Journal of Sea Research 112 (2016) 32–40

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Spatio-temporal representativeness of euphotic depth *in situ* sampling in transitional coastal waters

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ARTICLE INFO

Article history:
Received 18 December 2015
Received in revised form 15 March 2016
Accepted 19 March 2016
Available online 24 March 2016

Keywords:
Euphotic zone
Optical property
Sampling
Spatio-temporal dynamics
Coastal water
The Baltic Sea

ABSTRACT

In dynamic coastal waters, the representativeness of spot sampling is limited to the measurement time and place due to local heterogeneity and irregular water property fluctuations. We assessed the representativeness of *in situ* sampling by analysing spot-sampled depth profiles of photosynthetically active radiation (PAR) in dynamic coastal archipelago waters in the south-western Finnish coast of the Baltic Sea. First, we assessed the role of spatio-temporality within the underwater light dynamics. As a part of this approach, an anomaly detection procedure was tested on a dataset including a large archipelago area and extensive temporal coverage throughout the ice-free season. The results suggest that euphotic depth variability should be treated as a spatio-temporal process rather than considering spatial and temporal dimensions separately. Second, we assessed the representativeness of spot sampling through statistical analysis of comparative data from spatially denser sampling on three test sites on two optically different occasions. The datasets revealed variability in different dimensions and scales. The suitability of a dataset to reveal wanted phenomena can usually be improved by careful planning and by clearly defining the data sampling objectives beforehand. Nonetheless, conducting a sufficient *in situ* sampling in dynamic coastal area is still challenging: detecting the general patterns at all the relevant dimensions is complicated by the randomness effect, which reduces the reliability of spot samples on a more detailed scale. Our results indicate that good representativeness of a euphotic depth sampling location is not a stable feature in a highly dynamic environment.

1. Introduction

Solar radiation penetrating seawater is a prerequisite for photosynthesis in aquatic organisms, and thereby its availability is a key environmental parameter in aquatic ecosystem research. Photosynthetically active radiation (PAR) constitutes approximately the wavelengths visible to the human eye, 400–700 nm, and is efficiently attenuated by water molecules, as well as by organic and inorganic matter dissolved or suspended in the water (Kirk, 2011). Thus, in practise, photosynthesis and consequent primary production occur in the surface layer of seawater. The lower limit of the illuminated surface layer is often indicated by euphotic depth, in which 1% of the PAR entering the water remains (*e.g.* Kirk, 2011; Tett, 1990). This approximation is commonly used to reflect the zone where photosynthesis mostly occurs. Because underwater light availability is known to vary dynamically especially in coastal waters (*e.g.* Luhtala et al., 2013; Suominen et al., 2010b; Tolvanen et al., 2013), the euphotic depth can be regarded as an important variable in coastal research. For instance, macrophyte species distribution is strongly impacted by the depth of PAR penetration (*e.g.* Duarte, 1991; Eriksson and Bergström, 2005).

Water property measurements have traditionally been based on *in situ* sampling, usually executed as spot sampling. Information retrieved by a sample is unique to the particular location and time (Madrid and Zayas, 2007), which causes problems whenever all the relevant time and space scales are not reached (Sathyendranath and Platt, 1990). Moreover, it has been stated that spot sampling may be unrepresentative even within its immediate surroundings and on consecutive days (Erkkilä and Kalliola, 2004). This implies that even the measurements that are highly accurate for the exact sampling spot may not correspond well with a sample taken at a nearby location or on another occasion. The consequent discrepancy may propagate and cause misinformation during further analyses and application of the data. For example, small variation in vertical PAR penetration could lead to large variation in illuminated seafloor area (see Tolvanen et al., 2013), especially in areas of complex bathymetry and gentle slopes.

We hypothesised that individual casts, *i.e.* single *in situ* measurements, are unrepresentative in assessing underwater illumination conditions. We assumed that the representativeness of light data is affected by multidimensional fluctuations on a general scale and the impact of randomness on a more detailed scale. We focused on the representativeness of spot sampling through two approaches. First, we investigated the geographical and seasonal variability of the underwater light field, emphasising spatio-temporal euphotic depth dynamics in a coastal archipelago region. The study area covered a large part of the SW-

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http://dx.doi.org/10.1016/j.seares.2016.03.004
1385-1101/

Finnish archipelago coast, ranging from the shallow and sheltered inner archipelago with turbid waters to the outer archipelago, on the edge of the Baltic proper. Based on data ranging over the growing season from April to October, we present a procedure for detecting spatio-temporal anomalies from the overall spatial and seasonal patterns. Second, we assessed the local representativeness of spot sampling stations through statistical analysis of comparative data from points within a few kilometres of the reference stations. The three study sites are located across the inner–outer archipelago transition, and the networks were sampled during the summertime minimum and maximum of euphotic depth, in order to cover a variety of situations occurring throughout the year. We further assessed the capacity of detecting a wider range of variation by increasing the number of sampling stations in an area.

2. Material and methods

2.1. Study area and sampling scheme

2.1.1. Study area

The Baltic Sea is a marginal sea located in northern Europe. It is a brackish water basin where tidal activity is negligible. The case examples of this paper focus on the coastal archipelago waters in the central Baltic Sea, in the south-western corner of Finland. The coastal sea is a complex archipelago area where three major basins of the Baltic Sea intersect (Leppäranta and Myrberg, 2009). The average depth is approximately 20 m with the deepest points reaching 100 m. The varying bathymetry is structured by small sub-basins separated by shallow sills. Therefore, the water exchange within the complex archipelago is very restricted and turbid waters are efficiently retained within the area (Erkkilä and Kalliola, 2004).

