Focusing of sunlight by sea surface waves: new results from the Black Sea*

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Underwater flashes
Marine optics

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Abstract

Under clear skies, strong fluctuations in the downwelling irradiance E_d prevail in shallow water as a result of the focusing and defocusing of sunlight by surface waves. Such temporal fluctuations were measured in the Black Sea, usually at a depth of 1 m, from a fixed platform located 600 m off the coastline. Thresholding analysis was applied to 109 time-series records of E_d(525 nm), each of which lasted 10 min. The frequency of occurrence of intense foci flashes (intensity exceeding the time-averaged irradiance $\bar{E}_d$ by > 50 %) decreased exponentially with increasing flash intensity. The frequency and intensity of flashes, hence the slope of the exponential relationship, both varied with wind-wave conditions and atmospheric illumination. The best conditions for wave focusing were characterised by light winds of 2 to 5 $\mathrm{m\,s^{-1}}$, solar elevation > 40°, and diffuseness of surface irradiance < 40 %. Then, at a depth of 1 m, flashes > $1.5\,\bar{E}_d$ occurred at rates as high as 6 Hz. The most intense flashes exceeded $\bar{E}_d$ 5-fold at rates of 10^{-3} Hz. These results, consistent

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with our previous observations, substantially improve the database on still poorly-documented wave focusing effects.

1. Introduction

It has long been recognised that the light field in a shallow aquatic environment exhibits fluctuations, due to surface waves, whose duration ranges from fractions of a second to several seconds. The primary mechanism for intense fluctuations in downwelling irradiance under sunny surface conditions is the focusing and defocusing of sunlight rays refracted by waves (Schenck, 1957; Snyder and Dera, 1970). A familiar manifestation of this effect is the randomly fluctuating pattern of bright lines (caustics) bounding darker regions observed on the bottom of a swimming pool or shallow sea whose perturbed surface is illuminated by the sun.

While a number of theoretical and experimental attempts have been made to understand wave-induced light fluctuations in general terms (Dera and Gordon, 1968; Fraser *et al.*, 1980; Nikolayev *et al.*, 1972; Schenck, 1957; Shevernev, 1973; Snyder and Dera, 1970; Sudbin *et al.*, 1974), relatively few studies have specifically investigated the sharp focusing effect that occurs in the top few meters of the water column (Dera and Olszewski, 1978; Dera and Stramski, 1986; Stramski, 1986a,b; Stramski and Dera, 1988). In these previous experiments, we observed that the time series of the downwelling irradiance $E_d(t)$ under a wind-disturbed sea surface consists of a train of high-intensity pulses whose frequency decreases exponentially with increasing pulse amplitude. The intense foci exceeding the time-averaged irradiance $\bar{E}_d$ by $> 50\,\%$ are referred to as light flashes. Such light flashes $> 1.5\,\bar{E}_d$ (at a light wavelength of 525 nm) were observed at frequencies as high as 4 Hz at a depth of 1 m in the Baltic Sea. The sharpest focusing yielded momentary increases of irradiance $> 5\ \bar{E}_d$. The typical duration of flashes, as measured at the amplitude level of $1.5\,\bar{E}_d$, was between 10 and several tens of milliseconds. In addition, we observed that the focusing effect was rapidly attenuated with depth and that the statistical properties of fluctuating irradiance were strongly dependent on the atmospheric illumination and wind-wave conditions.

In situ measurements of the focusing effect at shallow depths are difficult and more high quality data are needed to improve our understanding of this effect. Moreover, such data can have biological applications (Dera *et al.*, 1975; Greene and Gerard, 1990; Queguiner and Legendre, 1986; Stramski and Legendre, 1992; Walsh and Legendre, 1983). It is known that the production rates of aquatic plant communities depend not only on the amount of radiation received by the plants but also on the manner in which the radiation arrives. Other areas of scientific interest might also profit from a further study of focusing effects (McLean, 1990; Weidemann *et al.*, 1990).

In this paper we report on a series of measurements of wave focusing effects in the Black Sea. These measurements were made from a fixed platform, which allowed us to collect data of high quality under a wide range of wind-wave conditions. Importantly, the accuracy of these platform-based measurements is much better that of measurements obtained from on board a research vessel.

