Maximum effects of sunlight focusing under a wind-disturbed sea surface*

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Abstract

The intense fluctuations of natural (downward) irradiance E within the green spectral range (525 nm) caused by the focusing of solar beams by the surface waves have been experimentally examined in the uppermost few metres of the photic zone in different sea and oceanic areas. The frequency of underwater light flashes, *ie* irradiance pulses that exceed the mean irradiance $\bar{E}$ by a factor of more than 1.5, as great as about 200 min^{-1} at a standard depth of 1 m. The decrease of frequency with increase in flash intensity was found to be exponential, so that the frequency of strongest flashes ($E > 5\bar{E}$) is at most on the order of 1 *per* minute. The most probable duration of underwater flashes (on the $1.5\bar{E}$ level) at a 1 m depth appears to lie between 10 ms and 30 ms. The probability of density function of flash durations is skewed and shows, in many cases, a quite close agreement with a log-normal distribution. As the water depth increases, the intensity of irradiance fluctuations becomes smaller and the flash durations tend to increase. The focusing of sunlight under a wind-disturbed sea surface was found to be most effective in clear waters under clear skies with high sun altitudes and light winds between 2 and 5 $\mathrm{m \cdot s^{-1}}$, which correspond to relatively smooth water surface.

1. Introduction

A typical property of the natural underwater light field close to the sea surface under clear sky conditions is the large, rapid in the fluctuation of downward irradiance induced by wind-generated surface waves. The point sensor measurements indicate that these short-term fluctuations occur at time scales of fractions of a second to 20 seconds or so. This optical phenomenon, being open to everyone's observation, can be clearly seen in shallow water as bright caustic lines of light sweeping across the bottom.

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Such a mosaic of bright bands, each of which is a distorted image of the sun due to sunlight refraction by surface waves, is presented in Figure 1. Berry and Nye (1977) suggested that the generic forms of such caustic patterns are governed by the mathematics of catastrophe theory.

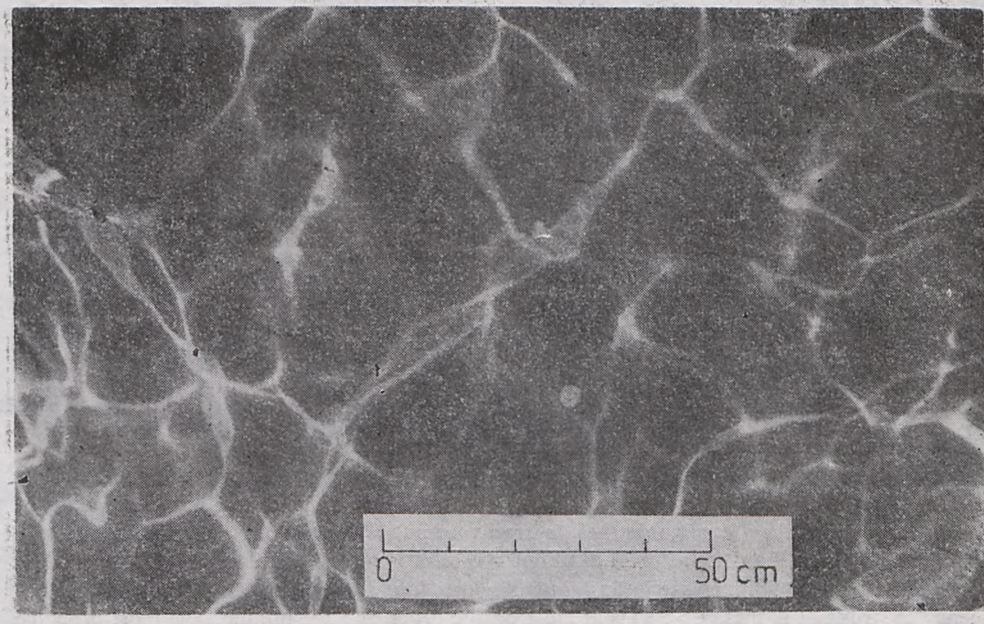

Fig. 1. Typical pattern of bright lines of focused sunlight traced on the bottom at a 1.5 m depth of water. An approximate scale is also given

In obtaining a closed-form theoretical solution of the problem of temporal fluctuations in underwater irradiance encounters serious difficulties related to the randomness of surface-wave and irradiance fields, and to the nonlinear nature of the problem are encountered. Over the years, however, many theoretical studies of irradiance fluctuations have been made as will be outlined below.

Schenck (1957) was the first to suggest that the intense fluctuations close to the sea surface are mainly produced by the focusing of sunlight by surface waves. He considered the perpendicular collimated light incident on the trochoidal and sinusoidal air-water interface, and showed that sun rays which are refracted into different directions may thus be spread out under some areas of the surface wave and bunched under others. The concept of a simple two-dimensional model has proven useful in describing general features of irradiance fluctuations and was further developed (Nikolaev and Khulapov, 1976; Khulapov and Nikolaev, 1977; Iakubenko and Nikolaev, 1977; Nikolaev and Iakubenko, 1978; Prikhach and Ivanov, 1979).

The more detailed explanation of the fluctuation mechanisms has been given in an analytic demonstration by Snyder and Dera (1970). Their theory identifies several refractive effects as being sources of underwater irradiance fluctuations, the most important of which is the focusing and defocusing of solar beams by fluctuations of surface curvature.

The statistical theories with some simplifications have also been proposed recently (Shevernev, 1973; Sudbin, Pelevin and Shifrin, 1974; Luchinin and Sergievskaya, 1982; Veber, 1982). These highly complicated treatments of the phenomenon have some marked shortcomings. First, an evaluation of the validity of model results is a hard task. Some model parameters are abstract, and the experimental checking of the reality of the models is difficult. Second, the model results are generally in agreement with observation over a limited range of frequencies and at moderate depths within the photic zone in the sea. They are inadequate, or at least questionable, in view of low quality of predictions of large-amplitude fluctuations close to the sea surface. Third, for most applications model results may be too cumbersome in terms of computation.

In short, one must conclude that mathematical difficulties seriously limit the understanding of this complicated random process. Under such circumstances one is naturally motivated to turn to experiment for deeper insight. For the last two decades many experimental studies of short-term irradiance fluctuations in the sea have been made (Dera and Olszewski, 1967; 1978; Dera and Gordon, 1968; Shifrin, Pelevin and Sudbin, 1972; Nikolaev *et al.*, 1972; Neuimin and Tolkachenko, 1974, Prokopov *et al.*, 1975; Li, Solovev and Tolkachenko, 1975; Prokopov and Nikolaev, 1976; Nikolaev and Prokopov, 1977; Sudbin and Mozgovoy, 1979; Fraser, Walker and Jurgens, 1980; Nikolaev and Khulapov, 1983; Stramski and Dera, 1983). Until now, however, very few data are available concerning the maximum sunlight fluctuations occurring under clear sky conditions in the uppermost few metres of the sea (Dera and Olszewski, 1978). Important findings of the cited study show that these fluctuations appear in the peculiar form of successive irradiance pulses (called 'flashes') having short duration and high intensities, which can exceed the actual mean irradiance — at a given point under water — by a factor of as 5. This would justify use of the term 'underwater light flash'.

The present study is an accumulation of several years research on the maximum sunlight fluctuations in the sea, performed under an adequately wide range of sky and sea conditions. The principal motivation for undertaking the experiments to be described here has been to determine typical intensities, frequencies and durations of underwater light flashes and to infer the connections between the flashes and prevailing natural conditions. The main mechanism involved in the phenomenon studied is the focusing of sunlight by sea surface waves, and accordingly, an emphasis is placed on the dependence of flashing light on wind velocity, *ie* on the parameter in terms of which the sea surface structure is expressed.

In addition to filling an obvious gap in the literature, the reason for studying the maximum sunlight fluctuations in the upper layers of the sea is that there is a need for a better knowledge of this phenomenon in view of its implications for biology. The strong short-term irradiance fluctuations should have some effect on the marine organisms living close to the sea surface. There is increasing evidence that these fluctuations influence primary productivity in marine algae (Dera, Hapter and Malewicz, 1975; Frechette and Legendre, 1978; Walsh and Legendre, 1982; 1983).

2. Methods

2.1. Experimental procedure

The temporal fluctuations of underwater downward irradiance $E_{\downarrow}(t)$* were measured with an uplooking meter consisting of a photomultiplier tube viewing a small diffusing disc of 2.5 mm diameter through a green interference filter (525 nm – with a 10 nm band width). The meter was lowered into the water approximately 5 m from a measuring post exposed to the sun and wind waves. The diffusing collector ensured

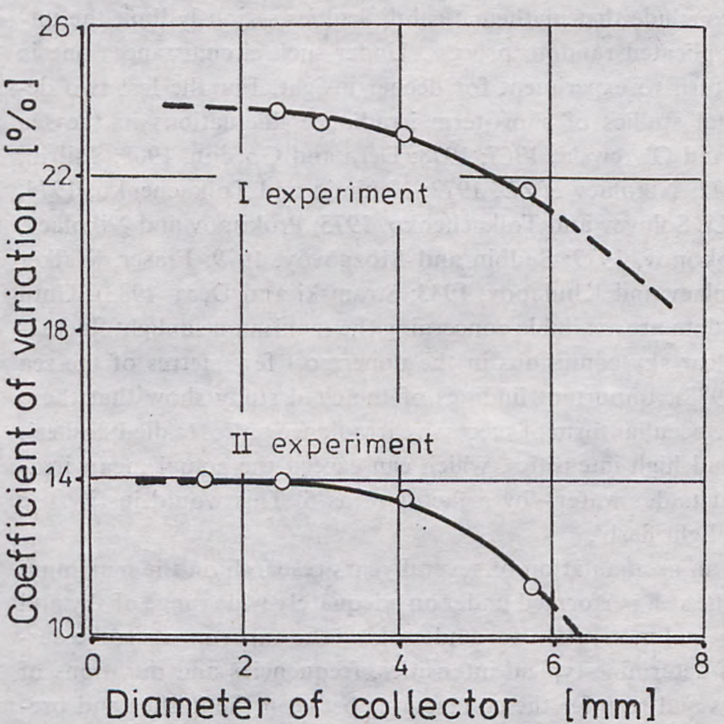

Fig. 2. Coefficient of variation of underwater downward irradiance as a function of collecting size of the irradiance meter. Results of two experiments made in the Gulf of Gdańsk (Baltic) under clear sky conditions and light winds are presented

good compliance with the Lambert cosine law. An area of collecting surface of the irradiance meter is a crucial parameter in analysis of magnitude of fluctuations, particularly when measurements are made at small depths. This is understandable,

