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Annual and long-term water transparency variations and the consequent seafloor illumination dynamics in the Baltic Sea archipelago coast of SW Finland

Harri Tolvanen, Tapio Suominen and Risto Kalliola

Department of Geography and Geology, FI-20014 University of Turku, Finland

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The availability of photosynthetically active radiation (PAR) is one of the limiting factors of marine primary production. In coastal waters, the proportions of optical constituents vary, causing changes in water transparency, and consequently the rate of seafloor illumination. We illustrate this phenomenon geographically in seasonal and long-term perspectives on the archipelago coast of SW Finland in the Baltic Sea, using data from 21 Secchi measurement stations. The results indicate vast spatial and temporal variation of the proportion of illuminated seafloor area, which, in this study, is defined as the seafloor above the estimated euphotic depth (where over 1% of the surface PAR remains). The seafloor illumination undergoes an annual cycle, during which a quarter of the studied seafloor area is illuminated only for a part of the growing season. Based on long-term Secchi data, we estimate a 50% decrease in the total illuminated seafloor area from 1930 to 2007.

Introduction

Water transparency is a significant environmental variable in marine ecosystems, since it affects the thickness of the surface water layer where photosynthetically active radiation (PAR, 400–700 nm) is available. PAR is scattered and absorbed in the water column, and its intensity decreases as a function of depth (e.g. Kirk 2011). As the availability of PAR limits the occurrence of photosynthesis, water transparency should be seen as a critical variable of marine ecosystem functionality, comparable in significance to water temperature or nutrient supply (e.g. Schramm 1999, Kirk 2011).

The availability of PAR affects not only the phytoplankton ecology, but also the benthic ecosystems, since it sets the depth limit for macrophyte occurrence (Kautsky *et al*. 1986, Breuer and Schramm 1988, Dennison *et al*. 1993, Schramm 1999, Domin *et al*. 2004), and controls the vertical distribution of biomass within the euphotic zone (Pierson *et al*. 2008). It also influences the vigour of aquatic species, populations and communities.

The euphotic depth, Z_{eu}, determines the lower limit of the euphotic zone, which is usually defined as the layer of natural water from the surface until the depth where 1% of the surface PAR remains (Tett 1990, Kirk 2011). This definition is generally used to represent the lower limit of the water column where photosynthesis can occur, even though Z_{eu} is a complex function of the local optical water properties, which change

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in different time scales according to biotic and abiotic processes.

Coastal waters are especially prone to seasonal and random changes in the optical water properties, and consequently to dynamic variation of the seafloor illumination. In shallow coastal waters, the euphotic zone often extends to the seafloor, and sustains benthic primary production by seagrasses, macroalgae, microphytobenthos, and corals (Gattuso *et al*. 2006).

Season, time of day, latitude, atmospheric conditions, and water surface roughness affect the amount of solar radiation that penetrates the water. Downwelling irradiance, E_d, (the light energy transmitted downwards in the water) weakens approximately exponentially with depth (Beers law) (e.g. Kratzer *et al*. 2003, Kirk 2011). The attenuation coefficient of PAR ($K_{d(PAR)}$) indicates the rate of visible light loss per distance travelled in the water. The Secchi disc is a robust, quick, and simple method to measure water transparency *in situ*. Observing the visibility of a disc lowered to water results in a quantified figure as depth in meters, which is called the Secchi depth (Z_{SD}), even though it is rather a qualitative measure of the water transparency. However, Z_{SD} provides a good estimation of water transparency concerning the visible light wavelengths in general. Z_{SD} can be used to estimate $K_{d(PAR)}$ when local conditions are known (Poole and Atkins 1929, Holmes 1970, Gordon and Wouters 1978, Walker 1982, Devlin *et al*. 2008). However, in practice Z_{eu} is often roughly estimated in coastal waters by multiplying Z_{SD} by 3 (Holmes 1970). It should be noted, however, that the availability of underwater PAR is not directly proportional to the water transparency. In this paper, we refer to Z_{eu} as the computational estimate of the lower limit of the euphotic zone rather than the actual euphotic depth, which must be established by other means.

We introduce a geographical approach to the dynamic light conditions of the coastal benthic environment by estimating the magnitude of the seasonal patterns and long-term trends in the spatial arrangement of the illuminated seafloor areas. We apply annual *in situ* Z_{SD} data, as well as results from longer time series to compute the extent of the permanently or temporarily illuminated seafloor, and thereby identify the spatiotemporal developments at different scales. Our study area is located on the Baltic Sea coast in SW Finland, characterized by shallow and variable bathymetry, and highly dynamic hydrological conditions. During the recent decades, the decreasing seafloor PAR availability has been an apparent consequence of coastal eutrophication (Bonsdorff *et al*. 1997), and both seasonal and short-lived changes in water transparency have been observed (Erkkilä and Kalliola 2004, Suominen *et al*. 2010a).

