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Annual spatio-temporal variation of the euphotic depth in the SW-Finnish archipelago, Baltic Sea*

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Abstract

We measured depth profiles of underwater PAR (photosynthetically active radiation) together with optically derived turbidity and chlorophyll fluorescence values at 11 sampling stations in the South-West Finnish archipelago of the Baltic Sea. The data were collected eight times during the spring, summer and early autumn of 2010. The results illustrate complex and multidimensional variations in the euphotic depth, which was subject to fourfold and twofold differences in the geographical and seasonal dimensions respectively. The spatio-temporal inconsistency and non-linearity of the seasonal euphotic depth variation calls for further studies at different spatial and temporal scales.

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1. Introduction

Many biological functions in aquatic ecosystems are driven by solar radiation penetrating into the water. Photosynthetically active radiation (PAR, 400–700 nm) – which approximately corresponds to visible light – is crucial to aquatic primary production, for example. Underwater radiation is attenuated as a function of distance by two mechanisms: absorption and scattering (Kirk 2011). The efficiency of these processes varies according to the optical properties of the water, as natural waters contain, in addition to water molecules, an assortment of suspended and dissolved substances. Consequently the quantity and quality of the underwater light vary in space and time, induced by changes in the concentrations of these substances (Dera & Woźniak 2010, Suominen et al. 2010, Woźniak et al. 2011). Thus, underwater light availability must be examined as a multidimensional phenomenon with several spatial (including both horizontal and vertical dimensions) and temporal scales.

In clear oceanic waters, the PAR attenuation is dominated by the seawater itself, and additionally, if present, by chlorophyll and other photosynthetic pigments of living phytoplankton. The optical properties of coastal waters are usually also influenced by the concentrations of suspended particulate matter (SPM) and coloured dissolved organic material (CDOM) (Kirk 2011). In the Baltic Sea, the exceptionally high CDOM concentration places particular demands on optical water research in the area, as many models and algorithms developed elsewhere are not directly applicable (Kratzer et al. 2003, Darecki & Stramski 2004).

The layer in which photosynthesis takes place can be studied by assessing the ratios of photoautotrophic production and heterotrophic consumption within a given time-scale. The compensation depth is the depth at which primary production is equal to all community loss processes, and the critical depth refers to the lower limit of the water column at which vertically integrated productivity balances out integrated losses (Sverdrup 1953, Tett 1990, Kirk 2011).

The thickness of the photosynthetically active water layer can also be estimated indirectly on the basis of underwater light conditions. This is usually done by defining the thickness of the euphotic zone, limited by the euphotic depth, at which 1% of the sea surface PAR remains (Kirk 2011). The absolute amount of PAR at this 1% depth varies somewhat according to the instantaneous conditions, such as cloudiness and solar zenith angle (e.g. Dera & Woźniak 2010). Also, the minimum radiation requirement for photosynthesis varies among phytoplankton species (e.g. Kirk 2011). Nevertheless, according to a study conducted in Finnish and Estonian lakes, the depth at which 1% of the surface radiation remains corresponds well to the depth at which primary production approaches zero (Reinart et al. 2000). Since the definition of euphotic depth based on 1% radiation is commonly used in many underwater light field studies, and since this depth is relatively easy and accurate to determine (Lee et al. 2007), it is used to define the lower limit of the euphotic zone in this study, too.

We present the results of a broad, multidimensional field survey quantifying the dynamics of the euphotic depth in a complex archipelago environment of the Baltic Sea. So far, knowledge about the underwater light field in the area has been based on Secchi depths or indirect estimates according to concentrations of optical constituents. As far as we know, this is the first attempt to quantify the light field in a more direct and accurate way. We address the principal spatio-temporal variations in the euphotic depth and PAR attenuation from a geographical perspective, emphasizing their significance in the region's environmental dynamism. The research questions are: 1) what kind of changes take place in the underwater light field during the growing season, and 2) are these changes geographically and temporally consistent? Additionally, we compare these changes with the changes in suspended sediment and phytoplankton concentrations estimated in situ by optical sensors.