2. Experimental

The data were obtained during a 2-week period in September 1989 at an experimental site located 600 m off the coast of the Crimea, Black Sea (latitude 44°23′N, longitude 33°39′E). Measurements of the light fluctuations were carried out using an upward-facing irradiance meter with a 2.5 mm diameter cosine collector, interference filter (525 nm with a 10-nm passband) and silicone photodiode. The size of the collector was appropriate for the small spatial scale of these light fluctuations (Dera and Stramski, 1986). The meter was usually positioned at a depth of 1 m. The platform was fixed to the bottom (the water depth 30 m). Several measurements were also made at other depths between 0.5 and 4 m. The fluctuating signal $E_d(t)$ was digitised at a sampling interval of 1 ms for 10 min runs. A 12-bit analog-to-digital converter provided a full scale resolution of 1/4096.

For each 10 min run, we determined the probability density function of the irradiance $P(E_d)$ and the distribution of flash frequencies $N(E_d)$. In order to obtain $N(E_d)$, we counted the number of times that the irradiance signal crossed irradiance levels E_d from below to above. These levels were defined as multiples of the time-averaged irradiance $\bar{E}_d$. The values of $N(E_d)$ represent the average number of counts for a given E_d per unit time. Note that although we may express $N(E_d)$ in Hz, the occurrence of flashes is not a periodic event. $\bar{E}_d$ was determined by averaging $E_d(t)$ in 65.5 s segments throughout a 10 min run. Such an averaging time was long enough when compared to the wave-induced light fluctuation periods and allowed us to check whether the signal $E_d(t)$ was stationary within a 10 min run.

At the same time we measured the diffuseness of the surface irradiance d_E and the mean wind speed U during each 10 min underwater light measurement run; the solar elevation was also determined. These are convenient parameters for characterising atmospheric illumination and wave conditions in the study of focusing effects (Dera and Stramski, 1986; Stramski, 1986a,b). The irradiance meter for measuring d_E above the sea surface was similar to the underwater meter. The diffuse components of the downwelling irradiance $E_d(sky)$ and the global irradiance $E_d(sky + sun)$

were measured in rapid succession, and d_E was determined as the ratio $E_d(sky)/E_d(sky+sun)$ (Dera and Stramski, 1986; Stramski, 1986b).

The mean wind speed for the 10 min runs was obtained by averaging the signal from an anemometer located 14 m above the sea surface. Note that winds at the standard height of 10 m can only be slightly weaker (3 to 5%). Our experiment covered a range of winds between 0.9 (calm sea) and 17 $\mathrm{m\,s^{-1}}$ (rough sea, wave height of 1.4 m), irradiance diffuseness values between 0.17 and 0.68, and solar elevations between 14° and 48°. Furthermore, to characterise water clarity, we measured the diffuse attenuation coefficient of downwelling irradiance K_d(525 nm) in the top few meters of the water column. K_d(525 nm) varied between 0.09 and 0.19 $\mathrm{m^{-1}}$ throughout the experiment, indicating that the optical type of seawater ranged perhaps from 'oceanic type III' to 'coastal type 3' in Jerlov's classification (Jerlov, 1976). A total of 109 runs were recorded under stationary wind-wave conditions and clear skies when the solar disk was clearly visible and the cloudiness $< 30\,\%$; 92 of these measurements were made at a depth of 1 m.

3. Results and discussion

The density functions of the downwelling irradiance probability distribution $P(E_d)$ in shallow water have shapes that are asymmetrical about

