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Review

# Wave forecasts and small-vessel safety: A review of operational warning parameters

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A R T I C L E I N F O

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Traditionally most meteorological offices forecast height, direction and period of wind sea and swell based on phase-averaged wave models. In recent years, there has been special interest in whether it is possible to produce better forecasts, which include information about high-risk situations that are not resolved by the traditional wave parameters. Here we will review and discuss sea-state parameters and safety warning-indices that have been suggested and investigated in recent years. In this review we particularly focus on parameters that are important for small vessels. Some of the findings are:

- A current trend in marine forecasts, going beyond the usual parameters, is tailoring of the product to the end users. The extent to which wave forecasts are tailored to small vessels differs quite a lot among meteorological offices.
- Single wave and crest heights are adequately described by first- and second-order theory, respectively. Present understanding of mechanisms behind abnormally high single waves suggests that modulational instability is limited to almost unidirectional seas.
- Combining wave height and steepness or calculating the risk of synchronous waves is useful, especially in relation to safety of smaller vessels.
- Ship accident statistics suggest that the $H_{m0}$ value of sea state is not as important as whether this value is unexpected, due to rapid development or compared to local wave climate.

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- Severe waves can occur in areas where strong currents oppose the waves, and operational warnings exist for some areas.
- The best way to communicate the directional composition of the wave field still seems to be a division of the sea state into wind sea and swell.
- In spite of incomplete physics, the predicted level of wave dissipation can be used to highlight potentially dangerous seas in some areas.
- Local experience-based warnings are necessary if dangerous sea states can occur that are not resolved by prognostic wave models.



## 1. Introduction

It is essential that meteorological offices give good marine forecasts with intuitively clear and informative wave parameters, as proper knowledge of the expected sea states is a significant factor in vessel safety.

Traditionally, most meteorological offices forecast spectrally averaged wave parameters such as height, direction and period of wind sea and swell. The forecasts are based on phase-averaged wave models that are driven by forecasted marine wind fields. The strengths of these models are their relatively low computational cost and their ability to forecast the full directional wave spectra. These models do not resolve the phases of the forecasted waves, and can therefore not say anything explicitly about the properties of the individual waves. On the other hand, investigations have shown that statistical distributions of different properties of the single waves, e.g., height, period, shape etc., are linked to the shape of the wave spectrum.

Through time, numerous new wave parameters and warning criteria have been suggested, and it is the main goal of this paper to review these developments and summarize the present knowledge of sea-state parameters related to vessel safety that can be forecast by operational wave models. There is an intuitive link between the size of a vessel and the size of the waves that can pose safety hazard. For this reason, sea-state parameters related to small-vessel safety are particularly emphasized in this paper.

In recent years, a lot of effort has been put into determining whether it is possible to predict unusually large waves, often termed freak or rogue waves. Such waves can be dangerous even for large marine structures, but for smaller vessels there are other and much more frequent wave situations that can be hazardous. Most literature cited in this paper is motivated by physics or statistics of waves, and not by wave situations that are known to be dangerous for smaller vessels. The human factor is typically overlooked and parameters are derived assuming e.g., passive vessel steering. For this reason a short introduction to dangerous-wave-vessel situations and the human factor in these situations is given in Section 2 of this paper. In Section 3, we describe typical wave forecasting models used for operational wave forecasts and the most common forecasted wave parameters. Section 4 reviews literature on potentially dangerous sea states and suggested warning parameters. The paper ends with a summary and discussion on the present state of warning parameters.

## 2. Small-vessel safety

A vessel will be considered to be small compared to a wave if its length is short compared to the wavelength. If we use fully developed sea states at 10–20 m/s wind speeds as a reference (Pierson–Moskowitz spectrum), the average wavelengths are on the order of 50–200 m (e.g., [141]). The term 'small-vessel' is therefore quite broad, but in this paper it will typically agree with the definition given by Dahle et al. [24], that small vessels are shorter than 45 m.

The design and stability characteristics of a small vessel are of utmost importance if the vessel is to be operated under severe weather conditions (e.g., [23]). Here we shall not discuss design practices, but only note that stability criteria often are derived from static situations [108], which lack potentially important dynamic effects [117], and not all classes of smaller vessels are properly represented by these methods [152].

### 2.1. Potentially dangerous-wave situations

Comparing the safety of a vessel operating in calm waters with that of the same vessel operating in rough seas raises the following generic situations: waves can compromise the structural integrity and stability of the vessel through direct action of the waves, or the waves can pose an indirect threat to stability, e.g., due to water on deck and progressive down-flooding. Finally the risk of accidents in regular crew operations can increase due to excessive rolling caused by the waves. In any case, it is quite clear that safety is directly related to the severity of single waves and the sea state in general. Looking at fishing-vessel accident statistics as an example, accidents are not typically caused by the sea state directly [143] but the relative incidence rate increases with deteriorating weather conditions [54,153].

#### 2.1.1. Directional wave-vessel aspects of safety

*Head sea*: Sailing against the waves is in most cases the best way to negotiate a series of large waves, but this also inflicts the most violent forces on the vessel, increasing the danger of slamming and shifting of cargo. The impact forces can be limited, to some extent, by reducing the vessel speed, or altering course [76].

*Following sea*: There are many factors that can have a negative impact on stability and ship handling when sailing in the same direction as the waves if the waves are high compared to a vessel [3,151]. The most notorious is broaching, whereby the vessel is turned violently to one side, leaving it broadside to the oncoming waves. The risk of broaching can be reduced by reducing ship speed to a fraction of the wave speed; but this again increases the risk that overtaking waves wash along upper decks from astern without this being noticed by the operators on the bridge [76].

*Beam sea*: Sailing in beam seas can results in large roll angles and, in extreme conditions, the vessel can capsize. Small-vessel model tests suggest that capsize typically occurs in beam seas [1].

*Quartering sea*: Large quartering waves are unfortunate because the vessel stability is affected by the negative effects of both beam and following seas. Investigating the nonlinear dynamics of fishing vessels, Senjanovic et al. [116] confirmed that voyage in quartering seas could be very dangerous for vessel stability.

*Crossing sea*: It is always difficult to handle small vessels in severe sea, but severe crossing sea is particularly dangerous as the waves will approach a vessel from different directions. In such circumstances, the captain loses the ability to use the vessel heading to protect against beam seas.

#### 2.1.2. Shape of dangerous waves

The impact of non-breaking waves increases with height; however, the largest impact does not come from the highest waves but from breaking waves [58]. A vessel is particularly vulnerable to broadside breaking waves that are relatively large compared to the size of the vessel. The relative dimension implies that smaller vessels operating in unsheltered regions, such as fishing vessels, are more often exposed to such circumstances. Experimental evidence from model tests on a variety of forms and vessel types has shown that a breaking-wave height equal to the breadth of the boat is sufficient to result in capsizing [150]. Capsize can occur due to one large steep wave, or due to synchronous rolling in a series of waves with a period close to the vessel's own roll period [20].