* The subscript ↓ is later omitted for the sake of abbreviation.

since the diffuse collector is essentially a spatial integrator, and therefore its size should not be larger than the scale of typical heterogeneities of the underwater irradiance field. In order to select the proper size of collector special tests at a 1 m depth in the sea were made under clear skies and light winds. The results expressed in terms of coefficient of variation of downward irradiance ($\sigma_E/\bar{E}$)* are plotted against the diameter of the collector in Figure 2. As seen, coefficient of variation, which is a measure of magnitude of fluctuations, shows a trend to increase with decreasing diameter of the collector and to reach a saturated value for the diameter less than about 3 mm. The irradiance fluctuations can be adequately measured with the diameter corresponding to saturated portion of the presented curve. Accordingly, the collector of diameter 2.5 mm (*ie* the collecting area of about 5 mm^2) was taken as a standard in our experimental investigations. The selected collecting area gives and added advantage, first of being comparable to the surroundings of a single phytoplankton cell, and second – of being relatively close to the ideal point collector. It is remarkable that, unlike our instrument, the collectors applied in routine underwater irradiance measurements have, more frequently, the diameter of several centimetres, so they would not detect actual fluctuations on a smaller scale (see also scale in Fig. 1).

A method of rapid determination of statistics of intensities and durations of underwater light flashes was developed. The method, described in detail elsewhere (Dargiewicz, 1975) utilized a specialized measuring arrangement as a recording device, namely a ten-channel threshold analyzer. The analyzer enables an automatic recording, first, of the number of times that the input signal $E(t)$ crosses with positive slope (*ie* from below to above) certain amplitude levels, and second, of the durations of pulses on a certain level. This measuring system gives a great advantage in the case of statistically fluctuating impulsive signals. Ten levels of irradiance $E=x\bar{E}$, expressed as some multiple of the mean irradiance E, were experimentally selected as follows: 1.25 $\bar{E}$; 1.5 $\bar{E}$; 1.75 $\bar{E}$; 2 $\bar{E}$; 2.25 $\bar{E}$; 2.5 $\bar{E}$; 3 $\bar{E}$; 3.5 $\bar{E}$; 4 $\bar{E}$; 5 $\bar{E}$. The mean irradiance $\bar{E}$ was automatically determined by continuous averaging over the last 30 seconds of the signal. Record lengths were 10–20 min to acquire large enough quantity of stable data. Data were assumed to be stable if the sea state and incident solar flux were constant during the recording period.

The output signal from the light detector was also occasionally recorded on a FM tape recorder in runs if about 10 min duration. These records were subsequently converted into digital form for further data processing.

In Figure 3 a portion of a typical time record of downward irradiance under a wind-disturbed surface of the sunlit sea is shown, plotted from the tape recorded signal. The principle involved in the measurement by means of the threshold analyzer is illustrated together with the definition of the introduced concept of 'light flash'. In order to study intense fluctuations, the light flash was defined to be the pulse of underwater downward irradiance exceeding its mean value by more then 50%, ie $E>1.5\,\bar{E}$. The defining criterion has also some physical motivation as, apart from stormy seas and highly turbid waters, only the focusing of sunlight may be sufficient to produce

* The standard deviation of irradiance (σ_E) divided by the mean irradiance ($\bar{E}$).

such large variations in underwater irradiance (Stramski, 1984). Thus, the definition implies that the small fluctuations below the level 1.5 $\bar{E}$, which may be equally well caused by other mechanisms than the focusing (Snyder and Dera, 1970), as well as by possible disturbances during the measurement, are here ignored.

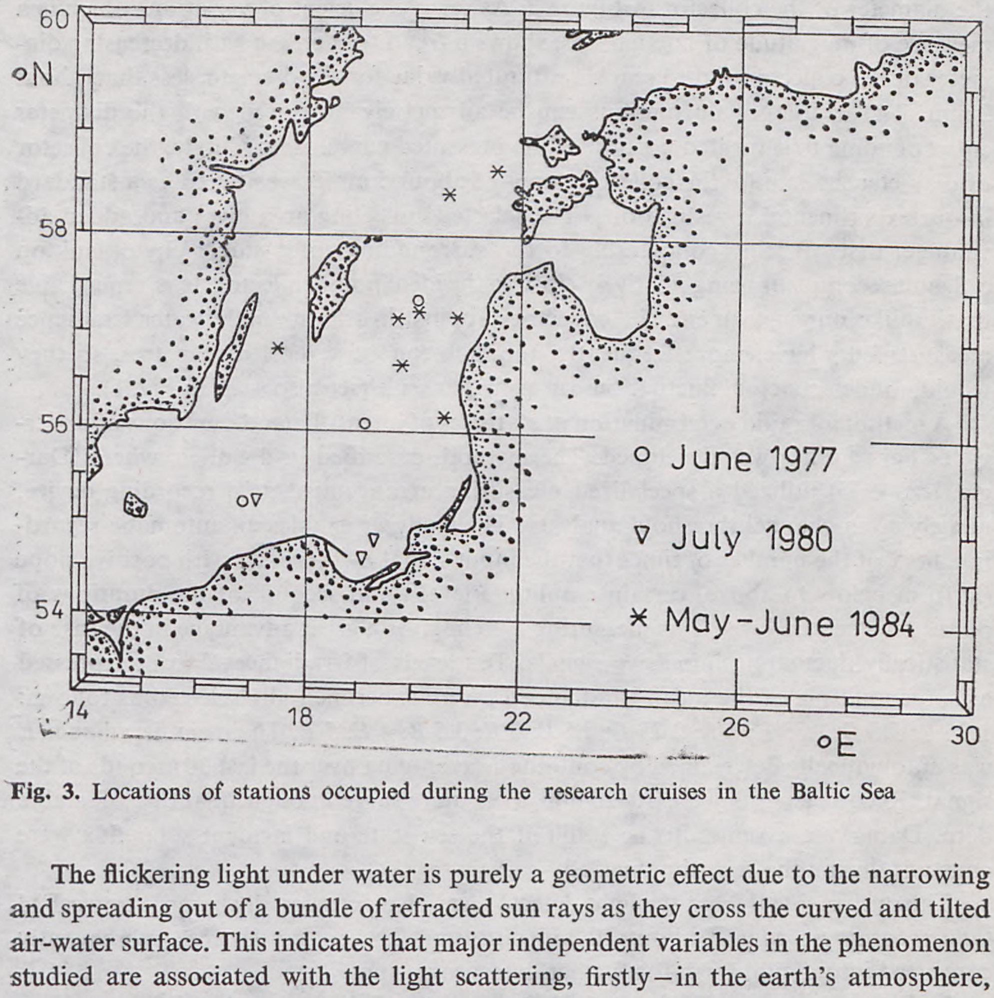

Fig. 3. Locations of stations occupied during the research cruises in the Baltic Sea

The flickering light under water is purely a geometric effect due to the narrowing and spreading out of a bundle of refracted sun rays as they cross the curved and tilted air-water surface. This indicates that major independent variables in the phenomenon studied are associated with the light scattering, firstly—in the earth's atmosphere, secondly—at the disturbed sea surface, and thirdly —in the water, which in turn combine to determine the geometric properties of the radiant energy flow at a given depth. To obtain a description of light flashes over a wide range of sky and sea conditions in terms of independent variables special observations were made in conjunction with underwater measurements of irradiance fluctuations.

The ratio of diffuse to total downward irradiance above the sea surface, termed diffuseness (d_E), provides a quantitative measure of geometrical flow of radiant energy in the atmosphere. This ratio was measured using a deck irradiance meter with a flat collector of cosine response, a 530 nm filter having a 60 nm passband, and a photocell. The signal from the photocell was displayed on a strip-chart recorder. With the aid of a shadow target the direct solar beam was obscured, thus allowing the diffuse radiation to be measured.

The wind velocity (U_{10}) with an averaging over a few minutes at a height of 10 m above the mean water level was used as an indicator of the sea surface structure. From practical standpoint, it is clearly very attractive to relate the underwater flashes to wind velocity, which is conveniently and precisely measured. The choice of wind velocity has, however, a disadvantage resulting from the fact that the sea surface structure at any instant is not well defined by the mean local wind alone. More desirable would be the use of slope and curvature statistics of a wind roughened sea surface. Unfortunately, the precise field determinations of sea surface microstructure encounters serious difficulties (Hughes, Grant and Chappel, 1977; Wu, Haimbach and Hsu, 1981) and they were not possible to accomplish at the present stage of our studies.

