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ABSTRACT

Water wave breaking represents one of the most arduous problems in fluid mechanics. Understanding the process of wave breaking and developing an ability to quantify the associated energy losses and redistribution are critical across a wide range of coastal oceanic applications, maritime navigation, and climate and hydrodynamic research. Naturally, waves become steeper toward the inception of breaking; however, there is still a lack of unanimity regarding the relationship between breaking probability statistics and wave steepness. Here, we present a detailed investigation of breaking vs non-breaking statistics estimated using a recently developed method for accurate detection of breaking waves, based on the phase-time approach to identify breaking-associated patterns in the instantaneous frequency variations of surface elevation fluctuations. The findings are based on data collected both in the open sea and in a laboratory wind wave flume. An in-depth examination of celerities and steepnesses of breaking and non-breaking waves is presented. The analysis, which involved wave-by-wave examination, produced skewed Gaussian-like steepness histograms, revealing that non-breaking waves and breaking waves can reach steeper profiles, above the Stokes limit. All extreme steepness values were investigated and are presented here.

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I. INTRODUCTION

The evolution of wind-forced ocean surface waves in time and space is a complex phenomenon, affected by many processes, such as nonlinear wave interactions, interactions with currents and bathymetry, and wave breaking. Wave kinematics and dynamics are sensitive to those interactions, resulting in changes in wave field parameters, such as wavenumbers, peak frequency, wave heights, etc. Empirical and observational experience teaches us that the energy transfer from the wind to the waves is usually distributed within a narrow band of waves' wavenumbers/frequencies. Due to the complexity of the actual seas, where waves under the influence of the wind appear to be non-symmetric both vertically and horizontally, a statistical approach for analyzing the surface elevation fluctuation records (Rice, 1945) was adopted, with spectral analysis as the most commonly used statistical tool (Longuet-Higgins, 1952). The wave field that evolves under steady wind forcing (fetch-limited growth) constitutes a specific spectral shape known as the Pierson–Moskowitz spectrum (Pierson, Jr. and Moskowitz, 1964). The modern standard for the parametric

description of the fully developed wind wave field is the JONSWAP spectrum, suggested by (Hasselmann *et al.*, 1973)

$$S(f) = \alpha_j g^2 (2\pi)^{(-4)} f^{(-5)} \exp[-(-5/4)(f/f_p)^{-4}] \gamma^{\left(\exp(-(f-f_p)/(2\sigma_i^2 f_p^2))\right)}, \quad (1)$$

where $S(f)$ is the power density frequency spectrum of the water surface fluctuations $\eta(t)$ obtained by means of Fourier transform, g is the gravitational acceleration, f_p is the frequency corresponding to the spectrum peak S_p , and γ is known as the empirical peak enhancement parameter. The JONSWAP spectrum is asymmetric: its width is defined by σ_i , when subscript i refers to the right and left sides of the spectrum, σ_R and σ_L , respectively (Tucker and Pitt, 2001). The amplification factor, α_j , can be parametrized using the wind speed and fetch over which the waves are forced as

$$\alpha_j = 0.076 \left(\frac{U_{10}^2}{xg} \right)^{0.22}, \quad (2)$$

where U_{10} denotes the mean wind speed at the height of 10 m above the mean water level (MWL), and x denotes the fetch (Janssen, 2004 and Miles, 1993). Further analysis is possible using spectral moments derived as

$$m_i = \int_0^\infty (2\pi f)^i S(f) df \quad | i = 0, 1, 2, 3, \dots, \quad (3)$$

where m_0 , m_1 , m_2 , m_3 are the mean, variance, skewness, and kurtosis, respectively. Wave field characteristic parameters can be obtained from the spectral moments, such as significant wave height, mean wave height, zero-crossing time periods, and more.

In this framework, the wave field evolution can be explained in energy budget terms. Whereas wind pumps energy into the waves, making them grow in height and elongate, energy moves through the wave field by nonlinear interactions and eventually dissipates. The basic energy budget equation, also called the action balance equation, is

$$\frac{dN}{dt} = S_{in} + S_{nl} + S_{ds}, \quad (4)$$

where $\frac{dN}{dt}$ denotes the rate of changeover time of the action density, which represents the overall continuous wave spectrum energy. The water waves' energy budget consists of energy input (S_{in}) into the wave field in the form of airflow and water current input, on the one hand, and dissipation/losses (S_{ds}) ejected as heat transport and breaking waves energy (S_{bw}), on the other. Nonlinear interactions (S_{nl}), such as breaking water waves and other interactions mentioned above, are responsible for energy moving between spectral components, the kinetic energy of water motion, and the products of breaking wave whitecaps, such as water spray and air bubbles.

The breaking of waves dissipates the waves' energy, part of which may contribute to the generation of surface current (D'Asaro, 2001). Hence, wind waves represent an underlying source of turbulent kinetic energy moving in and out the ocean surface, therefore contributing to mixing heat, mass, and other tracers throughout the upper boundary layer of the ocean. Induced mixing in the upper ocean layers, produced by the velocity spatial gradients associated with wave orbital trajectory in the breaking process, could be one of the fundamental causes (Babanin, 2006). It is, however, difficult to provide experimental evidence of these processes due to a lack of detection abilities and of high experimental effort in oceans. Forces associated with breaking of the more energetic ocean wave components, hydro-dynamically enhanced by all the above-mentioned phenomena, constitute a significant challenge in ocean and coastal engineering applications. Several processes at the air-sea interface also depend on waves breaking, such as spray generation and gas exchange rates (Deane, 1997; Loewen and Melville, 1991; and Manasseh *et al.*, 2006), rendering wave breaking one of the most important energy and mass transfer mechanisms on the ocean surface.

The breaking process of a wave can be described as follows: a wave becomes highly asymmetrical and at some instant, a bulge forms on its leading side at or close to the crest. At that specific moment, the wave is considered to be a broken wave and an energy loss occurs (Babanin, 2011). Some of the breakers generate a significant amount of foam, also commonly referred to as whitecaps. Depending on wind forcing and the breaking crest propagation speed, the whitecaps can also remain on the backside of a breaking wave. In other cases, the

whitecaps propagate at the same speed as the breaking wave front. At the core of breaking wave research is the need to deduce a universal breaking criterion, a threshold in a parameter or set of parameters that changes toward the inception of breaking, the crossing of which causes the wave to break. Historically, the geometric criterion, which stipulates that waves break when they reach a critical steepness, was the most popular. However, definition of steepness in rapidly evolving and highly asymmetrical steep waves on the verge of breaking is ambiguous. The last decade saw a rise in popularity of the kinematic criterion (KC; often expressed in terms of kinetic energy) as a universally valid criterion for wave breaking. KC postulates that wave breaking is initiated when the slowing crest propagation speed equals the accelerating horizontal water surface velocity at the crest. Mounting experimental and numerical evidence supports the applicability of KC to a wide range of breaking wave conditions (e.g., Barthelemy *et al.*, 2018; Derakhti *et al.*, 2018; Itay and Liberzon, 2017; Liberzon and Shemer, 2011; Saket *et al.*, 2017; Stansell and MacFarlane, 2002; and Khait and Shemer, 2018).

The last decade saw progress also in the understanding of the onset of wave breaking (e.g., Babanin *et al.*, 2010; Barthelemy *et al.*, 2015; Derakhti *et al.*, 2018; Hwang *et al.*, 2016; Itay and Liberzon, 2017; Liang *et al.*, 2017; Martins *et al.*, 2017; Saket *et al.*, 2017; Shemer and Liberzon, 2014; Toffoli *et al.*, 2010; and Pizzo *et al.*, 2021). Several experimental studies were conducted to investigate the geometrical characteristics of the breaking waves (Diorio *et al.*, 2009 and Vollestad *et al.*, 2019). The intermittency of the breaking process, however, poses tremendous experimental challenges, the basic one being the availability of a reliable, cost- and computationally effective method for detection of breaking waves that is capable of detecting breaking crests across a wide range of waves' scales and breaking wave severities. The most common methods so far rely on the detection of whitecaps generated by the most powerful breakers, e.g., using stereo imaging systems (Schwendeman and Thomson, 2017) or LIDAR (light detection and ranging) technology (Kleiss and Melville, 2011). Ultimately, all of the above-mentioned methods rely either on human decisions made by the naked eye, camera post-process observations, or computationally heavy algorithms, which are either subjective or costly, and often both. Liu (1993) and Liu and Babanin (2004) detected breaking waves by applying a threshold on increasing instantaneous frequency obtained by wavelet analysis, while calibrating against visually or instrumentally observed whitecaps. Breaker detection using the instantaneous surface elevation fluctuation frequency threshold, obtained by the Hilbert transform, was also reported by Irschik *et al.* (2011). Detection of only the most powerful, whitecap-generating breakers inevitably results in underestimation of the breaker count and, consecutively, of the breaking wave energy in the total energy budget of the wave field. Inevitable omission of gentler breakers also renders such methods less applicable in laboratory setups of wind wave research. To address the challenge of detecting breakers, a new breaking waves detection method (see Sec. III C for details) was developed recently, which is capable of accurately detecting individual breaking crests in simple wave gauge (WG) records, across all scales and intensities of breakers (Liberzon *et al.*, 2019). This method, hereafter referred to as DL, is based on the detection of specific patterns associated with breaking crests in the augmented signal of the instantaneous frequency variations of surface waves. Relying on statistical comparison of detected patterns, the DL method requires sufficient sampling

frequency and a large number of individual crests, $O(\min. 100)$ in the processed ensemble. This method achieved a 95% true positive and <15% false positive detection rate. Marking each crest in the ensemble as breaking or non-breaking enables direct calculation of the breaking parameter, b_t , as the ratio between the breaking and the total number of crests,

$$b_t = N_b / N_{tot}. \quad (5)$$

This method also enables direct quantification of various wave properties, such as wave steepness, celerity and crest propagation speeds, and energy, and a relative comparison between such properties of non-breaking and breaking crests in the ensemble.

