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Seasonal Changes in the Underwater Light Milieu in a Finnish Baltic Sea Coastal Locality

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Abstract

Total quantum flux density and spectral distribution of light at different depths were recorded in a Baltic Sea coastal locality, SW Finland, at intervals from May 1989 to July 1990. The total amount of light incident on the surface, during ideal conditions, changed by about 80 % on a yearly scale. At 25 m the change was more than 2 orders of magnitude because of the narrowing light spectrum. Phytoplankton blooms decreased subsurface light quickly, thereby changing the underwater light spectrum and intensity. Light transmission maximum changed towards shorter wavelengths when moving from a bay receiving a small river, through the archipelago to the open sea. Dawn-to-dusk incident light is presented for selected dates. Responses of aquatic crustaceans to changing light conditions will also briefly be discussed.

Key words: Underwater light spectrum, seasonal changes, Baltic Sea

1. Introduction

The boundary between the terrestrial and the aquatic environments, the water surface, not only divides the world into “dry” and “wet”. The surface also forms a boundary between “light” and “dark”. Above the water surface the daylight has almost the same, almost flat, spectral composition from day to day and place to place, although the intensity of course may change rapidly. But the sky doesn’t become dark and monocoloured if we descend into a valley, a hundred meters deep, as it does under water. Neither does it become dangerously brigth if we ascend a hilltop. Also, in water the pressure is doubled by descending about 10 meters from the surface, while above the surface one has to ascend vertically about 5 500 metres before the pressure has decreased to about half of that at the sea level. Terrestrial organisms living at the sea level can depend on a fairly constant partial pressure of oxygen, while aquatic animals may encounter low-oxygen or anoxic conditions by moving a few metres. The very special features

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of the underwater environment thus put special requirements on the aquatic organisms. Many life functions in the aquatic organisms are dependent on light. For plants and algae light is necessary for the photosynthesis. For animals light is necessary for vision and/or circadian activities. Light absorbed in the water is largedly responsible for the heath balance of the earth. Marine optics is thus a discipline examined both by marine biologists and marine physicists.

Many investigations in aquatic ecology, concerning for example plankton production, visual ecology or behaviour of organisms, require knowledge of light intensities and spectral distribution of light at different depths and times (e.g. *Donner and Lindström,* 1980; *Lindström and Nilsson,* 1988; *Leskinen et al.*, 1992; *Bäck and Ruuskanen*, 2000). The optical properties of sea water with its optically active substances affect the underwater light (UWL) by acting as a filter, cutting off the irradiance spectrum on the infrared (IR) low energy (wavelength more than about 750 nm) side already in the first meter (*Jerlov*, 1976). On the ultraviolet (UV), high energy, side water absorbs most of the light within a few metres. In the open Baltic Sea the transmission of 310 nm UV light is only about 9% m^{-1} (*Jerlov*, 1976).

The UWL milieu depends on how light beams of different wavelengths are able to penetrate into the water. This wavelength-dependent light attenuation leads to a gradual narrowing of the spectrum with increasing depth (e.g. *Tyler,* 1959; *Kirk,* 1983). Light intensities at PAR (photosynthetically active radiation) wavelengths set limits for the depths at which photosynthesis is possible. Light and photosynthesis have been discussed thoroughly for instance by *Kirk* (1983) and the ecology of vision by *Lythgoe* (1979). Spectral distribution of light in different water bodies, as well as the theory of light penetration have been discussed e.g. by *Jerlov* (1976)**.** Although the light absorption in the Baltic Sea has been measured as early as 1910 by *Witting* (1944) and later by *Jerlov* (1976), there are no measurements on changes in light spectral distribution and intensity during different seasons or times of the day. At the location of this investigation (see below) the sun inclination varies considerably during the year, thus adjusting the number of light hours from a minimum of about 6 h in winter to a maximum of about 19 h in summer. Phytoplankton blooms may alter the spectral distribution of the UWL to some extent. These changes may be fast, from one day to the next.

The UWL measurements started in the study area in1984 to serve as a basis for investigations on the adaptation of the crustacean visual system to the available UWL spectrum (*Lindström,* 1990, 2000; *Lindström and Nilsson,* 1984, 1988; *Lindström et al.,* 1991). The present author has, however, repeatedly been asked to provide these light data to other scientists. Changes in the UWL milieu were recorded in the Baltic Sea off the Tvärminne Zoological Station, SW Finland, during the ice-free period for 414 days in 1989–1990. The present paper deals with light intensity and spectral distribution of UWL on a temporal basis. It is also intended to give some guidelines for field work in this particular area as well as for laboratory experimental work in which mimicking the natural light milieu often is necessary for creating close-to-natural conditions. The time-series of light quantum intensity are shown for selected depths down to 30 m. The spectral distribution of light at different depths is shown for some dates of interest, e.g. for very clear water or strong algal bloom. The daily cycle of surface light intensity is shown for 8 dates unevenly distributed over the recording period.

2. Location and methods

2.1 Location

The main measurement site was Tvärminne Storfjärd, at a location about 1 500 meters off the Tvärminne Zoological Station, University of Helsinki (geographical location 59°50'N, 23°15'E), over a depth of 35 m, salinity ≈ 0.7 % (Fig. 1, B). The site is situated between the outer archipelago with treeless skerries and the inner archipelago at the mouth of the Pojo Bay. An additional site is situated at the Sällvik depth (about 40 m) in the Pojo Bay (Fig. 1, C), the salinity of which changes from fresh water to about 0.6 % at the outlet (*Niemi,* 1973). A small river supplies the bay with fresh water, and the dissolved humus colours the water brownish (35–45 g Pt m^{-3} in the surface water (*Niemi,* 1973)). The outflowing humus-rich surface water from the bay mixes gradually with the more saline sea water and affects the transparency still at the site of the main light measurements (*Niemi,* 1973)**.** At the third measurement site, the Ajax buoy (Fig. 1, A) the influence of the bay water is low. The UWL measurements were performed 28 times at irregular intervals, depending on weather conditions, ice cover, boat availability etc., between May 2, 1989 and June 6, 1990.