2. Material and methods

2.1. Study area and sampling scheme

A non-tidal marginal sea located in northern Europe, the Baltic Sea is a brackish water basin that has very limited water exchange with the North Sea, and which is partially ice-covered every winter. This study focuses on the SW-Finnish archipelago, where thousands of islands make up one of the largest archipelago areas in the world (Leppäranta & Myrberg 2009). The sea surface openness decreases gradually from the outermost archipelago towards the mainland. The water area is very shallow, 23 metres on average, with the deepest points reaching 100 m. The varying bathymetry gives rise to small sub-basins separated by shallow thresholds that restrict water exchange, retaining turbid waters (Kirkkala et al. 1998, Erkkilä & Kalliola 2004, Suominen et al. 2010).

The water column is mixed vertically every spring and autumn, causing the summer and winter thermoclines to disappear. The summer thermocline typically lies at a depth of 15–20 m. The water salinity in the region varies between 5.5 and 6.5, and there is no stable halocline. Wind, water inflow and temporary currents form local, short-lived water layers of different densities (Kirkkala 1998).

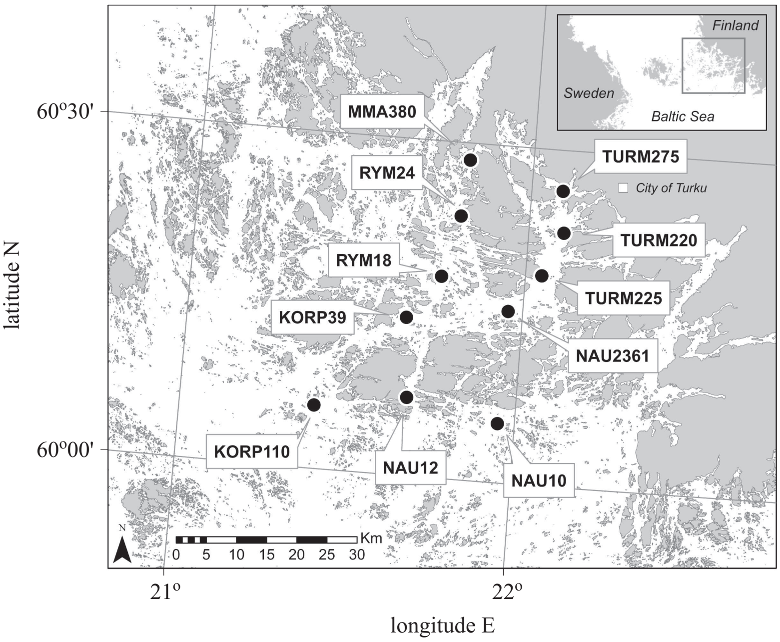

Figure 1. The study area and the sampling stations

Our in situ measurement campaign comprised 11 sampling stations covering a range of environmental settings, including inner, middle, and outer archipelago zones; shallow and deep waters; and areas with high or low human influence (Figure 1). The stations are located within an area 45 km by 40 km, with distances of 7–16 km separating adjacent stations. With one exception, the measurements were made every third week from late April to early October in 2010. Each station was visited eight times during the field season.

The weather conditions during 2010 were variable, but rather typical of the region. The preceding winter had been colder than average, but some periods of April and May were warm. June was relatively cold. The surface waters warmed up rapidly during the warm high summer season in July and August, when several heat peaks occurred (FMI 2010). In July, mass occurrences of cyanobacteria were abundant, but during the late growing season their levels were low (The Baltic Sea Portal 2010).