The wave breaking probability, p_b , is defined as the ratio between the average total length of breaking fronts to the unit surface area. This approach is more suitable for image analysis and whitecap counting, and provides a spatial and temporal assessment of breakings. [Banner and Morison \(2010\)](#) proposed the following formulation of the wave breaking probability:

$$p_b = \frac{\int C\Lambda(C)dC}{\int C\Pi(C)dC}, \quad (6)$$

where C is the wave celerity, and $\Lambda(C)$ and $\Pi(C)$ are the total breaking crest and total crests per unit area, respectively ([Phillips, 1985](#)).

The required breaking statistics can be calculated from one point in time or one 2D unit area, depending on how the wave data were collected. Past works focused on evaluating the statistical properties of a wave field and particularly the breaking parameter (e.g., [Banner et al., 2000](#); [Babanin et al., 2001](#); [Banner and Morison, 2010](#); [Phillips, 1985](#); and [Stringari et al., 2021](#)).

As mentioned above, the ambiguity in wave steepness definition often hinders the ability to conduct comparable experimental and numerical studies of breaking waves. The first attempt at finding a systematic method can be attributed to pioneering works by [Stokes \(1847, 1880\)](#), who derived a solution in the form of progressive waves of finite amplitude on water of uniform depth, however, limited to examining the permanent shape of wave trains. A fundamental result of Stokes's research is the idea of estimating wave breaking using a limiting wave steepness with a value of 0.44 ([Williams, 1981](#)). Generally, wave steepness, ε , can be calculated as the product between the individual wavelength (applying the linear theory to calculate k) and the amplitude, a , that can be obtained from positive zero-crossing analysis. Contemporary methods of calculating steep surface waves are said to have originated with [Schwartz \(1974\)](#), who discovered that the first Fourier coefficient, a_1 , in Stokes's series (1880) was not a monotonically increasing function of wave steepness. Hence, a_1 could not be used as an expansion parameter over the entire range of waves.

Subsequently, the approach of limiting steepness per individual wave to distinguish between breaking and non-breaking waves, based on comparison of periodic waves, was derived both theoretically ([Longuet-Higgins, 1975](#)) and empirically in the laboratory ([Van Dorn and Pazan, 1975](#)). In their study, Van Dorn and Pazan measured dissipation in unsteady breaking waves generated by a converging channel wall and found that the initial wave steepness played a fundamental role in the dissipation of the wave energy. Another laboratory study

on breaking waves, probably the most comprehensive of them all, was by [Rapp and Melville \(1990\)](#), who used the dispersive character of deep-water waves to focus a wave packet that generated a single unsteady breaking event at a prescribed location in the wave channel. [Rapp and Melville \(1990\)](#) found that the growth rate and steepness of the waves prior to breaking were important factors in predicting breaking, findings that are in full agreement with the results of [Van Dorn and Pazan \(1975\)](#).

Furthermore, a considerable number of numerical studies showed that steep nonlinear waves are susceptible to several instabilities. Whether or not instabilities lead to breaking is of paramount interest. The rapidly growing ultimate-crest instability has been shown to lead to breaking in all deep-water cases studied ([Longuet-Higgins, 1987](#)). This instability is restricted to wave steepness values greater than the Stokes limit ($\varepsilon = 0.44$). [Tanaka \(1983, 1986\)](#) investigated instabilities of steep waves due to upper harmonic perturbations and showed how a traveling wave of near limiting steepness may be triggered to break. He deduced that waves are most unstable at high steepnesses corresponding to those of waves of maximum energy density, for both deep-water and solitary waves.

Experimental evidence suggests, however, that the limiting steepness is not a robust parameter for the evaluation of breaking occurrence; it has been shown that breaking occurs also when the initial steepness exceeds a threshold value. [Toffoli, Babanin, Onorato, and Waseda \(2010\)](#) analyzed several datasets and found steepness values of up to 0.55, hereafter referred to as TBOW steepness. A numerical simulation conducted by [Iafrafi \(2009\)](#) showed even higher values of steepness, up to 0.65. [Barthelemy et al. \(2018\)](#) observed waves steepness values exceeding 0.44 in their 3D numerical simulations, suggesting the limiting steepness value of ~ 0.8 based on the 5th order Stokes steady theory ([Fenton, 1985](#)). A laboratory study conducted in a wave-current flume showed that the extreme wave steepness was confined to the range 0.38–0.52, with an average steepness of 0.47, higher than the theoretical steady limiting steepness of Stokes waves ([Ma et al., 2013](#)). Other laboratory experiments, including those by [Brown and Jensen \(2001\)](#) and [Tian et al. \(2010\)](#), showed the onset of breaking to be near the Stokes limiting steepness. Conversely, the results of laboratory wave measurements, using linear dispersive focusing of waves ([Rapp and Melville, 1990](#)) and field experiments ([Holthuijsen and Herbers, 1986](#)), suggest that waves also break well below the Stokes steepness, at ε values of 0.15–0.22.

Using a Waverider buoy moored at a height of 17.5 m, 10 km from the Netherlands coast, [Holthuijsen and Herbers \(1986\)](#) counted whitecaps in open waters while also recording the surface elevation fluctuations. Their aim was to verify an analytical theory regarding non-breaking and breaking wave parameters. Addressing the steepness parameter, obtained as ak from negative zero-crossing analysis, they found no limiting steepness differentiating breakers from non-breakers. Another work, by [Schwendeman and Thomson \(2017\)](#), compared statistically derived parameters obtained by stereo video imaging and buoy data. Breakers were detected by whitecap tracing and then analyzed for excluding geometric parameters. One of this study's results was a probability distribution function of wave steepness related to breaking waves and all ensemble waves, while wave heights were obtained by negative zero-crossing analysis similar to the work of [Holthuijsen and Herbers \(1986\)](#). These results reinforce the understanding that waves can break at any steepness value below a specific

limit, while Toffoli *et al.* (2010) showed that waves can exceed the Stokes limit without breaking.

In this work, we rely on the newly available breakers detection method, the DL, to produce a comparative investigation of breaking vs non-breaking wave statistics. The available datasets include small-scale waves from a wind wave flume and large-scale deep-water open sea waves. The DL breaking detection method, which provides accurate detection of breaking waves across a wide range of scales, enabled us to update the knowledge on the relationship between wave steepness and the wave's probability to break.

The report is organized as follows: Sec. II describes in detail the experimental setup of both sea and laboratory datasets used in this work, and Sec. III elaborates on the method's performance test using available datasets. In Sec. IV, we present the results, and in Secs. V and VI, we discuss the main outcomes and conclude our report, respectively.

II. EXPERIMENTAL SETUPS

This section provides detailed description of both the open sea and the laboratory flume experimental setups, data acquisition techniques, and lists the processed datasets.

A. Wind wave flume

The laboratory data were collected in a wind wave flume at the Technion's Sea Atmosphere Interactions Research Laboratory (T-SAIL) and consisted of wind-generated waves recorded under various wind forcing conditions at several fetches along the flume. The flume test section is 17.4 m long, 1.1 m wide, and 1.5 m high (Fig. 1). The water depth was kept at 0.7 m, leaving 0.8 m for the airflow. The T-SAIL flume is equipped with a wave energy-absorbing beach, which was set at a 1:8 slope. The upper part of the wind wave flume consists of the wind-generation and guide tunnel comprising a 10-horsepower blower, two silencers, a settling chamber, and a series of honeycombs for wind flow alignment at the flume entrance.

Two in-house manufactured resistance-type wave gauges, WGs, provided the time series of surface elevations at a 320 Hz sampling frequency. Each gauge, spaced at 30 mm from each other along the flume, constituted a pair of 28 AWG (0.455 mm diameter) stainless steel (SL316) wires stretched at edges of a C-shape support. The gauges were mounted on a PC-controlled motorized linear stage and

positioned at prescribed fetches by means of a motorized instrument carriage. The four 500 mm-long double wire wave gauges were calibrated prior to each experimental run by moving through numerous vertical positions relative to the MWL without waves.

Data acquisition and instrumentation control were performed by National Instruments (NI) LabVIEW software routines, using two analog-to-digital (A/D) cards (NI USB 6211 and NI cDAQ9184-1B560CB), thus achieving a high level of experiment automation.

The mean wind velocity profiles were obtained by a Pitot tube (Prandtl type) coupled with a dedicated differential pressure transducer. At each fetch and wind forcing condition, set by the blower controller speed, the Pitot tube mounted on a dedicated motorized linear stage scanned the vertical wind speed profile. Measurements were conducted at two fetches along the flume's test section: $x = 550$ cm and $x = 1115$ cm. Three different airflow rates were applied, hereafter denoted as 25, 32, and 40 Hz, signifying the blower motor controller frequency. In these experiments, in the absence of the wavemakers, the origin of the test section $x = 0$ was set at the end of the airflow inlet, where the air makes first contact with the water surface (see Fig. 1). Under each experimental condition, i.e., combination of fetch and airflow rate, the MWL was detected by a special water level probe, and the vertical wind speed profile was measured in a coordinate system starting at that location. The instantaneous water surface fluctuations were measured simultaneously with the scanning of the airflow velocity profile, resulting in 60 min-long wave datasets.