### 2.2. Human element of safety

The human factor is important, and in general terms it is estimated that approximately 80% of all shipping casualties are due to human error [32,43]. There are typically several contributing factors that result in an accident, and the human element is only one of these. Contributing human causes are, e.g., misjudgment and attention problems of large-vessel operators [73], negligence and lack of safety mentality of fishing-vessel crew [81,143,147] or alcohol consumption in motor boat accidents [75].

There is no doubt that the best way to survive extreme weather situations is to avoid them in the first place, and given the quality of present weather forecasts and weather routing systems, this is possible most of the time [128]. However, good forecasts are only one part of the solution to improving safety at sea.

Operator experience is also vital as the best maneuvering strategy in severe seas is highly dependent upon the specific ship type, size and given capabilities [79]. Preparation of a vessel for bad weather is particularly important for small-vessel safety. In their guide to fishing-vessel stability Womack and Johnson [151] mention a series of dangerous situations that can be prevented by human actions. Some of these are: *Overloading*, which results in less freeboard and possibly also in a raised center of gravity, both of which cause reduced stability. *Unsecured cargo*, which could shift in bad weather and reduce stability. *Unsecured openings*, which could lead to swamping of the vessel or progressive down-flooding in bad weather. *Slack tanks*, which reduce stability due to the free-surface effect. *Closed freeing ports* in bulwarks (caused e.g., by debris on deck), which could trap water on deck and thus reduce stability.

### *2.3. Sea-state features that need to be forecasted*

Wave forecasts ought to reflect the fact that the users often are experienced sailors, with a strong desire for independence [100], who might have a natural reservation against academically derived warnings [56]. A good way to communicate graphical forecasts is therefore through wave parameters directly linked to the visible properties of the ocean surface. Such parameters enable sailors to make their own evaluation of the validity and usefulness of these parameters. Information that is not understood or respected will most likely be ignored by the crew [150].

The main objective of meteorological offices must therefore be to give as intuitively clear information as possible so the vessel operators easily can make informed decisions. Complex safety indices are better suited in vessel-specific forecasts or in decision support for forecasters when they issue marine text forecasts.

To summarize what has been said in this section, small-vessel safety is linked to the severity of the sea state, the occurrence of particularly dangerous waves (based on size and shape), directionality of the waves, and finally vessel and operator preparedness to encounter these circumstances.

## 3. Present wave forecasts

The state of the art in operational sea-state forecasting are the third-generation wave models [134]. The most common of these are WAM ("WAve Model"; [60,142]), WW3 ("WaveWatch III"; [139]) and SWAN ("Simulating WAves Nearshore"; [10,104]). These models solve the wave transport equation explicitly without ad hoc assumption about the shape of the wave-energy spectrum. The propagation of wave energy is based on linear wave theory; wave growth $S_{in}$ and wave dissipation $S_{ds}$ can be based on different parametric functions and the nonlinear wave–wave interaction $S_{nl}$ is usually, in operational settings, approximated by DIA [40].

Given good quality wind forecasts these models accurately forecast integral properties of the sea (wave height, period and direction) while the shape of the one- or two-dimensional spectra is less accurate [134].

### *3.1. Usual forecast parameters*

The wave model calculates the evolution of the two-dimensional wave spectrum $S(f,\theta)$ which gives wave energy as a function of frequency and direction at each of the model's grid points. Spectral information is usually too complex and comprehensive for general purposes [34], and the meteorological offices, therefore, typically present the forecasted sea state as spectrally integrated parameters, based on the moments, $m_n$, of the spectrum:

$$m_n = \int_0^\infty \int_0^{2\pi} S(\theta,f) f^n \, \mathrm{d}\theta \, \mathrm{d}f, \quad where\ n = -1, 0, 1, 2, \ldots$$

The most common parameters are:

- Significant wave height $H_{m0} = 4\sqrt{m_0}$.
- Wave periods, such as peak period, $T_p$, corresponding to the most energetic wave period in the spectrum, energy period $T_{m-10} = m_{-1}/m_0$, so called for its role in computing wave power and mean wave period $T_{m02} = \sqrt{m_0/m_2}$, equivalent to zero-crossing period. The last is known to be problematic due to its sensitivity to high frequencies; see e.g., Niclasen and Simonsen [89].
- Direction of the wave field, either given as mean wave direction, $D_{mean}$, or the direction of the most energetic frequency, $D_p$.

A common procedure is to divide the wave spectrum into swell and wind sea before calculating the above-mentioned parameters. In WAM, wave components forced by the wind are termed wind sea and the rest is labeled swell [29]. In WW3 several additional swell fields can be identified [140] and in SWAN, swell is simply defined as all wave components below a user-defined frequency [132].

### 3.2. Advanced forecast parameters

In a survey of common operational practices by Savina and Lefevre [112], it was found that most national meteorological services merely provide general information, with only a few exceptions, such as rogue waves in the Agulhas current (South Africa) or breaking sea in the Gulf Stream (USA). There have been some further developments in forecasted parameters sine then, and some are mentioned here.

In order to overcome inaccuracies in wave forecasting, some institutions provide probabilistic wave forecasts based on ensembles. Outputs from these forecasts are mean value, spread and probability at different thresholds of wind speed and wave height [15,111]. Forecast skill can also be improved at locations where measurements are available. This procedure, known as consensus forecasting, uses past performance of one or several models to produce a combined and improved forecast at the specific locations [27].

Several meteorological offices forecast ocean currents, but most do not include the effect of the currents on the waves. One example of a forecast that includes this effect is the hazardous wave delineation (www.wrh.noaa.gov/eka/swan) of the National Oceanic and Atmospheric Administration (NOAA).

The European Centre for Medium-Range Weather Forecasts (ECMWF) provides large-wave warnings [48,47].

The Icelandic Maritime Administration (IMA) provides dangerous-wave forecasts based on the high and steep wave distribution given by Myrhaug and Kjeldsen [86], in a manner that is directly related to the stability of smaller vessels [22].

National meteorological offices also issue text advisories/warnings for small vessels. Here are some examples from the NOAA (www.noaa.gov).

- Small Craft Advisory (SCA): issued if regionally set limits of wind speed and wave height are exceeded.
- SCA for Winds: issued if wave height is below SCA limit but the winds speed is potentially dangerous.
- SCA for Hazardous Seas: issued if the wind speeds do not exceed the limits in SCA, but waves or seas are potentially hazardous due to wave period, steepness, or swell direction.
- SCA for Rough Bar: issued for specific nearshore areas where interaction of swell and tidal or river currents can pose a hazard. Local thresholds are based on parameters such as wave steepness, wind speed and direction, and local bathymetry.

## 4. Potential dangers inflicted by the sea

Predicting the significant wave height is the single most important task of operational wave models. In spite of advances in the accuracy of wind and wave modeling, it is still a challenge to predict severe levels of $H_{m0}$ accurately (e.g., [70]).