2.2. Field measurements

Light measurements were made using LI-COR quantum sensors (LI-COR Biosciences, USA), which measure the amount of radiation as μmol s^{-1} m^{-2} in the 400–700 nm wavelength area. We used an underwater spherical quantum sensor (model LI-193) that measures the scalar irradiance of PAR range from nearly all directions, and is therefore highly suitable for photosynthesis studies (Kirk 2011). Scalar PAR measurements are also less sensitive towards changes in the Sun's altitude than measurements of downwelling PAR (Stramska & Frye 1997). Determining the complete spectrally resolved irradiance would be the most informative way of measuring underwater PAR. However, if this is not possible, measuring the entire PAR waveband as a spectrally integrated single reading (combining all the wavelengths within 400–700 nm) is more suitable for studies addressing photosynthesis than concentrating on only single wavelengths or very narrow wavebands (Kirk 2011). In parallel to the underwater measurements, a terrestrial quantum sensor (LI-COR model LI-190, cosine collector) was used to monitor the changes in the incoming radiant flux above the sea surface.

The measurements were made from a small (length $\sim$5 m) boat with an outboard motor. During the measurements, the motor was turned off to prevent false readings caused by water turbulence or exhaust emissions. The measurements at each station took 10–15 minutes, during which time the boat drifted freely. All the measurements were performed between 08:00 and 19:00 hrs, which was considered appropriate given the prevailing summer solar angles at latitude 60°N. Solar noon is around 13:30 hrs in this area. All times are local daylight saving times.

We started by measuring the scalar irradiance of the PAR range just below the sea surface in order to establish the amount of radiation entering the water. The surface measurements were made by holding the instrument underwater by hand, as close to the surface as possible without actually breaking the surface, and recording several irradiance readings. After the surface measurement, the recordings were made at one metre intervals. The maximum depth of the profile was adjusted to the depth of each sampling station, the shallowest station allowing only a 5 m measurement depth. At deep water stations, the maximum measurement depth was 20 m. At least three separate data recordings were logged from every depth using an LI-1400 data logger (LI-COR Biosciences, USA).

We recorded water quality parameters with a YSI 6600 V2 multiparameter sonde (YSI Inc., USA) simultaneously with the measurements of the scalar irradiance of PAR. Their synchronized use was possible as the underwater PAR sensor and the YSI sonde were fixed together in the same instrument set. We measured chlorophyll fluorescence (sensor model YSI 6025) to estimate the amount of phytoplankton, and turbidity (6136) as a proxy for the concentration of suspended solids. Both parameters were measured in situ by optical sensors. The turbidity sensor emits near infrared radiation and registers the amount of light scattered by the particles in the water. Similarly, the chlorophyll sensor emits blue light (a peak wavelength of approximately 470 nm) and measures the red wavelengths that are re-emitted by the fluorescence of photosynthetic pigments (YSI 2009). These are commonly used proxy parameters even though the correlation between turbidity and total suspended solids varies somewhat according to changes in the properties of the particles (e.g. size and shape) (Minella et al. 2008); moreover, besides chlorophyll, phytoplankton species also contain varying amounts of other photosynthetic pigments (Kirk 2011). The data were saved in a hand-held data logger (YSI 650MDS) using a recording interval of two seconds. The multiparameter sonde measures the depth of the instrument, which enables very accurate depth profiling.

The optically derived readings of the YSI sonde should be controlled by laboratory analyses of water samples. The sonde used in this study was calibrated during a previous research campaign conducted in the same sea area, and the experience gained from those measurements supports the use of optical sensors (Suominen et al. 2010), which enable a large number of samples essential for geographical studies of water quality parameters, to be taken. Therefore, we did not repeat the laboratory control with our optical data; hence, the chlorophyll concentration RFU (chlorophyll, Relative Fluorescence Units) and turbidity NTU (turbidity, Nephelometric Turbidity Units) values reported in this study are not regarded as absolute concentrations. Instead, they are internally coherent relative values that allow the spatio-temporal comparisons to fulfil the needs of this study.