B. Black Sea (BS) setup

The open sea waves data used in this work were recorded in the northwest region of the Black Sea, hereafter BS, shown in Fig. 2. The data collection setup and various analyses of the waves were reported in numerous publications over the years.

Instantaneous water surface fluctuations were sampled from an oil rig, located near Crimea, with a fetch ranging from 60 to 400 km from the shore (Banner *et al.*, 2000) over a horizontal bathymetry 30 m deep (Babanin and Soloviev, 1998a, 1998b). The instantaneous water surface fluctuations, here analyzed, were measured by four resistance-type wave gauges at a sample rate of 20 Hz. A wind anemometer sampled 1 min average samples at intervals of approximately 1 h. A

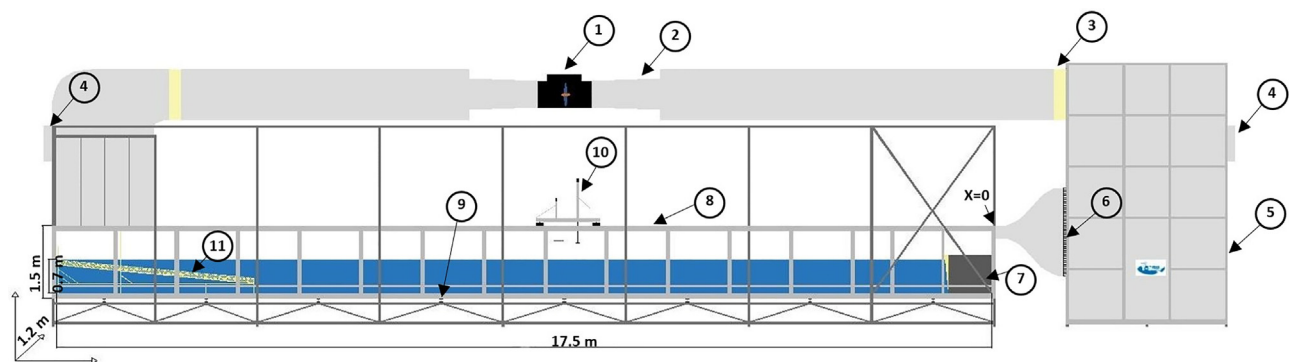


FIG. 1. Cross section of the wind wave flume: (1) blower, (2) silencers, (3) flexible connections, (4) flow rate control hatches, (5) settling chamber, (6) contraction with honeycomb, (7) mechanical wavemakers, (8) test section, (9) shock-absorbing pads, (10) instrument carriage, and (11) wave absorber—beach.

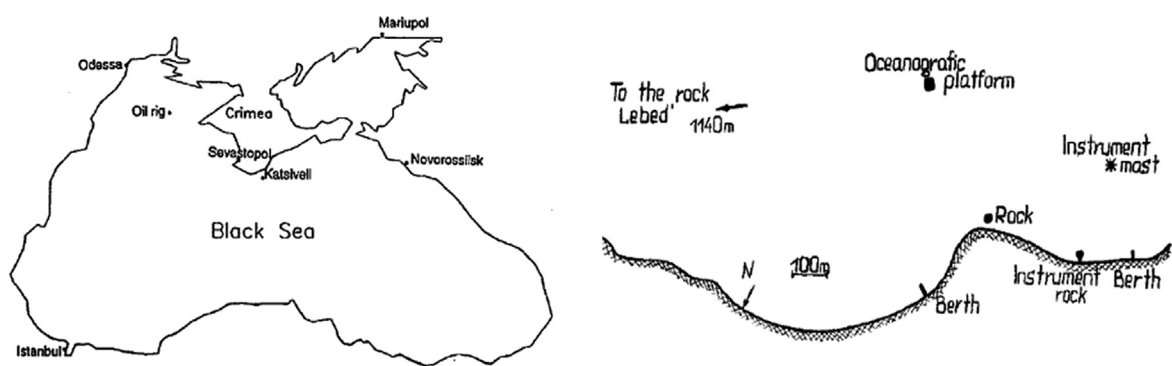


FIG. 2. Left—location of the oil rig and the research platform in the Black Sea; Right—near shore research platform.

fundamental description of the experimental setup and surroundings were given by Verkeev *et al.* (1983) and Efimov *et al.* (1986). The BS data processed here yielded four specific datasets, numbered 211, 238, 242, and 244, aiming at comparing the results with the previously published b_i values obtained by visual observation of white-caps (Banner *et al.*, 2000). An observer was located on the platform, 16 m above sea level, and was charged with spotting and counting breaking waves passing the wave gauge array. Each dataset was treated as an ensemble consisting of two to four subsets of measurements produced by two to four wave gauges, depending on the available data records and their quality. Each gauge encounters each individual crest at a different time and, hence, constitutes an individual contribution to the ensemble, addressing the four wave gauges in the array effectively increasing the total ensemble size. Table I lists all the datasets and subsets used. Subsets that were too short or suspected of being corrupt are marked in gray, and were

excluded from the analysis, resulting in datasets of variable length as noted in the last column.

III. METHODS

The Methods section is presented in three parts. The first (Sec. III A) and the second (Sec. III B) subsections elaborate the processing methodologies for laboratory and field experiments, respectively. The last (Sec. III C) subsection delineates the breaking waves detection method.

A. Laboratory data processing

In the laboratory experiments, a positive zero-crossing analysis was applied on the free surface fluctuations records obtained from two WGs, separated by a known distance, Δx . The two consecutive WGs provide the ability to compute an autocorrelation for each individual

TABLE I. Black Sea datasets.

Dataset	Subset	Record duration (s)	Subset	Record duration (s)	Subset	Record duration (s)	Subset	Record duration (s)	Total ensemble (min)
211	211-1	182.9	212-1	92.77	213-1	182.9	214-1	92.77	24.39
	211-2	182.9	212-2	90.2	213-2	182.9	214-2	90.2	
	211-3	73.15	212-3	182.9	213-3	92.77	214-3	182.9	
	211-4	90.2	212-4	182.9	213-4	90.2	214-4	182.9	
238	238-1	182.9	239-1	92.1	240-1	182.9	241-1	17.5	18.29
	238-2	182.9	239-2	90.13	240-2	182.9	241-2	17.5	
	238-3	83.1	239-3	182.9	240-3	90.13	241-3	17.5	
	238-4	89.83	239-4	182.9	240-4	90.13	241-4	17.5	
242	242-1	182.9	243-1	182.9					18.29
	242-2	182.9	243-2	182.9					
	242-3	182.9	243-3	182.9					
	242-4	0	243-4	0					
244	244-1	182.9	245-1	182.9	246-1	182.9	247-1	182.9	31.50
	244-2	182.9	245-2	182.9	246-2	182.9	247-2	182.9	
	244-3	182.9	245-3	182.9	246-3	182.9	247-3	182.9	
	244-4	0	245-4	0	246-4	0	247-4	0	

wave crest moving across them. First, each wave located between two consecutive positive zero-crossings was identified and three time marks were collected: the positive zero-crossing, t_p ; the crest, t_c ; and the negative zero-crossing, t_n . Therefore, for each crossing between the two wave gauges, the time mark delay was calculated as

$$\Delta t_i = t_{i2} - t_{i1}, \quad (7)$$

where subscripts 1 and 2 are the wave gauge numbers, and $i = p, c, n$ signifies the time mark type (positive, crest, and negative) of the same wave as it passes between the two wave gauges. The average time delay for each passing wave was then calculated as

$$\Delta t = (\Delta t_p + \Delta t_c + \Delta t_n)/3, \quad (8)$$

and the actual celerity of each detected wave was obtained by

$$C = \Delta x / \Delta t. \quad (9)$$

Also, for each wave, the mean time period T and mean angular frequency ω , across the two wave gauges, were calculated using a combination of the three time mark values measured at each wave gauge. An examination of the time period values obtained by different pairs of time marks showed only small variations and is not discussed here; the average across all three time marks was used. Finally, for each detected wave, the corresponding wavenumber was obtained as

$$k = \frac{\omega}{C}. \quad (10)$$

Therefore, by taking each wave amplitude, a , as the crest height above the mean water level, the representative steepness of each laboratory data wave was estimated as $\varepsilon_L = ak$.

A common parameter of interest, in relation to waves breaking, is the high frequency tail exponent, n , of the power density spectrum of the surface elevation fluctuations, S_η . To obtain the power exponent for all experimental ensembles, the surface elevation fluctuations spectra was first calculated, followed by the removal of the bound waves energy by implementing a nonlinear Schrödinger invariants methodology developed by Tayfun (2008) and Fedele *et al.* (2010), resulting in a spectrum describing the energy of the free waves only. The power exponent, n , was then obtained by means of curve fitting the high frequencies tail of each ensemble spectrum.

All measured mean wind speed profiles $U(z)$ were found to be of logarithmic shape and were fitted with

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \quad (11)$$

where z denotes the height above the determined MWL, u_* is the friction velocity, $\kappa = 0.41$ is the von Karman constant, and z_0 is the representative water surface roughness. Values of friction velocity and the characteristic wind speed at 10 m above the mean water level, U_{10} , were obtained from the fits.