In the literature related to wave forecasting, it is usually assumed that it is not the average waves in a given sea state that are the major threat, but rather single waves that are extreme either in size or shape, or come from an unexpected direction. Here we will review processes that can lead to this kind of dangerous waves.

### 4.1. Areas with increased wave height

When we limit our attention to phase-averaged propagation effects of wave energy, as they are implemented operational wave models, then there are only two processes that influence energy levels as the waves propagate through a region. These processes are called wave refraction and shoaling. Wave refraction represents changes in the propagation direction of the waves, while shoaling involves changes in the propagation velocity and height of the waves. Refraction causes wave energy to be focused or defocused due to geometry of the bathymetry, in a similar manner as lenses can focus or defocus light. Areas where wave energy is focused are known as caustics and some illustrative examples of bathymetry-driven caustic areas are given in Mei [77]. When waves travel from deep to shallower water, the wave speed is affected by the depth. In such shallow regions, waves from deeper water are slowed down, resulting in more energy entering the area than leaving it. A good example of this kind of shoaling is the rising and breaking of waves approaching a beach. Diffraction can also lead to local increases in wave height in sheltered regions, but diffraction is, at most, only partially included in phase-averaged wave models [44].

Typical operational wave models are based on Eulerian propagation, which is not quite as accurate as ray-tracing models (e.g., [107]), which most likely means that caustic areas are not represented as strongly as they would have been if more accurate propagation were utilized.

Shallows are dangerous, not only because of the potential direct danger of vessel grounding in low tides, but also because long waves will break when propagating across such areas, generating large breaking crests. Janssen and Herbers [52] found that refractive focusing of a long-crested wave field can result in extreme waves as nonlinearity is enhanced. If the shallow features are resolved, then depth-limited wave breaking can be modeled [5]. The physics on which phase-averaged wave models are founded assume that the model grid length is coarse compared to the wavelengths it resolves [60] and that gradients in bathymetry, wind and currents are smooth compared to the resolution of the model. This implies that small-scale features with significant gradients compared to the dominant wavelengths (reefs etc.) cannot be properly resolved by the usual linear phase-averaged wave models. One way to warn against small-scale features not resolved by the models is by incorporating local experience into text warnings in a similar manner as it is done for the small craft advisories at NOAA.

### 4.2. Large single waves: linear theory

Rudnick [110] was the first to observe that wave dynamics in deep water can be considered to be a Gaussian random process, and Barber [4] was the first to notice that single-wave heights seemed to follow a Rayleigh distribution.

The Gaussian property of wave heights is generally valid in deep water, whereas this property is only applicable in shallow water if the sea severity is very mild [90]. In the following we will assume deep water, and focus on single-point wave-height statistics.

Assuming a stationary, Gaussian and narrow-band process, Longuet-Higgins [68] demonstrated that the amplitude of the waves can be described by a Rayleigh distribution. This distribution has also been used to describe the probabilistic properties of the wave height, $H$, which is approximated by twice the amplitude. The general expression for the Rayleigh probability density function is

$$f(x) = \frac{2x}{R}\exp\left(-\frac{x^2}{R}\right), \quad 0 \le x \le \infty$$

Given the variance of the wave field, $\sigma^2$, the Rayleigh parameter $R = 2\sigma^2$ if $x$ is the wave amplitude, or $R = 8\sigma^2$ if $x$ is the wave height [123].

It can be shown [68,90] that when $x$ is Rayleigh-distributed, the most probable largest value out of $N$ waves is asymptotically given as

$$E\left(x_{1/N}\right) \cong \sqrt{R \cdot \ln N}$$

The estimated maximum wave height is therefore only increased marginally by the number of waves. For example, if the number of waves were increased from 1000 to 2000 the estimated increase in the largest wave height would be less than 5%. Therefore, it is clear, under the given assumptions, that it is mainly variations in $R$ that determine the distribution of the extreme values. Thus the narrow-band assumption indicates that the zero-crossing wave period $T_z$ or its spectral equivalent $T_{m02}$ [103], which is inversely proportional to the number of waves per time, has a limited influence on the distribution of the expected highest wave or crest per unit time in a given sea state.

The Rayleigh distribution is known to overpredict the probabilities of the higher waves, and there exist several alternatives to the Rayleigh distribution; a good review of this subject is given in Massel and Sobey [74]. There is a variety of other wave-height or wave-crest distributions, but most of them are quite similar to the Rayleigh distribution, in the sense that they primarily depend on the total energy in the wave spectrum, and not, or much less, on the shape of the spectrum.

The shape of the spectrum does influence the wave-height statistics to some degree. Based on numerical Gaussian simulations, Massel and Sobey [74] found that sharper spectral forms were associated with higher maximum waves. Using numerical simulations of Gaussian mixed seas, Rodriguez et al. [106] inspected how different combinations of swell and wind sea (two-peaked spectra) affected the wave-height statistics. They found, in all but one case, that the Rayleigh model systematically overestimated wave heights higher than the mean wave height, and that none of the alternative models tested could characterize adequately all the different cases of bimodal seas. A partial measurement validation of these results is given in Soares and Carvalho [124].

It is therefore clear that the shape of the 1D wave spectrum is related to the distribution of oceanic wave heights. The link between the shape of the 1D wave spectrum and large crest heights is more direct as the average shape of large crests is scaled to the auto-correlation function [9,66], which, in turn, is the Fourier transform of the spectrum according to the Wiener–Khintchine theorem (e.g., [101]).

Looking at data it is found that crest heights much more frequently than wave heights can be termed extreme compared to the Rayleigh distribution [53,72,83,131]. This reflects the fact that the Rayleigh distribution does not include second-order effects (longer and shallower wave troughs and sharper and higher crests) making it only first-order accurate in wave-crest statistics. In wave-height statistics, on the other hand, second-order effects cancel out, making the Raleigh distribution second-order accurate in deep water for narrow wave spectra.

As mentioned, the shape of the 1D spectrum has an influence on single-point distributions. Following this it could be speculated whether the directional composition of the 2D wave spectrum had similar influence; but it turns out that linear single-point statistics of wave and crest heights are only affected by the shape of the 1D spectrum (e.g., [88]). However, if higher-order approaches are used, then directionality has an influence on the crest-height distribution [138].

Alternatives to the Rayleigh distribution that give better fit to wave-height data are: Forristall's [31] empirical distribution based on buoy data, the $H_{m0}$-adapted Rayleigh distribution [69], Tayfun's [129,130] distribution, which does not assume a narrow-band process and Naess's [87] model for Gaussian seas. More accurate distribution for crest heights is Forristall's [30] second-order distribution that takes wave steepness and water depth into account.