2.2 Recording methods

In biological systems the effect of light is mediated by the number of photons absorbed, not by the energy of the photons. This holds as well for photosynthesis (e.g. *Kirk*, 1983) as for vision, (*Dartnall*, 1953). For that reason the quantum flux density per nanometer (QFDn) was recorded. The instrument used was a QSM 2500 quantaspectrometer (Techtum Instruments, Umeå, Sweden) with underwater housing, which was factory calibrated for the wavelengths 400–750 nm. The QSM measured $qu \times m^{-2} \times s^{-1} \times nm^{-1}$ in the scanning mode. The continuous spectra were recorded with a Beckman 10 inch Linear and Linear-Log recorder or a Gould BS 272 recorder. The recorded curves were read manually at 10 nm intervals for calculation of the curves shown in Figs. 4 and 6–9. The integrating unit measured the total quantum flux density (QFD_t) in $qu \times m^{-2} \times s^{-1}$. It could not, however, integrate the smallest spectra recorded by the scanning module, because of its dark current of the order of 0.02×10^{18} $qu \times m^{-2} \times s^{-1}$ (see below). In those cases the curves were either integrated over short (5.83 nm, depending on paper lineation) wavelength distances or by copying the curves on standard thickness paper, cutting them out by scissors and weighing them on a precision balance. The QFD_t:s were calculated using a calibration curve constructed by weighing squares of different sizes cut from the same paper. The accuracy of the method was tested by comparing "weighed" QFD$_t$:s with the QFD$_t$:s recorded by the QSM using spectra big enough to be accurately integrated by the integrating module At that sensitivity level the accuracy was ± a few percent. For conversion of quantum irradiance into energy units, use the method described by *Reinart et al.* (1998).

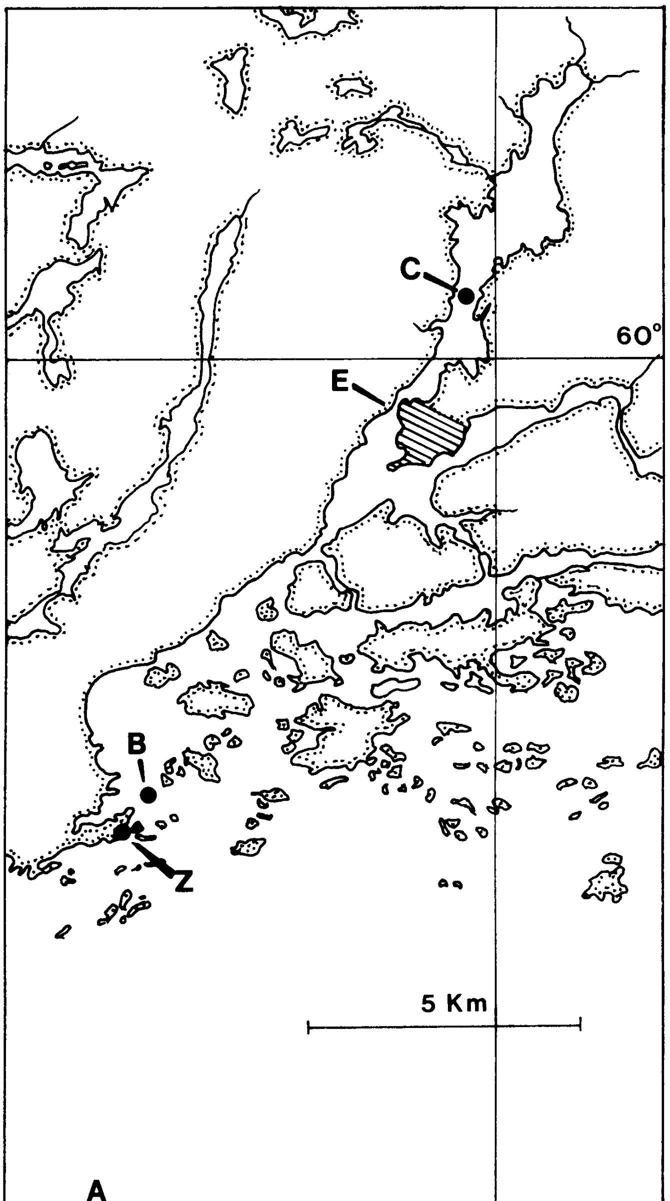

Fig. 1. Geographical locations of the three stations where underwater light measurements were performed. A, Ajax buoy, B, Tvärminne Storfjärd, C, Sällvik depth, Pojo Bay, E, Town of Ekenäs, Z, Tvärminne Zoological Station.

The measurements were as far as possible performed at noon local time under clear sky in calm weather conditions. The light conditions were recorded in the following depths: surface, 1 m, 3 m, 5 m, 7 m, and from 10 m at 5 m intervals down to 35 m.

At each depth two spectral runs were performed; 400 nm to 750 nm and back. During spectral scans the sky was carefully watched, so not to record when clouds shaded the area. The measurements were made on the sunny side of the boat. The dark-current of the integrating unit was measured by covering the light sensor with a light-tight hood and lowering it to a depth below the thermocline. As the dark-current was slightly temperature dependent, scans were made with the hood on, until the dark current value remained unchanged. The hood was thereafter removed by an attached string, and the measurements could begin. During the spectral run the incident light perpendicular to the surface was measured in µE units ($1\mu E = 6.022\times10^{17}$ $qu\times m^{-2}\times s^{-1}$) with a Li-Cor LI-190SA sensor and a LI-1100 data logger, from a high, unshaded position on top of the boat. The incident light intensity (5 seconds rolling integration time) was followed during the spectral scan and was noted when the UWL spectrum reached its maximum. If the incident light intensity varied considerably during the spectral run, the measurement was rejected. All spectral curves were recorded on paper. Scanning time in one direction was 65 seconds. The spectral range of the Li-Cor was 400–700 nm (= PAR). Because of the different spectral ranges of the two meters, the skylight measurements differed about 20%, the QSM giving higher values. The QFD:s of each depth were corrected to correspond to the highest incident QFD_t recorded on date in question. The logarithmic curves were corrected using the same correction factors.

The corrections were based on light recordings on top of the laboratory building at Tvärminne Zoological Station where no trees or antennas could shade the view. They were performed during clear days at local noon with the Li-Cor apparatus. Some morning-to-evening series were recorded as well. On March 3, 1994 a measurement was made under the ice. The recording device was put in place by a diver.