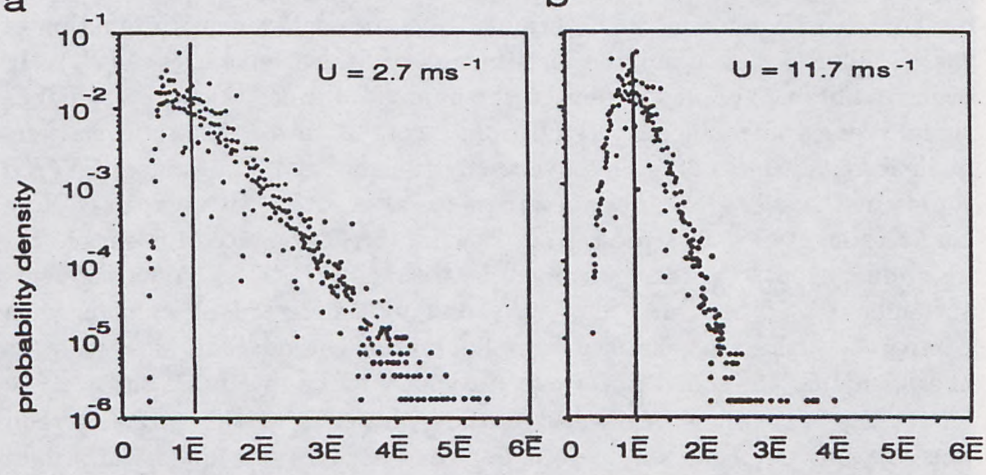

Fig. 1. Data points representing the probability distribution of downwelling irradiance at a depth of 1 m for different wind speeds. The coefficient of variation is 44% for light winds ($U = 2.7\ \mathrm{m\,s^{-1}}$) and 23% for strong winds ($U = 11.7\ \mathrm{m\,s^{-1}}$). The skewness of the distribution is 1.53 and 0.59 for light and strong winds respectively

the mean $\bar{E}_d$ (Fig. 1). This is because the regions where solar rays become focused are small compared to those where light divergence occurs (Schenck, 1957). The rapid divergence and convergence of solar rays can result in a 20-fold difference between the minimum and maximum values of E_d, which are approximately 0.3 $\bar{E}_d$ and 6 $\bar{E}_d$ respectively. The most frequent values of instantaneous irradiance fall within the range from 0.6 $\bar{E}_d$ to $\bar{E}_d$. Fig. 1 also shows that the $P(E_d)$ function is affected by winds, and hence, by the surface wave spectrum. Under similarly cloudless skies, very high instantaneous irradiances $E_d > 4\bar{E}_d$ are much more likely to occur under a lightly wind-blown surface than under a rough one. The coefficient of variation (standard deviation to mean irradiance ratio) and the skewness of the $P(E_d)$ distribution are higher for light winds. This indicates that the magnitude of irradiance fluctuations decreases under a strongly wind-blown surface.

We expect that similar changes in $P(E_d)$ associated with the dampening of the focusing effect will occur when skies become more diffuse, the water becomes more turbid or the depth of observation increases. This is because a surface wave will focus efficiently only collimated sunlight, so the focusing effect must decrease owing to the scattering of solar rays in the atmosphere and water (Dera and Stramski, 1986; Stramski, 1986a,b). The reduction of the focusing effect will clearly be more pronounced with increasing depth because light is scattered along a longer path within the water.

We will now discuss the effect of wind speed on the statistical properties of light flashes. Fig. 2a shows the frequency of flashes exceeding given irradiance levels $N(E_d)$ for different wind speeds U. These data were collected with the surface irradiance diffuseness d_E between 0.2 and 0.3 and the solar elevation between 34° and 46°. The contribution of these factors to differences between the plots is probably minimal, so the varying wind speed is most important. The plotted lines represent the best fit to the data points in the form of the exponential function

$$N(E_d) = N(0)\exp(-AE_d), \qquad (1)$$

where A is the slope parameter characterising the rate of flash frequency decrease with increasing irradiance level and $N(0)$ is an intercept with no physical meaning. Note that E_d is expressed as a multiple of $\bar{E}_d$, hence A is in units of $\bar{E}_d^{-1}$. Our previous work provided evidence that this relationship holds under diverse, stationary environmental conditions whenever wave focusing effects are detectable (Dera and Olszewski, 1978; Dera and Stramski, 1986; Stramski, 1986a). In the present experiment, 98 out of 109 measurements were characterised by a squared correlation $r^2 > 0.94$ (between $\log N(E_d)$ and $\log E_d$ for $E_d > 1.5\,\bar{E}_d$). An example of the fit accompanied by data points is shown in Fig. 2b.