The optical properties of the sea were controlled by measurements of a diffuse attenuation function of downward irradiance ($K_\downarrow$) in the upper 5 m of the water column. These measurements were made using a standard irradiance meter with a flat cosine collector, interference filter (525 nm with a 10 nm band width), and photomultiplier. The time-integrating over tens of second was used to average the fluctuations in signal from the photomultiplier. The recorded irradiance totals allowed us to calculate the coefficient $K_\downarrow$. Although the coefficient $K_\downarrow$ can serve as an useful indicator of the optical type of the water, it is, in great part, inadequate with a view to characterizing the water turbidity effect on sunlight focusing under water. The detailed interpretation of this effect will be realized when irradiance fluctuation measurements can be used for comparison with simultaneous measurement of light scattering in the water.

In addition to the measurements, the visual observations were made to document the cloud cover, visibility in the atmosphere, sea state, and significant wave height. The average sun altitude for each time interval of underwater measurement was calculated.

2.2. Description of data

A total of about 250 records available for statistical analysis of underwater light flashes were obtained in different sea and oceanic areas under various conditions. A summary of the experimental observations is provided in Table 1. Data were recorded more frequently at a 1 m depth during periods of clear or almost clear sky with relatively high sun and light to moderate winds, *ie* under conditions in which the focusing of sunlight definitely occurred. Because of the complexity of possible behaviour of focusing effect in optically different waters and the large quantities of data required to examine it, most studies have concentrated on selected region, namely the Baltic Sea. Location of measurements in the Baltic are shown in Figure 4. Among the records taken in the Baltic, 145 were in open waters with the range 0.14–0.28 m^{-1} in the irradiance attenuation coefficient $K_\downarrow$ (525 nm) representative approximately of water types 2–4

Table 1. Summary of experimental observations

Location	Period of experiment	Measuring post	Number of records	Sun altitude	Diffuseness of surface irradiance d_E [%]	Wind velocity U_{10}[$m \cdot s^{-1}$]	Irradiance attenuation coefficient $K_{\downarrow}$ (525 nm) [m^{-1}]
Baltic*	June 1977	drifting or anchored ship	15	25–51°	not measured	1.2–9.7	0.18–0.45
Baltic*	July 1980	as above	60	16–57°	26–100	1.5–11.5	0.17–0.44
Baltic*	May – June 1984	as above	86	11–58°	23–100	1.8–11.5	0.14–0.36
Atlantic (off Portugal)	October 1976	drifting ship	5	*ca* 40°	not measured	2.0	0.15
Atlantic (19°54' N, 23°40′ W), (15°09′ S, 37°10′ W)	November December 1977	drifting ship	16	30–82°	not measured	3.7–5.8	0.05–0.06
Mediterranean (off Spain)	October 1976	drifting ship	7	*ca* 35°	not measured	3.0	0.08
Ezcurra Inlet (62°10' S, 58°33' W, semi-enclosed area)	December 1977 March 1978	anchored ship	30	23–51°	not measured	0–17 (gusty wind)	0.16–0.24
Black Sea coastal zone (42°57' N, 27°54' E)	September, October 1979	stable platform situated 300 m from the coast line at a depth of 6 m	27	26–46°	24–70	0–8.0	0.29–1.0

* for geographical coordinates see Fig. 3

according to Jerlov's (1976) optical classification. These open sea data were obtained under clear sky or thin clouds (*ie* clouds through which the sun is visible) with the diffuseness of surface irradiance d_E from nearly 20% to more than 90% and the sun

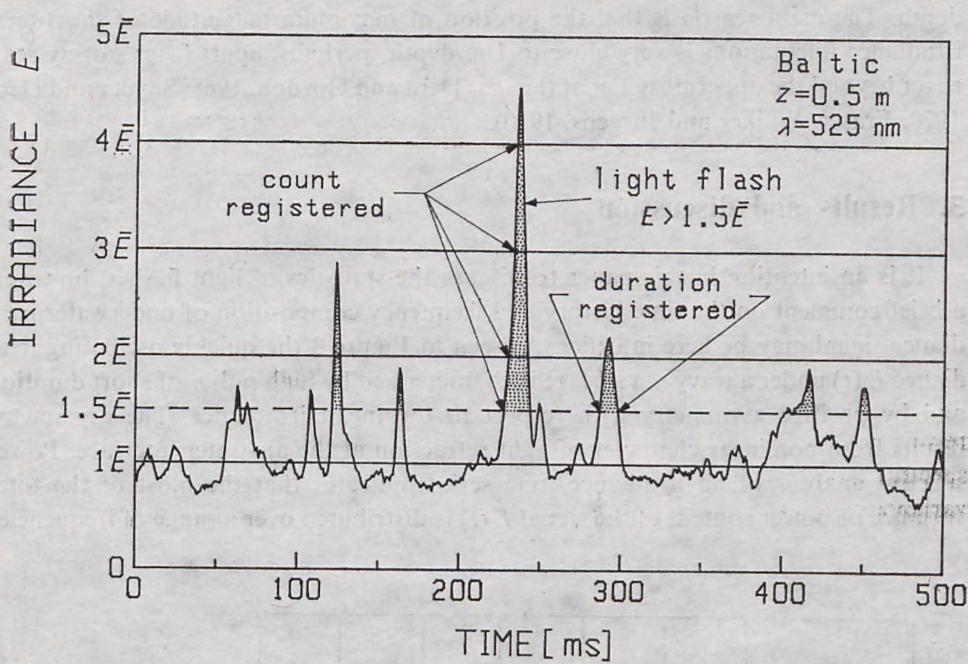

Fig. 4. Typical time record of short-term irradiance fluctuations under a wind-disturbed sea surface. Light flashes are marked as shaded pulses, z denotes the depth, and λ denotes the light wavelength

altitude $h_{\odot}$ in the range 11°–58°. With the diffuseness approaching 100%, that is when the sun is obscured by opaque clouds, the focusing effect disappears completely and the measurements are redundant. Therefore, among others, the heavily overcast conditions are beyond the limits of our interest. Furthermore, the winds varying from nearly calm to about 12 $m \cdot s^{-1}$ were covered by the data, so all these observations fall between very calm and moderate seas with maximum wave height up to about 2 m that correspond to sea states up to 4 on a 0–9 scale. Due to the difficulty of maintaining a stable instrument at small depths under a rough surface the consideration of high winds and very rough seas is beyond the scope of this study. To be precise, such conditions involve bobbing of measuring instrument in and out of the water and make the measurement exceedingly unreliable.

The data from the open Baltic, as being within a given water type, are assumed to represent the same statistical process and are treated as the main base of analyses in this paper. The remaining data from other regions are scarcer and they provide only a very rough information due to statistical shortcomings.

The analytical techniques used are purely statistical ones, aimed at determining the frequency distributions of light flash intensities, probability distributions of flash durations, and establishing the existence of connections between flash statistics and variables describing the prevailing conditions. Another comment is here in order on a depth of measurements. The depth of 1 m was assumed to be standard in studies of underwater light flashes, and as a result, all relationships are formulated for this depth. The main reason is that the position of maximum magnitude of short-term irradiance fluctuations is very close to 1 m depth, perhaps, apart from stormy seas, never beyond the uppermost 2 m of the sea (Dera and Gordon, 1968; Snyder and Dera 1970; Fraser, Walker and Jurgens, 1980).

3. Results and discussion

It is an intention in this paper to discuss the statistics of light flashes, however, a brief comment on the time history and frequency composition of underwater irradiance signal may be here in order. As seen in Figure 3 the quickly oscillating irradiance $E(t)$ under a wavy sea surface is characterized by high pulses of short duration and by positive asymmetry with respect to the mean irradiance. The asymmetry results from nonlinear character of light refraction at the air-water interface. Power spectral analysis of an irradiance time series indicates that the most of the total variance or power content of the signal $E(t)$ is distributed over a range of frequencies

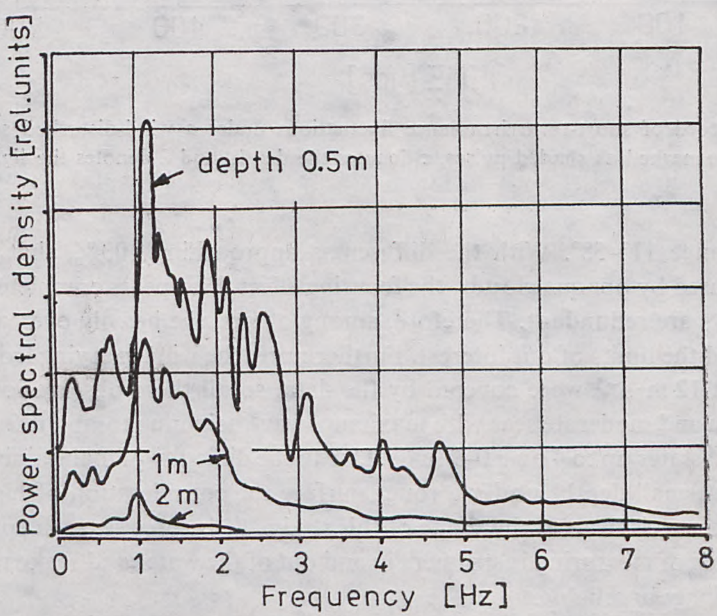

Fig. 5. Typical power spectra of short-term irradiance fluctuations for different water depths near the sea surface (Black Sea, coastal zone). Spectra were calculated using the fast Fourier transform (FFT) algorithm. The records of over 5 min length were digitized with a rate of 50 points per second and the obtained time series were broken up into 15 parts of equal length, each of which contained 1024 points. The spectral estimates computed for each part were averaged at the corresponding frequencies to obtain a reasonably smooth spectrum

from about 0.5 to 5 cps (Fig. 5). This range is located far from energy–carrying maximum of the elevation spectra of a wind roughened sea surface. Considering the sea surface statistics (Pierson and Stacy, 1973), thus it is suggested that the dominant source of irradiance fluctuations under conditions of interest is associated with fluctuations of surface curvature and slope, and not with the water surface displacement. On the other hand, it is known that the shorter length of waves and ripples, that is the high-frequency components of surface waves, are the major contributor to curvature and mean-square slope of the sea surface. Let us to note also that the properties of small waves on wind-blown water surfaces are known imperfectly.

