solitons may lead to much larger risks in practical situations. There is thus a necessity to introduce combined indicators for ãrogueness in such conditions that would also account for a certain estimate of risk for a particular (economical, engineering, etc.) background.

This line of thinking is acutely needed in studies into rogue waves in nearshore and coastal hydrodynamics. The potential consequences in these environments are drastically different from those in deep or even in intermediate waters. The presence of coasts and/or gently sloping seabeds in the nearshore raises a number of related questions such as the possibility of conversion of rogue waves into sneaker waves with extremely high run-up or, more generally, the consequences in terms of coastal management.

The direct impact of surface waves on the nearshore and on the coast plays a decisive role for a large pool of research areas such as physical coastal oceanography, coastal engineering, coastal processes, coastal management, studies into marine-induced natural hazards, etc. A striking and not completely understood issue is the strong wave amplification in the process of wave run-up along certain profiles, especially the drastic dependence of the resulting inundation on the shape of the approaching wave. Also, the reaction of bottom sediments and the entire coastal zone to the rogue waves may be drastic.

As the statistics of high humps created by interactions of shallow-water solitonic waves are a function of crossing wave heights and propagation directions, the potential changes in incoming wave heights, periods and approach directions may lead to drastic changes in the probability of occurrence of shallow-water freak waves.

I would expect that a subculture of studies into rogue waves in the nearshore, their conversion into highly energetic horizontal motions of water masses and the resulting consequences in terms of coastal processes and coastal management will emerge in the near future. There is an acute need to understand, for example, what actually happens with rogue wave motion in the nearshore, whether the resulting wave can be described in the same framework that describes its growth (or the increasing nonlinearity and interaction with the bottom requires the use of some other viewpoint), how the presence of a large-scale rogue wave changes the entire geometry of the nearshore and, in turn, the wave propagation environment, etc.

Georg Lindgren

The theory and practice of 'rogue ocean waves' is practically and intellectually stimulating, as illustrated by the many high-level papers in this volume. This is all the more surprising as even the basic concept of a 'wave' has no obvious and unique definition – you know what is a wave when you see one! Being 'rogue' then means unusually high, steep, sudden, deviating from the surrounding environment, but also unlikely, under the current theory or hypothesis.

Being a statistician, thinking not only in stochastic terms, my expectations on a realistic ocean wave theory in general are that (A) it should be based on reasonable physical principles that can be formulated in mathematical terms, and (B) it should generate useful predictions about what can happen, based on physically meaningful observations and parameters. A complete theory should not only describe the physics in mathematical terms, but it should also produce a statistical distribution for the whole wave field. As I see it, one of the major challenges for ocean wave theory research is to find a way to satisfy both requirements (A) and (B).

If the first requirement is satisfied, then the mathematical solutions will automatically agree with the observations. It seems as if the present theory based on the NLS equation is quite successful in this respect. Physics, mathematical theory and experiments agree quite well with each other. The second requirement, however, is far from satisfactory, within the NLS equation framework, even if several studies have shown the importance of directional seas, for example in marine safety studies; see the contribution by Onorato et al. in this volume.

It is obvious that a useful theory that describes the statistics of rogue waves, regardless of how they are defined, must go beyond the *linear* stochastic Gaussian wave theory based on frequency decompositions, which also violates some of the physical requirements. The first-order stochastic Lagrange model, dealt with in the contribution by Lindgren et al. in this volume, is also a linear model, with its superposition of elementary waves, but the result is a typically *nonlinear* vertical wave process. In particular, it can reproduce steep and asymmetric waves, without any complicated mathematics. One possible way of introducing further phenomenology in the Lagrange model is to include second- or higher-order interactions, similar to the Stokes waves, but in a Lagrangian setting. I expect this to be feasible at the expense of considerably increased mathematical complexity.

As a final general comment, I would like to see more attempts at introducing realistic stochastic generators, coupled to meteorological variables, in the deterministic NLS equation models, so that their statistical properties can be systematically analyzed and calibrated. This would include not only wave height distributions, but also steepness, groupiness, skewness and other variables of practical interest for ocean safety.

Michael Ruderman

The mechanism of large-amplitude wave generation through soliton amplification caused by the interaction with other solitons is very interesting. But this mechanism does not reproduce one property of freak waves that, to my knowledge, is considered as important. I mean the short-lived nature of freak waves 'that appear from nowhere and disappear without a trace.' Were long-lived freak waves ever observed?

Nail Akhmediev

I completely agree with Ruderman's comment. The mechanism of amplification of solitons ('survival of the fittest') considered in our work has its origin in the optical experiments of John Dudley and his team (see PLA, 374, 989 (2010)). Whether this mechanism is valid in the case of ocean waves is still an open question. Experiments in this area are costly and dangerous, so presently we cannot argue on this. Nevertheless, some speculations can be made.