3. Results and discussion

3.1 Daily changes in light intensity

The light intensity changes during a day, being highest at local solar noon (Fig. 2). For the Tvärminne area at 23°15’E the sun is at zenith about 27 minutes (± 15 minutes depending on the time of the year) after the official East European Time (EET) at 30° E. The recorded measurements have all been transformed to official normal time, which means that recordings made during the seven months of summertime have been depleted of one hour. In winter time the amount of light entering the water surface at noon was only about 11% of that in the summer. At the location of this investigation the official length of the day changes from a minimum of about 6 hours in winter (December 21) to a maximum of about 19 hours at midsummer (June 21). Cloudy weather in the summer may decrease the light incident on the water surface to winter levels.

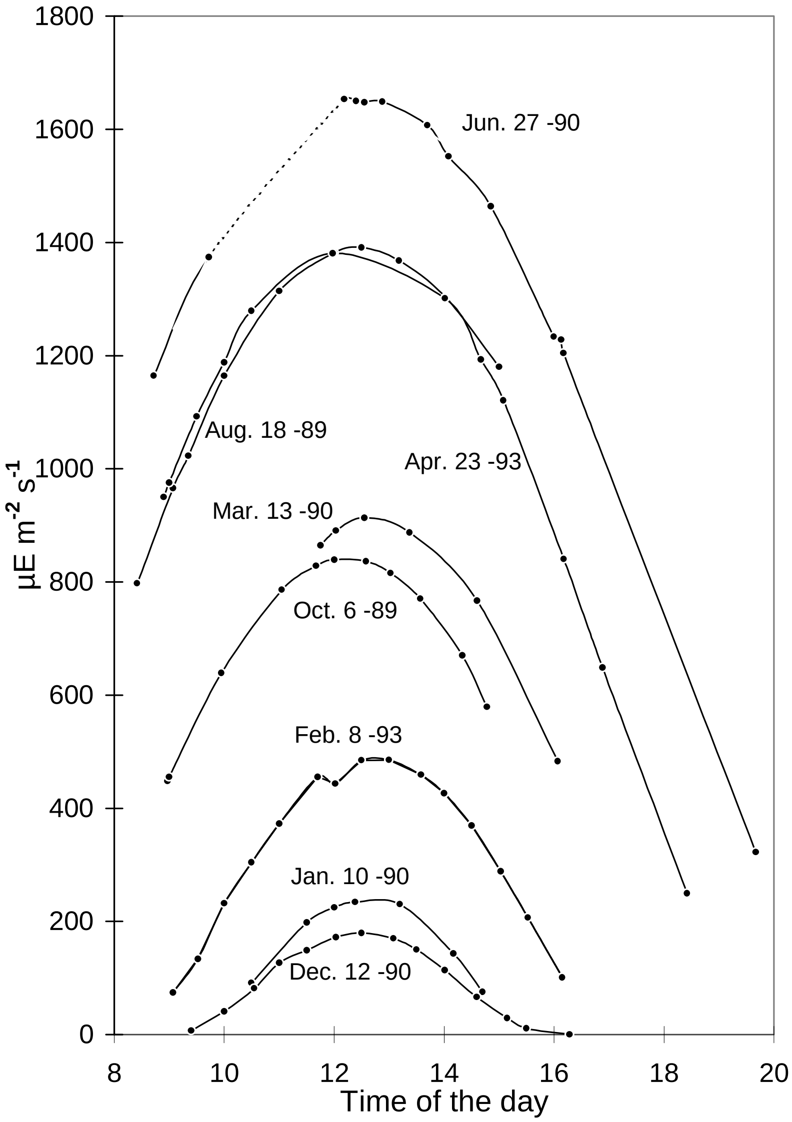

Fig. 2. Changes in total quantum flux density during the day, measured on top of the laboratory building at Tvärminne Zoological Station. On February 8, 1993 a cloud passed at noon, causing a notch in the curve. Local solar noon ≈ 12:40, time = GMT + 2 hrs.

3.2 *Total quantum flux density (QFD)$_t$*

The maximum noon QFD$_t$ changed from about 1.3×10^{21} qu×m^{-2}×s^{-1} in June, when the sun was at its highest altitude, to roughly 1.6×10^{20} qu×m^{-2}×s^{-1} in January (Fig. 3). The apparent minimum in surface light on November 30 is an artefact due to the a lack of recordings during the winter because of unsuitable weather and, occasionally, also ice cover. The real minimum should appear on December 21–22. No recordings were performed under the ice during this period.

In ideal conditions the light intensity at 1 m was within less than one order of magnitude on a yearly scale in ice-free conditions (on March 3, 1994 the light intensity at 2 m was 4.9×10^{17} qu$\times$m$^{-2}\times$s^{-1} under 0.45 m of ice covered by ca 0.2 m of loose snow. The light level was then about similar to that at 6 to 7 m in the ice-free early May 1989 measurement). As the light spectrum becomes narrower with depth (*Tyler,* 1959) the QFD_t decrease is also enhanced with depth, and the range exceeded one order of magnitude already at 3 m (Fig. 3). At 25 m the range exceeded 2 orders of magnitude. During the study period there were several situations with rapid changes in the UWL. The most remarkable light fluctuations took place in the beginning of May and July–August 1989 and February–April 1990. The short-term fluctuations depend on the amount of suspended matter in the water column, mainly plankton biomass. In early May 1989 the water was dark and brownish and there was a heavy plankton bloom which decreased the UWL considerably. Unfortunately there is no plankton data available from that period, but in May most of the algal biomass is normally composed of chain-forming diatoms and dinoflagellates (*Heiskanen,* 1998). At the time for the recording in the beginning of March 1990 there was no permanent ice in the area. The decrease in light intensity was caused by increased plankton biomass. Plankton blooms may also occur under the ice in the study area (*Hällfors and Niemi,* 1974; *Niemi and Åström,* 1987). Plankton biomass may extend deep down, and at 10 m chlorophyll-*a* values 2 to 3 times higher than at the surface have been recorded (*Kuosa*, 1990).

