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Green light penetration depth in Puck Bay

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The optical penetration depth z_{90} defined for the purposes of remote sensing in oceanographical investigations is identified as the depth from above which originates 90% of the diffusively reflected radiation observed under a given incident angle just over the sea surface (Gordon, McCluney, 1975). On the basis of the normalized model of light transmission in water *i.e.* the so-called quasi–single–scattering model (Gordon, 1973; Gordon *et al.*, 1975), and assuming that the sea is uniform and infinitely deep, the penetration depth z_{90}

- is almost the same for all directions of radiation,
- coincides with the depth at which the amount of downwelling irradiance (E_d) is e times smaller than its value just under sea surface

$$\frac{E_d(z_{90})}{E_d(z=0)} = \frac{1}{e}, \tag{1}$$

The decrease in downwelling irradiance with depth in the sea can be described as follows (Dera, 1983):

$$\frac{E_d(z)}{E_d(z=0)} = exp[-\int_0^z K_d(z)dz], \tag{2}$$

where
$K_d(z)$ – downwelling irradiance attenuation coefficient.

In practice, the penetration depth can be obtained when the mean value of the surface layer coefficient K_d is known (in a layer no shallower than the assumed z_{90}). This follows from equations (1) and (2), from which one can obtain

$$z_{90} = (\bar{K}_d)^{-1}. \tag{3}$$

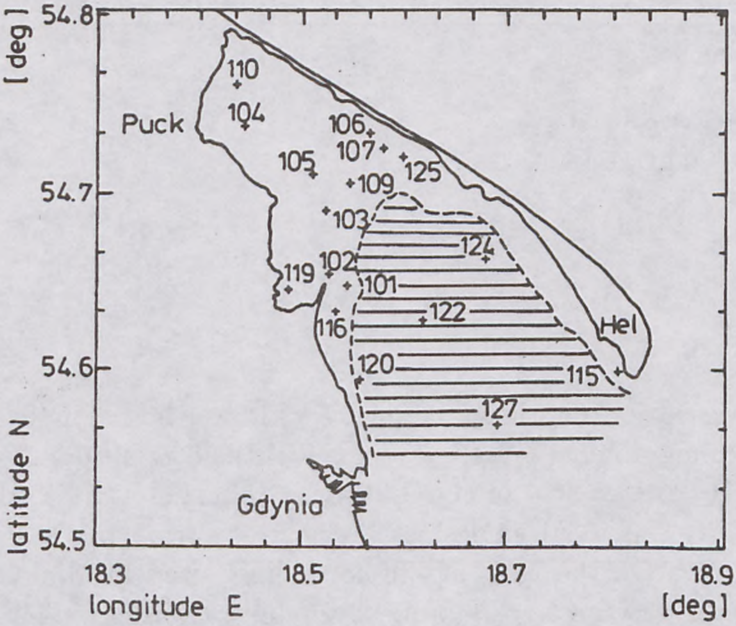

Fig. 1. Part of Puck Bay (bounded by the 10 m isobath) where, with a high degree of probability, continuous satellite pictures, undisturbed by light reflected from the bottom, can be obtained in the green part of the spectrum (+ – location of sampling stations)

The penetration depths were calculated from (3) by determining the $\bar{K}_d$ coefficient, which was evaluated from the vertical profiles of the downwelling irradiance. The measurements were carried out in Puck Bay (Fig. 1) in 1974 (June, August, November, December), 1975 (June, July), 1976 (August) and 1988 (May, June, November), with an irradiance meter equipped with a 530 nm (± 60 nm) broad band filter. Soundings were carried out from the sunny ship's deck in stable light conditions. The values of E_d and the actual parameters of the state of the atmosphere were recorded every for meter of depth.

The data most numerous and representative for the study area were collected in June, July and November.

Table 1. Statistical analysis of light penetration depth data (values of z_{90} in [m])

Month	June	July	November
Sample size	17	16	11
Max. value	5.18	3.45	6.94
Min. value	1.71	1.48	1.31
Average	3.25	2.55	3.50
Standard deviation	0.93	0.58	1.63

The results (Tab. 1) show a clear dependence on the biological activity of the water ecosystem – minimum values of $\bar{z}_{90}$ and σz_{90} in July, *i.e.* during the phytoplankton bloom period.