Material and methods

Study area

The Baltic Sea is a stratified, brackish marginal sea on a shallow basin at the NW Eurasian continental edge. Due to the high proportion of coloured dissolved organic matter (CDOM, also called yellow substance) and suspended particulate matter (SPM), the Baltic Sea is considered an optical Case-2 water area (Mueller and Austin 1995, Siegel *et al*. 2005, Kowalczuk *et al*. 2006, Pierson *et al*. 2008), where the optical conditions are influenced also by factors other than phytoplankton and their products. CDOM absorbs light especially in the blue and green parts of the spectrum, and CDOM content has been shown to be inversely related to salinity (Højerslev *et al*. 1996, Bowers *et al*. 2000, Siddorn *et al*. 2001, Kratzer *et al*. 2003, Branco and Kremer 2005, Kratzer and Tett 2009).

The regional differences in the ratio of organic to inorganic substances in the Baltic Sea are caused by variation in the timing and volume of local phytoplankton occurrences, as well as the river sediment load (e.g. Gallegos *et al*. 2005, Kratzer and Tett 2009). Despite the optical classification, the phytoplankton blooms have a major cyclical influence on the water transparency in the Baltic Sea coastal waters. The Baltic Sea has a positive water balance by high freshwater input and limited water exchange with the North Sea (Kowalczuk *et al*. 2005). The Baltic Sea surface water shows a horizontal salinity gradient from the north and east to the narrow straits in the south-west. Thus, also the CDOM content has a north–south gradient, adding to the

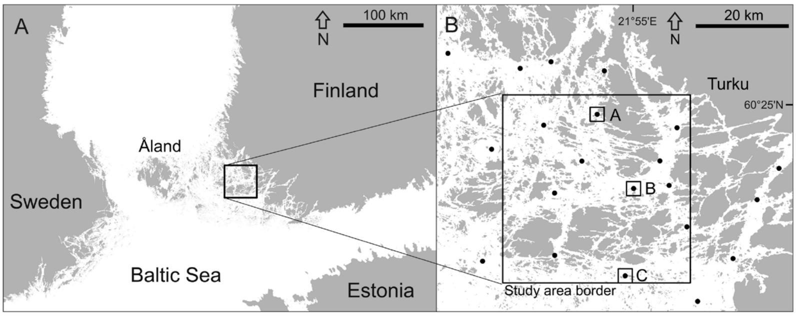

Fig. 1. Location of (**A**) the study area, and (**B**) the study sites (A, B and C) on the SW Finnish coast. The dots indicate the 21 Secchi depth measurement stations used to create the interpolated Z_{SD} surfaces. The study area border indicates the area for which the illuminated seafloor estimations were calculated.

complexity of the water optics. Earlier studies of the underwater light conditions of the Baltic Sea have focused mostly on the southern coasts (Dera and Woźniak 2010).

The SW Finnish archipelago is a complex, shallow coastal zone, which acts as a threshold and mixing area between the Baltic Sea Proper and the Gulf of Bothnia (Fig. 1). The region includes thousands of islands, straits, and semi-closed sub-basins of different sizes and shapes. Several small rivers discharge into the inner archipelago, contributing to the sediment and organic substance content of the sea water. The average water depth in the region is 22 m, which suggests that the PAR availability is significant not only for phytoplankton, but also for the benthic habitats.

There are spatial and seasonal gradients in Z_{SD}, chlorophyll content (Suominen *et al.* 2010a), and salinity (Suominen *et al.* 2010b), indicating complex interactions between the different processes that contribute to the optical water properties. Turbidity is, in general, high close to the mainland, and decreases gradually towards the open sea (Suominen *et al.* 2010a). In the inner archipelago, the suspended material consists predominantly of inorganic particles from river discharge, while in the outer parts, it is increasingly dominated by organic material (cf. Kratzer *et al.* 2003). Short-lived flow events and water mass amalgamation occur in the area in response to temporary Baltic Sea water balance deviations and wind influence (Erkkilä and Kalliola 2004).

We analysed the seafloor illumination dynamics on the SW Finnish archipelago coast on the northern Baltic Proper in a study area of 40 km by 40 km (1600 km^2), out of which 63.1% (1009 km^2) is water (Fig. 1). Three study sites were established for detailed analysis, each 3 km by 3 km (9 km^2) in size with a Z_{SD} sampling station in the middle. Site A is located in the inner archipelago, site B in the middle archipelago, and site C on the edge of the outer archipelago.

Data collection and analysis

Altogether we measured 168 Z_{SD} values *in situ* at 21 sampling stations, 11 of which are within and 10 around our study area (Fig. 1). Each station is located in relatively open and deep water. Z_{SD} values were measured using a round disc with 100 mm diameter during the growing season 2007 in three-week intervals on eight occasions from mid-May to early October (Suominen *et al.* 2010a). We defined the Z_{SD} as the depth where the Secchi disc became completely invisible. The measurement series form a spatio-temporally coherent, general model of the water transparency dynamics in the area during the year 2007.