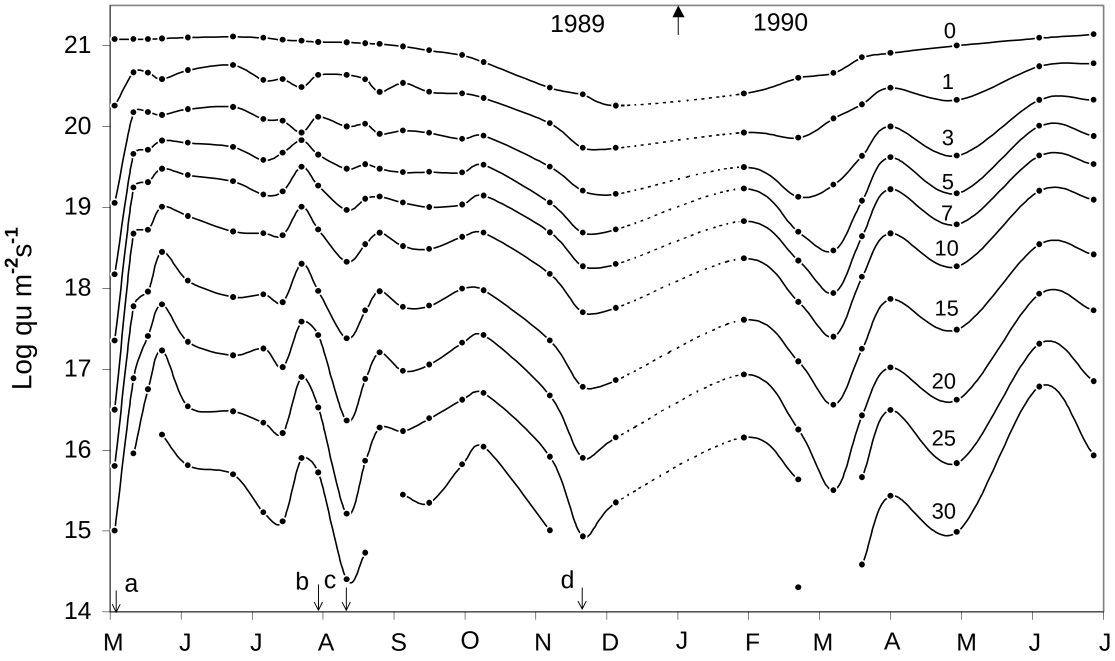

Fig. 3. Log total quantum flux density at 9 depths and water surface from May 2, 1989 to June 20, 1990. Depths, 0–30 m, indicated above the curves. Spectral distribution of light shown for a) May 2 1989, b) July 27 1989, c) August 8 1989, d) November 16 1989 in Figs. 3–6.

3.3 *Spectral distribution of light*

Jerlov (1976) in his classification of different water types in terms of spectral transmittance of downword irradiance classified the open Baltic Sea water as the type "coastal 3", with peak transmission around 550 nm. The spectral distribution of the UWL recorded at the Tvärminne locality shifted somewhat from that value towards longer wavelengths and a clear maximum was observed at about 567 nm (Fig. 4). The difference was probably due to a higher influence of dissolved humus (yellow substances) originating from land at the Tvärminne locality. A series of measurements was performed within a narrow time span on September 12, 1989 at the three different locations. The Pojo Bay is separated from the main water body of the Baltic Sea by a

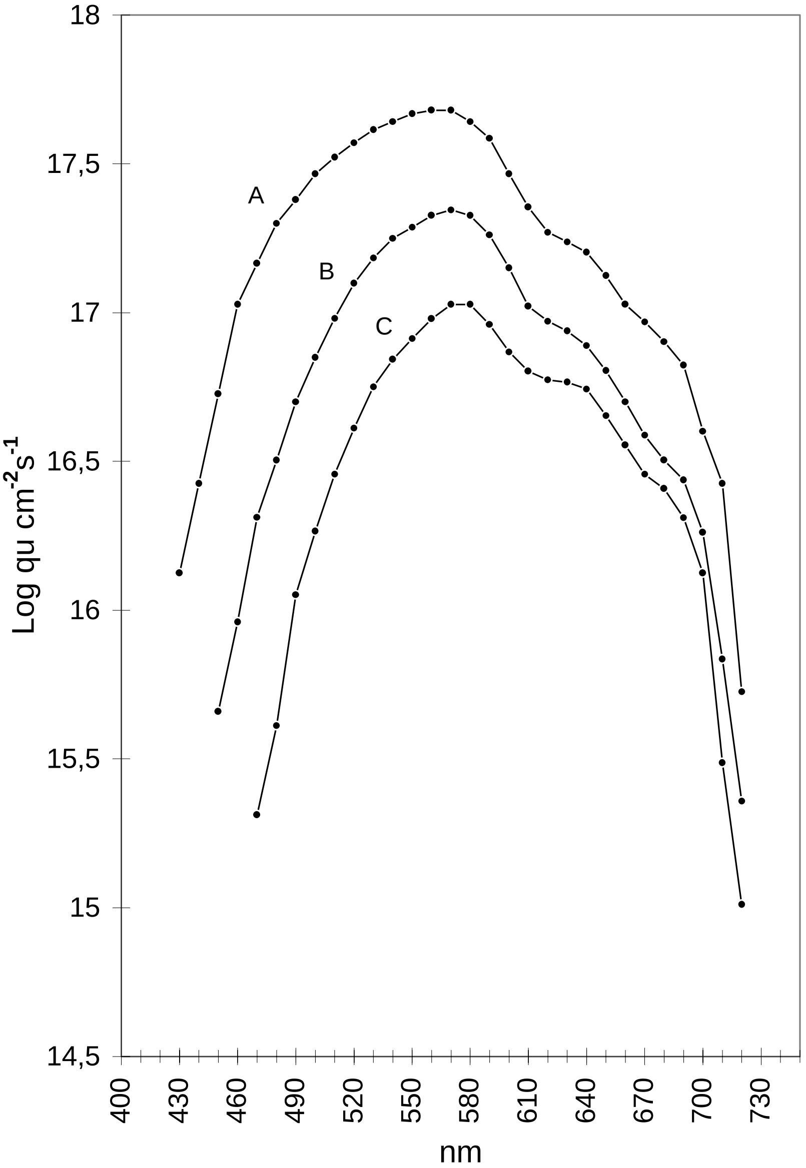

Fig. 4. Spectral distribution of light at 5m depth at A) Ajax, B) Tvärminne Storfjärd and C) Sällvik depth, Pojo Bay on September 12, 1989.

shallow (depth about 6 m) sill, which limits free water circulation, and the colour of the water is fairly brown, 35–45 g Pt m^{-3} (*Niemi,* 1973), if compared to less than 10 g Pt m^{-3} in the open sea at the Ajax buoy, where the influence from land is smaller. The optical properties of the three water types differed in relation to spectral distribution of light (Fig. 4) and transparency (Fig. 5). The dilution of land-originated organic substances is clearly seen in increasing light transmission and a small change of transmission maximum towards shorter wavelengths with increasing distance from the shore. A shift to the opposite direction can be seen when going eastwords along the coast of the Gulf of Finland (*Rissanen et al.,* 1995).