2.3. Data processing

The levels of the scalar irradiance in the PAR range at the different measurement depths were defined by first removing the outliers, if they existed, and then computing the average of the remaining readings. The outliers, identified as values that deviated by more than 20% from the median of the particular depth, occurred most often in the uppermost part of the water column and were predominantly caused by wave action (fluctuations in the light level due to the focusing effect, and difficulties in holding the sensor immediately underwater when measuring below-surface values in rough sea conditions). The averaged absolute PAR values were then calibrated using the incoming solar flux above the sea surface as a reference. The reference level, defined separately for each PAR profile, was the level of solar radiation measured with the terrestrial sensor at the time of the below-surface measurement. The amount of increase or decrease in incoming radiation was assumed to increase or decrease the underwater readings by the corresponding percentage. After this calibration, for each depth, the corrected values of PAR (expressed as μmol s^{-1} m^{-2}) could be converted to relative values representing the amount of radiation remaining (in per cent) from the below-surface level. The lower limit of the euphotic zone was determined as the depth to which 1% of PAR penetrated.

The attenuation efficiency in the water was quantified by calculating $K_{(\mathrm{PAR})}$, which is the attenuation coefficient for the total spectrum of PAR expressed in units of m^{-1}. The coefficients were defined by plotting the natural logarithms of the absolute PAR values against their measurement depths and computing the slope of the resulting line (Kratzer et al. 2003, Pierson et al. 2008). These coefficients were defined according to the attenuation profiles within the euphotic zone, and thus represent the average diffuse attenuation within the zone (Lee 2009). Furthermore, the attenuation coefficients per metre were calculated according to

$$K_{\mathrm{m}}(\mathrm{PAR}) = \frac{\ln(I_1/I_2)}{Z_2 - Z_1},$$

where I_1 and I_2 are the respective measured underwater light intensities at depths Z_1 and Z_2.

The proxies for suspended solids and phytoplankton concentrations were averaged for each depth from six consecutive readings of the original data measured with the YSI sonde's turbidity and chlorophyll sensors (see also Suominen et al. 2010). Negative values, slightly below zero, resulting from the sensors' inability to detect extremely low values, were converted to 0. When comparing the stations with each other, we used averaged water quality values from 1 to 5 m, as this is the maximum range covered in all the depth profiles.

We used hierarchical cluster analysis to classify the sampling stations in the SW-Finnish archipelago according to their optical water quality. The input data included each station's euphotic depths, and the averages of in situ measured chlorophyll fluorescence and turbidity, using data from all eight measurement weeks separately. We used linear regression analysis to identify the importance of the two measured attenuating components to the attenuation efficiency in the surface waters of the three optical zones.

3. Results

The attenuation profiles revealed major differences among the sampling stations in general but also among the sampling dates of the respective stations (Figure 2). The minimum, maximum and average attenuation coefficients ($K(\mathrm{PAR})$) covering the euphotic zones were 0.25, 1.73 and 0.57 m^{-1} respectively. The vertical diffuse attenuation coefficient also varied within the profiles, as in less than half of the cases the log-linear plots resulted in straight lines. Straight lines would have indicated optical

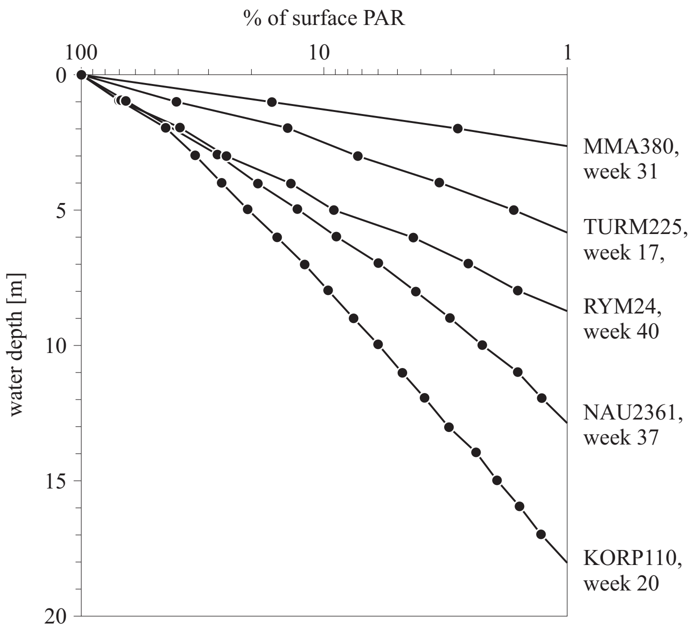

Figure 2. Examples of actual PAR attenuation profiles from the surface to the euphotic depth (note: log-linear scales). The sampling station and week are indicated for each profile. MMA380 shows the highest and KORP110 the lowest attenuation in our data

homogeneity of the water masses. Generally, the light attenuated more efficiently near the surface than in the deeper layers of the euphotic zone.