B. Black Sea data processing

For BS data, the wavenumber was derived based on the linear theory dispersion relation, $\omega^2 = gk \tanh(kh)$, where h denotes the water depth. The angular frequency is a function of the wave time

period, $\omega = 2\pi/T$, which along with the crest, a , were calculated by zero-crossing analysis for each individual wave and its crest. The representative wave steepness derived from the linear dispersion relation for open sea conditions was, therefore, estimated as $\varepsilon_S = ak$ for each wave detected by the zero-crossing analysis.

As showed above in Table I, the BS data consist of four different ensembles (211, 238, 242, 244) recorded at a 20 Hz sampling frequency. The initial evaluation provided a mean wave period in the range of 2.8–4.6 s with an ensemble duration of 18–31 min (see Table III), leading to an estimated total number of crests in the range of 250–670 and thus satisfying one of the basic requirements of the application of the DL breaking detection method. Next, the BS data were oversampled to a 300 Hz sampling frequency by means of spline interpolation, to fit DL processing routines (Liberzon *et al.*, 2019).

C. Breaking detection algorithm

The breaking detection algorithm, based on a phase-time method (PTM) and wavelet transform (WT) pattern detection, was developed for the identification of breaking waves in the surface elevation fluctuations records obtained by simple wave gauges. The breaking detection algorithm is coded in MATLAB® and is compiled of several processing procedures, which are explained below in brief. (For a full description, see Liberzon *et al.*, 2019.) The basic principle of the method is the analysis of waves' instantaneous frequency fluctuations signal and the identification of patterns associated with wave crests undergoing breaking.

The PTM, suggested by Huang *et al.* (1992), was used to obtain the instantaneous frequency variations as

$$F(t) = \frac{\frac{\partial \nu}{\partial t} \eta - \frac{\partial \eta}{\partial t} \nu}{\eta^2 + \nu^2}, \quad (12)$$

where ν denotes the Hilbert transform of η . When waves go through the process of breaking, they become asymmetrical, and at some instant a bulge forms on the leading side of the wave, at or close to the crest. The manifestation of this bulge in the instantaneous frequency fluctuations takes the form of a distinct pattern, composed of a sharp rise followed by gradual decay, as detailed in Fig. 3.

The breakers are then detected by analyzing the $F(t)$ signal and applying a wavelet-based pattern recognition algorithm to identify the above-described patterns, resulting in the marking of each wave crest as breaking or non-breaking. The ratio between the number of breaking and non-breaking crests then provides the breaking parameter, b_t (5). As mentioned above, a combination of large enough ensembles [$O(100)$ of wave crests] and a sufficiently high sampling frequency will ensure accurate detection of breakers across a wide range of scales and intensities, hence ensuring calculation of a truthfully representative b_t ratio.

IV. RESULTS AND DISCUSSION

Fundamental parameters of laboratory wave fields and wind flow are listed below. Values of U_{10} and u of the mean wind velocity profiles for each experimental condition, i.e., fetch and blower speed, obtained by fitting the measured mean wind velocity with a logarithmic profile, are listed in Table II. This table also lists values of the waves' spectral peak frequency, f_p , the spectra's high frequency exponent, n , the breaking parameter, b_t , obtained by the DL method, and the wave age, WA,

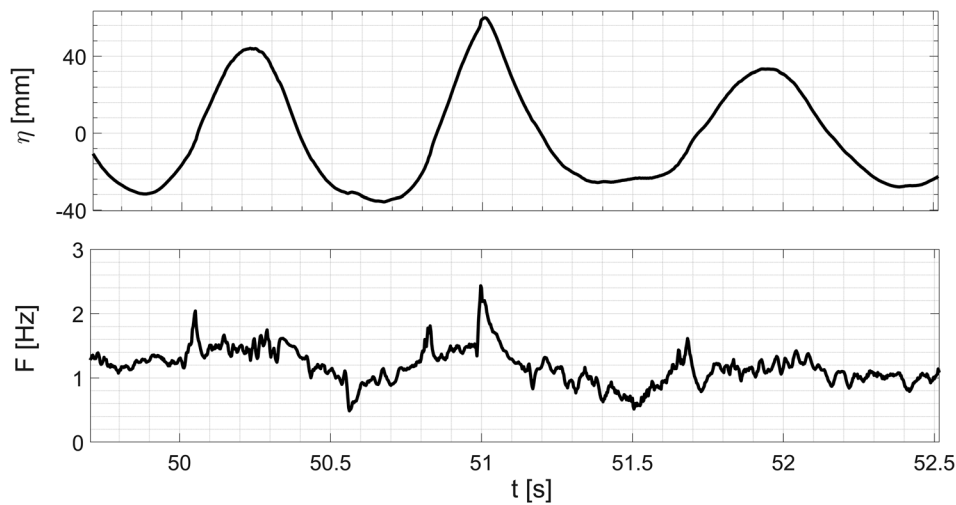


FIG. 3. (a) Breaking inception when bulge appears and (b) corresponding sharp rise and immediate decay in the instantaneous frequency variations (Liberzon *et al.*, 2019).

which was calculated using C_p , the celerity of the peak frequency component obtained from the linear dispersion relation.

Table III lists Black Sea datasets parameters, including b_t values as obtained by both methods, whitecap counting (AB) and DL. NBC and BC are the finite number of non-breaking and breaking crests in each ensemble, respectively.

The energy density spectrum of wind wave flume waves of the ensemble recorded by the second WG (at fetch of 1115 cm and blower controller frequency of 40 Hz), normalized to the peak value, is presented in Fig. 4 on a log-log scale. This spectrum is presented alongside the free-waves-only spectrum as obtained by removing higher order contributions, applying the nonlinear Schrödinger decomposition (Fedele *et al.*, 2010). The fitted high frequencies tail exponent and its power, n , are also denoted.

Next, the steepness exceedance distribution functions (EDFs) and the marginal histograms of breaking and non-breaking crests from both laboratory fetches, 550 cm and 1115 cm, at all wind flow rates data records together with all BS ensembles, are given in Figs. 5 and 6, respectively.

The probability of encountering a wave of steepness exceeding a specific value, ε_0 , was calculated by

$$p(\varepsilon \geq \varepsilon_0) = m/N, \quad (13)$$

where m is the rank of the steepness and N is the total number of steepness values in the ensemble.

All laboratory data are organized in ascending order of fetch, whereby Figs. 5 and 6 represent the 550 and 1115 cm fetches, respectively, and panels (a) to (c) are related to blower controller frequencies

TABLE II. Laboratory experiments: wave and wind flow parameters.

Fetch (cm)	Blower controller frequency (Hz)	$U_{10} \left(\frac{\text{m}}{\text{s}} \right)$	$u_* \text{ (m/s)}$	$f_p \text{ (Hz)}$	$C_p \text{ (m/s)}$	$WA = \frac{C_p}{u_*}$	n	$b_t \text{ (%)}$
550	25	8.65	0.26	3.66	0.60	2.31	5.06	22.04
	32	10.78	0.32	3.15	0.69	2.16	4.53	16.92
	40	13.39	0.42	2.56	0.82	1.95	3.93	17.58
1115	25	7.42	0.22	2.73	0.71	3.23	4.87	17.03
	32	9.71	0.31	2.39	0.93	3.00	4.56	17.20
	40	11.95	0.38	2.06	1.00	2.63	4.21	15.90

TABLE III. Black Sea data: wave parameters.

Dataset	NBC	BC	$b_{tDL} \text{ (%)}$	$b_{tAB} \text{ (%)}$	$f_{pDL} \text{ (Hz)}$	$f_{pAB} \text{ (Hz)}$	n —high frequency tail	fm	Mean time period (s)	Total ensemble (min)
211	288	11	3.67	0	0.16	0.16	3.86	0.22	4.61	24.39
238	240	3	1.23	0	0.15	0.17	3.55	0.23	4.35	18.29
242	306	55	15.23	3.4	0.27	0.27	4.54	0.34	2.93	18.29
244	733	43	5.54	5.8	0.23	0.25	3.73	0.36	2.81	31.5

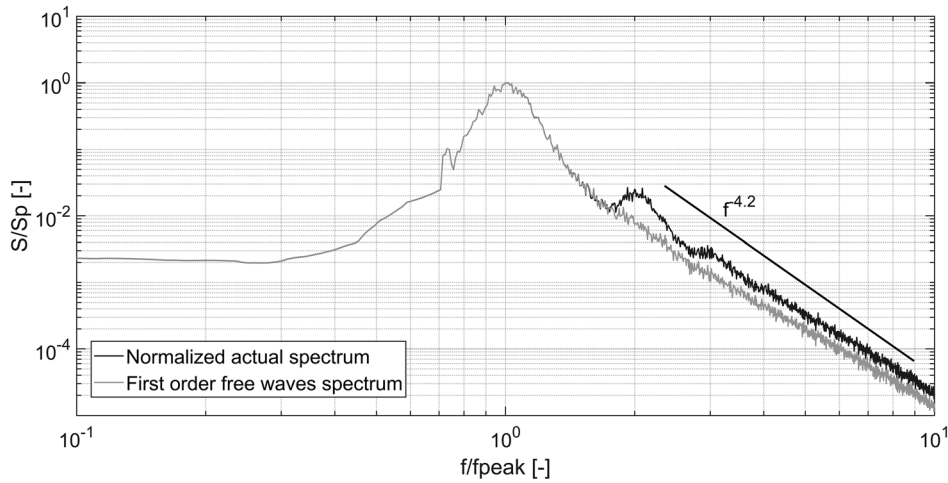


FIG. 4. Surface elevation fluctuations power density spectrum of waves measured by WG 2 at a fetch of 1115 cm and wind blower controller frequency set to 40 Hz. The free-waves-only spectrum (in black) was obtained after subtracting the higher order components' contribution (in gray) to fit the high frequency tail.