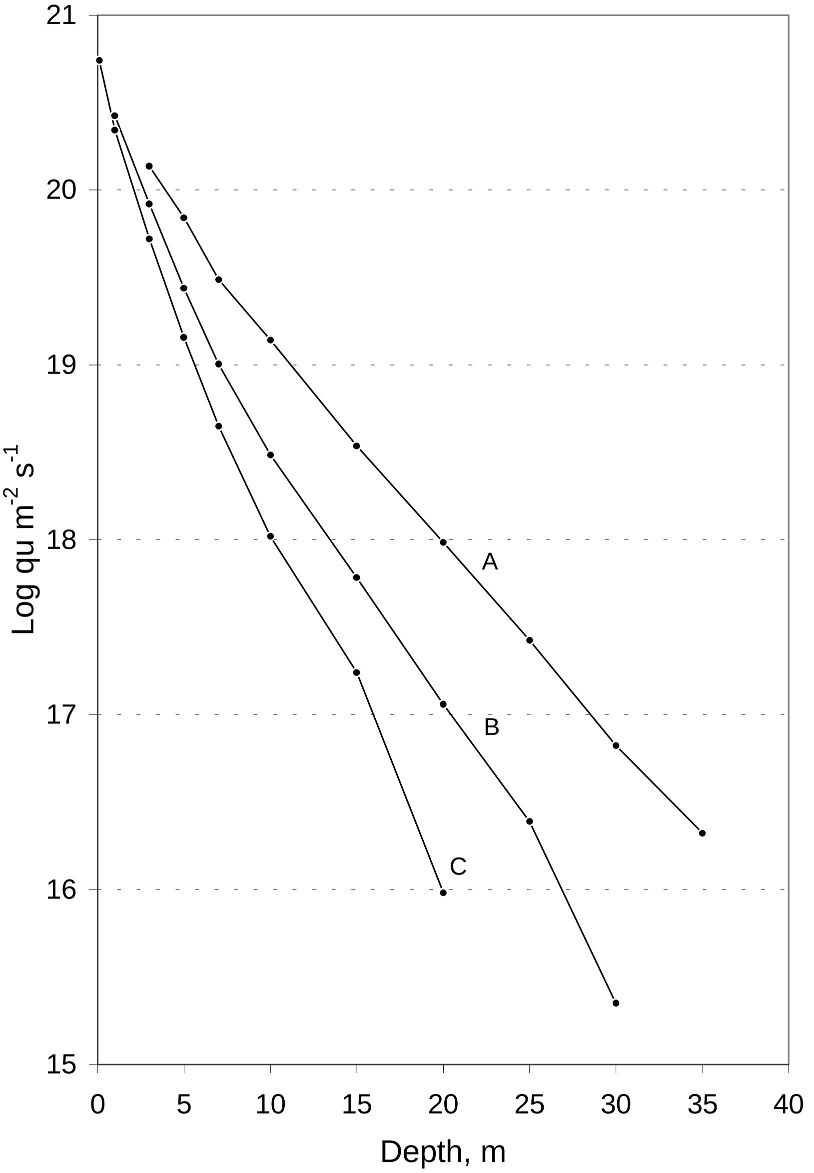

Fig. 5. Log total quantum flux density versus depth on September 12, 1989 at A) Ajax, B) Tvärminne Storfjärd and C) Sällvik depth, Pojo Bay.

The spectral distribution of light at the Tvärminne site remained more or less the same throughout the recording period. The spectral distributions at different depths are shown for periods with clear water (high light transmittance) at high and low solar altitudes, and for situations of intense phytoplankton blooms (Figs. 6–9).The chlorophyll values referred to below were measured by the Finnish Institute of Marine Research close to the dates of the recorded UWL measurements (Index 12, J. Bruun, pers. comm.). The situation on July 27, 1989 (Fig. 7, b in Fig. 3) with low biomass of algae (about 3 mg chl m^{-3} in the surface layers down to 5 m on July 6) in the water mass, may represent a typical spectral distribution of light on a clear summer day. Even at 30 m there is still a lot of detectable light.