Until now we have only mentioned distributions derived for wave or crest heights at a single point. Distributions of the largest wave heights or crest heights in a domain of some spatial scale is different from the single-point wave statistics. Using Gaussian simulations of directional seas, Baxevani and Rychlik [6] show that the probability of observing large waves within a given area is higher in confused seas than for the unidirectional case. This can be explained by the larger number of independent waves that occur per unit time in the area when the seas are confused compared to the unidirectional situation. The spatial distribution of large waves is therefore influenced by the directionality of the sea state, while the point distribution is not.

### 4.3. Extreme and freak waves: nonlinear theory

Large waves can be described as “extreme waves” if they are large compared to what could be expected in the given sea state; and if they are extraordinarily large, terms like “freak” or “rogue” waves may be used. These definitions have to be related to probability levels. The background probability distribution is usually the Rayleigh distribution. Waves are referred to as extreme if they exceed 2.0–2.2 times the significant wave height [57]. According to the Rayleigh distribution, extreme waves with abnormality index $AI = H_{max}/H_{m0}$ occur on average once out of $N_{AI}$ waves, where $N_{AI} \cong \exp(2AI^2)$; i.e., extreme waves with index $AI$ occur on average once every $T_{m02} \cdot N_{AI}$ s. According to the Rayleigh distribution, a wave with ratio $AI = 2.0$ will therefore occur about once every 4 h if $T_{m02} = 5$ s, and a wave with $AI = 2.2$ will occur about once per 53 h if $T_{m02} = 12$ s.

In linear wave theory, large waves only occur due to constructive interference between a large number of independent random waves. In nonlinear wave theory, very large waves can also be generated due to modulational instability, often referred to as Benjamin–Feir instability [95].

It has been shown, based on theory and laboratory data for long-crested waves, that there is a clear link between the so called Benjamin–Feir index (*BFI*) and the occurrence of extreme wave and crest heights [50,82,95,98,99]. Using the definitions given in Janssen [46], the *BFI* is given as

$$BFI = \varepsilon\sqrt{2}/\Delta$$

where $\varepsilon = \sqrt{k_p^2 m_0}$ is an integral measure of wave steepness ($m_0$ is wave variance and $k_p$ is peak wave number), while $\Delta = \sigma_\omega/\omega_p$ (frequency width over peak frequency) represents the relative width of the wave spectrum.

In Mori and Janssen [82] an expression for the probability of encountering a freak wave ($AI > 2$) is derived for long-crested conditions:

$$P_{freak} = 1 - \exp[-\beta N(1 + 8\kappa_{40})]$$

where $\beta = e^{-8}$, $N$ is the number of waves and the fourth-order cumulant $\kappa_{40}$ is derived to be $\kappa_{40} = \pi BFI^2/\sqrt{3}$. Using the definitions given in Mori and Janssen [82], $\kappa_{40}$ is related to the kurtosis, $C_4$, of the sea surface elevation, $\eta$, as $\kappa_{40} = \langle\eta^4\rangle/\langle\eta^2\rangle^2 - 3 = C_4 - 3$, where the angle brackets denote ensemble average.

Recent results from nonlinear simulations do nevertheless indicate that the link between *BFI* and extreme wave heights is limited to long-crested seas and does not exist for short-crested waves where wave statistics are nearly Gaussian [33,97,126,136]. This is also verified by 3D laboratory experiments [94,144].

From a physical point of view, one could say that nonlinear interactions between waves take time to develop (e.g., [19]), and this is why instabilities are more prone to happen in narrow-banded (little velocity dispersion) and unidirectional (little directional dispersion) seas.

Using new derivations and directional Monte Carlo simulations of the nonlinear Schrödinger equation in deep water, a new parametric version of surface-wave kurtosis, $C_4$, is now in operation at ECMWF [47,48]. This new version of $C_4$ depends on *BFI*, depth and directional spreading. For a large number of waves $N$ and small values of $C_4$, the expected value of the maximum wave height $E(H_{max})$, normalized by the significant wave height, is approximately given as

$$E(H_{max}) = \sqrt{z + \frac{\gamma}{2} + \frac{1}{2}\log\left(1 + C_4\left[2z(z-1) - \gamma(1-2z) - \frac{1}{2}\left(\gamma^2 + \frac{\pi^2}{6}\right)\right]\right)}$$

with $z = (1/2)\log N$, where $\gamma = 0.5772$ is Euler’s constant [47].

It is observed, as mentioned above, that directional spreading reduces the maximum estimated wave height to Gaussian levels for spread sea states. It is also observed that extreme wave heights are less frequent in shallow water [48,49].

Several sets of field data have been investigated in recent years to test theoretical and laboratory results, but they seem to be difficult to confirm e.g., [61,93]. Measuring extremes will always be problematic, since measurement uncertainty is expected to be high in these cases, and this will influence the statistics; e.g., Olagnon [91] argues that properly quality checked wave-height data do not deviate from the Rayleigh distribution. Present understanding is apparently that the occurrence rate of freak waves does not seem to be readily predictable by the phase-averaged wave spectra alone [109,127,145]. In their recent review on freak waves, Dysthe et al. [28] conclude that second-order theory is sufficient to describe wave statistics in most circumstances.

### 4.4. Steep and high waves

It is intuitively clear that waves that become too steep will break. The steepness of a wave is defined as the ratio between the height $H$ and the length $L$ of the wave. The majority of wave measurements are point measurements, measuring surface elevation as a function of time, so the wavelengths are not measured. If the water depth is large compared to the height of the wave, and assuming that the wave propagates approximately as a monochromatic wave, it is possible to estimate the length and thus the steepness of the wave from linear wave theory as

$$Steepness = \frac{H}{L} = \frac{2\pi H}{gT^2}$$

Here $H$ is the height, $L$ is the length and $T$ is the period of the wave. In time series analysis, the wave period $T$ is usually defined as the time interval between two successive upward (or downward) zero crossings of the mean water level. It should be noted that assuming a monochromatic wave before transformation from time domain to spatial domain leads to some level of error [67]. This error occurs because realistic surface waves do not propagate as single linear waves, but at best as a sum of linear waves having different amplitudes, periods and directions. It is in fact estimated that propagation of a realistic wave (composed of multiple linear components), is only accurate within one wavelength [71].

According to linear wave theory, the maximum wave steepness is 1/7, as a higher steepness would result in the wave crests overtaking the wave i.e., the wave would break [149]. Several field studies investigating the link between wave steepness and wave breaking clearly show that single-wave steepness is not the best estimator for wave breaking [141]. Myrhaug and Kjeldsen [85] argue that the crest-front steepness, $S_{cf}$, of a wave is a better indicator of asymmetric form and potential breaking of a wave.

$$S_{cf} = \frac{2\pi H_{crest}}{gTT_{cf}}$$

Here $H_{crest}$ is the height of the wave crest, $T$ the period of the wave and $T_{cf}$ the time between the upward zero crossing of the crest and the maximum height of the crest.