The power spectra of irradiance fluctuations at small depths are usually multi--modal curves whose shapes change in a characteristic way as the depth increases. Since the short waves have their point of maximum focus nearer the surface, and the longer waves focus at greater depths, the high-frequency portion of the spectra rapidly decays with depth, causing a sharpening of the spectral curves (see also Snyder and Dera 1970; Gordon, Smith and Brown 1971; Li, Solovev and Tolkachenko, 1975).

3.1. Frequency distribution of flash intensities – analytic and graphical representations

In representing the focusing of sunlight under water, it has been found convenient to use the frequency distribution of flash intensities $N(E)$ as a function to be studied. Figure 6 shows graphs of the function $N(E)$ plotted on a semi-logarithmic scale with a depth of measurement as a parameter. The graphs shown in Figure 6a may serve as representative examples for clear sunny conditions with light winds, and those in Figure 6b for the similar sky conditions but with stronger winds. The data clearly show an exponential decrease of frequency of flashes N with increasing flash intensity E, which was also suggested previously (Dera and Olszewski, 1978; Stramski, 1984). The solid lines in the presented figure are the least squares fit to the data.

The exponential law can be written as:

$$N = N_0 e^{-AE}, \tag{1}$$

and it was verified for $E \geqslant 1.5\,\bar{E}$, that is in excess of the critical level that defines the flashes. The notation used in equation (1) is as follows:

N – the frequency of those flashes which exceed the certain irradiance level E;
A – the slope parameter describing the exponential decay rate of frequency N;
N_0 – the parameter which cannot be interpreted physically.

We assumed a minute as the base unit of time, so the dimension of both the frequency N and the parameter N_0 is a reciprocal of minute. The parameter N_0, being dependent on prevailing conditions, varies generally over four orders of magnitude from 10^2 to 10^5 min^{-1} for a 1 m standard depth. Since the irradiance level E is defined in terms of some multiple of the mean irradiance $\bar{E}$, the inverse of the $\bar{E}$ is an unit of the parameter A. The values of A are typically from about 1 to 10 $\bar{E}^{-1}$ under diverse ex-

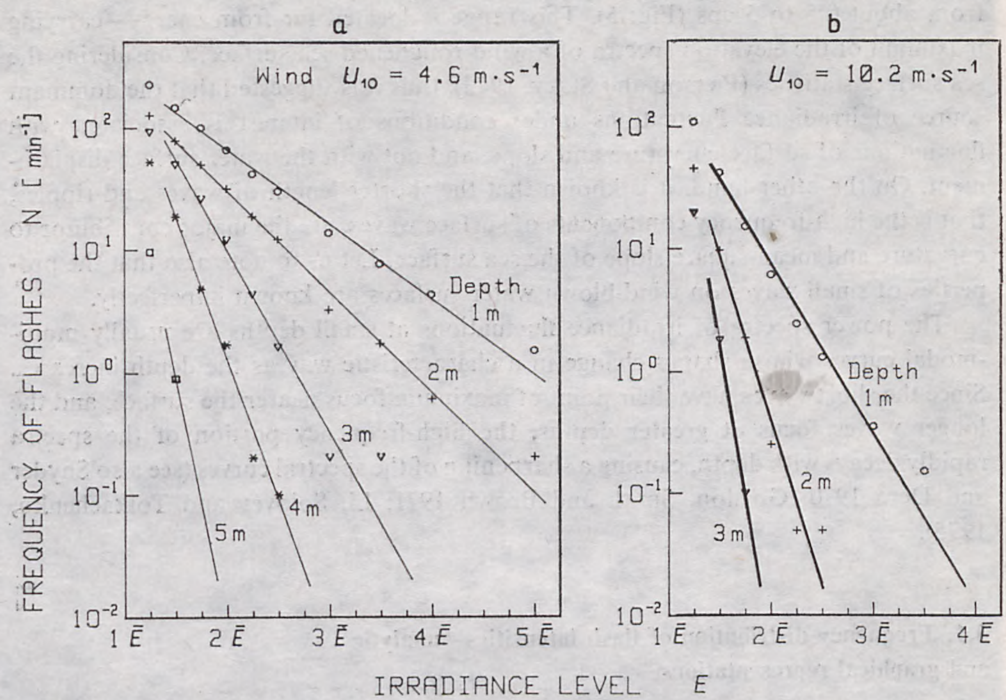

Fig. 6. Typical frequency distributions of flash intensities with depth as a parameter under two different wind sea conditions

a – Baltic: 56°42′ N, 19°51′ E, 25 May 1984, sea state 1–2 (on a 0–9 scale), cloud cover 0.1 (on a 0–1 scale) Ci, $h_{\odot}=40$–$49°$, $d_E=53$–62%, $K_{\downarrow}(525\text{ mn})=0.225$–$0.249\text{ m}^{-1}$. The estimated parameter values of the fitted lines for different depths (z) are as follows: 1 m: $A=1.41$, $N_0=1129.4$; 2 m: $A=1.90$, $N_0=1354.9$; 3 m: $A=3.44$, $N_0=9727.0$; 4 m: $A=5.34$, $N_0=57\,148.7$; 5 m: $A=9.47$, $N_0=1\,325\,607.2$. b – Baltic: 57°21′ N, 20°05′ E, 22 May 1984, sea state 4, cloud cover 0.1 Ci, $h_{\odot}=48$–$52°$, $d_E=35$–48%, $K_{\downarrow}(525\text{ nm})=0.198$–$0.200\text{ m}^{-1}$. The estimated parameter values for different depths (z) are: 1 m: $A=3.19$, $N_0=4357.0$, 2 m: $A=6.21$, $N_0=102\,062.5$, 3 m: $A=11.58$, $N_0=63\,642\,909.5$

perimental conditions. Note, that a greater slope parameter A indicates relatively less high-intensity flashes in relation to the number of low-intensity flashes.

The goodness of fit of the equation (1) to the observed data points can be best described by means of the squared correlation coefficient (r^2) between E and the logarithms of N. The squared coefficients have a practical interpretation, which is the degree of statistical explanation of the dependent variable offered by the independent one. The r^2 value based on all the available data is, on an average, about 0.98 – indicating nearly perfect linear relationship between the variables E and ln N. This might be expected as the points plotted on the exemplary graphs in Figure 6 scatter negligibly about the regression lines. Considering all the available data we can be sufficiently confident that the expression (1) portrays a law that is true for all conditions in which the sunlight focusing definitely occurs. A word or two may be in order on the least squares procedure applied for estimating the parameters N_0 and A. Although the data fit the exponential law (1) very well, the departures from the predicted line are, in some cases, noticeable for high irradiance levels, *eg* $4\,\bar{E}$ or $5\,\bar{E}$. This is expected because of the few actual counts of flashes at these levels and the associated statistical shortcomings. Thus, for higher irradiance levels there is a relatively greater chance of unusual value of the variable N. Therefore, the better fitting can be found after weighting the $N(E)$ values to account for differences in the uncertainties associated with the counting statistics over a full range of the irradiance level E. Assuming that the number of occurrences of the flashes in a time period of measurement obeys a Poisson's probability law, the uncertainty in the measured number can be estimated as an inverse of the square root of the counts (note the analogy to the measurement of radioactive decay by a scintillation method). For instance, a count of 1000 flashes gives an accuracy of about $\pm 3\%$, while that of 10 flashes gives about $\pm 30\%$. By the foregoing assumptions it was reasonable to perform the least squares procedure with weighting function being proportional to the inverses of the uncertainties associated with each data point.

One of the most important questions is the behaviour of the exponential law (1) under diverse natural conditions. Returning to Figure 6 one can see two ways that the focusing effect are masked. First, the increasing water depth implies a well-marked decrease in frequency of flashes and their intensities. To interpret this, we note that as the depth of observation is increased the underwater light will lose its collimatedness due to the light scattering along a longer path in the water. Hence, the focusing of sunlight, being geometric in its nature, is less effective. Second, the comparison of Figures 6a and 6b suggests that the effect of increasing wind, in fact through an increased surface roughness, is also to destroy the focusing under water. The wind effect will be discussed in greater detail in the next section.

As would be expected from physical arguments, the occurrence of light flashes is restricted only to the upper part of the photic zone in the sea. We would further expect the water turbidity to determine the depth range of flashes. Indeed, the above picture is in accord with our observations. Under favourable sky and sea conditions the flashes can be expected to occur once in a while at depths as great as about 6 m in open Baltic waters, being representative of optical types 2–3. In clear waters of oceanic type II (Mediterranean off Spain) the flashes were found to depths of about 10 m (Dera and Olszewski, 1978), whereas in highly turbid waters with coefficient $K_{\downarrow}$ (525 nm)$>0.8\ \mathrm{m}^{-1}$ there were no flashes even at a depth of 1 m. The latter fact was observed in the Black Sea in shallow coastal waters abundant in the suspended scattering particles.