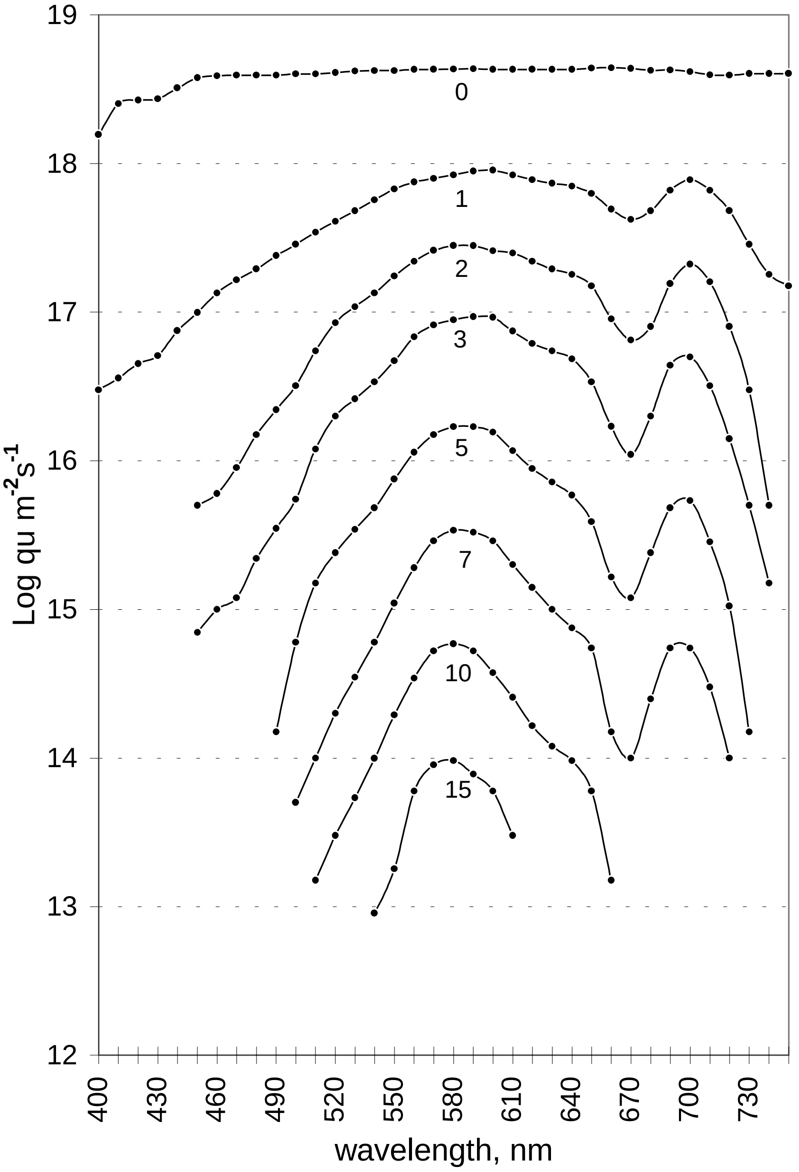

Fig. 6. Spectral distribution of light on May 2, 1989.

On August 8 (Fig. 8, c in Fig. 3) the surface light was about the same as on July 27, but the chlorophyll *a* content had increased to about 42 mg m^{-3} at the surface, 48 mg m^{-3} at 2.5 m and 4.4 mg m^{-3} at 5 m (measured on August 9). At 25 m there was only

10% of the light available less than two weeks ago. The amount of light at 25 m had thereby decreased by more than one order of magnitude. On November 16 (Fig. 9, d in Fig. 3) the light incident on the surface had already decreased to about 19% of the summer maximum. The water was very clear, and the chlorophyll *a* concentration was only about 2 mg m^{-3} in the surface layers (measured on November 21) and there was still measurable light at 25m. As compared to the summer UWL intensities, the intensities in the upper water layers were about one order of magnitude lower and even less at 10 m and deeper (Figs. 3 and 9).

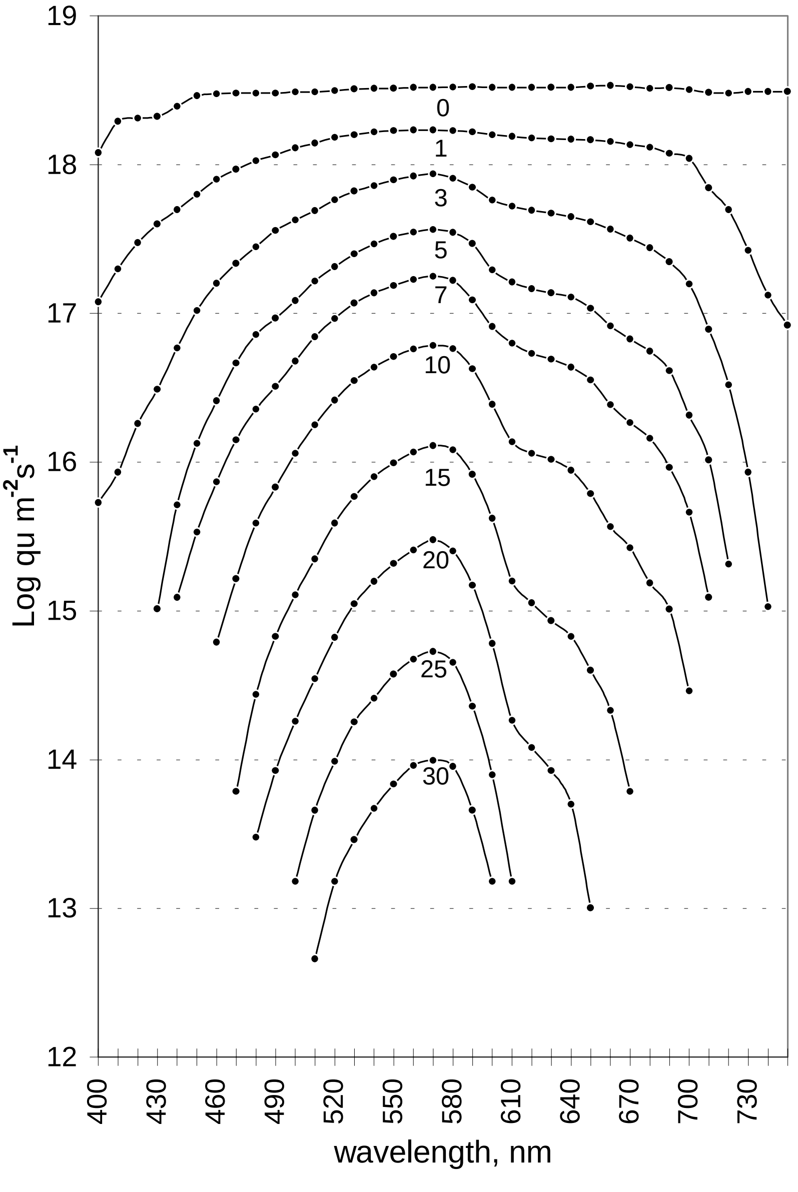

Fig. 7. Spectral distribution of light on July 27, 1989.