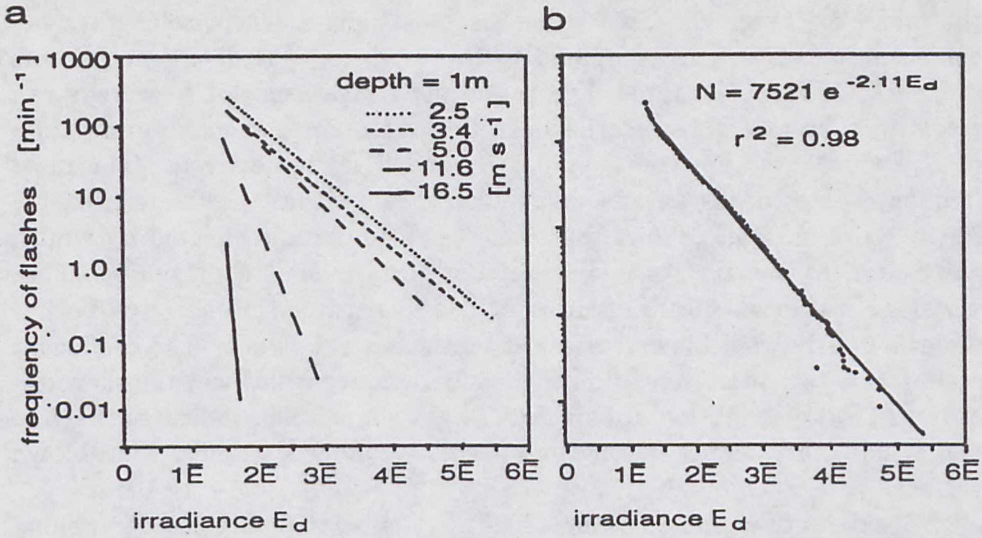

Fig. 2. Frequency of flashes exceeding certain irradiance levels at a depth of 1 m. Panel (a) shows the exponential fits to the data that were collected at various wind speeds as indicated. Panel (b) shows an example of data points accompanied by the best fit line. The regression equation and squared correlation coefficient are also given

The effect of increasing wind speed on the $N(E_d)$ distribution is twofold. Firstly, the flash frequency decreases. In Fig. 2a, $N(1.5\,\bar{E}_d)$ decreases over 100-fold as a result of an increase in wind speed from 2.5 to 16.5 $\mathrm{m\,s^{-1}}$. Secondly, the slope of the $N(E_d)$ distribution becomes steeper. So while under light winds the most intense flashes, exceeding the amplitude of $5\,\bar{E}_d$, occur at rates of up to 1 per minute, no such high intensities are detectable under strong winds.

These two effects are summarised in Figs. 3 and 4. When plotted against wind speed, the flash frequency data (measured at any irradiance level) display a characteristic pattern (Fig. 3). The maximum frequencies are observed at wind speeds between 1.5 and 5 $\mathrm{m\,s^{-1}}$; outside this range the frequency decreases dramatically. There are apparent reasons for this. In the absence of wind and swell, *i.e.* under a smooth sea surface, there is no focusing of sunlight, so none of the associated fluctuations occur. However, this is a rare occurrence in marine environments. On the other hand, at high wind speeds the increased surface roughness effectively diffuses the incoming sunlight, which destroys the underwater focusing effect. As a result, the conditions favouring the strongest focusing are characterised by a lightly