Based on analyses of time series from deep-water buoy data, Myrhaug and Kjeldsen [85] find that the root-mean-square values of the crest-front steepness and wave height can be correlated with the spectral moments, $m_0$ and $m_2$, of the respective sea state as

$$RMS\left(S_{cf}\right) = 0.0202 + 32.4\frac{m_2}{g\sqrt{m_0}}$$

$$RMS(H) = 2.8582\sqrt{m_0}$$

Using the same data set, Myrhaug and Kjeldsen [86] derive a normalized parametric probability density distribution for crest-front steepness and wave height:

$$p\left(\widehat{S}_{cf},\widehat{H}\right) = p\left(\widehat{S}_{cf}\middle|\widehat{H}\right)p\left(\widehat{H}\right)$$

where $\widehat{S}_{cf} = S_{cf}/\mathrm{RMS}(S_{cf})$ and $\widehat{H} = H/\mathrm{RMS}(H)$. $p(\widehat{S}_{cf}|\widehat{H})$ and $p(\widehat{H})$ were found to be log-normal and Weibull-distributed, respectively; the parameters are given in Myrhaug and Kjeldsen [86]. Based on previous work on safety for smaller vessels, they set the critical limit of potentially dangerous waves to be $S_{cf} \geq 0.25$ and $H \geq 4$ m. Using the normalized parametric probability density distribution in combination with the critical values, it is now possible to calculate the number of dangerous waves in any sea state if only $m_0$ and $m_2$ are known. This parametric distribution, hereafter labeled MK87, is in operational usage by IMA. The goal of IMA has been to relate the integral of vessel displacement multiplied with the area of the GZ-curve (curve of static stability) with Hc*. Hc* is the height of the breaking wave that will cause capsize of a particular ship when positioned upright. Dahle and Kjaerland [25] found the relationship for a particular ship by model experiments. In the experiments, the wave height, the superstructure and bulwark configuration and the loading condition (and hence GZ) were varied in a systematic manner, and Hc* was evaluated.

To apply Hc*, model experiments for a range of ships should be undertaken because other effects of breaking-wave impact are incorporated in Hc*. In particular, height and type of bulwark/rail and water on deck have notable effects.

One of the practical problems in application of Hc* has been to assess the ship stability and displacement under varying operational conditions. A simple instrument, measuring roll period, and thereby calculating metacentric height has been tested on Icelandic vessels, but is not in general use. Vessel displacement can be assessed by simple weight calculations (pers. com. Dag Myrhaug and Emil Aall Dahle).

In essence, Hc* should provide a good indication of the safety level when broadside to the sea for a wide variety of conventional types and sizes of fishing vessels in Iceland and elsewhere. One reason for implementation problems is that if an official institution present such guidelines, it will to some extent be held responsible for accidents that have occurred in the "grey zone" of guidelines based to a large extent on statistical information of the waves (pers. com. Dag Myrhaug and Emil Aall Dahle).

The empirical expression of RMS($S_{cf}$) shows that there is a strong link between RMS($S_{cf}$) and significant steepness $S_s = 2\pi H_{m0}/(gT_{m02}^2)$, indicating that sea states with the same $H_{m0}$ but with higher $S_s$ will contain a larger number of dangerous steep waves according to the MK87 model.

The work done in the MK87 model was followed up by Brodtkorb [13]. Using more field and laboratory data, Brodtkorb et al. [14] derived a new probability distribution, which we henceforth will label BMR00. It was observed that the spectral shape influenced the distributions of dangerous waves, and that this model is best suited for single-peaked spectra [14]. Further inspection showed that MK87 seemed to underpredict the number of dangerous waves ($S_{cf} \geq 0.25$ and $H \geq 4$ m) for a large fraction of the [$H_{m0}$, $T_{m02}$] space, and that the BMR00 model gave better results [12,13]. The BMR00 model is fitted directly to the data and is not expressed as an explicit parametric distribution, but is accessible through the WAFO toolbox [133].

It should be noted that MK87 and BMR00 are based on time series, and that $S_{cf}$ is calculated by transforming time intervals into lengths by using linear wave theory; as noted above, such transformations lead to some level of error. This could explain why Myrhaug and Dahle [84], using North Sea and laboratory data, found that $H_{crest}$ and an alternative version of the crest-front steepness, $S_{cf,t} = H_{crest}/T_{cf}$, was more strongly correlated than $H_{crest}$ and $S_{cf}$. This suggests that the data are somewhat distorted when the crest-front steepness is made dimensionless by using the dispersion relationship for linear waves. Some alternative definitions and statistics of single-wave shape parameters can be found in e.g., Soares et al. [125].

A warning index designed for a specific vessel type is suggested in Savina et al. [113], and the approach is related to the thoughts behind the MK87 model. The dimensionless index is given as

$$I_{Steepness} = \frac{Steepness}{0.05} \times \frac{H_{m0}}{h_0}, \; where \; h_0 = 4\,m$$

It is clear that the index will become large for sea states with $H_{m0}$ values above 4 m, which is the critical limit for these vessel types, and steepness above the PM-limiting zero-crossing steepness (0.0508). It is not clear how the occurrence rate of dangerous waves scales with this index, but this type of index can be tailored in an ad hoc manner to suit operators of different vessel types.

One observation that supports the need to combine wave height and steepness in relation to sea safety is given in Toffoli et al. [137]. Here it is noted that two out of three ship accidents, reported due to bad weather, occurred in sea states with $H_{m0}$ less than 4 m, while more than one out of two of the accidents occurred in sea states with steepness above the PM-limiting steepness.

### 4.5. Modeled estimate of breaking waves

In the previous section, steepness was used as a parametric estimate of the risk of encountering high breaking waves. Some types of modeled wave dissipation $S_{ds}$ could also be potential parameters. There is of cause differences in how specific types of wave dissipation relate to safety. There might be a link between modeled level of whitecapping and safety, but the link is expected to be stronger for depth-induced breaking and dissipation due to current-induced wave blocking.

The best option would be to have a model that predicts the height and severity of the breakers; but until this is available, some existing types of wave dissipation could be used as indicators of which areas have increased levels of breaking waves. There is ongoing research into improving the physics and parametric formulations of wave-dissipation source terms. The WISE Group [134] presents a recent state of the art in this respect.

The drawback of using wave dissipation as a safety parameter is that it is hard for the user to quantify, and the levels of dissipation can vary between different model implementations; as, e.g., whitecapping typically is used as a tunable closure function.

### 4.6. Synchronous waves

Resonance between ship and "synchronous" waves occurs when a vessel is sailing in beam or quartering seas and experiences two or more consecutive waves with an encountered wave period close to the vessels own roll period. This effect can cause the vessel to roll to potentially large angles, even though the height of each individual wave is moderate compared to the size of the vessel. As mentioned previously, large roll angles can be a threat to ship stability, either directly through potential capsizing or indirectly through water ingress or a shift in the cargo.