The seasonal and geographical variability of light attenuation induced substantial variations in the euphotic depth (boxplot in Figure 3). The euphotic depth varied from 2.8 m to 18.0 m within the 88 profiles, with an average of 9.6 m. Two major patterns were detectable in the euphotic depth dynamics. First, according to the general spatial trend, the euphotic depth increased from the inner archipelago towards the outer archipelago. The difference between the clearest and the most turbid station was approximately fourfold in any sampling week. Secondly, the general seasonal development in the euphotic depth showed distinctive periodicity: low values in early spring, an increase in late spring, a decrease in high summer, an increase in late summer and a decrease in autumn.

Comparisons made between the individual stations revealed major dissimilarities in both the spatial patterns and the temporal dynamics of the euphotic depth (map in Figure 3). At some stations, no distinctive decrease in the euphotic depth was observed in the autumn. At the most turbid stations of the inner archipelago, no clear seasonal pattern was found in the euphotic depth development. It is noteworthy, however, that even

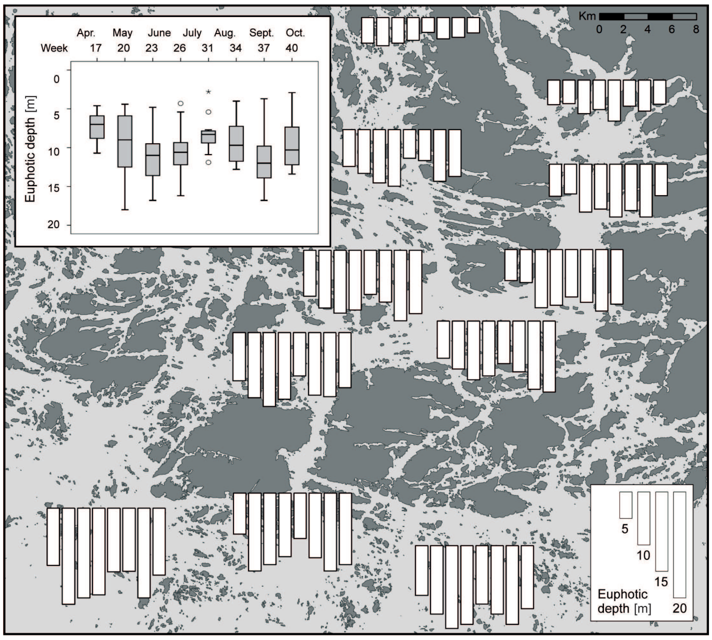

Figure 3. Spatio-temporal variation of euphotic depth shown on a map, where individual euphotic depths are plotted as time series graphs at the station locations (for exact station locations, see Figure 1). The boxplot shows the respective temporal variation of euphotic depth at the 11 sampling stations

at the stations where the seasonal variations were obvious, the timing and magnitude of these changes differed – even between adjacent stations. In other words, the development of the euphotic depth, meaning increases and decreases in light penetration, did not proceed simultaneously throughout the study area. In absolute numbers, the euphotic depth ranges were, in general, greatest in the outer archipelago, where the underwater PAR levels were the highest. However, the relative differences between the highest and lowest depth measured at one station during our field campaign were approximately twofold at all the stations throughout the study area.