In November, when the water is much more transparent, the average penetration depth in the Bay increases by about 1 m compared to that in July. The smaller amount of suspended organic matter means that the total volume attenuation coefficient $c(525)$ in the surface layer decreases (Tab. 2), and that inorganic suspended matter has a dominant influence on optical properties.

Table 2. Mean depth penetration in Puck Bay waters obtained from field measurements and computed using equation (5) with values of $\bar{\alpha}$, μ_m, c' as input parameters

Input parameters	June	July	November
$\bar{\alpha}$	0.53	0.51	0.74
μ_m	0.75	0.75	0.60
c' [m^{-1}]	0.58	0.98	0.58
$\bar{z}_{90}$ (meas.) [m]	3.25	2.55	3.50
$\bar{z}_{90}$ (50) [m]	3.39	2.15	3.31

The mean daily values of z_{90} within the Puck Bay area (in a given month) were calculated using the quasi–single–scattering model (Gordon, 1973) for a comparison with the experimentally obtained values of this parameter. According to this model

$$z_{90} = \frac{\mu}{a + b_b}\,, \tag{4}$$

where

μ – mean cosine of zenith distance, which gives the mean direction of radiance in the upper hemisphere in the subsurface layer of the sea,

a – volume absorption coefficient,
b_b – backward scattering coefficient.

The mean monthly value of z_{90} (Wensierski, 1983; Jankowski, 1989; Dera *et al.*, 1978) can be expressed as

$$\bar{z}_{90} = \frac{1}{0.34 \cdot c' + 0.04}[\mu_m(1 - \bar{\alpha}) + 0.85\bar{\alpha}], \tag{5}$$

where

$\bar{\alpha}$ – arithmetic mean of average monthly cloudiness measured at Rozewie, Hel and Gdynia meteorological stations (Marine Hydrometeorological Bulletin),

μ_m – cosine of mean daily solar zenithal distance (in a given month) as seen from below the sea surface; wind speed assumed to be $5\ \mathrm{m \cdot s^{-1}}$,

c' – mean monthly total volume attenuation coefficient at 525 nm in the surface layer down to 5 m in Puck Bay (Krężel and Sagan, 1987).

The mean depth penetration in Puck Bay waters computed from field measurements and from equation (5) are presented in Table 2.

In remote measurements of the sea, a significant error can arise in shallow water areas, when light reflected from the bottom returns to the surface. Under such conditions the radiance emerging from the sea cannot be interpreted as the radiance diffusively reflected by the water itself. In most cases (different types of water and bottom material), a sufficiently deep water can be assumed to exist when the round trip transmission of the total water column T^2 is less than 1% (Austin, 1974)

$$T^2 = \exp(-2 \cdot K_d \cdot z_b) < 0.01 \tag{6}$$

where

z_b – depth to the bottom. This condition occurs when $z_b > 2.3 \cdot K_d^{-1}$.

The measured values of z_{90} or $\overline{K}_d$ have been used to separate the area from which continuous satellite images, not perturbed by light reflected at the bottom, can be obtained. Assuming a probability level of 90%, such an area covers the region with water deeper than 10 m (Fig. 1). This means that 90% of all expressions, $(2.3 \cdot z_{90})$, do not exceed the value of 10 m (none of them during the phytoplankton bloom period).

In conclusion it is emphasized that the applicability of remote oceanographical measurements in Puck Bay is restricted to the upper few metres of the water body. It has been calculated for green light but also applies to the other wavelengths from the visible part of the spectrum.

The relatively small and highly variable penetration depths are characteristic of turbid coastal waters of low transparency, which agrees well with the observations.

It seems that one could estimate the mean monthly values of z_{90} if the mean cloudiness, solar zenithal distance and subsurface attenuation coefficients were known. It is worth noting that changes in the latter parameter have the most significant influence on changes of $\bar{z}_{90}$.

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