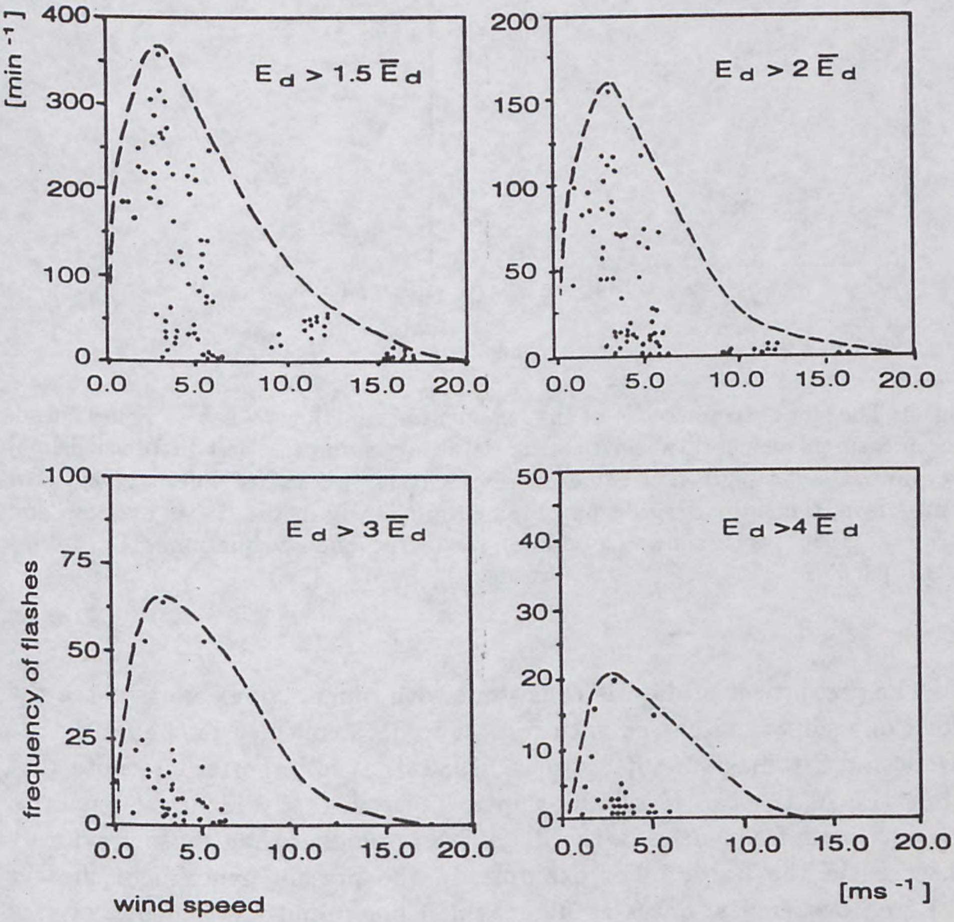

Fig. 3. Scatter plots of flash frequency *vs.* wind speed for different irradiance levels. Note the change in the ordinate scale between the graphs. The dashed line is the envelope to the data points

wind-blown surface (Dera and Stramski, 1986; Stramski, 1986a). The reasons for the scatter in the data describing wave focusing as a function of wind speed include ambiguity in the relationship between sea surface structure and mean local wind, the possible effect of other environmental variables on the focusing effect, and measurement inaccuracies.

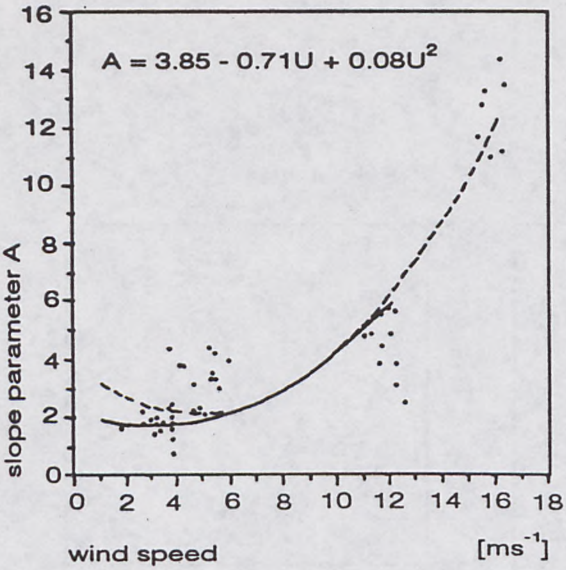

Fig. 4. The slope parameter A of the exponential function $N(E_d)$ *vs.* wind speed. The measurement depth was 1 m. The data points and the best fit (dashed line) are plotted. The regression equation representing the dashed line is given. For comparison, the similar regression obtained previously in the Baltic by Dera and Stramski (1986) is also shown (solid line); the corresponding equation is $A = 2.19 - 0.29U + 0.05U^2$

The present set of data is consistent with our previous work where the effect of wind was discussed with respect to data collected in the Baltic Sea (Dera and Stramski, 1986; Stramski, 1986a). It is important to note that while the $N(E_d)$ *vs.* U relationship exhibits virtually identical patterns, the maximum frequencies in the Black Sea are higher than those previously observed in the Baltic. For example, in the present experiment, flashes $> 1.5\,\bar{E}_d$ occurred at rates as high as 350 per minute at a depth of 1 m (Fig. 3, upper-left panel), in contrast to 230 per minute in the open Baltic. At a depth of 0.5 m in the Black Sea, we observed even higher values for $N(1.5\,\bar{E}_d)$ — as high as 458 min^{-1} under favourable light wind conditions. The frequency decreased to about 10 flashes per minute at a depth of 3 m. The point to be emphasised here is that for many measurements, the waters in the Black Sea were clearer than in the Baltic. In the Baltic $K_d(525\text{ nm})$ was always $> 0.14\ \text{m}^{-1}$, and most frequently *ca* $0.2\ \text{m}^{-1}$. Moreover, as the data in the Black Sea were acquired from a fixed platform, they are likely to be more accurate than those previously obtained in the Baltic from aboard ships.