Let us now turn to the effects of atmospheric lighting conditions which are here represented by sun altitude $h_{\odot}$ and diffuseness d_E of surface irradiance. In clear sky, as the sun goes down to the horizon, the proportion of direct light in the total downward irradiance decreases as more light is absorbed and scattered by increasing atmospheric path. Thus, the combined effect of oblique illumination and diffuseness on sunlight focusing is most likely to be observed, and in consequence, it is difficult to separate these two effects in field data. Very few truly representative data in the context of the above effects are presently available. Nevertheless, Figure 7 suffices to illustrate how the decreasing sun altitude, accompanying by increasing diffuseness, affect the frequency distributions $N(E)$. The graphs were selected amongst others so that the effect of unwanted parameters was minimized. The presented regularity becomes understandable as it is logical to think that the more diffuse radiance

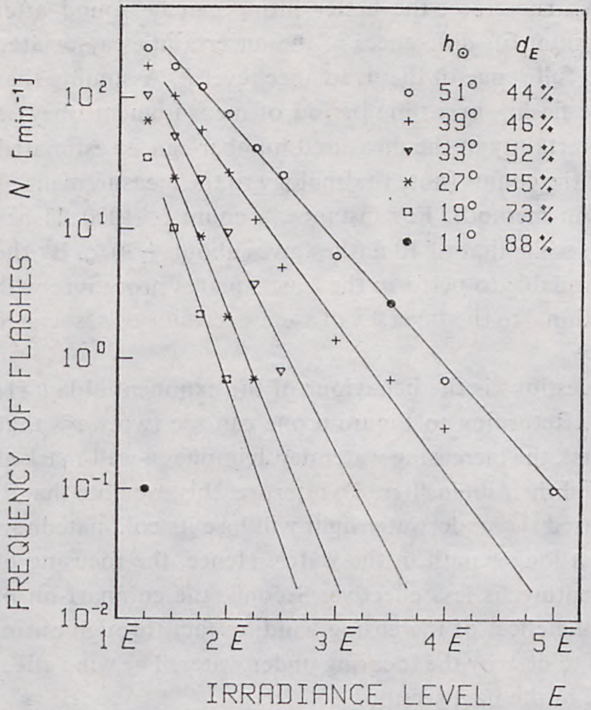

Fig. 7. The combined effect of sun attitude ($h_\odot$) and diffuseness (d_E) of surface irradiance on the frequency distribution of flash intensities
Baltic – depth $z=1$ m, 57°13′ N, 20°57′ E, 20 May 1984, $U_{10}=5.3$–$7.4\ \mathrm{m \cdot s^{-1}}$, sea state 2, cloud cover 0.1 Ci, $K_\downarrow(525\ \mathrm{nm})=0.16$–$0.24\ \mathrm{m^{-1}}$. The estimated parameter values of the fitted lines are: $h_\odot=51°$, $d_E=44\%$: $A=2.15$, $N_0=4954.8$; $h_\odot=39°$, $d_E=46\%$: $A=2.63$, $N_0=5213.3$; $h_\odot=33°$, $d_E=52\%$: $A=3.73$, $N_0=14\,518.5$; $h_\odot=27°$, $d_E=55\%$: $A=4.75$, $N_0=31\,183.0$; $h_\odot=19°$, $d_E=73\%$: $A=5.52$, $N_0=39\,155.7$

distribution input to the sea results in less effectiveness of sunlight focusing by surface waves. Although too little information prevents determining the form that the relationship between flash statistics – on the one hand – and sun altitude and diffuseness, on the other, should take, an examination of the data showed that drastic effects, *ie* a sharp decrease in intensity of light fluctuations occurred for low sun altitudes ($<20°$) and for high diffuseness ($>80\%$).

The graphs in Figure 6 and 7 will help fix in mind typical magnitudes of frequencies and intensities of underwater flashes. It follows that the intensity of strongest flashes exceeds the mean irradiance more than five fold. Thereby, during summer months – on sunny days near the noon, the instantaneous concentrations of solar energy within a green spectral band under a wind-disturbed surface in the Baltic are as high as more than 500 $\mu\mathrm{Wcm^{-2}nm^{-1}}$. These strongest flashes can occur with a frequency of the order of 1 *per* minute, whereas the flashes which exceed the defining level 1.5 $\bar{E}$ have typically the frequency of tens or one hundred and tens *per* minute at a standard depth of 1 m. Note that if the $N(E)$ curves have relatively little slope with A being smaller than about 2.5, the frequency N decreases on the order of 100 fold, 1000 fold or 10000 fold as the irradiance E goes from 1.5 $\bar{E}$ to 5 $\bar{E}$; but the greater slopes ($A > 3$) imply a completely undetectable frequency of flashes, higher than the level 5 $\bar{E}$.

3.2. The effect of wind

As long as we are not directly concerned with the mechanisms involved in the irradiance fluctuations the exact information of complex sea surface structure is not necessary; of more interest is to describe this structure by means of a convenient parameter, *eg* the mean wind velocity U_{10} which considerably facilitates the formulation and handling of the relationships. What is most worthwhile at present, is to raise such a question as: how are the underwater flashes related to wind and what conditions are most favourable to sunlight focusing by surface waves. In order to discuss the question, first the data were selected in such a way which leads to the preference

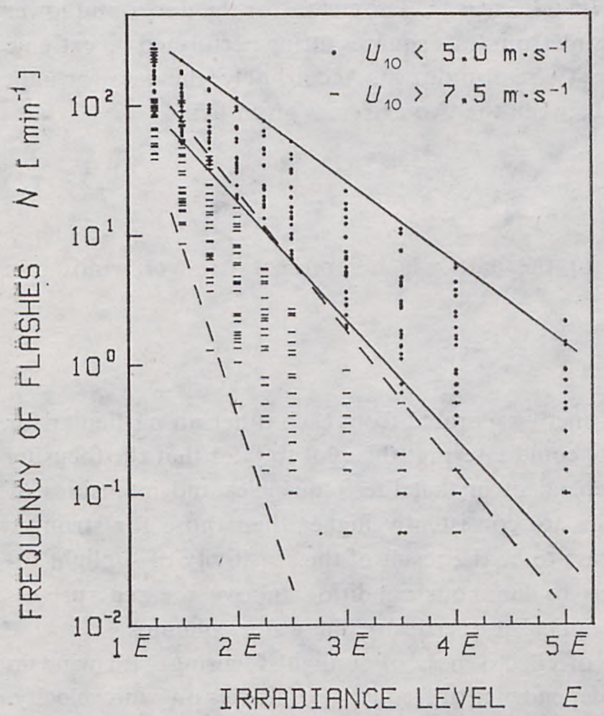

Fig. 8. Scatter plot of frequency of flashes *vs* flash intensity showing the effect of wind Data from 47 measurements made at a depth of 1 m in the Baltic included are. The bounds plotted as solid lines bracket the data for light winds and those plotted as dashed lines bracket the data for stronger winds

to a wind dependence only. Data from open water regions of the Baltic, characterized by the coefficient $K_\downarrow$ (525 nm) between 0.14–0.28 m^{-1}, showed only minor differences in flash characteristics due to water clarity and can therefore be discussed together. In other words, these data hold special interest owing to their representativeness of a given water type. Furthermore, as can be deduced from the preceding analysis the sensitivity of focusing effect to sun altitude $h_\odot$ and to diffuseness d_E of surface irradiance is sufficiently weak for relatively high sun ($h_\odot \geqslant 30°$) and relatively low diffuseness ($d_E \leqslant 60\%$); so we have excluded data for $h_\odot < 30°$ and $d_E > 60\%$. We obtained 62 data records for a 1 m depth satisfying the above conditions. Of these, 14 were taken during periods when there was no doubt that the prevailing wind sea conditions are unsteady. Interestingly, all these unsteady data fall approximately in the range 4–8 $m \cdot s^{-1}$ in wind velocity U_{10}. Among the remaining 48 data records, which are considered as steady in relation to the sea state and incident solar flux, one was in calm conditions with almost perfectly flat water surface, and in consequence with no focusing of sunlight. Note that assumption of steady conditions is only rough approximation of the reality.

A scatter plot of frequency of flashes N *vs* flash intensity E is shown in Figure 8. Steady data from 47 records are included. This overall data set was divided into two separate subsets: the one corresponding to light winds between 1.5–5 $m \cdot s^{-1}$ and the other to stronger winds between 7.5–11.5 $m \cdot s^{-1}$. The curves for the upper and lower bounds on the scatter of data, arising from least squares fitting performed on extreme points within each separated subset, are also drawn. Accordingly, the data for light winds can be usefully bracketed between the two extremes given by:

$$
\begin{aligned}
N_{\text{lower}} &= 1276.3 \cdot e^{-2.12\,E}, \\
N_{\text{upper}} &= 1938.2 \cdot e^{-1.44\,E}.
\end{aligned}
\tag{2}
$$

The corresponding expressions for the data which represent stronger winds are:

$$
\begin{aligned}
N_{\text{lower}} &= 72929.3 \cdot e^{-6.07\,E}, \\
N_{\text{upper}} &= 3208.6 \cdot e^{-2.49\,E}.
\end{aligned}
\tag{3}
$$

These two groups of data are distinctly separated from each other, in particular for high irradiance levels $E \geqslant 3\,\bar{E}$. One could interpret this plot to infer that the focusing effect is markedly wind speed dependent in that the frequencies and intensities of underwater flashes for light winds are consistently higher than those for stronger winds. The scatter in points appears to be the result of the sensitivity of sunlight focusing to anything what happens to luminous conditions above the sea surface, dynamic state of the surface, or optical properties of the water column.