There is one major difference between the description of ocean waves and the description of waves in optical fibers. Although in each case the NLS equation seems to be a valid model, what we observe in reality is another matter. In optics, we measure averaged intensity, i.e. the square of the modulus of the envelope. Carrier frequency is usually forgotten. In the ocean, we observe waves at the carrier frequency. Then an important parameter is the carrier–envelope phase difference. The latter has been extensively discussed in optics when dealing with ultrashort pulses that contain only a few cycles (e.g. by Cundiff), but has not been discussed in the case of ocean waves (at least in this special issue). Meanwhile, if this parameter is close to zero, then we can observe higher amplitudes in contrast to the case when this parameter is 180°.

Moreover, this parameter may change in the course of wave propagation. Then we may see the specific property of rogue waves that 'appear from nowhere and disappear without a trace'. In the ideal case, the effect would be periodic, but in a chaotic wave field, this may happen only once.

Of course, this is only a possibility. Rogue waves in the ocean are still mysterious. The 2D nature of these waves may also contribute to the 'rogue' behavior of ocean waves. We are working on these issues, but do not have answers yet.

Alexey Slunyaev

The first impression of a reader of this journal issue may be the surprising diversity of the applications, which the rogue wave problem is addressed to. However, as soon as the main mechanisms responsible for rogue wave formation were revealed, their generality promoted an anticipation of the rapid spread of the rogue wave concept, but I am not sure that many of us could foresee, for example, the appearance of rogue waves in economics.

Scientific interest in the rogue wave phenomenon was to a great extent supported by the fact that severe sea waves exceeded our expectations; hence the builders and customers of ships and onshore constructions are actually unable to adequately estimate the safety and risks.

Now in the context of oceanic rogue waves, we discuss fully dimensional/fully nonlinear models, wave breaking effects and wind influence to steep waves, realistic laboratory experiments and robust indicators of rogue wave occurrence in the sea. These issues confirm that some progress has already been made, and rogue wave studies are close to resulting in tangible changes and improvements in wave forecast, ship design, etc.

In my opinion, we are now at the bifurcation point, where the line of engineering rogue wave studies is going to branch off. On the other hand, many theoretical problems are still not solved, and rogue waves have recently been discovered in a number of applications, which is readily confirmed by the variety of papers in this collection. The mixture of these studies is very likely to result in new interesting findings on nonlinear wave field dynamics and stochastic dynamics as well.

It is important to remember that the rogue wave phenomenon is a balance between wave severity and the likelihood of wave occurrence. Although the discovery of deep water wave instability will in a few years celebrate its 50th-year anniversary, it attracted great interest just recently, when people *believed* that this effect *is able* to generate a rogue wave *in the real sea*. In fact, this ability is still not unconditionally accepted by all of the scientific community. This is because Benjamin–Feir instability may be suppressed by many unfavorable conditions. Therefore, even if Benjamin–Feir instability is present in physical applications, it is not given by default that the stochastic wave fields in realistic conditions will demonstrate a noticeable increase of large wave probability. However, in the case of oceanic rogue waves this seems to be the case: the effect of modulational instability leads to more frequent freak waves in comparison with linear theory.

Since research is going to fork, the definition of rogue waves may also diverge. It seems to be natural if this definition for engineering purposes is not just one and depends on the kind of impact on structures, boats, etc. Instead of defining the rogue wave, one may define rogue wave conditions as such, when the high wave probability is amplified. As for as the effect of nonlinearity is concerned, a reasonable rogue wave definition may require waves with statistics exceeding that established for the linear limit.

I suppose the following directions will be interesting for further research:

- 3D studies. Although there is already some stock of work, numerical and in the laboratory, the understanding is still quite poor. This is explained by the absence of a good model for deep-water 3D waves (e.g. integrable, as Miguel Onorato claims).
- Indicators for extreme sea conditions. Although the Benjamin–Feir index has been suggested, its practical application is not straightforward, as I may conclude from the literature.
- The study of coherent structures. When we fail to observe 3D solitary waves over the deep sea, but the nonlinear effects definitively play an important role in the wave dynamics, we

still have a hope of finding some long-lived nonlinear coherent structures, which could help us understand the wave dynamics. This research could aim, for example, at discovering the role of resonance clusters and at improving kinetic theories.

Daniel Solli, Claus Ropers and Bahram Jalali

In our research, we have been primarily concerned with the manifestations of rogue waves in optical contexts. In this area, we are very pleased to see that the study of extreme events in optical supercontinuum generation is growing into an exciting new field thanks to significant international effort from numerous research groups. In our opinion, there are three major areas in which this field can make important scientific contributions:

1) The use of optical experiments and fast real-time measurements to aid studies of rogue waves in hydrodynamics and extreme events in other systems.
2) To yield a greater understanding of the importance and subtleties of noise in supercontinuum generation.
3) Stimulation and optical control of coherent supercontinuum generation.