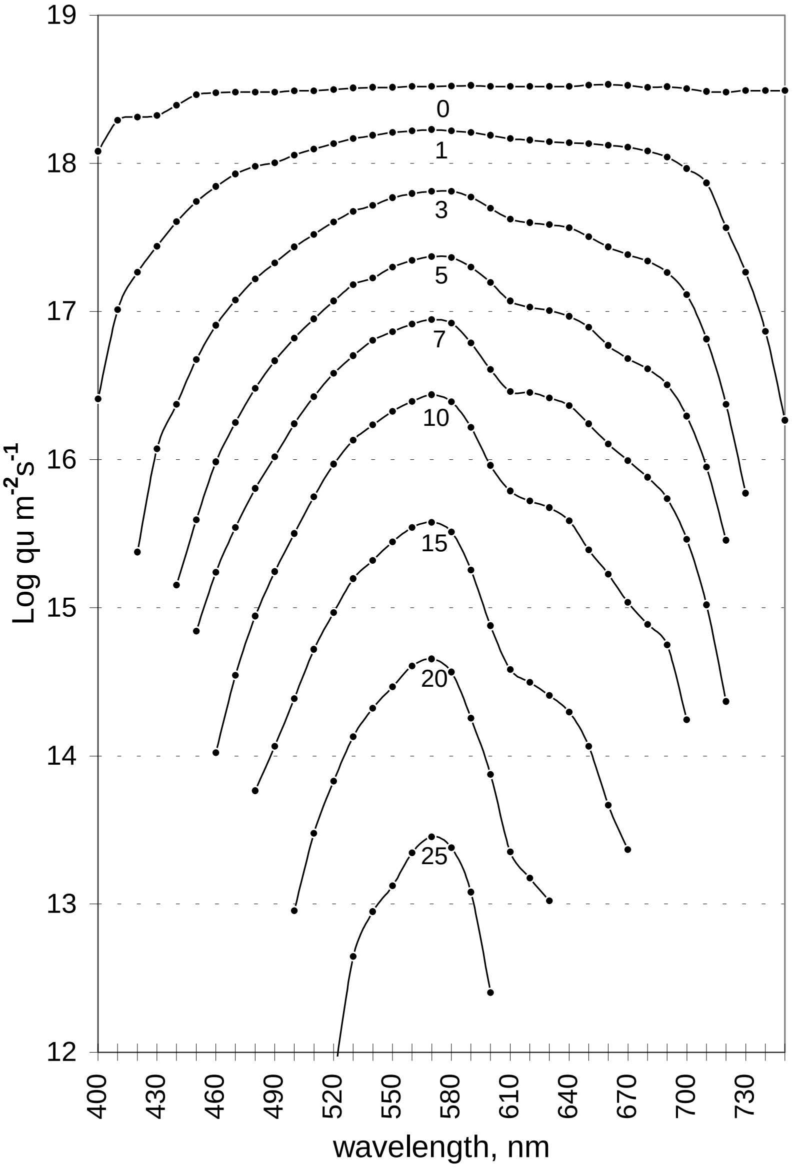

Fig. 8. Spectral distribution of light on August 8, 1989.

On May 2, 1989 there was a massive (65 mg chl m^{-3} at 2.5 m on May 3) phytoplankton bloom (Fig. 6, a in Fig. 3). The situation differed from that of low incident light in having a bimodal spectral curve. The light absorption by phytoplankton occurred at all wavelengths, but especially at the blue and red ends of the spectrum. A remarkable absorption maximum can be seen at 660–670 nm, which coincides with the absorption maximum of chlorophyll a, 665 nm. Although the UWL spectral distribution got a bimodal shape, the wavelengths of maximum transmission remained constant during the whole recording period. The dense plankton bloom in the uppermost water layers absorbed about 85% of the light in the first meter. At 15m there was less than 1% of the light present on July 27 (Fig. 4). The only measurement under the ice (March 3, 1994) also showed unchanged maximum of transmittance, 567 nm.

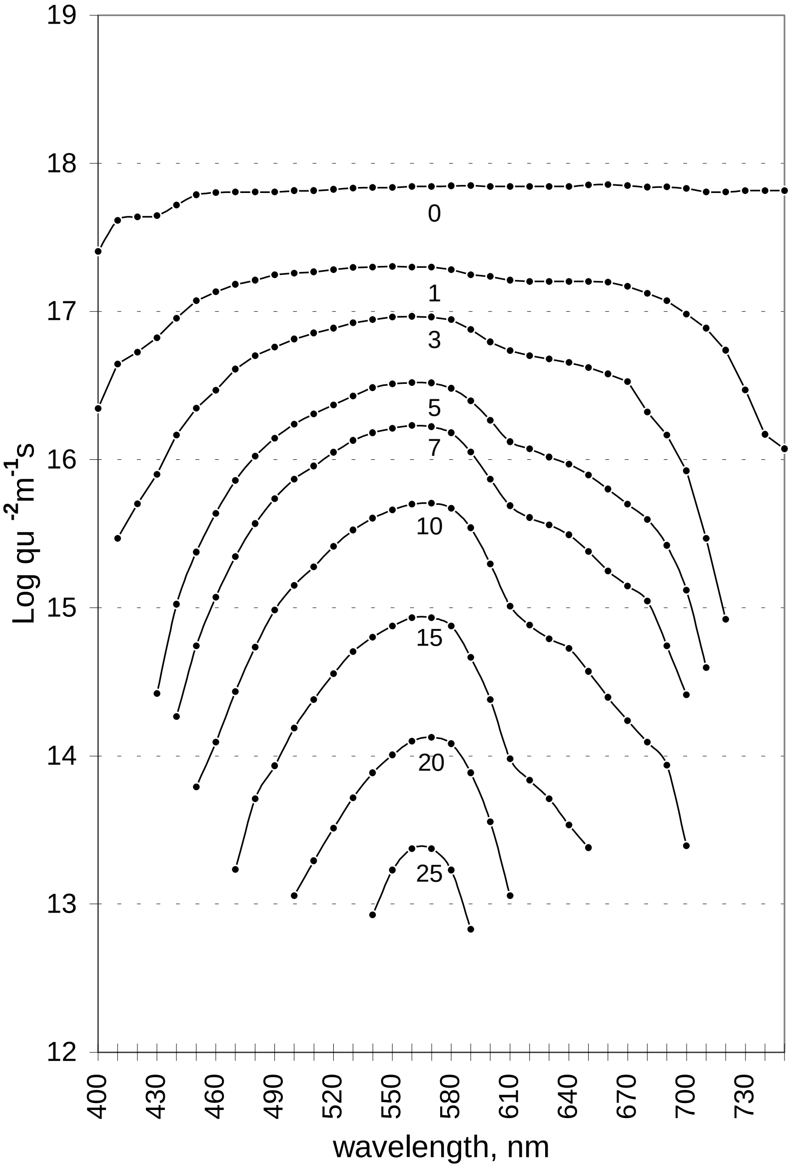

Fig. 9. Spectral distribution of light on November 16, 1989.