In order to resolve variation of effectiveness of sunlight focusing with wind in greater detail we now turn to the dependence of frequency of flashes on wind velocity. Scatter plots of frequency of flashes (N) *vs* wind velocity (U_{10}) for different irradiance levels ($E = x\bar{E}$) are shown in Figure 9. The definite trend in the data is fairly obvious even that the assessment is based on a paltry number of considerably scattered points. The light winds between 2–5 $m \cdot s^{-1}$ appear to be conducive to highest frequencies

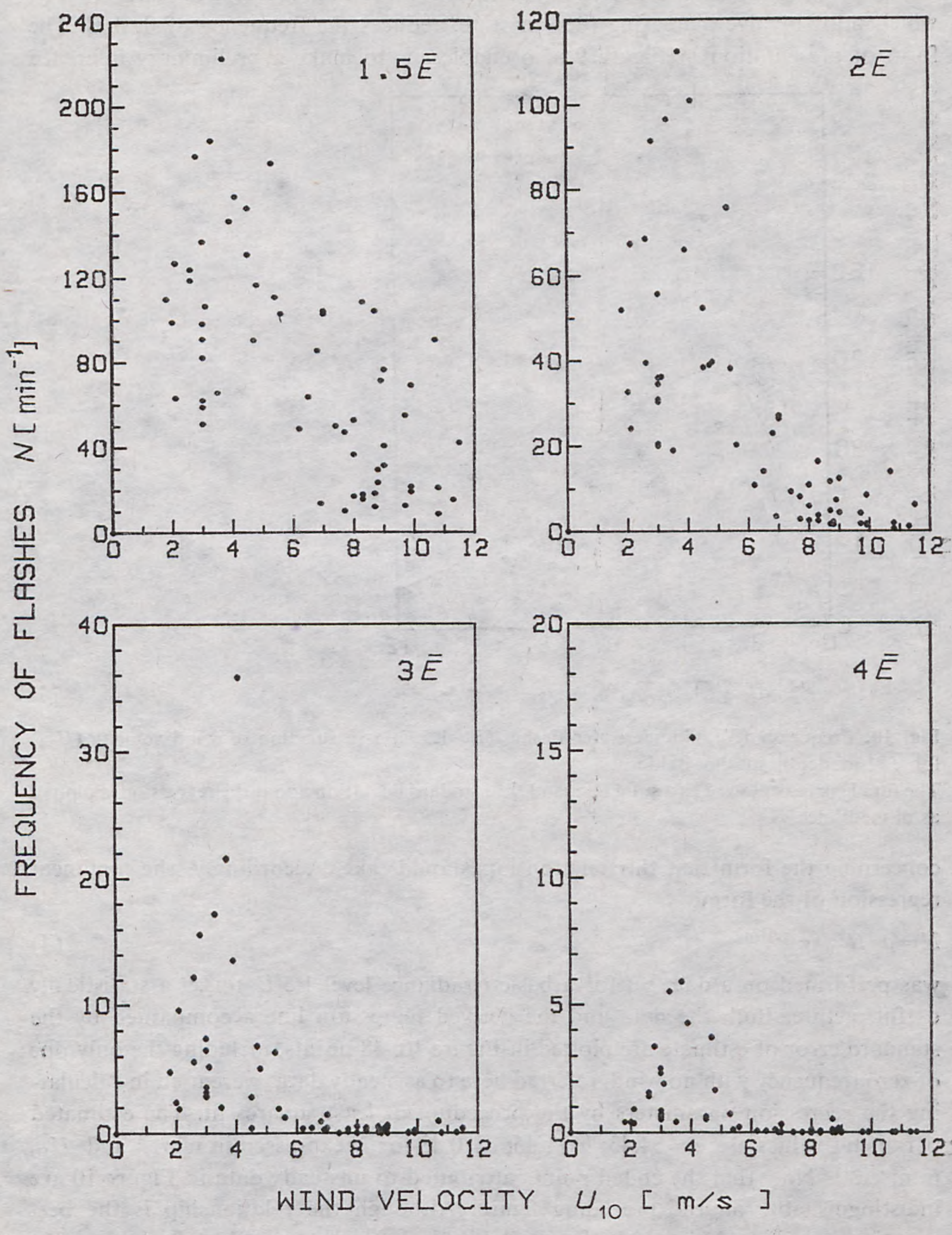

Fig. 9. Scatter plots of frequency of flashes versus wind velocity for different irradiance levels: $E=x\bar{E}$

Data from 62 measurements made at a depth of 1 m in the Baltic are included of underwater flashes, and also to high flash intensities. An increase in wind velocity, which must involve increasing the sea state, reduces the frequency of flashes. The form of presentation in Figure 9 also enables us to make a preliminary inference

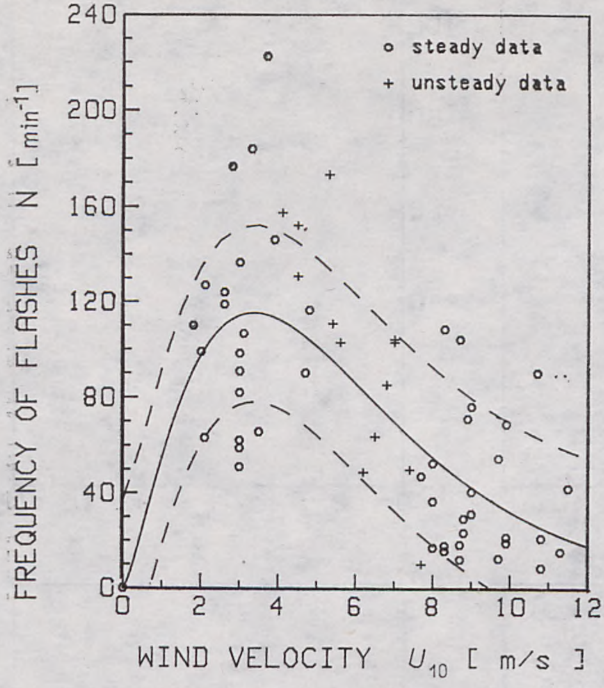

Fig. 10. Frequency (N) of underwater flashes ($E > 1.5\,\bar{E}$) as a function of wind velocity (U_{10}) for a 1 m depth in the Baltic

The fitted curve is plotted as a solid line, and the standard deviation about the regression is plotted as dashed lines

concerning the form that this relationship should take. Accordingly, the nonlinear regression of the form:

$$N = a \cdot N_{10}^{b} \cdot e^{-cU_{10}} \tag{4}$$

was performed on a data set for a basic irradiance level $1.5\,\bar{E}$ to get a statistically useful picture. Both the data and the derived regression line accompanied by the standard error of estimate are plotted in Figure 10. 48 points, including the only one of zero frequency with no wind, referred here to as steady data, were used in calculating the regression parameters by the procedure of least squares fit. The estimated parameter values are; $a=84.43$; $b=1.45$; $c=0.43$ for N expressed in min^{-1} and U_{10} in $msec^{-1}$. Note that the coded points attributed to unsteady data in Figure 10 are indistinguishable on the preceding figure. Although the relationship is the best one that we can achieve with the available data, the frequency of flashes cannot be predicted from the regression with much accuracy. The standard deviation of estimation is relatively large and amounts to 37.2 min^{-1}.

Having conceded the difficulty in measurements of fine sea surface structures, as a result, in obtaining the ideal data base, it is still of interest to attempt to interpret the relationship between focusing effect and wind velocity. It is obvious that the roughness of the sea surface affects the subsurface light field directly, so we need to know what happens to this roughness as the wind velocity increases. If the sea surface is absolutely calm in the absence of wind and swell, no effects of sunlight focusing are observed. In the usual case, however, the surface is roughened by action of the wind. Waves can form when the wind starts to blow over the surface, and then the flashes of focused light begin to occur. Under light winds between 2–5 $m \cdot s^{-1}$ and slight disturbances of the sea surface, the sunlight focusing under water is most effective. To interpret this, we note that the typical curvature as well as mean-square slope of the surface – both being mainly controlled by the short waves and ripples – are relatively small in these circumstances (Burcev and Pelevin, 1979; Cox and Munk, 1954; Cox, 1974). The unique field determinations reported by Burcev and Pelevin (1979) showed that the radius of curvature is typically of 20 cm or so for light winds, and decreases markedly with wind velocity. This fact, coupled with an ability to predict roughly the focal length of the air-water interface as being four times the radius of curvature (Gauss' formula in geometrical optics), suggest that the most favourable conditions to maximum sunlight focusing observable at depths of the order of 1 m would be expected under light winds indeed.

Our observations give also a strong indication that the frequency and intensity of underwater flashes are smaller at higher wind velocities. This must be related to increasing degree of malfocusing caused by an increased surface roughness which is accompanied with an increase in wind velocity. To be more precise, the changes in the sea surface structure with increasing wind velocity are attributable to increasingly developed short waves and ripples of steep shapes, so the short wave structure of the surface becomes rougher. This is quantitatively describable by increasing curvature (Wu, 1971; Burcev and Pelevin, 1979) and mean-square slope (Cox and Munk, 1954; Cox, 1974; Hughes, Grant and Chappel, 1977). The destructive effect of light scattering on focusing due to white-caps, foam patches, bubbles and sea spray is probably of minor importance under winds experienced during our experiments. It is also conceivable that the sea state can has an influence on the focusing effect since the small waves, that is those being of direct importance, are generally superimposed on the larger waves which grow with increasing wind velocity. This would imply the differences in perfection of lens effect of a particular wave component followed the raise and fall of carrier waves. Further experiments are, however, necessary before the complementary importance of sea state and small waves become known.