While the latter aspect is not generally concerned with generating rare events, the observation and study of such events has proven very useful in the intentional stimulation and stabilization of the underlying process. In this area, we see great potential for future device and laser source development.

As for studies of optical rogue waves and analogies with other physical systems, we believe that one need not demand a one-to-one correspondence between the extreme events in different systems described by variations of the NLS equation. Generally, the wave height appears as the main concern in the hydrodynamic case; on the other hand, in optics, many physically and technologically important variables, such as spectral bandwidth, peak amplitude or pulse arrival time, will show long-tail statistics. Depending on the variable, the underlying process, which separates the rare events from the common events, can be different. For example, considerations of collisions or soliton interactions may be useful for describing certain extreme-value observables, whereas others, including redshifted energy and spectral bandwidth, can be traced back to seeding conditions in the initial pulse noise.

In any case, the numerous recent publications, including this special issue, illustrate that there is still great potential for future research in this area, some of which may lead to practical applications.

Frederic Dias

I would emphasize only two points, which in my opinion are crucial for a better understanding of rogue waves:

(i) collect as much data as possible – even if the link between hydrodynamics and optics is not obvious, the great advantage of optics is the possibility to generate a plethora of data;
(ii) 3D aspects (crossing seas appear to be a very important candidate for rogue wave formation, as emphasized by a few authors).

The overall conclusion is that probably one mechanism is not sufficient to generate rogue waves in the ocean, but a combination of several mechanisms.

Alfred Osborne

Many fields of modern physics reflect a situation common with the field of physical oceanography. Physical science often emphasizes (1) experimental measurements, (2) data analysis by linear Fourier transform (or alternative variations such as wavelet transform, dynamical systems approaches, etc.) and statistical analyses, and (3) increasingly complex numerical models that are used to compare to the data.

In this context I would like to recall an amazing story. Only a dozen years ago the NLS equation had been effectively tossed away because it was too narrow banded to be of much use in broad-banded situations typical of the world's ocean. Today that equation has grown in value and has been found to be very useful by a large body of scientists not only in the field of physical oceanography but also in nonlinear optics, solid state physics, plasma physics, etc. How could such a simple equation be found useful at a time in history when complex models rule the landscape? The answer is simple: The Benjamin–Feir instability in the NLS equation leads to coherent structures that are now being studied by a number of investigators as giving rise to rogue waves in deep water. Amazingly, I know of no modelers (even those who have been running excellent codes for decades) who discovered these structures prior to studies of the NLS equation that revealed the correct initial conditions. Now, several authors have suggested that there are also shallow-water rogue waves arising as Mach stems or dromions when crossed cnoidal waves interact as solutions of the Kadomtsev–Petviashvili equation. Of course the modelers are benefiting from this work, because now they know what kinds of initial conditions lead to the coherent effects. Additionally, there are now a number of data sets that have been obtained, which illustrate how our physical understanding of the situation has improved over the past decade. Many other nonlinear wave equations, or sets of equations, also give rise to various types of other coherent structures, including shock waves (fronts), anti-solitons, vortices, breathers, etc. This leads to the intriguing idea that nonlinear waves in the 2+1 Euler equations must be host to a whole zoo of coherent activity! We have moved, in a data analysis context, from the linear superposition of sine waves to the nonlinear superposition of a significant number of coherent structures together with many other types of nonlinear waves. Who would have ever thought that such an intriguing and important situation could ever arrive in the study of water waves after 250 years of the study of the Euler equations? Indeed, it seems that we are going through a significant paradigm shift at the present time.

In my new book *Nonlinear Ocean Waves and the Inverse Scattering Transform* [Academic Press, 977 pages, 2010], I give a scenario for classifying and characterizing coherent structures in nonlinear partial differential equations. The method is based on the inverse scattering transform with periodic boundary conditions. The book suggests that we are now entering an era when the above list of activities for physical scientists could be supplemented for future studies by three important aspects of nonlinearity:

(1) Nonlinear Fourier analysis consists of the nonlinear superposition of coherent structures and other nonlinear wave trains.
(2) Experimental data can now be analyzed using nonlinear Fourier analysis. The coherent structures are nonlinear Fourier components in the theory. Nonlinear filtering allows them to be extracted from the data and examined for physical and dynamical behavior.
(3) New nonlinear modeling techniques arising from ideas inherent in periodic inverse scattering Transform are being developed, which are many orders of magnitude faster than traditional spectral methods.

The periodic inverse scattering transform is based on the Riemann theta function, a kind of multi-dimensional Fourier series, which replaces ordinary linear Fourier analysis. All three of these ideas are revisited a number of times in the book in different contexts. The two main themes are the analysis of data with nonlinear Fourier methods and hyperfast modeling.

Stay tuned, the next few years are going to be very exciting!