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Temporal analysis of remotely sensed turbidity in a coastal archipelago

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ABSTRACT

A topographically fragmental archipelago with dynamic waters set the preconditions for assessing coherent remotely sensed information. We generated a turbidity dataset for an archipelago coast in the Baltic Sea from MERIS data (FSG L1b), using CoastColour L1P, L2R and L2W processors. We excluded land and mixed pixels by masking the imagery with accurate (1:10 000) shoreline data. Using temporal linear averaging (TLA), we produced satellite-imagery datasets applicable to temporal composites for the summer seasons of three years. The turbidity assessments and temporally averaged data were compared to in situ observations obtained with coastal monitoring programs. The ability of TLA to estimate missing pixel values was further assessed by cross-validation with the leave-one-out method. The correspondence between L2W turbidity and in situ observations was good ($r = 0.89$), and even after applying TLA the correspondence remained acceptable ($r = 0.78$). The datasets revealed spatially divergent temporal water characteristics, which may be relevant to the management, design of monitoring and habitat models. Monitoring observations may be spatially biased if the temporal succession of water properties is not taken into account in coastal areas with anisotropic dispersion of waters and asynchronous annual cycles. Accordingly, areas of varying turbidity may offer a different habitat for aquatic biota than areas of static turbidity, even though they may appear similar if water properties are measured for short annual periods.

1. Introduction

Remote sensing products, such as maps of chlorophyll a, Coloured Dissolved Organic Matter (CDOM), Suspended Particulate Matter (SPM), attenuation of light and turbidity provide synoptic information of the marine environment. These data are essential for understanding of inter-annual long-term developments and for tracking the intra-annual progression. In the inner coastal and archipelago waters, however, the applicability of satellite imagery is hindered by the dynamic water properties and the fragmental environment. The more optical components the water possesses, the more complicated it is to separate them via remotely sensed absorption and scattering properties (Attila et al., 2013; Kratzer et al., 2008; Smith et al., 2013). Thus, standard image processing to obtain data on water properties is not always applicable in optically complex coastal waters (Koponen et al., 2007), and regional uncertainties in ocean colour data products require extensive error assessment using regional in situ observations (Zibordi et al., 2013).

The spatial resolution of the remote sensing instrument is a limiting factor in topographically fragmental archipelago waters due to pixels which are partially covered by land, littoral vegetation and shoals (Barnes et al., 2013). In the direct vicinity of the shoreline, mixed pixels can be masked out with buffers surrounding land areas. The spatial accuracy of satellite imagery, however, is not absolute, and resampling data to a regular grid or re-projecting them to a new coordinate system alters the spatial properties of the original data. Mixed pixels can also be identified and extracted by classifying reflectance data, but on the coastline there is a zone of partially contaminated pixels with gradually changing reflectance. On a broader scale, the adjacency effect, i.e. the atmospheric scattering of radiance originating from another pixel than that in the sensor element's field of view, may affect the reflectance data of water pixels located near land up to several kilometres from the coast (Kratzer and Vinterhav, 2010; Santer and Zagolski, 2009).

The third challenge in remote sensing in coastal basins is the irregular alteration of water properties, at time scales that cannot be followed with the temporal resolutions of polar-orbiting ocean colour instruments. Instruments such as MODIS, SeaWiFS and MERIS have temporal resolutions of 1–2 days. This would be adequate for most purposes, but their data are temporally