Based on linear simulations it can be found that synchronous waves occur more often than the single dangerous (high and steep) wave, as predicted from the MK87 or BMR00 models [20]. The roll period of vessels is highly dependent upon the vessel size, form and stability properties. The number of encountered synchronous waves depends on the given sea state [148] and roll period of the vessel, but the number is usually large if the roll period of the vessel is close to the average zero-crossing period, $T_z$, of the encountered waves [20].

### 4.7. Increasing severity of the sea state

It has been suggested that the occurrence of freak waves was correlated with the time history of the sea state, i.e., freak and dangerous waves occur more frequently in storms that developed rapidly with strong forcing [80,92]. Analyzing the time histories of different spectral properties of a large number of storms, Olagnon and Magnusson [93] found that the time history does not influence the probability of freak waves. This fits well with the findings of Brodtkorb et al. [14] that the distribution of large steep waves was not influenced by whether the trend in $H_{m0}$ was growing or decreasing.

At the same time it is reported by Toffoli et al. [137] that, in four out of five of the reported ship accidents, the wind component of the wave field had increased by 20% or more in 6 h.

We therefore apparently have diverging observations that, on the one hand there is no link between development histories of sea storms and the risk of abnormal waves, and on the other hand that there seems to be a link between rapidly changing wave-height values and ship accidents. This apparent contradiction can possibly be explained by the human factor, as the risk that the crew is caught off guard without implementing preemptive actions, is increased if the sailing conditions deteriorate faster than usual. If this is true, the predicted increase in wave height over some fixed time interval, $\Delta H_{m0}/\Delta Time$, could be a useful safety warning parameter.

### 4.8. Directionality of the waves

*Direction of single waves*: The impact that a wave has on a small vessel is, as has been discussed earlier, strongly dependent upon the relative direction of the incident wave. Vessel stability is most vulnerable to beam and quartering seas and it is therefore necessary to forecast the directional composition of the wave field as well as its severity. In spite of this, single-wave combined height-and-direction distributions have not received much attention in the reviewed literature. Isobe [45] derives a combined distribution for wave height and direction for a narrow-banded process and Kwon and Deguchi [62] expand the distribution to include also wave periods. From data inspections it is known that most of the steep wave crests are normal to the mean wind direction [115], and that rogue waves tend to come from the mean wave direction [61].

*Wave-field partitioning*: Toffoli et al. [137] found that one out of four accidents occurred in sea states with significant crossing of wind sea and swell, i.e., the vessel would experience some degree of beam seas regardless of its heading. It is not clear if this just reflects the average directional wave-field composition in the respective accident areas, or is evidence of a higher risk in crossing seas. Current wave models are capable of predicting mixed seas as 2D wave spectra, but it is difficult to communicate this information in an intuitive manner. The usual method of partitioning the forecast wave field is to separate wind sea and swell based on what wave components receive energy from the wind. Swells are not modeled separately in the models and further separation into different swell fields is done in postprocessing. A quite promising method in this respect is described by Tracy et al. [140]. The usage of wind sea and swell separation is, to our knowledge, a much appreciated part of marine forecasts.

*Directional spreading*: There are a variety of parameters that represent the directional spread of a given 2D wave spectrum, apart from the usual swell and wind-sea separation. We shall not go into details here, since the directionality of a wave field is no indicator of dangerous waves in its own right, as a directionally spread but calm wave field cannot be considered a general indication of danger.

The authors are only aware of one suggested index that combines the directional spread with severity of a sea state. Savina et al. [113] and Savina and Lefevre [112] suggested the following warning index, which combines the directionality and significant wave height:

$$I_{DirSpread} = \frac{1}{2} H_{m0} \exp\left( -10(\sigma_S - 1)^2 \right)$$

where $\sigma_S$ is the directional spreading parameter. The value of $\sigma_S$ is calculated from the directional wave spectrum as given in Bidlot [8]. $\sigma_S$ takes on values between 0 and $\sqrt{2}$ corresponding to unidirectional and uniform wave spectrum, respectively, and the index has a maximum when $\sigma_S = 1$. This index is intended for high-speed catamaran ferries, which, due to their hull shape, are particularly sensitive to high sharp crests (pers. com., Jean-Michel Lefevre, Meteo-France).

*Increased risk of single dangerous waves*: In mixed seas the wave dynamics can deviate from the usual because standing-wave components can appear and generate much steeper waves [141]. She et al. [118] found that crest-front steepness is dependent upon directional distribution of the wave field, and that breaking waves are more severe (higher and steeper) when they occur in spread seas. There are theoretical investigations which suggest that extreme waves can occur in crossing sea. Onorato et al. [96] used coupled nonlinear Schrödinger equations to investigate modulational instability growth rates in systems composed of two plane carrier waves traveling in different directions. They found that the instability region and growth rates are larger in a two-wave system compared to a one-wave system. Representing real wave fields by plane carrier waves is not a realistic approximation, but this study and the subsequent work by Shukla et al. [119] describe a process that could generate freak waves in crossing sea states.

There are also other investigations that suggest the opposite. In his investigation of steep and high crests Brodtkorb [13] observed that two-peaked spectra (an indicator of mixed seas) resulted in less dangerous waves than single-peaked spectra. It should be noted that directionality is not considered as an independent parameter in these investigations.

It has been argued that the chance of encountering large crests is increased if the sea state is composed of two independent wave systems, given that the crests in the combined sea state can be expressed as the sum of two Rayleigh-distributed parameters [26]. In retrospect, we think that the increased crest heights predicted here are due to the unintended assumption that the two independent wave systems always produce crests at the same time, i.e., that they always cause constructive interference.

### 4.9. Waves on currents

Non-uniform currents can focus wave energy in a similar manner as the bathymetry, but due to the varying nature of ocean and coastal currents, it is not as easy to predict where and how much the sea state is changed due to the currents. A good example of the devastating effect that a current can have on the sea state and vessel safety in its region is the Agulhas current [64,122].

Unexpected large waves can be encountered in areas with significant currents, as the current can trap wave energy or generate caustics due to wave refraction [65,77,146]. Assuming shallow water, Lavrenov and Porubov [65] also suggest that a nonlinear interaction, according to the Kadomtsev–Petviashvili equation [55], can generate large single waves in the region inside the current where trapped waves intersect from different directions.

White and Fornberg [146] suggested that random ocean currents of moderate strength can cause caustics and thus freak waves, given that the incoming waves are unidirectional. Janssen and Herbers [52] found that nonlinear interactions can further enhance wave heights in current-generated caustic areas, again given that the incoming waves are unidirectional. On the other hand it has been argued by Dysthe et al. [28] that unidirectionality is not fulfilled under realistic settings and that introducing realistic directional spreading smears out the caustic regions. In other words, random currents can focus swell energy, but only to a moderate extent under realistic conditions.