The plots of flash frequency N *vs* wind velocity U_{10} have considerable scatter which additionally complicates the translation of this statistical relationship into physical interpretation. A few reasons for this large scatter will be noted here. First, the actual sea surface structure depends on mean wind velocity in an ambiguous manner. During the experiments the conditions could be quite different from fully developed sea condition under which the wave field would depend solely upon wind velocity; in other words – under the idealization that a constant wind has blown for a sufficiently long time over a sufficiently large area. Therefore, the observed scatter in data would be partly related to the effects of wind duration, fetch, and earlier winds elsewhere resulting in swell. An important source of the scatter lies probably in the fact that the properties of short waves respond quickly to the turbulent gusts and lulls of the wind and to the lateral variations of the turbulent wind about the average wind direction. In particular, Pierson and Stacy (1973) suggested a drastic increase in capillary wave height slightly above the critical friction velocity of 12 cm$\cdot$s^{-1}, the

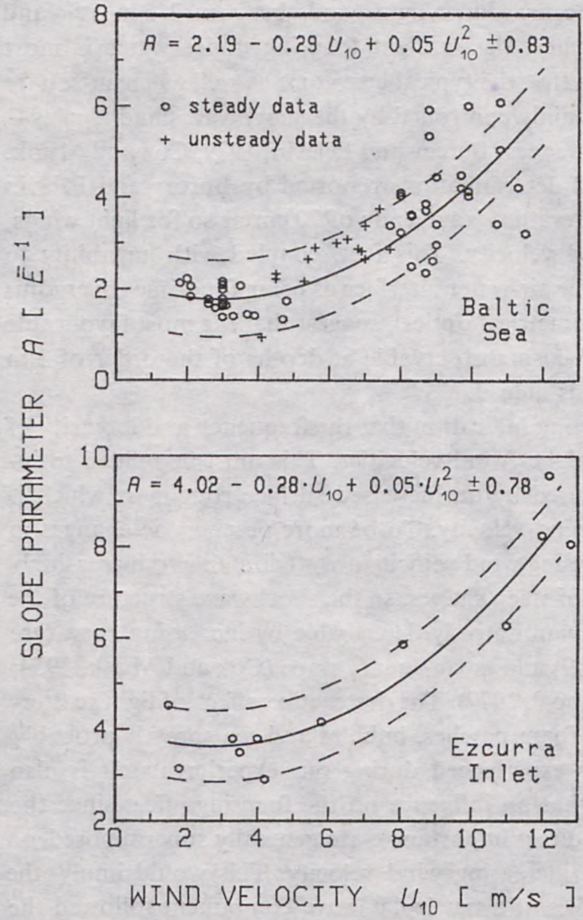

Fig. 11. Slope parameter A of the exponential law $N(E)$ as a function of wind velocity U_{10} for a 1 m depth

The fitted curves are plotted as solid lines and the standard errors about the regressions are plotted as dashed lines. The expressions obtained by the procedure of robust biweight fitting are given. The $\pm$ values give the standard error of estimate

value which corresponds to the wind at 10 m anemometer level given by about 3.3 m$\cdot$s^{-1} in a neutrally stratified atmosphere. This result was used by them to explain the patches of roughened water scattered over a relatively smooth surface, and it probably accounts for some of the large scatter in our data at lower wind velocities.

Second, there are other variables which may affect the focusing of sunlight and make a contribution to the scatter, such as sun's elevation and its azimuth position relative to the wind direction, cloud cover, air turbidity, water clarity, and the presence of impurities at the water surface (oil, natural slicks).

Third, the possible uncertainties in measurements of flash characteristics and wind velocity as well as in positioning the instrument under a disturbed water surface are superimposed on the data.

By virtue of the above reasons the ambiguities in the relationship between focusing effect and wind velocity become more understandable. Moreover, it has become clear that there are some sources of scatter in the data which are poorly understood. Nevertheless, we feel that the relationship we have shown is real and not a methodological artefact.

The effect of wind is definitely confirmed in Figure 11 showing the slope parameter A of the exponential law (1) *vs* wind velocity U_{10}. The upper graph demonstrates the open sea data from the Baltic, and the lower one – the data in the fetch-limited case from the semi-enclosed region of Ezcurra Inlet, South Shetland Islands. Although some scatter is apparent, the data display a marked minimum at light winds and a trend of steady increase towards greater wind velocities. This seems therefore to confirm the belief that the conditions favouring maximum effects of sunlight focusing prevail under light winds that correspond to relatively smooth sea surface described by the sea state of 1 to 2 on a 0–9 scale. The high values of the parameter A for stronger winds are reflections of the roughness of the sea surface which is great enough to mask the sunlight focusing due to refraction.

The regression of the slope parameter A on the wind velocity U_{10} over the range from 1.5 to 12 $\mathrm{m \cdot s^{-1}}$ can be described reasonably well by a quadratic parabola. Parameters of the regression have been estimated by the application of the robust bi-weight fitting technique described by Mosteller and Tukey (1977). This technique allows a regression model to be built iteratively using an ordinary least squares fitting with successive calculation of weights which reduce the influence of outrider points in the original data set. The procedure of robust regression was applied because it was felt to represent a better description of the main body of the data. This is particularly valuable under certain conditions when there is a greater chance of very unusual values drastically altering the regression parameters. Only steady data, that is 47 points, were subjected to regression analysis for the Baltic. It is worth remarking again that there is a data gap for winds between 5 and 7.5 $\mathrm{m \cdot s^{-1}}$ in a stationary wind-wave field. For the Ezcurra Inlet the regression is based on a selected subset of 12 data points corresponding to not obscured, relatively high sun ($h_{\odot} \geqslant 30°$), and steady wind sea conditions. The solid lines drawn in Figure 11 are those corresponding to expression determined by the technique of robust regression. The standard errors of estimate are plotted as dashed lines about the regression curves. There are no particular differences in the presented relationships except that the curve for the Ezcurra Inlet is shifted towards greater values of the parameter A. This indicates that the sunlight focusing in the Ezcurra Inlet is less effective than in the Baltic. To interpret this, we note that the waters of Ezcurra Inlet stand out as being abundant in suspended matter originating from erosion of surrounding land and melting ice. Hence, the focusing of sun rays is destroyed largely due to scattering-dominated attenuation of light in these waters. It is also not inconceivable that this marked difference in values of the parameter A may be in part related to the effect of short fetches on the sea surface structure in the Ezcurra Inlet.

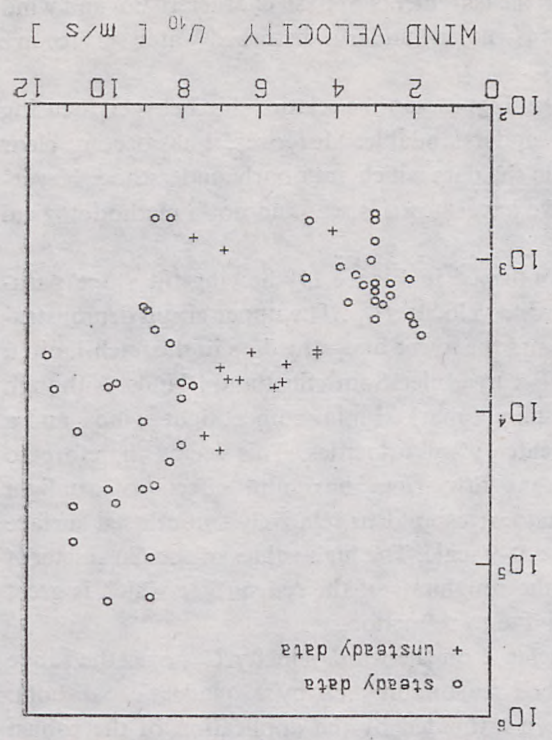

Fig. 12. Parameter N_0 of the exponential law $N(E)$ plotted against wind velocity U_{10} for a 1 m depth in Baltic

The other parameter from the exponential law (1), denoted by N_0, is plotted against wind velocity U_{10} in Figure 12. This presentation is based upon the same particular set of measurements from the open Baltic which was discussed with regard to the preceding figures. As seen, the parameter N_0 scatters over one, two, and even three orders of magnitude for the same wind conditions. However, the less well-defined tendency to increase with wind velocity is also noticeable. The values of N_0 are typically of the orders of 10^2 or 10^3 min^{-1} for light winds, and of 10^3 or 10^4 min^{-1} for stronger winds.

To summarize, from the above considerations has grown the belief that there is a definite effect of wind on the underwater flashing light, and that the available data disclose this effect in a reliable manner owing to their analysis with the help of physical reasoning. However, for a variety of reasons the established quantitative relationships between flash characteristics and mean wind velocity should be used with a great deal of caution. To what extent these relationships can be extrapolated to greater winds above 12 m$\cdot$s^{-1}, for which hardly any open-sea measurements in the subsurface layer are available, is unknown. There is, however, no particular reason why some disclosed qualitative features should be invalid for greater winds.

3.3. Durations of light flashes

A general outlook upon durations of underwater light flashes registered on the $1.5\,\bar{E}$ level is given in Figure 13. The two typical probability densities of flash durations $P(\tau)$ for quite different wind velocities are shown as smooth curves being drawn through the class midpoints of the data histograms. The remaining class midpoints correspond to the histograms obtained under different, more frequently intermediate,