The Z_{SD} values were converted to raster surfaces using a procedure based on the inverse distance weighted (IDW) interpolation method (e.g. Longley *et al.* 2001, Chang 2002). Instead of using Euclidean distances, we calculated path distances along the water surface from each sampling point, and named the method inverse path distance weighted (IPDW). This calculation was made by applying a cost raster surface, in which the water areas have a value of 1, with land areas assigned a high value to prevent the path from crossing land surfaces (for details, *see* Suominen *et al.* 2010b).

The interpolations resulted in eight weekly Z_{SD} layers over the area covered by the 21 sampling stations. The layers were computed

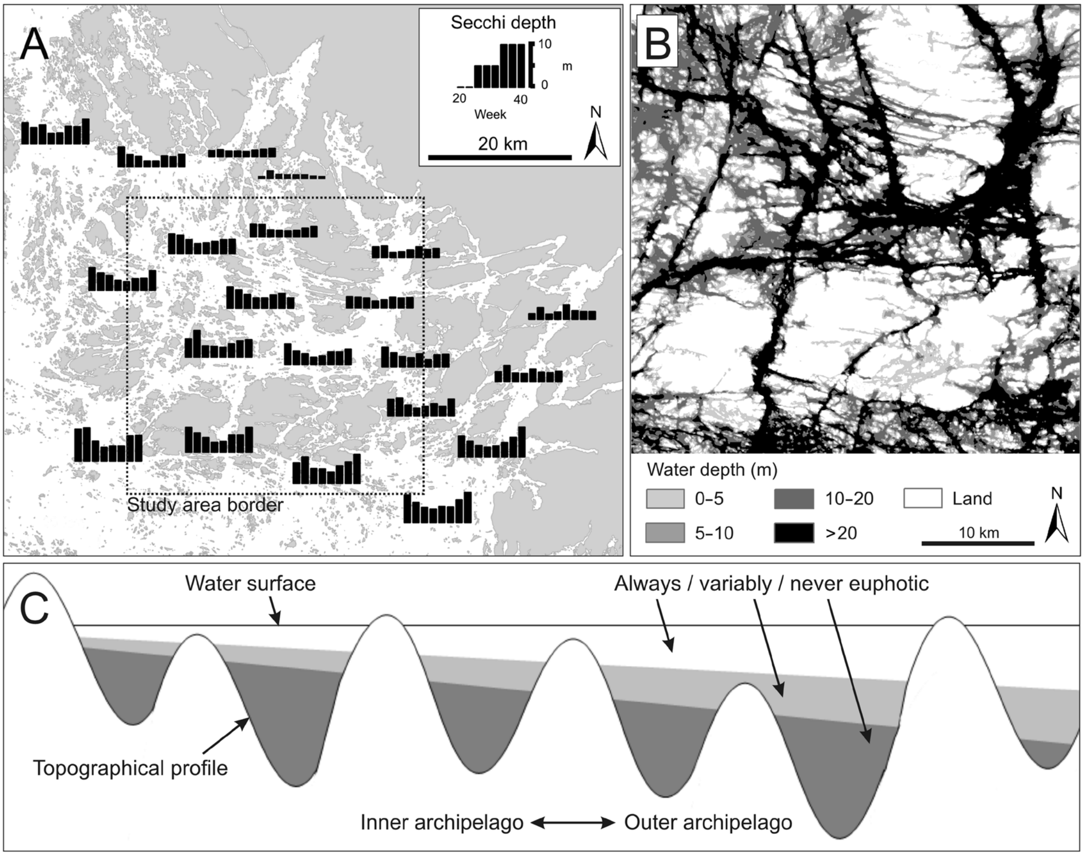

Fig. 2. (**A**) Z_{SD} in the 2007 (*in situ* data). Bar charts of the weekly values are placed at the locations of the measurement station. The bars indicate the Z_{SD} values from weeks 20, 23, 26, 29, 31, 34, 37 and 40. (**B**) Bathymetric map of the study area. (**C**) A schematic profile illustrating the effect of the spatio-temporal changes in water transparency upon the proportion of the illuminated seafloor on an archipelago coast.

in a raster cell 5 m in size to coincide with the bathymetric model. The 40 × 40-km study area was clipped from the interpolated layers, which were then converted to Z_{eu} by multiplying the Z_{SD} values by 3. The method is supported by Holmes (1970), who suggests that the factor 3.5 is the most appropriate conversion coefficient in waters with Z_{SD} smaller than 5 m, and the factor 2.0 should be used in waters with Z_{SD} between 5 m and 12 m. In our data, only 6% of the Z_{SD} observations exceed 5 m.

As the seafloor topography in this region is detailed and complex, we created an enhanced bathymetric model that combines the standard bathymetric data available from the Finnish Maritime Administration, and elevation data for the nearby shores (Fig. 2B) (for details, *see* Stock *et al*. 2010). The bathymetric model was computed with the same 5 m resolution than the Z_{SD} layers. Each of the eight weekly Z_{eu} layers was overlaid with the bathymetric model to identify the seafloor areas that fall within the computed euphotic zone. In practice, this was done by subtracting the Z_{eu} value from the depth value in the bathymetric model, and distinguishing the result as positive (seafloor above Z_{eu}) and negative values (seafloor below Z_{eu}). The spatio-temporal variability creates a complex system, where different parts of the region undergo different water transparency cycles, promoting variable seafloor illumination patterns (*see* Fig. 2C for a schematic presentation). We also calculated the variation in the number and area of continuous illuminated areas, or patches, to portray the effect of the potential light availability as a spatial ecosystem factor in the benthic habitats.