Operational wave models have the theoretical wave propagation framework to incorporate the effects of spatially non-uniform and time-varying depth-averaged currents [134] through wave action conservation [11]. This makes it possible to forecast areas where currents can generate dangerous seas, but the phase-averaged wave models still have some shortcuts, which limits their ability to accurately describe the influence of the currents on the waves. The main issues are listed below:

*Unresolved phases*: The fundamental problem of phase-averaged wave models is that all characteristics of the wave profile are lost due to the unknown phases. This implies that the reported dangerous profile of waves traveling against non-uniform [64,122] or depth-varying current [59] is not resolved.

*Vertically averaged currents*: Restricting wave propagation to depth-averaged currents, as is presently done in most models, is at best an approximation [135], although some shortcuts have been suggested [42]. Theoretical derivations have been conducted [2,78,102] that will make it possible to jointly model depth-varying currents and phase-averaged linear waves.

*Unresolved physical processes*: The physical processes observed in strong opposing currents, e.g., wave blocking [17], are not included in present operational models, which give incorrect levels of both wave dissipation and spectral distribution of the frequencies affected by dissipation [105,121,154]. Some parametric dissipation source functions have been suggested and applied to laboratory test cases [16,105,120,154] but they are presently not standard in operational wave models. An alternative procedure is to incorporate the equilibrium range constraint to the absolute wave spectra [41] as suggested by Benoit and Bazou [7].

*Nonlinear wave-wave interactions*: One of the strengths of the state-of-the-art wave models is the use of an independent source term for the nonlinear four-wave interactions. The derivation of the wave-wave interaction is based on assumptions about homogeneous bathymetry and absence of non-uniform currents [37–39]. It can therefore be questioned if these models are suitable in areas with strong and variable currents [114].

In the literature review, no clear limits or guidelines were found with respect to when a sea state becomes dangerous due to wave–current interactions. The above-mentioned uncertainties also suggest that, if such guidelines existed, they would probably depend on which parameterizations of the physical processes are used in the specific model.

How to display increased risk due to currents is also a problem. In many circumstances the currents will affect the wave height and period, but these subtle differences are not always visible in the online graphics, as these typically have an absolute color scale with somewhat coarse resolution.

The Hazardous Wave Delineation forecast (www.wrh.noaa.gov/eka/swan) provided by NOAA is one operational service that includes the effect of the current on the waves in spite of the difficulties mentioned. Here, two separate criteria are used to assess regions where significant wave hazard is expected, based on wave-energy dissipation according to Smith et al. [120] and significant steepness $S_s$.

When the model's wave-energy dissipation rate or wave steepness at some grid location is greater than a prescribed threshold value, the region is flagged as likely to be hazardous. More detailed information on this service will be available in a future publication (pers. com. Greg Crawford, Humboldt State University).

### *4.10. Rough conditions relative to local norm*

In an investigation into how to reduce the risk for fishing vessels, Dahle and Myrhaug [23] and Dahle et al. [21] stated not only that it was necessary to have marine forecasts for the respective fishing grounds, but also that knowledge of the local wave statistics was important so that appropriate preempt measures could be implemented.

In their investigation of 270 ship accidents reported as being due to bad weather, Toffoli et al. [137] found, by comparing the accidents to wave forecasts for the respective locations, that there was a surprisingly low correlation between high waves and accidents. On the other hand, it was observed by comparing to local wave statistics that three out of four of the accidents occurred with $H_{m0}$ higher than the 0.8-quantile of the monthly climate data. This means that encountered wave height was clearly above the average conditions for the specific region given the time of year. This suggests that the ratio between the predicted wave height and the 0.8-quantile could be a useful parameter in relation to safety.

In this context, it is important to mention that ECMWF produces a quite similar statistically based index for meteorological parameters. This index is called the Extreme Forecast Index (EFI) and scales from $-1$ to 1, indicating extremely low or high parameter values compared to the modeled local climate [63,155]. Originally only meteorological parameters were considered, but recently EFI for wave height is also included (pers. com., Jean R. Bidlot, ECMWF).

The work presented by Toffoli et al. [137], is a valuable comparison between reported damage due to heavy seas and wave-model parameters. It is nevertheless important to keep in mind, on the one hand, that the model used here has coarse resolution in time and space, and on the other hand that there might be a human effect in the statistics. With respect to the accuracy of the model, Toffoli et al. [137] found that the predicted wave height correlated well with satellite data. The human factor is hard to quantify but, e.g., lack of preemptive measures prior to a storm could explain why relatively modest wave heights are the reported cause of damage.

## 5. Summary and discussion: present state of forecasting parameters

Vessel safety is dependent on many aspects amongst which the human factor is estimated to be the most important. Marine forecasts of good quality are an important factor, but only to the extent that they are taken into account, i.e., to prepare vessel and crew for the incoming weather.

Vessel safety is highly dependent upon the size, stability properties, heading and speed of the vessel in any given sea state. It is therefore not surprising to see that tailoring the forecast to the end user is the present trend in marine forecasting. Larger vessels can be part of ship routing systems or can have advanced on-board systems that take vessel-specific information into account before interpreting the forecast. Such support systems are less usual in smaller vessels, and several meteorological offices therefore have separate forecasts and warnings specifically aimed at small vessels.

The present state of forecast wave parameters, linked to vessel safety, is summarized below.

### *5.1. Prediction of unusually large single waves*

It has been suggested that sea states with a high average steepness and narrow spectrum [36,51,80,92,95,113] could be linked to an increased probability of encountering abnormally high waves. It has also been suggested that sea states with bimodal spectra [18,26,35,80,113], or sea states that have evolved rapidly [35,80,92], could be linked to the occurrence of particularly high waves. In the previous sections it has been argued that it is primarily the total energy in the wave field (i.e., $H_{m0}$) and the number of encountered waves (i.e., $T_{m02}$) that are proven to be linked to any substantial increase in the expected maximum single-wave height, $H_{\max}$. The shape of the spectrum has an effect on the size and shape of the wave crests but only a minor effect on $H_{\max}$. The most promising link between spectral shape and high waves due to nonlinear wave-wave interaction is given by the kurtosis estimate of Janssen [50] and Mori and Janssen [82], which is included in operational forecasts at ECMWF [47,48]. The significance of the nonlinear effect is, however, limited to sea states with narrow directional spreading.

Overall, the deviations from the Rayleigh estimate of $H_{\max}$ are quite limited in directional deep-water waves. It can further be argued that as long as wave models have problems predicting local spectral shapes [134] predictions of advanced parameters that are sensitive to spectral shape will always be problematic.