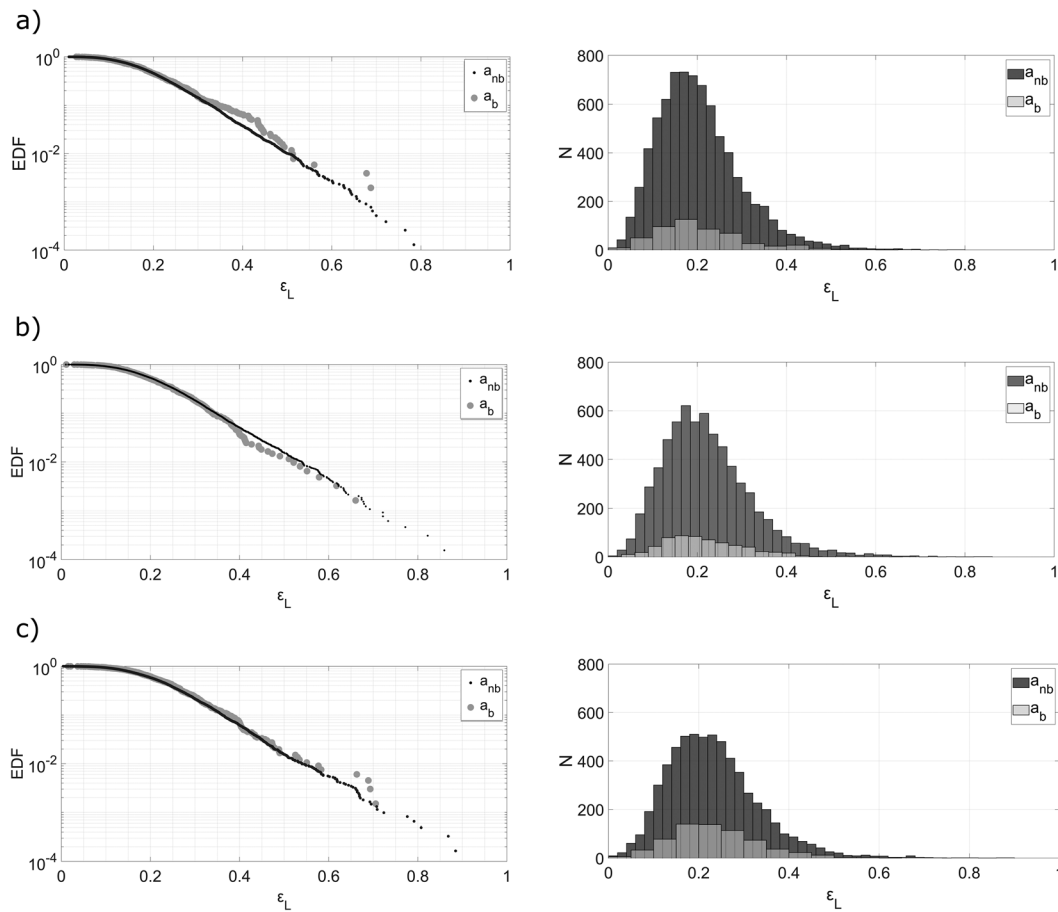


FIG. 5. Steepness EDF and steepness histograms at fetch 550 cm; (a) blower rotational frequency 25 Hz; (b) blower controller frequency 32 Hz; and (c) blower rotational frequency 40 Hz.

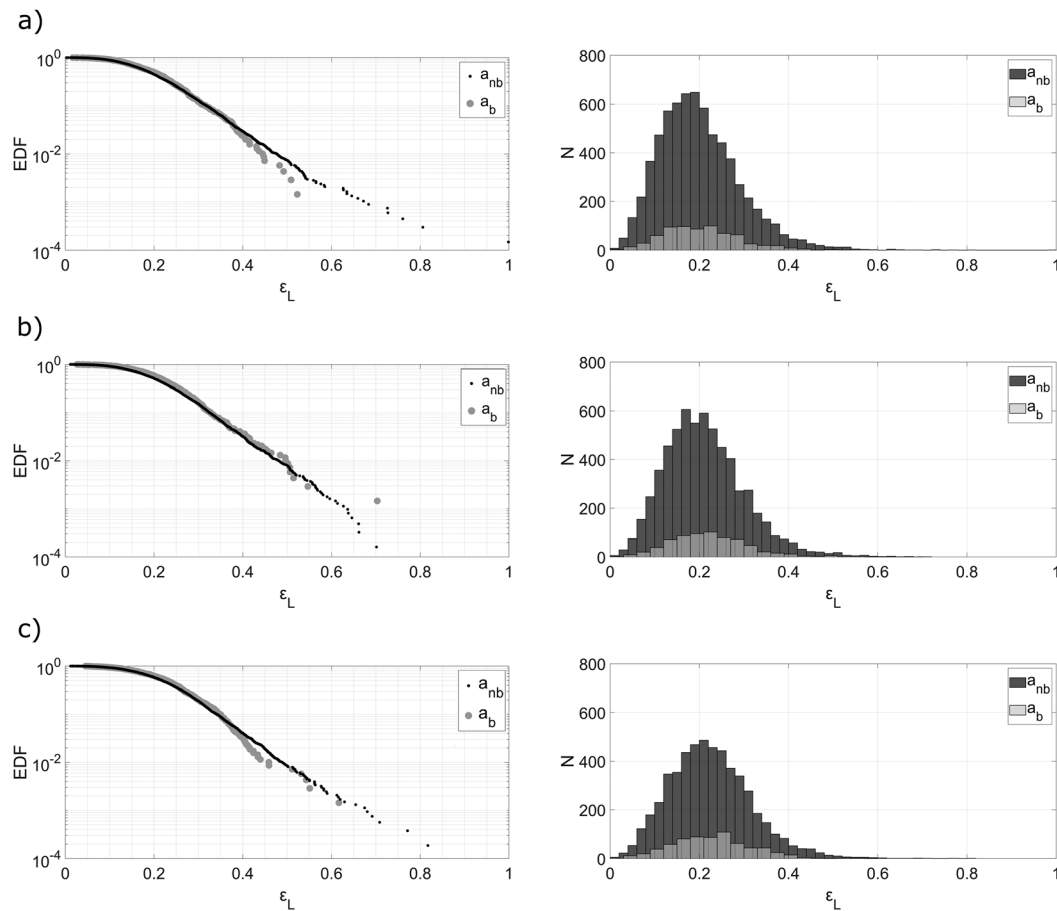


FIG. 6. Steepness EDF and steepness histograms at fetch 1115 cm: (a) blower rotational frequency 25 Hz; (b) blower controller frequency 32 Hz; and (c) blower controller frequency 40 Hz.

of 25, 32, and 40 Hz, respectively. Figure 7 presents the EDFs of the BS data and marginal histograms, in ascending order of dataset number with respect to Table III, and panels (a) to (d) represent datasets 211, 238, 242, and 244, respectively. Finally, combined cumulative EDFs and marginal histograms for both laboratory fetches and BS data are plotted in Figs. 8 and 9, providing a direct comparison. For all EDFs and histograms, non-breaking crests are indicated in the dark gray and breaking crests are indicated in light gray.

Figure 5 presents the results of laboratory datasets at the 550 cm fetch. The probability trend in all datasets, although collected under different wind forcing conditions, are very similar with no preference for any one steepness value or wind speed. Laboratory data reveals a similar steepness EDF for breaking or non-breaking. Specifically, the EDF for breaking waves is slightly higher at lower steepness, and then slightly smaller for ϵ_L values above 0.3–0.45. Additionally, some very steep waves are identified in the ensembles, which require additional examination (see Figs. 10–15 and the accompanying discussion). The vast majority of waves with $\epsilon > 0.6$ are non-breaking waves.

Figure 6 presents the results of laboratory datasets at 1115 cm fetch, exhibiting EDFs of breaking and non-breaking waves that are very similar to those obtained at a smaller fetch of 550 cm. Here too,

the probability trend for all wind speeds is very similar, with no preference for any one steepness value or wind speed. Furthermore, the laboratory data for the higher fetch show similar steepness EDFs for both breaking and non-breaking. The maximum detected steepness at this fetch is lower, with only two breaking crests exceeding a steepness of 0.55, unlike the 550 cm fetch results. The histograms of steepness distributions from both fetches reveal a Gaussian distribution around the steepness value of 0.2 for both non-breaking and breaking crests, with a slight skew to the left. A few very steep waves were identified in these ensembles as well, and again most were non-breaking waves.