3.4 *Short-term changes in spectral distribution of light*

During short periods, some few minutes, at dawn and dusk the underwater light spectrum will change into a two-peak spectrum due to the so called Chappuis effect. At twilight, when the sun is low, the light rays have to pass through a much thicker atmospheric layer before reaching the earth than when at a higher elevation. The atmospheric ozone specifically absorbs yellow-orange light, which will change the shape of the remaining spectrum into a two peak one with maxima below 500 and above 650 nm (*Munz and McFarland*, 1973; *Lindström and Nilsson*, 1988; Fig. 3b). The effect is reset in less than 5 metres due to the absorbing properties of the Baltic water.

3.5 Adaptations of vision to the UWL milieu

The autecology of those aquatic animals which are dependent on light, either for predation or migration, may be strongly affected by changes in the intensity of UWL during the year e.g. because the depths at which they can use their vision will change. In the open Baltic Sea it has been calculated that the amphipod crustacean *Monoporeia affinis* can still see light at 80–90 m depth (*Donner and Lindström*, 1980). At greater depths the light is below the perception threshold of the animal even at full daylight. Light controls the reproduction cycle of *Monoporeia* (*Segerstråle* 1967, 1970, 1971). At greater depths the reproduction is not adjusted to November–December as in shallower waters, and reproduction occurs round the year. The UWL conditions may thus regulate the autecology of a species in different ways in localities not very far from each other.

The amphipod *M. affinis* has a pronounced circadian swimming activity rhythm with a period of 23.4 hours which will persist for almost two weeks in darkness. (*Donner and Lindström,* 1980). The species swims actively during the night. It has however got another rhythm as well, which changes the shape of the nocturnal activity curve in accordance with the length of the night. When kept in constant 12:12 hour light:dark conditions, the latency time before activity onset is long in the summer and short in the winter. Also, in the summer the swimming activity decreases well before light-on, but in the winter activity is high until light-on. *Monoporeia* thus possesses an persistent endogenous rhythm tuned to the slow change of the daylength (*Lindström and Lindström,* 1980).

The spectral sensitivity of the eyes of deep-living aquatic animals is often tuned in nature close to the wavelengths of UWL maximum transmission to be able to maximize the visual information. In *M. affinis* the eye sensitivity maximum is at 550 nm. The animal stays in the bottom mud during the “light” period (*Donner and Lindström,* 1980). It uses its eyes mainly as light indicators, giving information on when it is dark enough (=safe) to ascend from mud. The physiology of eye visual pigment reisomerization of *M. affinis* supports this view (*Donner et al.,* 1994). The mysid crustacean *Mysis relicta* sp. *I* (*Väinölä,* 1986) occurs in waters with different light transmission properties (*Lindström and Nilsson,* 1988). Their eye spectral sensitivities are tuned in direction of the respective UWL transmission maxima. *Hemimysis anomala,* a new mysid species in the Baltic Sea, has its spectral sensitivity maximum at 500 nm (*Lindström,* 2000), which indicates that it originates from waters more clear and better blue-transmitting than the Baltic Sea. The Chappuis effect discussed above speculatively may give a short-time advantage to H. animala because of its blue-tuned eye spectral sensitivity.

The intensities and spectral distributions of light described above represent different times of the year and include different successional phases of phytoplankton at defined depths and times. The light milieu may vary markedly in different water bodies but also within the same water body there may be great annual variations. Great changes in UWL light conditions appear from year to year, depending on climatic factors, amount of melting snow, ice cover, development of phytoplankton bloom e.t.c. The described UWL situations should not be applied to, for instance, lakes with waters of very high or low light transmission. The deep, 86 m, Lake Pääjärvi has maximum transmission at ≈ 672 nm (own measurements) or 652–663 nm (*Reinart et al*., 1998), and at 10 m light could no longer be detected with the QSM (*Lindström and Nilsson*, 1988; for location of the lake see Fig. 1). Animals living in very dark conditions may be extremely sensitive to light, but are also easily damaged by light, because they have no, or weak, eye protecting mechanisms. The mysid shrimp *Mysis relicta* is common in the Baltic Sea but also in lakes. The eyes of the lake Pääjärvi *M. relicta* population are easily destroyed by light, but the population living in a bay of the Baltic Sea does not suffer from light exposure (*Lindström and Nilsson*, 1983; *Lindström et al.*, 1988; *Lindström and Meyer-Rochow*, 1987; *Dontsov et al*., 1999). It is proposed that shrimps living at great depths around thermal vents along the mid-oceanic ridges would become permanently depleted of vision because of the strong lights used by diving equipment (*Herring*, 1999). When designing laboratory experiments or conditions for rearing animals it is important not to over-expose them to light. When designing experiments on primary production it is important to do it in such a way that the light exposure between sample recovery and preparation should not exceed, or contribute to the amount of light absorbed during hours of incubation at specified depths.

4. Conclusions

UWL measurements were performed in the Baltic Sea close to the Tvärminne Zoological Station, University of Helsinki, for 14 months at 9 depths during the ice-free period. The normal annual fluctuations in QFD_t remained close to one order of magnitude in the surface layers, but were enhanced by increasing depth because of the gradual narrowing of the spectral range. Algal blooms rapidly changed the QFDt:s by about one order of magnitude in the surface layers and almost three orders of magnitude at 20 m and deeper. The transmission maximum of light (567 nm) remained the same throughout the year, although the spectrum got a second peak at about 700 nm during plankton mass occurrences, due to heavy light absorption by chlorophyll-*a* at 665 nm. The light transmission maximum changed to slightly shorter wavelengths and the water transparency increased when moving from the Pojo Bay site, with its high input of yellow substances, through the Tvärminne Storfjärd site out to the Ajax buoy site, which is practically unaffected by discharges from land. Morning-to-evening measurements in air showed that the maximum light intensity on the water surface at noon decreased to only about 11 % in winter compared to midsummer intensity, parallel to an official daylength shortening from about 19 hours to only 6 hours. UWL available for photosynthesis and vision thus varied considerably in terms of intensity and duration, thereby imposing physiological and behavioural stress on the aquatic organisms.

Acknowledgements

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