Fig. 4 shows the slope parameter A as a function of wind speed, and provides further evidence that light winds favour the strongest focusing effects. The minimum values of A, which imply the occurrence of high-intensity flashes, are observed within the same range of light winds as the highest frequencies $N(E_d)$. A polynomial of the second degree was fitted to the data; this is also shown in Fig. 4. This fit compares well with the similar regression curve representing the Baltic Sea data.

As mentioned above, the focusing effect also depends on the atmospheric illumination, which can be characterised by the diffuseness of surface irradiance and solar elevation. Our previous experiments (Dera and Stramski, 1986; Stramski, 1986a,b) indicated that increasing diffuseness and/or decreasing solar elevation results in changes of the distribution $N(E_d)$ qualitatively similar to those induced by increasing wind speed. Separating the effects of diffuseness and solar elevation from each other is difficult because the contribution of diffuse light to surface irradiance usually increases when the solar elevation decreases (due to an increase in the atmospheric path length). Therefore, we here present $N(1.5\,\bar{E}_d)$ and A as functions of diffuseness and solar elevation in the form of contour plots (Fig. 5). Note that only the data obtained under light winds < 6.5 m s^{-1} are included, so the unwanted effects associated with the varying surface wave field are minimised.

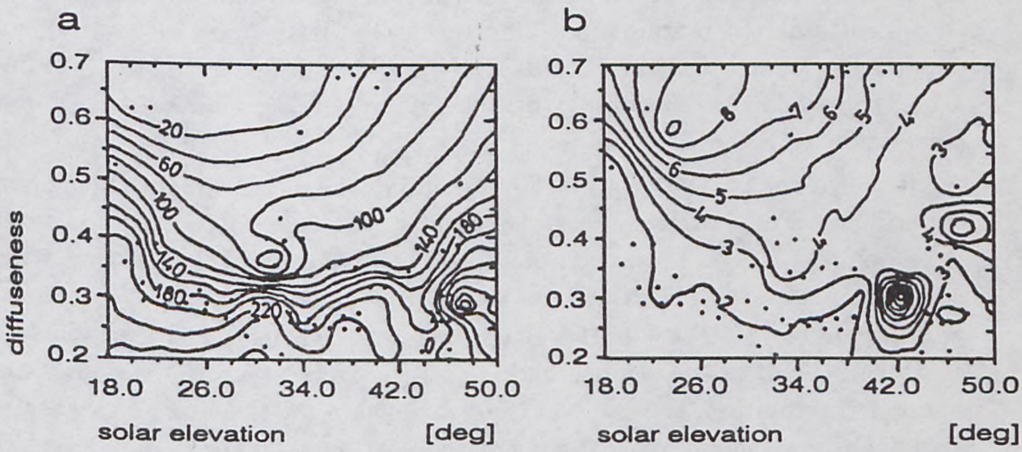

Fig. 5. Contour plots of the frequency of flashes exceeding the irradiance level of $1.5\,\bar{E}_d$ (panel a) and the slope parameter A (panel b) as a function of surface irradiance diffuseness and solar elevation. The data points were obtained at a depth of 1 m; isolines are plotted. Each panel includes 58 data points at wind speeds $<$ 6.5 m s^{-1}

While the interpretation of any detail in these plots could be meaningless because of the limited number of data, the general features are worth remarking on. Firstly, the regions in Fig. 5a where the frequency $N(1.5\,\bar{E}_d)$ is highest (lower-right) and lowest (upper-left) are evident. Secondly, there is a more or less regular decrease in $N(1.5\,\bar{E}_d)$ with increasing diffuseness. Finally, a similar pattern is observed for the slope parameter A which assumes the smallest values at high solar elevation and low diffuseness (Fig. 5b). Unfortunately, our present data set is still insufficient for making detailed comparisons with the model developed by Stramski (1986b) to describe specifically the effect of diffuseness on the characteristics of underwater light flashes. This model predicts a gradual change in $N(E_d)$ and A with increasing diffuseness and a dramatic reduction of focusing effects, for $d_E > 0.7$–0.8, resulting eventually in the disappearance of the flashes.