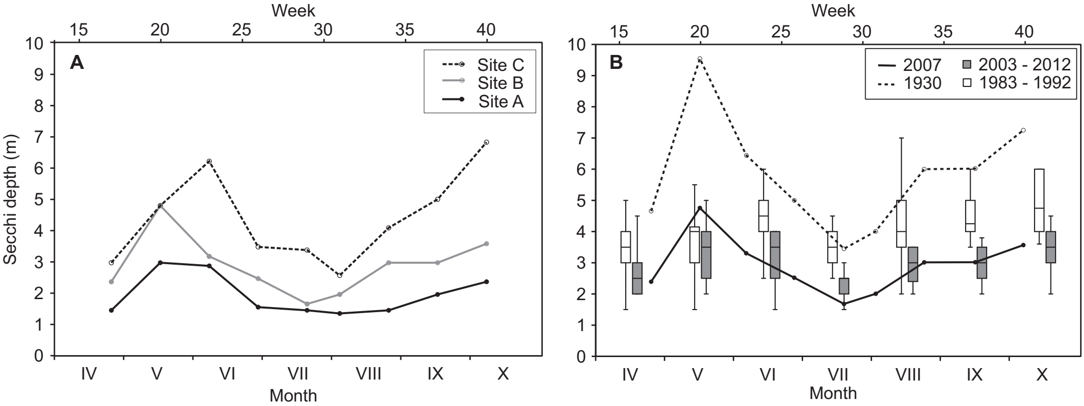

Fig. 3. (**A**) Z_{SD} of 2007 measured *in situ* at study sites A–C. (**B**) Comparison of the Z_{SD} values at study site B: the 10-year periods 1983–1992 and 2003–2012 are presented as box-plots, and the *in situ* data of 2007 with the doubled Z_{SD} scenario for 1930 are presented as lines.

The Z_{SD} time series in the Baltic Sea spans over a century (Sandén and Håkansson 1996, Laamanen *et al*. 2004). Statistical studies of these time series suggest that average Z_{SD} in the northern Baltic Sea and the SW-Finnish archipelago has decreased annually by about 0.05 m (Sandén and Håkansson 1996), causing a collapse from 10 m to 5 m between 1930 and 2007 (Laamanen *et al*. 2004). Following these results, we addressed the long-term changes in our study area by assuming an equal Z_{SD} decrease of 50% throughout our study area from 1930 to 2007. Thereby, our assessment of the annual Z_{SD} development in 1930 in our study area is made by doubling the corresponding values of the *in situ* data from 2007.

Results

Water transparency

The Z_{SD} values in the region in 2007 indicated low water transparency in early spring, followed by clearer water in late spring and early summer, decreasing transparency in high summer, gradually increasing again towards autumn (Fig. 3A). However, considerable differences among the Z_{SD} values occurred at different stations (Figs. 2A and 3A). At stations near the mainland, water transparency was generally low, while in the outer parts of the study area, the water was clearer (Figs. 2A and 3A).

The Z_{SD} values ($n = 168$) ranged from 0.6 m to 7.8 m, with the median of 2.7 m, and standard deviation of 1.5 m. The highest weekly median (4.6 m) occurred in week 20, and the lowest (2.1 m) in week 29. The highest seasonal Z_{SD} range by station was 4.7 m (2.3–7.0 m), and the lowest was 0.7 m (1.2–1.9 m). The general seasonal Z_{SD} patterns at local study sites A–C resembled each other, yet there was some variation in the timing of peak events (Fig. 3A). A distinctive spatial water transparency gradient from the inner to the outer archipelago was also apparent.

We used the Finnish Environment Institute's database to study the Z_{SD} values from study site B, the only sampling site in the region for which a longer coherent data series is available. The monthly average Z_{SD} values for two 10-year periods (1983–1992, $n = 119$ and 2003–2012, $n = 139$) reveal a clear Z_{SD} decrease between the two periods (Fig. 3B). Our *in situ* data from 2007 are comparable to the data from 2003–2012 (Fig. 3B).