The study area is ice-covered during winters. The length of the ice-cover period varies annually, and may last up to 3–4 months (Kauppila and Bäck, 2001; Seinä and Peltola, 1991). Furthermore, the vertical mixing of water columns occurs every spring and autumn, causing the summer and winter thermoclines to disappear (Leppäranta and Myrberg, 2009). The water salinity in the region varies between 5.0 and 6.5, and no stable halocline exists (Suominen et al., 2010a). Local currents and temporary density differences are formed, for example, by winds, sea level changes, and freshwater inflows (Kauppila and Bäck, 2001).

The Baltic Sea is known to have high concentrations of coloured dissolved organic material (CDOM) (*e.g.* Ferrari and Dowell, 1998; Kowalczuk et al., 2005), which inevitably has a great influence on underwater PAR attenuation, especially on shorter wavelengths (Kirk, 2011). The CDOM concentration undergoes seasonal variation, typically reflecting changes in river runoff (Asmala et al., 2012; Kowalczuk et al., 2010). Suspended particulate matter mostly originates from terrigenous inputs or bottom resuspension (Håkanson and Eckhéll, 2005), and may dominate underwater light attenuation, especially close to the mainland (Luhtala et al., 2013). The phytoplankton related PAR attenuation follows well-recognised seasonal development that is controlled by biogeochemical cycles of nutrients: the spring bloom is dominated by diatoms and dinoflagellates exploiting nitrogen, and after the early summer phytoplankton minimum, nitrogen-fixing cyanobacteria bloom, utilising the remaining phosphorus better than the species that suffer from nitrogen limitation (Hällfors et al., 1981). In general, the SW-Finnish archipelago waters are regarded as nitrogen rather than phosphorus limited (Hänninen et al., 2000).

The two main patterns of the local euphotic depth dynamics have been described by Luhtala et al. (2013). The general spatial trend consists of increasing euphotic depths – together with increasing sea surface openness – from the inner archipelago in the northeast towards the outer archipelago in the southwest. The prevailing seasonal development follows distinctive periodicity attributable to biogeochemical cycles: shallower euphotic depth in early spring and high summer, and deeper in late spring and late summer. However, major dissimilarities occur both in the spatial and temporal dimension. Timings and magnitudes in the main patterns differ notably (Luhtala et al., 2013).

2.1.2. Sampling networks

The spatio-temporal approach requires comprehensive data in temporal and spatial dimension. Network A, which was established in 2010, included 11 sampling stations that were visited eight times during the growing season, resulting in 88 euphotic depths measured *in situ*. The sampling ranged from late April to early October (Table 1), providing an extensive temporal coverage of the ice-free period in the area. The stations covered the transition from the inner bays to the edge of the open outer archipelago, and the distances between adjacent stations ranged from 7 to 17 km (Fig. 1). The stations are located within a 45 km by 40 km area, approximately at latitude 60°N and longitude 22°E.

To provide a better view on the local representativeness of spot sampling, three detailed study sites were created and sampled in early June and early August 2011. Each study site included 15–16 study points selected by stratified random sampling (Fig. 1), which was based on a grid of sixteen 2 km by 2 km squares. One sampling point was randomly created in each square excluding land and <10 m deep water. In some squares, there was an existing station from the larger network created in 2010, which was used instead of creating a new random point.

2.2. Field measurements

Light measurements were made from a small boat (length ~5 m) using two LI-COR quantum sensors (LI-COR Biosciences, Lincoln, NE, USA), which registered the amount of radiation (μmol s^{-1} m^{-2}) in the 400–700 nm wavelength area, referring to spectrally integrated values of PAR. The amount of underwater light and incoming radiant flux above the sea surface were registered simultaneously with a spherical quantum sensor (model LI-193) and a terrestrial quantum sensor (model LI-190, cosine collector), respectively. All the measurements took place in a time range between 08:00 and 19:00 h, local daylight saving time. The solar elevation angles were always carefully considered when measurements were made in the morning and in the evening. The angles at 60°N latitude allowed full hours in June, but limited sampling to mid-day in spring and autumn.

For underwater light, scalar irradiance measurements were used. These are practical when there is interest in aquatic photosynthesis (Kirk, 2011). Scalar measurements are also less sensitive towards changes in the solar elevation angle than measurements of downwelling PAR (Stramska and Frye, 1997). The underwater measurements were carried out by first recording PAR readings just below the sea surface, and then proceeding downwards with an interval of one metre. The maximum measurement depth was 20 m, except at the stations where the seafloor was reached before that. At the shallowest sampling station, the measurement range was 0–5 m. The light readings were recorded with LI-1400 data logger (LI-COR Biosciences, Lincoln, NE, USA), and at least three separate measurements were logged from every depth.

Euphotic depths were later calculated according to the rule of 1% PAR penetration. This rule refers to the depth at which 1% of solar radiation entering the water remains. In order to make underwater measurements of different depths comparable with each other, the incoming flux was mathematically normalised to a fixed level by using the readings of the terrestrial sensor. Thereafter, outliers, which deviated more than 20% from the median of the particular depth, were removed, and the averages of the remaining measurements were

Table 1
Sampling patterns: networks of sampling stations and measurement weeks.

Year	Network name	Number of stations	Measurement weeks
2010	Network A	11	17, 20, 23, 26, 31, 34, 37, 40
2011	Study sites S1, S2, S3	15, 16, 16	23, 31