Recently, Stramski and Legendre (1992) re-examined our earlier data, and concluded that when the focusing effects are attenuated, the statistical properties of flashes exhibit a characteristic, qualitatively similar change, regardless of the factors responsible for that attenuation. The point is that a decrease in the frequency $N(1.5\,\bar{E}_d)$ is usually accompanied by a steepening of the slope parameter A. As already discussed, the attenuating factors include increasing diffuseness of incoming irradiance, increasing sea surface roughness, increasing water turbidity and increasing depth of observation. By pooling 162 data points obtained from on board ship at depths of 1 to 5 m in different marine areas (mostly in the Baltic) and in a variety of conditions (Dera and Stramski, 1986), Stramski and Legendre (1992) found a fairly good linear relationship between $\log N(1.5\,\bar{E}_d)$ and $\log A$ (squared correlation $r^2 = 0.672$).

Here we update this relationship by adding the data from our Black Sea experiment. Fig. 6a shows these new data accompanied by the regression of A *vs.* $\log N(1.5\,\bar{E}_d)$. This is compared in Fig. 6b with all the data that were collected previously (Dera and Stramski, 1986) and analysed by Stramski and Legendre (1992). For the Black Sea experiment, there is much less scatter in the data and a much higher correlation between the variables examined. In addition, the slope of the relationship for the Black Sea data is significantly steeper. While the decreased scatter in the data may have resulted largely from the better accuracy of platform-based measurements as compared to shipboard measurements, the difference in the slope between the regression lines is difficult to interpret. It is possible that this regression is affected by certain site-specific conditions (*e.g.* wave spectrum characteristics), so a general relationship may not exist. More high quality data are needed to solve this problem.

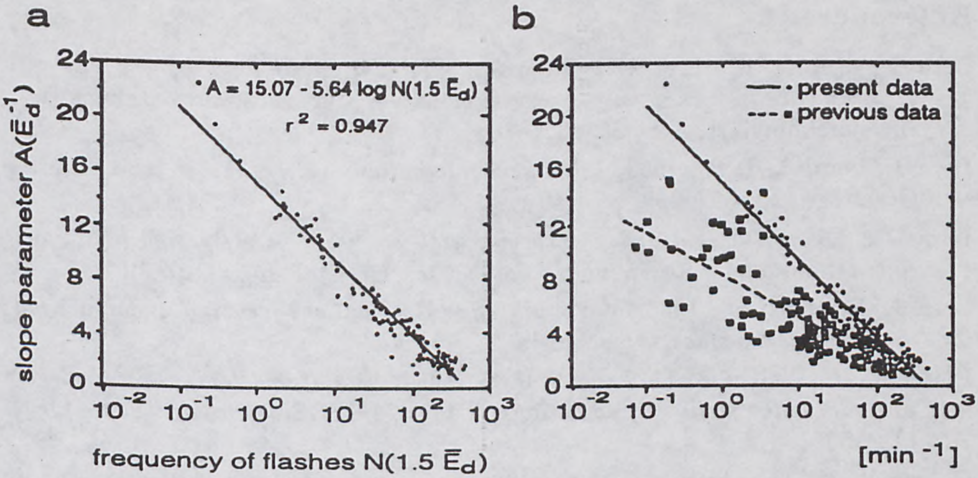

Fig. 6. The slope parameter A *vs.* flash frequency $N(1.5\,\bar{E}_d)$. Panel (a) shows 109 data points from the present experiment in the Black Sea and the best fit regression line. The regression equation and squared correlation are given. In addition to the present data, panel (b) includes 162 data points from previous experiments and the corresponding best fit (dashed line) which is described by equation $A = 828 - 3.12 \log N(1.5\,\bar{E}_d)$ (after Stramski and Legendre, 1992)

In summary, the platform-based experiment described in this paper has significantly improved our database on surface wave focusing at shallow depths. To date, we have been acquiring data primarily for the moderately turbid waters of continental seas and for a light wavelength of 525 nm. One of our major observations is that the strongest focusing occurs under a lightly wind-blown surface when the sun is high in a clear sky. In future studies, it would be desirable to direct more attention to open ocean environments and examine wave focusing for other light wavelengths.

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