### 5.2. Prediction of dangerous shapes of single waves

*Steepness*: The steepness of a sea state is one parameter that can be used to indicate the level of breaking waves in a given sea state. There are, nevertheless, some concerns connected to the use of steepness as a warning parameter. 1) It can be calculated in several ways, giving different values. 2) It needs to be connected to wave height before it is useful in safety evaluations. 3) It is an academic parameter in the sense that its value cannot be determined by eye without experience and knowledge of the given definition. This being said, the predicted average steepness of a wave field is known to be a useful parameter for experienced end users, especially if the wave field is first partitioned into wind sea and swell (pers. com., Hendrik L. Tolman, NOAA-NCEP-EMC).

*Height and steepness*: One way to combine wave height with wave steepness is given by Myrhaug and Kjeldsen [86] and Brodtkorb [12]. This data- and model-derived approach is developed for fishing vessels; but, by adapting the critical limits, the method is scalable to any vessel type. Another way to combine wave height and steepness into a single index is suggested in Savina et al. [113].

*Synchronous waves*: It has been shown that synchronous rolling is a significant safety concern [23]. Warning against synchronous rolling is a vessel-specific task as important factors are size, loading condition, speed and direction of the ship and whether anti-roll systems are installed. If stability criteria are known, it is possible to produce polar plots that indicate the capsize probability of the ship as a function of the ship's heading and speed [76]. Average wave period, $T_{m02}$, is an interesting parameter in this respect as the number of potentially dangerous synchronous waves is usually large if the roll period of the vessel is close to the average zero-crossing period of the encountered waves [20].

*Breaking waves*: Wave models can predict the level of depth-limited wave breaking; but, apart from this, the level of wave breaking is not explicitly modeled. An indication of the level of wave breaking can be obtained from modeled wave dissipation.

### 5.3. Hazardous directionality of the waves

There is no doubt that high and steep waves coming from unexpected directions are a major concern for small-vessel operators. There exist several ways to express the directional spread of a given sea state, but the practical implications of these values are unclear and it is difficult for the end user, without empirical experience with these values, to link these quantities to danger in a given sea state.

One suggested way to combine wave height and directional spreading is given in Savina et al. [113]. In this particular case the index is intended for catamaran ferries but, in principle, similar types of directionally sensitive indices could be tailored to suit other vessel types as well.

The present practice of partitioning the predicted wave spectrum into wind sea and swell still seems the best, and most general way, to communicate the directional composition of the forecast wave field.

### 5.4. Operational warning of unexpected events

In the review of suggested wave parameters, it became apparent that one re-occurring topic is the importance of predicting unexpected events. These events can either be unusually large single waves, unusually complex seas or unusually severe sea states. An investigation of the ship accidents reportedly due to severe weather, Toffoli et al. [137] found that many of the accidents occurred at low $H_{m0}$ values, but they occurred after a relatively fast growth in $H_{m0}$, especially the wind-wave part of $H_{m0}$. Another observation was that, although the $H_{m0}$ values were not that high, they were high compared to the seasonal wave climate in the given area. These sudden changes of $H_{m0}$ and high quantiles (rough event compared to wave climate) suggest that the human factor (unprepared crew and vessel) is perhaps more important than the possible freak wave-generating mechanisms.

If these speculations constitute a correct interpretation of the ship accidents reported in Toffoli et al. [137], then forecasting and notifying vessels of more-rapid-than-average or more-severe-than-average sea states is just as important as forecasting warnings for extreme events.

### 5.5. Current-induced caustic areas

It is generally accepted that unusually large and dangerous waves can occur in areas where the waves are strongly influenced by opposing currents. There exist operational warnings for such areas, e.g., the Agulhas current, when the waves travel in the opposite direction to that of the current.

Operational wave models can incorporate most of the effect that currents have on wave propagation, but the physics describing the dissipation processes in caustic regions is not complete, and it is not clear if the usual way of implementing the wave–wave interactions is suitable in such regions. Wave models do, nevertheless, capture some of the effects that the currents have on the waves, and there exist operational warnings for such areas based on the level of wave dissipation.

### 5.6. Features beyond the limits of the operational model

There will always be small-scale features that are not properly resolved by the wave model. The best approach in this context is to incorporate local sailor experience into the local marine forecasts. One such good example is the Small Craft Advisory for Rough Bar as forecast by NOAA.

Dangerous sea states caused by high levels of wave grouping [36,18] or other types of phase locking, e.g., in caustic areas, cannot be resolved by the present type of phase-averaged wave models.

## 6. Outlook

There has been a focus on developing better wave-dissipation functions that do not only function as closure terms for the wave models. There has been progress on parts of the processes but there is still a long way to go [134]. Getting good predictions of wave dissipation is vital for vessel safety, especially if it becomes possible to forecast the height and severity of the breaking waves.

One of the big problems with operational wave models, in relation to predicting abnormal waves, is the missing phase information. Phase-resolving models will most likely always be too computationally expensive for operational forecasts, whereas forecasting the phase information in a statistical sense through bispectral modeling might become an option.

As computing power and transmission capabilities become more readily available on all vessel types, it is possible that on-board safety systems will compute vessel responses from the full predicted 2D wave spectra, and thus make the search for better warning parameters redundant.

## 7. Conclusions

A series of operational and proposed wave parameters has been reviewed which can be used in sea-state forecasts. There has been a lot of research into this field, and only some major trends are reviewed here. Overall it can be said, that:

- Forecasting and distributing correct wind and $H_{m0}$ levels is still the most important task of marine forecasting centers. To ensure accuracy during rapidly evolving sea states, updated forecasts ought to be available as frequently as possible.
- Wave-height statistics for sea states with common levels of directional spreading are found to be quite close to the Rayleigh distribution, whereas crest-height statistics are better estimated by distributions based on second-order theory.
- Modulational instability can generate extreme waves, but recent research shows that this mechanism is mainly active in long-crested seas, i.e., it does not play a major role in sea states with common levels of directional spreading.

- The main trend in marine forecasts, going beyond the usual parameters, is tailoring of the product to the end user.
- It is possible to make statistical predictions of the risk of encountering waves with dangerous shape by using derived distributions of simultaneous high and steep waves, or synchronous waves. The level of danger that these waves induce is, however, highly dependent on vessel size, stability properties, heading and speed.
- Prediction of complex seas is straightforward for most wave forecasting models, but communicating this information and its effect on vessel safety in an intuitive manner is not trivial. The best procedure still seems to be a division of the sea state into wind sea and swell, leaving the interpretation of the vessel-specific consequences (degree of beam seas etc.) up to the user.
- Unexpectedly high and steep waves can occur in regions where currents significantly effect wave propagation. Operational wave models cannot resolve such single-wave phenomena, but the models can include most of the effects that depth-averaged currents have on phase-averaged wave propagation.
- In spite of incomplete physics, the predicted level of wave dissipation can be used to highlight areas that are potentially dangerous.
- One way to include potentially dangerous situations not properly resolved by the wave model is by incorporating local sailor experience into local text forecasts.
- Ship accident statistics indicate that moderate but rapidly evolving sea states, and sea states that are severe compared to local seasonal wave climate, are linked to a higher risk of accidents on vessels.

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