Of the two water quality parameters measured, the chlorophyll fluorescence changed simultaneously with the euphotic depth in the outer archipelago, while the impact of the changes in turbidity was more evident close to the mainland (maps in Figure 4). The optically estimated proxy for phytoplankton concentration usually peaked during the first measurement week, but then decreased, to slightly grow again in high summer. Temporal changes in the turbidity estimates were more irregular, the most notable patterns being geographical rather than temporal. Turbidity was strongly

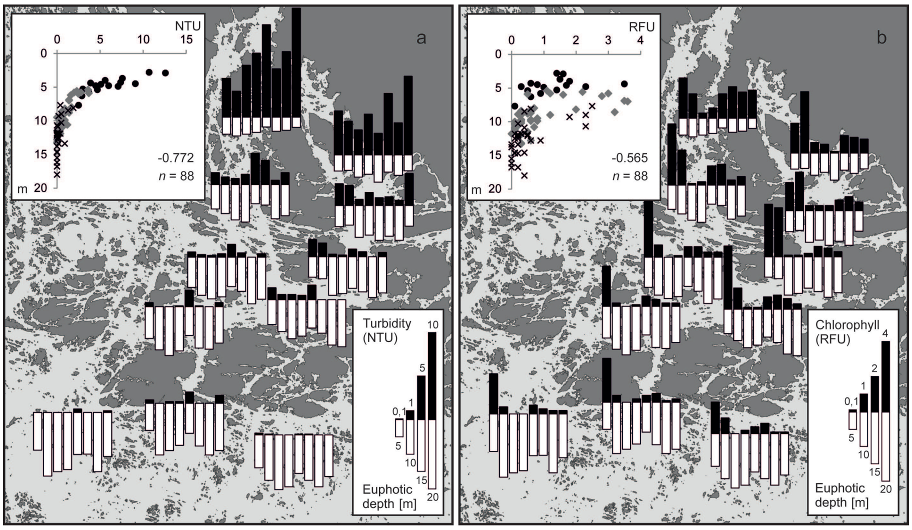

Figure 4. Variations of a) turbidity and b) chlorophyll fluorescence with euphotic depths (for timings, see Figure 3; for exact station locations, see Figure 1). The scatter plots and correlation coefficients (Pearson) show the relations between the parameters: each point represents the average value of the water quality variable (1–5 m depth) and the corresponding euphotic depth at the different sampling stations and weeks. The stations are classified into three archipelago zones according to the hierarchical cluster analysis; black dots represent the innermost archipelago zone, grey dots the middle zone, and crosses the outermost zone

correlated with euphotic depth, but the correlation between chlorophyll fluorescence and euphotic depth was somewhat weaker (scatter plots in Figure 4). The correlation between the in situ measured chlorophyll fluorescence and turbidity was, as such, weak (R^2 value 0.288).

The hierarchical cluster analysis grouped the stations into three optical zones: the innermost zone with the most turbid waters (MMA380, TURM275), the outermost zone with the clearest waters (KORP110, NAU12, NAU10 and KORP39), and the middle zone between these extremes. The ability of turbidity values to explain the variation of the attenuation efficiency was high in the innermost archipelago zone, but decreased towards the middle and outermost zones (R^2 values 0.913, 0.781 and 0.436 respectively). Conversely, the role of estimated chlorophyll concentration increased towards the outer archipelago (0.108, 0.413 and 0.511 respectively). The combined explanatory power of these two parameters (data not shown) decreased with distance from the mainland. All the results are statistically very significant (p-values 0.000), except in the case of chlorophyll fluorescence in the inner zone (0.213).

4. Discussion

Our results quantify strong multidimensional variations in the efficiency of underwater light attenuation and the euphotic depth within the studied coastal sea. The temporal changes in the euphotic depth are approximately twofold, and the geographical differences are fourfold. Previous studies from the Baltic Sea coasts have revealed patchiness in the distribution of optical water quality parameters (e.g. Giardino et al. 2010, Suominen et al. 2010). This patchiness is also visible in our results, which link water quality variations to variability in the underwater light field. These results highlight the optical complexity and dynamism of this coastal archipelago area.