Illuminated seafloor

In 2007, the seafloor illumination was at its widest during the late spring (week 20), when 49% of the studied seafloor area was illuminated (Fig. 4). The smallest proportion of illuminated seafloor (25%) occurred in late July and early August (weeks 29 and 31). Thus, 24% of the seafloor was illuminated for only a part of the

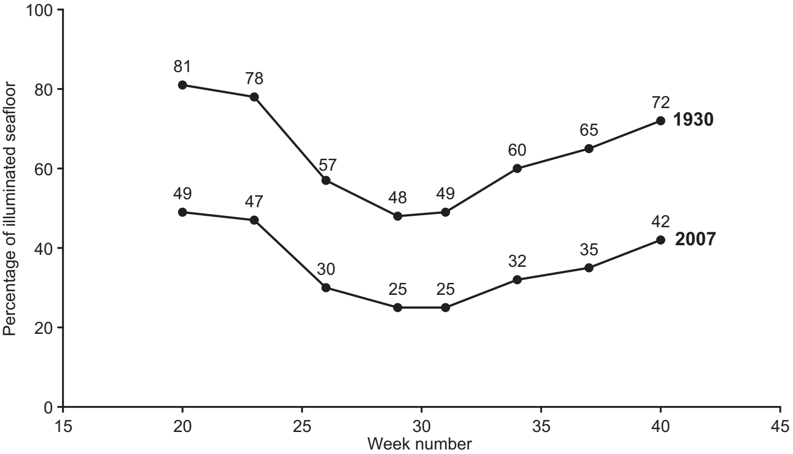

Fig. 4. Calculated percentages of illuminated seafloor in the study area (1009 km^2 of seafloor) in 1930 and 2007.

study period. The least seafloor illumination on the part-time illuminated areas occurred during the warm-water season from June to early September. The computed estimate for the year 1930 suggests that the maximum extent of the illuminated area covered 81%, and the minimum illumination corresponded to 48% of the total seafloor area. Thereby, the proportion the seafloor that was illuminated for only a part of the modelled season in 1930 was 33%.

The duration of the illuminated periods at different water depths also changed considerably from 1930 to 2007 (Fig. 5). For example, the depth class 15–20 m varied between ~0% and ~90% illuminated in the season 1930, but the same class was dark for almost the entire season in 2007. Respectively, nearly 100% of the depth class 5–10 m was illuminated throughout the season in 1930, but in the 2007, the proportion of illuminated seafloor at this depth varied between 30% and nearly 100%.

In spatial examination, the illuminated seafloor areas occurred as large patches in late spring when the water transparency was the highest (Fig. 6). The less transparent the water became towards the high summer, the more fragmented the illuminated seafloor grew to be. This is indicated by the increase in the number of illuminated seafloor patches, and a subsequent decrease in their average size (from nearly 25 ha to under 10 ha).

The spatial configuration of the illuminated seafloor showed seasonal and inter-annual dynamics (Table 1 and Fig. 7). When comparing

Table 1. The percentages of illuminated seafloor at study sites A–C during the minimum and maximum Z_{SD} events in 1930 (estimated values) and 2007 (after actual Z_{SD} data). Percentages in boldface are the proportions of part-time illuminated seafloor. Spatial patterns of the respective computed light field areas are shown in Fig. 7.

Site		Week	1930 (estimate)		2007	
			Z_{SD} (m)	Illuminated seafloor (%)	Z_{SD} (m)	Illuminated seafloor (%)
A	Minimum	31	2.8	33.1	1.4	17.6
	Maximum	20	6.0	72.5	3.0	35.2
	Range		3.2	**39.4**	1.6	**17.6**
B	Minimum	29	3.4	21.8	1.7	9.2
	Maximum	20	9.6	56.4	4.8	35.3
	Range		6.2	**34.6**	3.1	**26.1**
C	Minimum	31	5.2	46.1	2.6	18.3
	Maximum	40	13.6	99.5	6.8	60.4
	Range		8.4	**53.4**	4.2	**42.1**