Next is Fig. 7, which presents the results from the Black Sea data. Here, we observe significantly higher EDF values for breaking waves, with an almost constant difference from the non-breaking EDF across all steepness values, indicating no steepness threshold preference for the appearance of breakers. It is worth emphasizing that the 211 and 238 datasets both contain a relatively small number of waves and their results may, therefore, not be statistically significant. The other two datasets contain a large number of waves, with four breaking and several more non-breaking crests of steepness larger than 0.6 were detected in these sets. The histograms of the non-breaking waves are

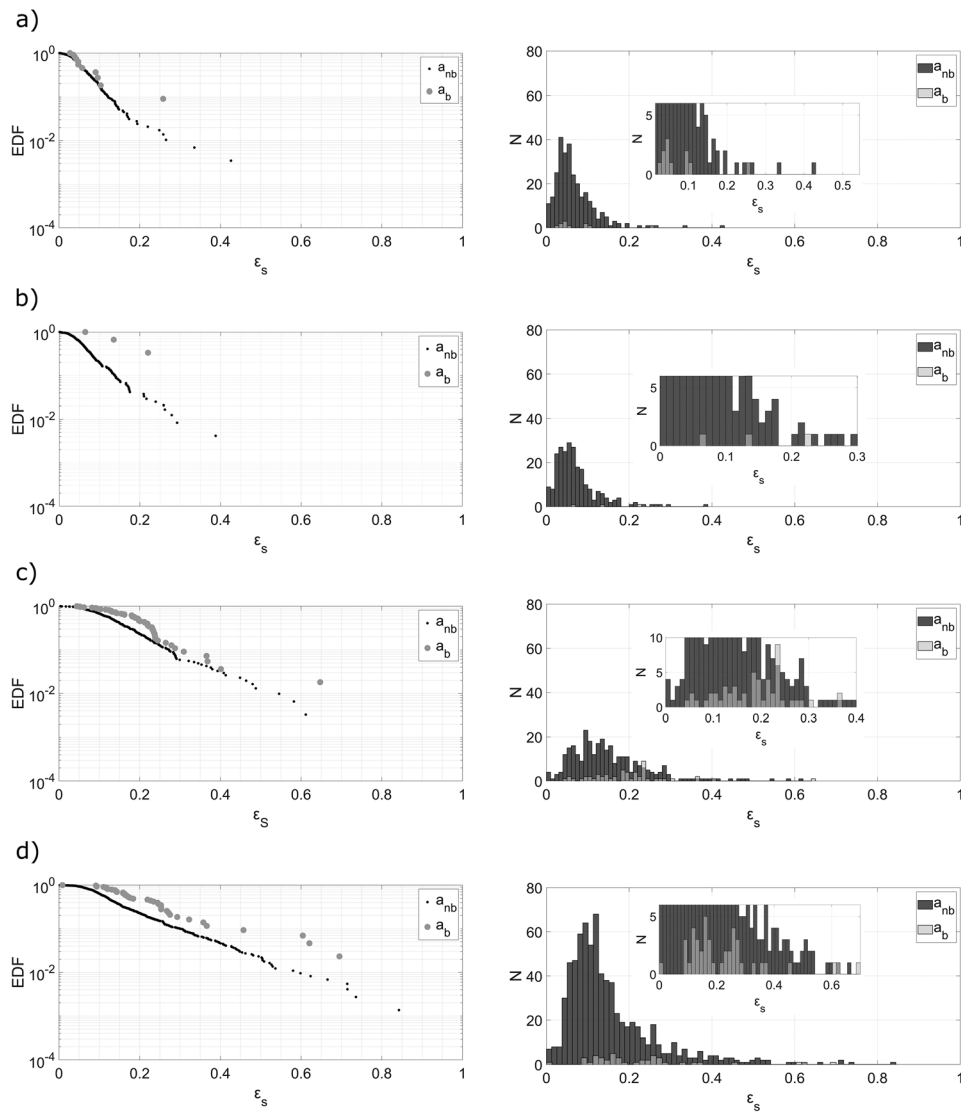


FIG. 7. Black Sea EDF and histogram plots; (a) dataset 211; (b) dataset 238; (c) dataset 242; (d) dataset 244.

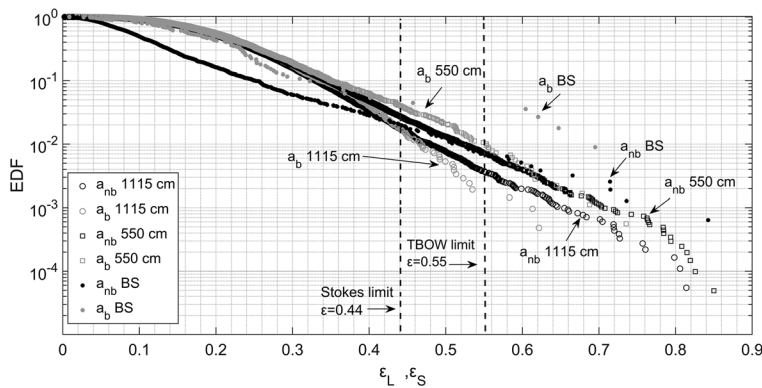


FIG. 8. Cumulative steepness EDF for all laboratory and Black Sea data.

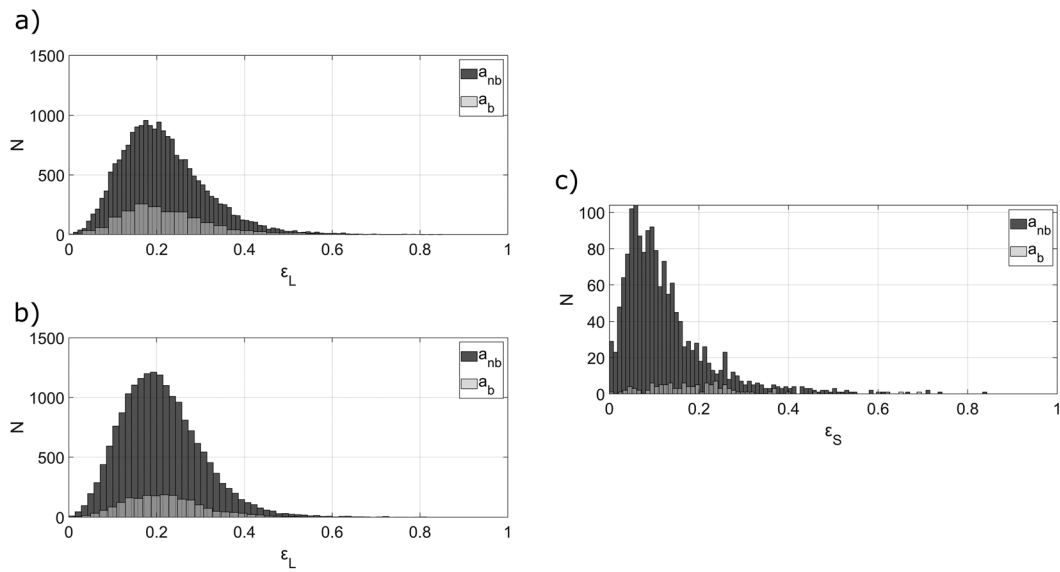


FIG. 9. Cumulative histograms (a) laboratory data at fetch 550 cm (b) laboratory data at fetch 1115 cm; and (c) Black Sea data.

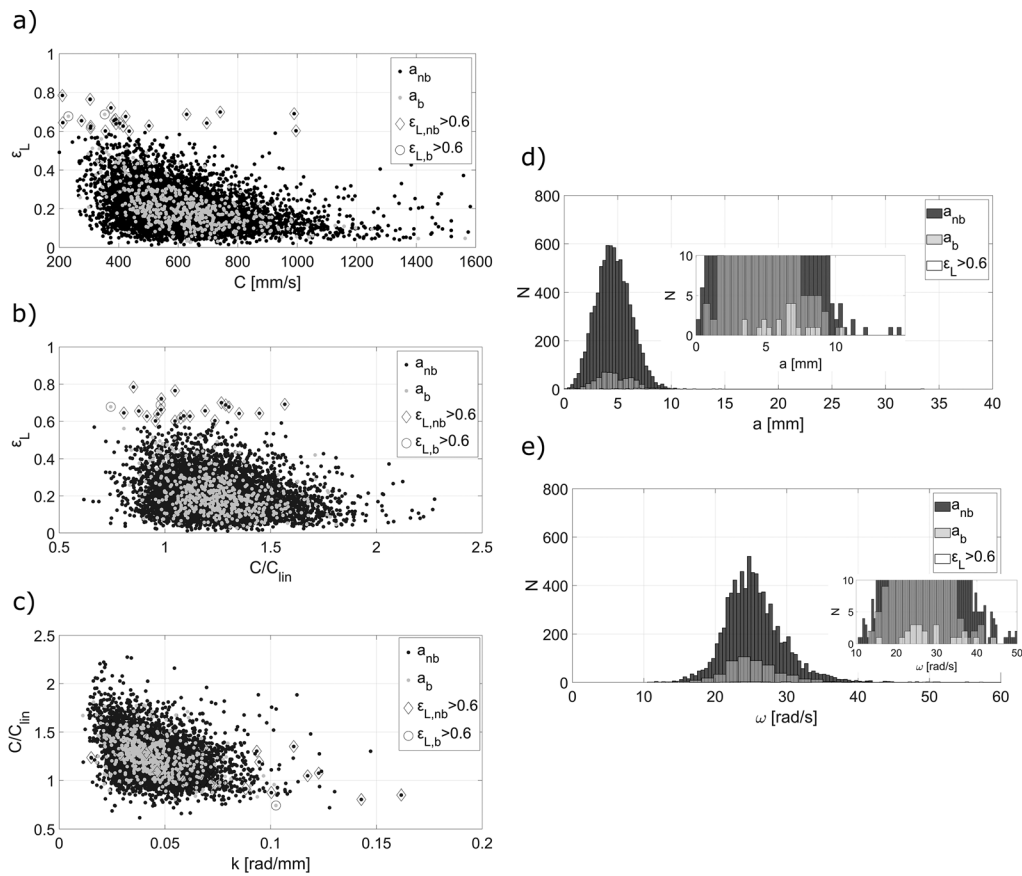


FIG. 10. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 550 cm and 25 Hz blower controller frequency.