Of the two water quality parameters that we measured, turbidity, the proxy for suspended particulate matter, appears to have a stronger influence on the water optics in the inner archipelago, whereas chlorophyll fluorescence, the proxy for phytoplankton concentration, plays a strong role in the outer archipelago. However, the remarkably high turbidity near the mainland may simply be overriding the effects of attenuation by phytoplankton. Additionally, since the chlorophyll sensor is not designed to detect cyanobacteria, the overall effects of the summer blooms are probably underestimated.

CDOM is often referred to as the primary absorber of PAR in the Baltic Sea (e.g. Kowalczuk et al. 2005, 2010). In coastal waters, the main sources of CDOM are river discharges, bottom sediments and biological production, whereas photo-oxidation processes at the surface act as a CDOM sink (Boss et al. 2001). In the Baltic Sea, there is great seasonal variability in CDOM characteristics, concentrations typically reflecting changes in river runoff (Kowalczuk et al. 2010, Asmala et al. 2012). Consequently, as Finnish rivers tend to carry relatively high CDOM concentrations, the highest CDOM attenuation efficiencies of Finnish coastal waters are found close to the river mouths (Asmala et al. 2012). The importance of CDOM in the total attenuation process is lower in highly turbid coastal waters, where the concentrations of other substances are high (Lund-Hansen 2004). This could explain why, in the innermost archipelago, suspended solids and phytoplankton are estimated to have a greater combined effect on total attenuation than in other parts of the study area. The lower coefficient of determination in clearer waters suggests a stronger dominance of CDOM absorption.

The SW-Finnish archipelago acts as a mixing zone for the runoff from the mainland and the water flow from the surrounding pelagic areas. From time to time, the euphotic depth is affected by a momentary surface layer flow event, rather than by stable local conditions. Occasional currents and the amalgamation of water masses may give rise to radical changes in surface water quality even within short time periods (Erkkilä & Kalliola 2004). More frequent measurements and a denser sampling network would be needed to detect such changes, yet in situ sampling will never be sufficient to detect all the relevant seawater changes in time and space (Sathyendranath & Platt 1990).

Due to the complex spatio-temporal variation of the optical constituents, we discourage the use of simplified mean values describing the underwater light field in the coastal waters of the Baltic Sea. For instance, using the average euphotic depth of this study (9.6 m) as a static input variable in ecological models would be a harsh oversimplification, and much of the observed variation (range 2.8–18.0 m) would be lost as a result.

Our study shows that a thorough understanding of the dynamic underwater light field is needed in the parameterization of underwater optics in coastal waters. Alvarez-Cobelas et al. (2002) expressed concern about the common practice of measuring optical properties of lakes only once a year: they pointed out that one measurement from one site at one time did not enable the underwater light field of the whole lake to be properly characterized. According to our results, this notion is also valid in the coastal environment. But again, more extensive datasets may be problematic if they are spatially or temporally biased. Moreover, no great advantage is to be gained from using datasets with good coverage in only one dimension, be this geographical or seasonal, as they do not consider the multidimensional dynamics of the underwater light field. In conclusion, we urge caution whenever any aspect of underwater solar radiation is used as a parameter in models of the coastal marine environment.

5. Conclusions

The underwater light field in the archipelago coastal waters of SW Finland is a dynamic and complex environmental variable, which is crucially important to the coastal ecosystem. The efficiency of light attenuation varies in many dimensions and scales across space and time. Summarizing, the geographical differences in euphotic depth remained about fourfold within our study area for the duration of the growing season, whereas the seasonal variability within each sampling station was approximately twofold. Even though the amount of underwater PAR generally increased from the relatively turbid waters of the inner archipelago towards the outer archipelago, where the temporal fluctuations are more strongly linked to the phytoplankton concentration, the internal dynamism within both the study area and period varied rather a lot. The light attenuation efficiency also varied in the vertical dimension. Future attempts at water quality assessment and ecological modelling should increasingly acknowledge the complex spatio-temporal dynamics of the underwater light field in the coastal waters of the Baltic Sea.

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