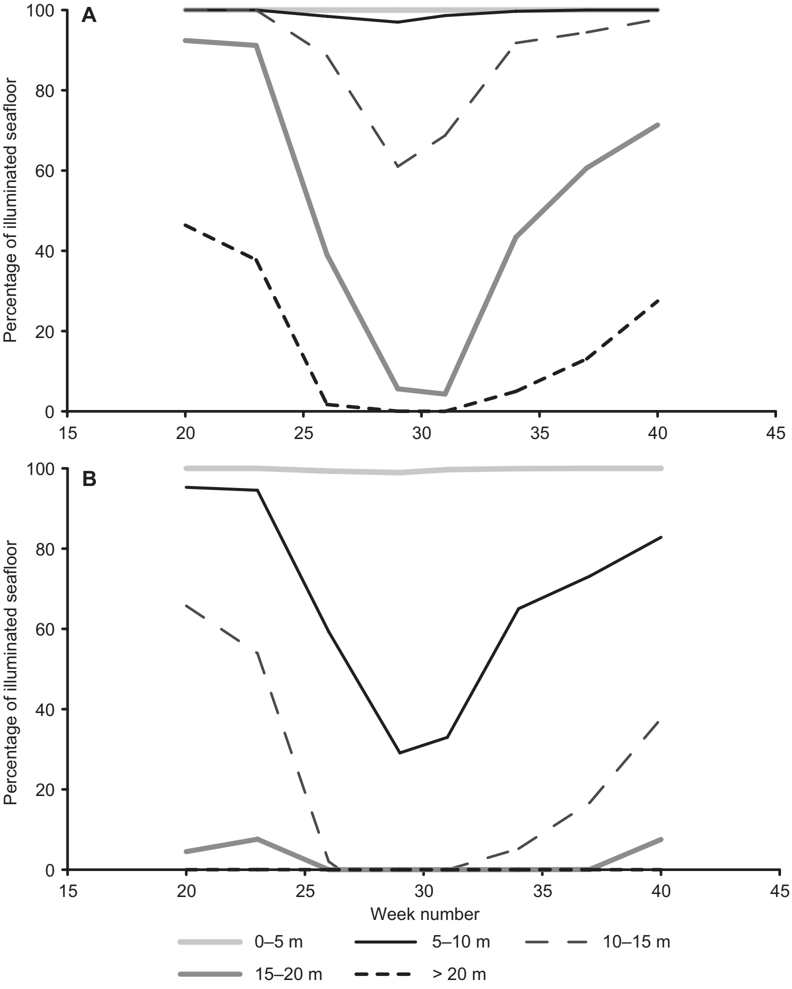

Fig. 5. Calculated percentages of illuminated seafloor in 5-m depth classes throughout the growing seasons of (**A**) 1930 and (**B**) 2007 in the study area.

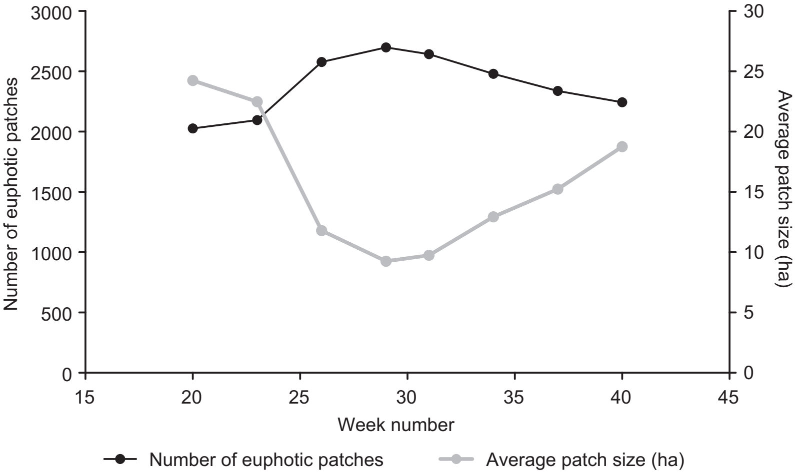

Fig. 6. Number of illuminated patches and the average illuminated patch size (ha) in the study area in 2007.

the years 1930 and 2007, both the absolute areas of the illuminated seafloor and their seasonal change patterns were dissimilar. For example, in the outer archipelago (site C), the seafloor was

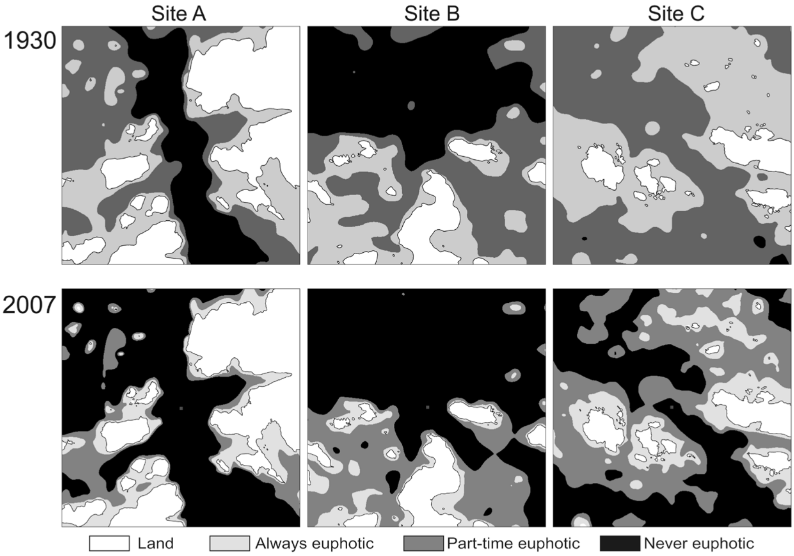

Fig. 7. Projected extents of the annual minimum and maximum illuminated seafloor at study sites A–C in 1930 and 2007. See Table 1 for details.

predominantly illuminated in 1930, while 39% of its area was permanently dark in 2007. When considering permanently illuminated seafloor areas alone, their extent has diminished by 60% at site C. At sites A and B, the respective reductions were 47% and 58% in the permanently illuminated seafloor, and 52% and 37% in the maximum extent of part-time illuminated seafloor. Study site C is shown as an example of the spatial patterns of the seafloor illumination in terms of the number of illumination days per season during 2007 (Fig. 8). This classification indicates different zones within the part-time illuminated area, which may support species that tolerate different periods of darkness during the growing season.