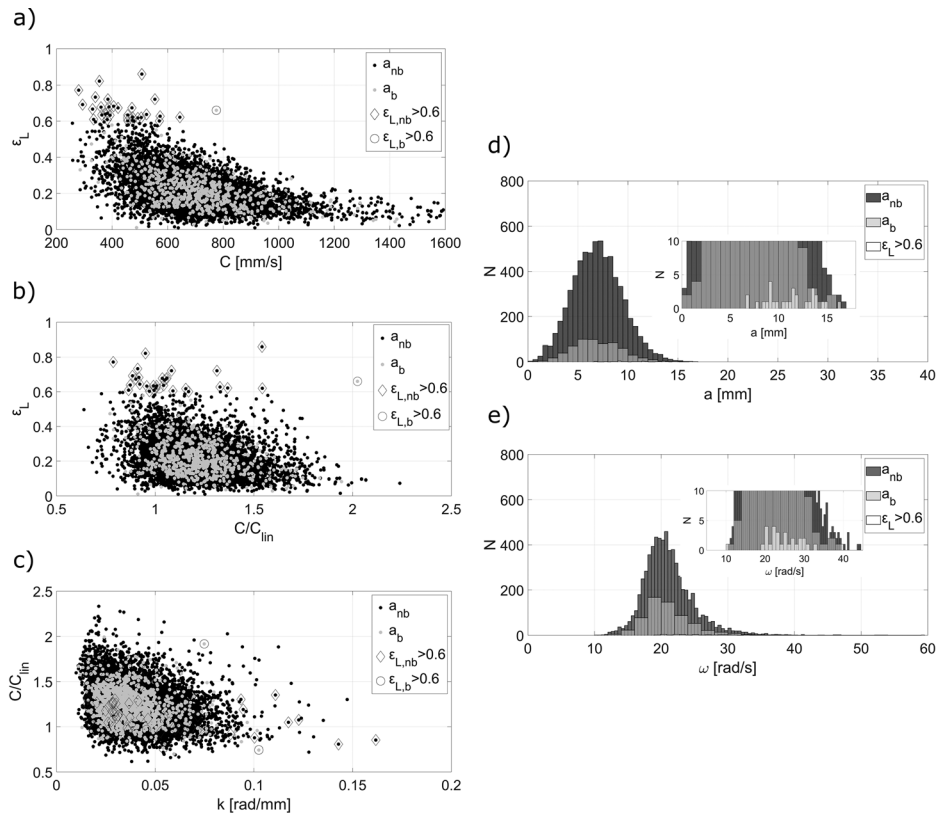


FIG. 11. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 550 cm and 32 Hz blower controller frequency.

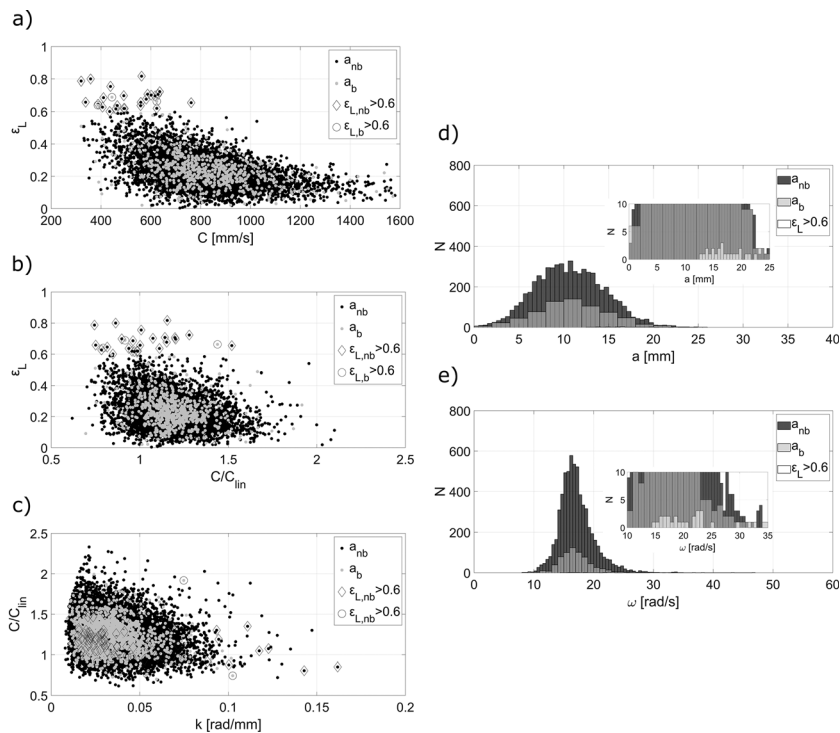


FIG. 12. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 550 cm and 40 Hz blower controller frequency.

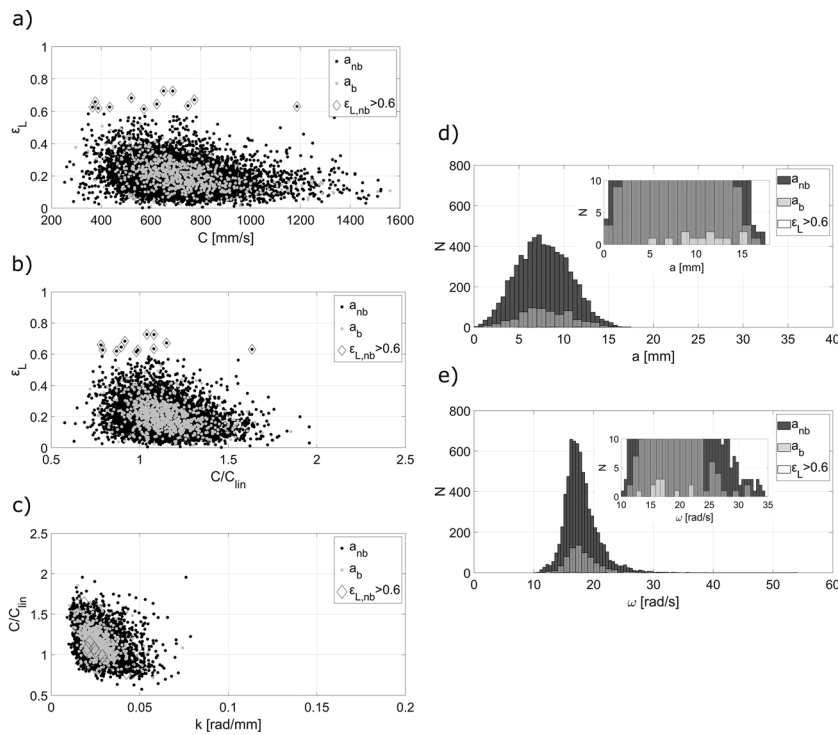


FIG. 13. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 1115 cm and 25 Hz blower controller frequency.

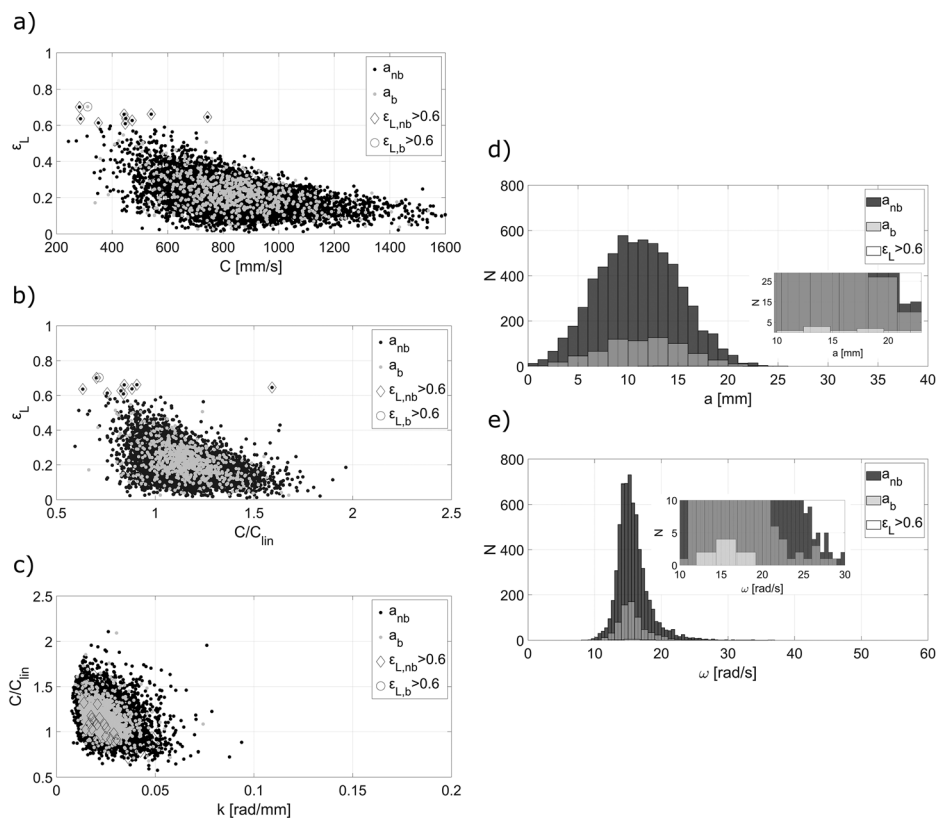


FIG. 14. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 1115 cm and 32 Hz blower controller frequency.