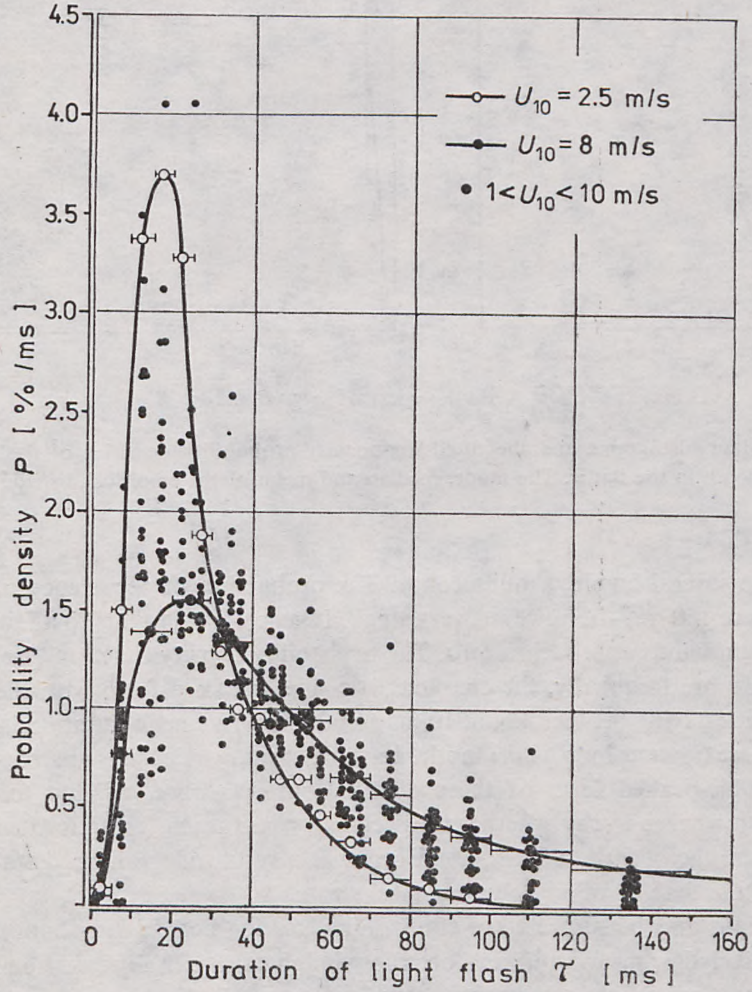

Fig. 13. Typical probability densities of flash durations registered on the $1.5\,\bar{E}$ level for a 1 m depth in the sea
31 data sets obtained at different wind velocities U_{10} under clear sunny conditions are included

wind-sea conditions. It is clearly seen that the functions $P(\tau)$ are influenced by the actual structure of the sea surface, so indirectly by the wind; in that the probability curves tend to become flatter and less skewed with increasing wind velocity. A tendency of flash durations to become longer with increasing wind velocity is probably a result of the blurring action of sunlight refraction at the sea surface which conduce to more diffuse foci under water. The durations of flashes at a 1 m standard depth

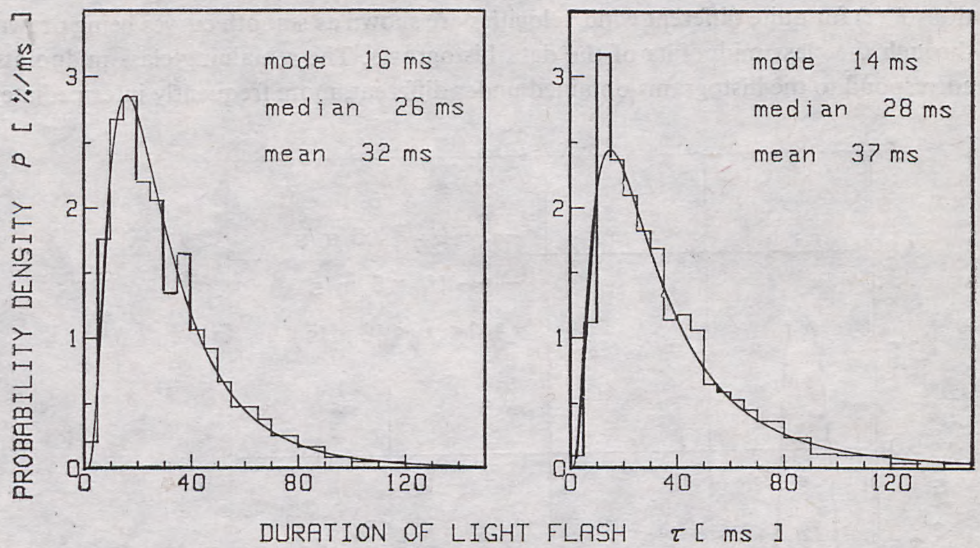

Fig. 14. Exemplary data histograms and the fitted log-normal probability densities of flash durations for a 1 m depth in the Baltic. The mode, median and mean of the empirical distributions are given

in the sea are up to several hundred milliseconds. The probability of occurrence of long duration – above 150 ms – is, however, very small. It generally amounts to a few per cent, and for light winds approaches zero. The probability density function $P(\tau)$ is skew and it has, more frequently, the characteristic single-peaked form with the most probable duration lying between about 10 ms and 30 ms. The mean duration is, in general, two – three times as long as the mode. In some cases, particularly at stronger winds, the double-peaked form of these distributions was observed, but too little information now exists to say whether the secondary maximum, being located at durations in the range of 50 to 90 ms, could occur as a result of the limited statistical accuracy of the data or of any physical mechanism.

The flash durations may be suspected of conforming to a log-normal distribution as they have a relatively low mean value and occasional high values. In Figure 14 one of the examples shows quite close agreement with a log-normal distribution, whereas the other is indicative of consistently smaller empirical probabilities than the fitted line predicts around the mode. The hypothesis that flash durations are log-normally distributed was checked using the Kolmogorov-Smirnov test. Twenty five sets of observations taken at a 1 m depth in the Baltic, each consisting of over 100 to about 1300 numbers representing flash durations, were tested. Of these, twenty did not fail the test for log-normality at the 1 per cent significance level.

Concluding this brief survey of flash durations we wish to point up an apparent increase of durations with depth in the sea (Dera and Olszewski, 1978; Stramski, 1984). This result can also be obtained by more intuitive physical arguments; the focusing effect is eliminated with depth in that the foci grow more diffuse which, in turn, implies that the flashes are less sharply peaked.

One final comment may be here in order. The frequency of flashes and the distribution of flash durations combine to determine the total duration of irradiance signal above the 1.5 $\bar{E}$ level. Note that this quantity is equivalent to the probability of instantaneous values of irradiance higher than 1.5 $\bar{E}$. The values of total duration were found to be typically of the order of a few per cent of a time period of measurement which was 10–20 min. Under most favourable conditions in which the sunlight focusing by surface waves is the most effective, these values can exceed 10 per cent. It is here interesting to note that the energy contained in the high irradiance pulses is so small that the flashes of focused light will be of little, if any, importance in radiant flux considerations on a larger time scales (day, month, *etc*). On the other hand, the time history of underwater irradiance during the daytime cannot be ignored from the ecological point of view.

4. Concluding remarks

We have presented herein measurements of flashing light being formed close to the sea surface when sunlight is focused after refraction by wind-generated waves. In conclusion it may be stressed that the observational difficulties were immense, but the results, whatever their shortcomings, provide probably the most comprehensive survey to date of the intense short-term fluctuations in underwater daylight. It is now fairly well established that, within the limits imposed by prevailing natural conditions, the variations of characteristics of flashing light, whether the result of lighting conditions above the sea surface or of water turbidity, may be as large as those caused by the sea surface structure. Therefore, in studying intense fluctuations of underwater irradiance, prevailing experimental conditions should be carefully controlled. In spite of all, it is difficult to separate the effects of different variables in field data which makes the analysis of underwater flashes quite complicated. Thus, the quantitative data are extremely hard to acquire in sufficient quantity to be statistically useful. It does seem clear that further comprehensive measurements are needed if we are to improve understanding of the discussed optical phenomenon and to get a statistically complete picture.

Data of the sort presented herein raise a few particular questions to be considered. The first problem is to describe in some way, statistical or otherwise, typical shapes of the surface waves under different wind sea conditions and to find how underwater flashing light is related to these shapes. Some high quality measurements of the sea surface microstructure could settle the question completely but this is not likely to be obtained in the near future, owing to massive logical and instrumentation problems. In view of these many difficulties, laboratory experiments under more easily controlled conditions seem to be desirable. Moreover, the considerations in this paper suggest that field measurements should include not only the mean wind velocity, but also, at least, the parameters of the turbulence in the wind stream.

The second question is that posed by the effects of both atmospheric lighting conditions and optics of the water on the underwater flashing light. In particular, the role played by inherent optical properties of the sea still needs careful examination. Also, additional experiments are necessary before the behaviour of flashing light as a function of depth become perfectly known.

Thirdly, all the characteristics of underwater flashes are a function of light wavelength. Our studies have been restricted to the green light which is generally most penetrating in moderately turbid waters represented by types 1–5 according to Jerlov's (1976) optical classification. For the red light regardless of water type being considered, and for the violet in special circumstances, other mechanism than focusing (*ie* wave-produced changes in the optical path) may be the most important determinant of fluctuations. We must await, however, further information before the detailed comparison over a whole range of light wavelengths is possible.

Finally, it is worth noting a question: how meaningful is the flashing light in the ecology of marine organisms ? Note that the light flashes appear to be the highest transient concentrations of solar energy in nature which suggests their influence on different aspects of life of marine organisms. The possible ecological significance of short-term irradiance fluctuations for the response of phytoplankton photosynthesis in the most biologically active surface layer has been proven recently (*eg* Walsh and Legendre, 1983), however, so little is known about this problem that further experiments must be designed with photosynthetic process in mind. The shortcoming of some previous papers which have reported on experiments under laboratory conditions (Walsh and Legendre, 1982; Queguiner and Legendre, 1986) is that the fluctuating light regimes have not precisely reproduced those experienced by phytoplankton in the natural environment as the natural high frequency light fluctuations are usually characterized by much higher light intensity levels corresponding to the saturated or photoinhibited range rather than to the initial linear response of photosynthesis. Additional problem arises here from the fact that phytoplankton in natural environment is exposed to a diurnally varying light over a wide range of frequencies as the short-term fluctuations induced by surface waves are superimposed on slower fluctuations caused by the passage of the sun, weather and vertical water movements.

From our studies has also grown the hope that the results of observations can provide an improved foundations for the construction of theoretical models of intense rapid fluctuations in underwater irradiance. To date, unfortunately, the theoretical side of the subject is in some disarray. A large part of the problem here results from an insufficient knowledge of the quantitative details of the high-frequency, short wave structure of the sea surface. Note, however, that irradiance fluctuations cannot be, of course, conveniently described in deterministic terms but must be treated on a statistical or probabilistic basis. Therefore, the highly sophisticated theoretical treatments may be too cumbersome for many applications.

Acknowledgments

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