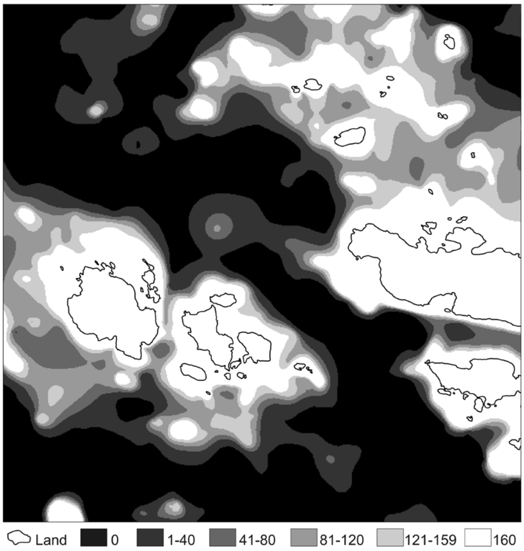

Fig. 8. The number of days when the seafloor was classified as illuminated at the study site C during the studied 160-day period in 2007.

Discussion

Seafloor illumination changes

There are major alterations in the quality and spatial arrangement of the seafloor illumination in the coastal waters of the Baltic Sea. Focusing on one of the key elements of photosynthesis, the results draw attention to the physical controls of benthic ecology from a spatio-temporal point of view. Light energy distribution patterns may, for example, provide a meaningful framework for box-core sampling during ecological inventories, or help to map successional mosaics in benthic community structure and associated biogenic processes (Rhoads and Germano 1986). Some seasonal events, such as spring runoff turbidity peaks or pelagic algal blooms were not simultaneous throughout the study area. For example, the highest Z_{SD} of the measurement period occurred in the middle archipelago in week 20 (study sites A and B), but not until in week 23 in the outer part (study site C).

The estimated 47%–60% decrease in the permanently illuminated seafloor at our three study sites between 1930 and 2007 indicates a directional environmental change and potential ecological stress. This implies that all seafloor areas in the region have experienced decreasing illumination, and considerable seafloor areas have become permanently dark. The reduction of always or part-time illuminated seafloor likely leads to a decrease in the nutrient binding capacity of the ecosystem through a decrease in photosynthetic biomass. Eutrophication itself causes further decrease of Z_{eu} by inducing a shading effect on the surface layers through increasing algal biomass (Krause-Jensen *et al.* 2009).

Also, the seasonal patch dynamics of the seafloor illumination may be ecologically important. The type of light regime that was typical to the middle archipelago in the 1930s exists nowadays only in the outer archipelago. The effects of these changes are reflected in a decline of seafloor vegetation and macroalgae (e.g. Vogt and Schramm 1991, Schiewer 1998, Koch 2001), and as an upward migration of the littoral zones (e.g. Cederwall and Elmgren 1990, Kiirikki 1996, Schramm 1999, Malm and Isæus 2005, Krause-Jensen *et al.* 2009). The illuminated patch dynamics are particularly striking on fragmented archipelago coasts of the Baltic Sea, whereas on simple coastlines, the patch number variation is much smaller.

Although the availability of PAR on the seafloor is not simply on or off, the physical controls of the shallow water benthic ecology may be addressed as a cumulative function of the quantity, quality, and periodicity of available light. For example, the duration of the illumination time during a single growing season may be critical for some species, and thereby also for the benthic habitat characterization. However, the ecological significance of the underwater patch dynamics is hardly known at all, considering the abundant studies on landscape, patch, and within-patch factors that contribute to species survival and abundance in the terrestrial environment (e.g. Thornton *et al.* 2011).

Methodological considerations

The Baltic Sea coasts present a special case, where many independent and interacting processes, such as phytoplankton growth, turbidity, and yellow substance affect the optical properties of the sea water (Siegel *et al.* 2005). The complexity of seafloor illumination dynamics extends beyond the water transparency, and the optical properties of the sea water. The number of daily and yearly sunlight hours depends on latitude, and atmospheric conditions contribute to the local quantity and quality of incident light that reaches the water surface (e.g. Dera and Woźniak 2010, Keevallik and Loitjärv 2010). The water surface reflects a part of the incoming radiation, according to the solar angle and surface roughness, i.e. waves and ripples. On the Baltic Sea coasts, also the winter season ice cover with overlying snow causes periods of darkness in the water.

Our *in situ* measurements and respective analyses confirm considerable spatio-temporal variation in the water transparency, and consequently in the computational illuminated seafloor. These changes occur annually over short time spans during the ice-free season, as well as over decades. Essentially, our study is a simplification of a very complex natural phenomenon, which is affected by a multitude of co-existing factors. Thus, even though our aim is to present the geographical dynamics of seafloor illumination as accurately as possible, we do not claim that the presented values are absolutely precise. Rather, our results offer a quantified basis to assess the ecological importance of the phenomenon.