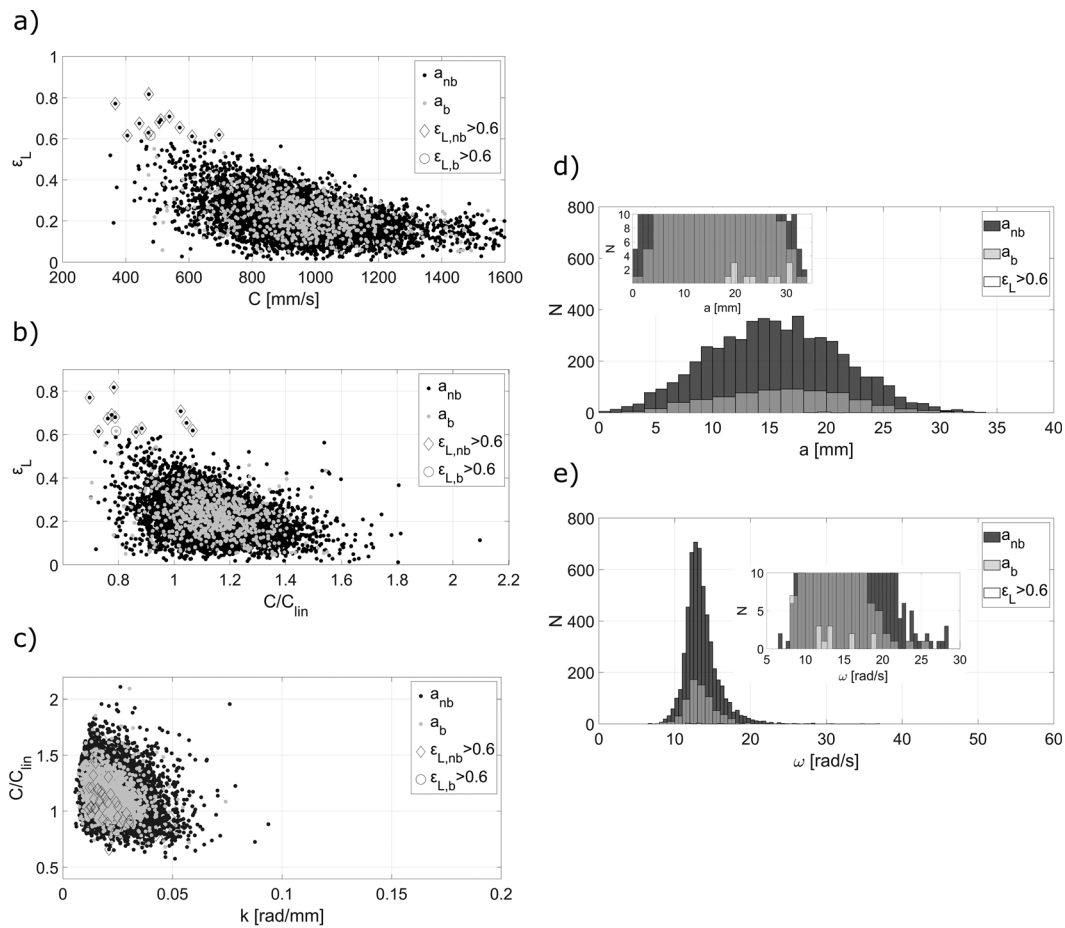


FIG. 15. (a) Steepness vs celerity; (b) steepness vs normalized celerity; (c) normalized celerity vs wavenumber; (d) amplitude histogram; and (e) angular frequency histogram; all represent fetch 1115 cm and 40 Hz blower controller frequency.

also skewed to the left around mean steepness ϵ_S values of 0.1, while those of breaking crests are not even Gauss shaped due to the low number of samples.

To conclude the breaking vs non-breaking wave steepness EDF analysis, a cumulative plot of all laboratory and Black Sea data ensembles is presented below in Fig. 8. Steepness distributions of non-breaking crests are in shades of gray and those of breaking crests are in black. Popular limiting steepness values of Stokes (0.44) and TBOW (0.55) are marked by vertical dashed lines.

It seems that all ensembles, except the non-breaking crests of the BS, show similar exceedance probability values up to the Stokes limit of 0.44. The BS breaking crests EDF curve deviates slightly from the rest of the data at steepness values higher than 0.22. Above the Stokes limit, the breaking waves EDF show a clear dependence on the wave age, WA, whereby younger waves (550 cm fetch) demonstrate a lesser probability for breaking occurrences than the more mature waves, especially those in the Black Sea. In all wave ensembles, a significant number of waves had steepness values that exceeded both the Stokes limit (0.44) and TBOW steepness (0.55). Only 8 flume waves and a single Black Sea wave exceeding steepness of 0.8, suggested

as a limiting value by Barthelemy *et al.* (2018), were observed, all non-breaking. It is important to emphasize that only a few breaking crests were identified at higher steepnesses, above 0.55, and no trend could be observed due to insufficient statistics. An in-detail analysis of the very steep waves, exhibiting steepness value of 0.6, is provided later in this section.

Cumulative histograms of both laboratory and BS ensembles are presented in Fig. 9. The laboratory cumulative ensembles are significantly larger than the BS data ensemble, $O(10^5)$ vs $O(10^3)$. The BS non-breaking crests histogram has no clear shape, a fact that can be attributed to a very small ensemble size. Histograms of laboratory wave ensembles are characterized by a mean steepness of about 0.2, while the mean steepness of BS non-breaking crests is approximately 0.1. All histograms exhibit histograms tail steepness values higher than the Stokes limit (0.44) and TBOW steepness (0.55).

Next, we conducted an in-depth analysis of the small number of waves exhibiting a very high steepness of above 0.6. To this end, wave steepness vs celerity distribution ensembles were plotted for each experimental condition, using celerity values computed using Eq. (9). Steepness was also plotted vs celerity values that were normalized by

the equivalent deep-water gravity-capillary linear dispersion relation, C_{lin} . Finally, histograms of empirical amplitude and angular frequency values are also presented. All plots are presented in Figs. 10–15.

For all experimental conditions, the plots of breaking and non-breaking waves steepness vs celerity demonstrate similar distributions at both fetches and all wind speeds. In these datasets, the extreme steepness waves are mostly of low celerity and amplitudes higher than the ensemble averages. The frequency distribution of the extreme steepness waves shows no significant deviation from that of the general ensemble. All these indicate that the steepest waves identified are high-crested waves of low celerities (the shortest waves in an ensemble) and are mostly non-breaking. Moreover, the normalized celerity values are greater than unity and are distributed in the range between 1 and 1.6.

V. CONCLUSIONS

The implementation of the new DL breaking detection method enabled us, for the first time, to produce detailed statistics of wave fields in terms of breaking vs non-breaking wave parameters of individual crests, while accounting for breakers across the entire range of severities. A direct comparison between young flume wind waves and mature deep-water sea waves was performed. The short-crested wind waves were recorded in a 17.4 m-long wind wave flume at the Technion's T-SAIL, and long-crested waves were recorded in open sea conditions from an oil rig in the northern part of the Black Sea. A total of six laboratory datasets at two different fetches and three wind forcing conditions contained a large number of crests in each ensemble $O(10^5)$. The four open sea ensembles contained up to $O(10^3)$ waves, resulting in diverse wave field conditions and statistics.

A comprehensive work of wave-by-wave autocorrelation between consecutive wave gauges in the flume and positive zero-crossing analysis has enabled us to determine each individual wave frequency, wave-number, celerity, and eventually a representative steepness at the crest. Use of the DL breaking detection method enabled to account for all breaking waves, including the less powerful breakers usually omitted from the statistics when using the traditional whitecap counting methods. Hence, as expected, the breaking parameter values, b_t , in the Black Sea data were higher than those previously obtained whitecap counting (Banner *et al.*, 2000).

The results provide empirical evidence that the observed breaking wave steepness at the crest is not subject to any specified steepness value limit. Breaking waves detection presented a Gaussian distribution of steepness values, similar to that of the non-breaking waves. Steepness values well-exceeding both the Stokes (0.44) and TBOW (0.55) limits were observed, reaching up to 0.88. The extreme steepness analysis indicated that the steepest waves observed are high-crested waves of low celerities and are mostly non-breaking.

At their face value, our results support the possibility that no limiting steepness exists, and breaking occurrence probability cannot be determined based on steepness alone. A conclusion made possible due to the ability of the DL breakers detection method to account for breakers across a wide range of severities and not only the most powerful, whitecap-generating breakers. A different interpretation, however, must also be considered within the widely accepted assumption of the Stokes steepness limit. As the breakers are detected during the

process of breaking, these may represent the waves that started their breaking process after crossing the Stokes limit steepness of 0.44, and continued to grow while also shrinking (Babanin *et al.*, 2007), hence appearing at higher “transient” steepness values when observed and detected before their final collapse. This interpretation, however, leaves the appearance of numerous non-breaking waves at high steepness values unexplained.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

D.L. conceived the project and designed the laboratory experiments. A.B. conducted the open sea experiments. S.K., E.W., and D.L. conducted the laboratory experiments and processed the data. S.K., D.L., and A.B. analyzed the results and provided conceptual advice. S.K., E.W., D.L., and A.B. prepared the manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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