The analysis methods should be critically assessed in order to interpret the results. First, the Z_{SD} measurements, which are primary data, comprise a quantitative parameter as depth in meters, but qualitative in nature as a simple visual index of water transparency (Tyler 1968, Holmes 1970, Preisendorfer 1986). However, Z_{SD}, while robust, measures many of the variables that affect the underwater PAR attenuation, and it is relatively independent of measurement conditions, the person who measures, and the size of the Secchi disc (Tyler 1968, Holmes 1970, Preisendorfer 1986). Thus, the observed spatial and temporal dynamics of Z_{SD} are considered to correspond relatively well with the true variation of the sea water optics in the area.

Z_{SD} is also, by far, the most widely available data type for studying the Baltic Sea water transparency, and the time series over several decades make the Z_{SD} records the only source data type that enables long-term change detection.

Second, the use of a fixed coefficient (3.0) in computing the Z_{eu} likely causes some local error in a complex archipelago environment. However, there are no reference data available for using a scalable coefficient when converting Z_{SD} to Z_{eu}, and no available independent variable to which the scalar coefficient could be tied to. Thus, the fixed coefficient provides the best overall estimate of the Z_{eu} (*see* e.g. Holmes 1970). Additionally, as the estimated Z_{SD} values for 1930 are two times higher than those measured in 2007, they would, theoretically, require a smaller coefficient when converted to Z_{eu}. However, even though a higher proportion of the Z_{SD} observations fall into the 5–12 m category in the case of 1930, the fixed coefficient 3.0 was used to avoid a step from coefficient 3.0 to 2.0 when crossing the 5 m threshold Z_{SD} value (*see* Holmes 1970).

Third, the bathymetric source data are occasionally sparse, and the inevitable inaccuracies in the bathymetric model alone cause some local deviation. However, the occasional shortage of the bathymetric source data occurs mostly either in very shallow areas, where the seafloor is practically always illuminated, or in areas deeper than 20 m, where the seafloor usually is not illuminated. Also, the spatial interpolation of Z_{SD} data from 21 points over a complex archipelago area does not portray the true local variability, especially in embayments and other shallow semi-enclosed waterbodies. As our goal is not to present site-specific water transparency data, but to focus on the range and magnitude of the variation in general, our spatial and temporal sampling frequencies serve this purpose well.

For all the above mentioned reasons, our analysis does not provide detailed and accurate local illuminated seafloor data everywhere, and it is not intended to do so. Instead, it is a conceptual model from which summaries of seafloor illumination dynamics of larger areas can be made. Even though the individual illumination values may not be accurate at every raster pixel, the regional and temporal variation ranges are representative, and the general variation patterns around the study area reliably reflect the reality.

Methodological limitations are not uncommon in marine studies. For example, standard water quality monitoring data may be collected from a few sites once or twice a year only, but they are nevertheless used to represent the conditions over long periods and large areas of the coastal sea (Erkkilä and Kalliola 2007). In comparison, our three-week sampling interval is temporally quite dense, but it might still miss very short-term dynamic events, especially the growth and drifting of phytoplankton.

Remote sensing data offer comprehensive spatial coverage, and provide feasible data for many oceanological studies, including estimations of Z_{SD} and Z_{eu} (e.g. Morel *et al.* 2007, Shang *et al.* 2011). However, they suffer from the lack of uninterrupted water pixels in shallow and scattered archipelago areas. Improvements in spatial resolution, together with algorithm development improve their usability in studies of coastal water transparency, also in Case-2 waters of small-scale archipelagos (Doerffer *et al.* 1999, Kratzer *et al.* 2003, Darecki and Stramski 2004, HELCOM 2004, Kowalczuk *et al.* 2005, Kratzer *et al.* 2008).

The optical constituents of the coastal waters show strong interdependences, and some parameters can be used as proxies for others (Foden *et al.* 2008, Devlin *et al.* 2009). Development of geographical analysis methods for the quantification of environmental parameters improves the understanding of the spatio-temporal relationships between different coastal phenomena (e.g. Tolvanen and Suominen 2005, Allen *et al.* 2007). A more thorough and detailed understanding of the local and regional underwater light field would require a study that focuses on the optical constituents of the water, as well as actual the underwater PAR distribution.

The understanding of the seafloor illumination is essential in the management and conservation of the coastal marine environment (Tolvanen and Kalliola 2008). Future monitoring efforts would also benefit from an improved spatio-temporal detail of the aquatic light field modelling, and an increased understanding of its ecological significance. However, the details of in-water optics and underwater light properties are very complex (e.g. Schubert *et al*. 2001, Kirk 2011), and further research beyond the Z_{SD}-based approach is needed.

Conclusions

The relevance of the seafloor illumination dynamics in coastal areas in different spatial and temporal scales is indisputable. The seafloor areas of the SW Finnish coast have suffered from a trend of general darkening for decades. Using the long-term Secchi data, we estimate a 50% decrease in the total illuminated seafloor area from 1930 to 2007 in our study area. The seafloor illumination in the area undergoes an annual cycle, during which about 25% of the studied seafloor area is illuminated throughout the growing season, and 25% is illuminated for a portion of the growing season. The alternating light energy distribution patterns on the seafloor induce physical patch dynamics that may provide meaningful framework for ecological studies, and the mapping of benthic community structure and associated biological processes.

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