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incomplete due to atmospheric disturbance, such as clouds and – especially at high latitudes – sun glint and the lack of daylight for part of the year. Geostationary platforms like Geostationary Ocean Color Imager (GOCI) would offer temporally frequent data at intervals of hours (Ruddick et al., 2012; Ryu et al., 2012), but availability of such high temporal resolution data, together with adequate spatial resolution, is limited. Data from multiple instruments have been merged for a single time-step to improve temporal and spatial resolution (e.g. Maritorena et al., 2010; Mélin et al., 2011; Kahru et al., 2015; IOCCG, 2007; Vanhellemont et al., 2013). Zhang et al. (2002) applied empirical neural network with simultaneous optical data (Landsat TM) and microwave data (ERS-2 SAR) to improve the estimations of water characteristics. In a fragmented coastal archipelago, the multi-sensor approach is, however, hindered because resampling and collocating multiple datasets with different spatial resolutions into a congruent grid would reduce the spatial accuracy of pixels. Also other unconventional sensors, such as Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard Meteosat Second Generation 2, are used for ocean colour studies in order to enhance temporal coverage of the imagery (Alvera-Azcárate et al., 2015; Ruddick et al., 2014). However, SEVIRI's spatial resolution in high latitudes is several kilometers, preventing its use in fragmented archipelago coasts.

Gap-filling techniques intended for completing temporally and spatially fragmental remote sensing data with artificial estimations (Alvera-Azcárate et al., 2007; Poggio et al., 2012; Sirjacobs et al., 2011; Wang et al., 2012) are most applicable when the studied phenomena have regular annual cycles, such as the vegetation indexes (Julien and Sobrino, 2010; Gao et al., 2008; Borak and Jasinski, 2009). In temporally dynamic and topographically fragmented coastal waters irregular changes hinder the use of temporal gap-filling methods based on temporally adjacent values, as they cannot follow irregular changes over long intervals. Spatial gap-filling such as interpolation techniques, in turn, are limited because of the anisotropic characteristics of coastal waters, due to barriers, currents and tides (Dunn and Ridgway, 2002; Little et al., 1997; Suominen et al., 2010).

All the above-mentioned challenges are present in the northern Baltic Sea, where the coasts are in many cases bordered by archipelagos. Water bodies are divided into multiple sub-basins, where water properties may differ over a small distance. Our study area, the Archipelago Sea in the northern Baltic Sea, is topographically exceptionally fragmented and the area covered by mixed land-sea pixels is substantial. The annual cycles of light and temperature have wide amplitudes and set the frame for vertical thermal stratification, water turn-overs, run-offs and primary production; these in turn affect SPM, CDOM, abundance of phytoplankton and eventually the optical properties of water. Ocean colour data and geophysical data products are available, but the fragmental physical and dynamic temporal environment requires localized methods. Frequently used processors, considering especially MERIS data, are the MERIS Ground Segment Development Platform (MEGS), the Freie Universität Berlin Water processor (FUB/WeW) (Schroeder et al., 2007), the Case-2 Regional processor (C2R) (Doerffer and Schiller, 2007), and CoastColour processors L1P, L2R and L2W. The performance of the processors varies according to the water constituent to be retrieved. In the optically complex coastal waters of the northern Baltic Sea, in particular the high CDOM concentration hinders the usability of standard algorithms (Beltrán-Abaunza et al., 2014). The abundance of phytoplankton, estimated by the chlorophyll a content in the water, is frequently the main interest in ocean colour studies, due to its ecological relevance and its role as a water quality indicator. The assessment of chlorophyll a and CDOM has nevertheless proved to be less accurate than assessing for example SPM (Attila et al., 2013; Beltrán-Abaunza et al., 2014).

Of the three above-mentioned challenges, this article considers mainly the latter two; obtaining data from the vicinity of shorelines in a fragmental archipelago and producing time series from temporally incomplete satellite imagery for image composites. Our primary aim is to study the temporal characteristics of water properties and to find new ways to distinguish areas by their divergent temporal behaviour.

We used turbidity (FNU) as a measure to reflect the seasonal cycle. Turbidity is the reduction of transparency of a liquid due to the presence of undissolved matter (ISO 7027 Standard, 1999), and FNU indicates the scattering of light from particles in water. The concentration of suspended particles depends on both allochthonous factors, such as fluvial run-offs and water movements, and autochthonous factors, such as the abundance of phytoplankton. Along with Secchi depth, turbidity describes the state of the water; since in situ observations of turbidity are more readily available than attenuation coefficients, it can also be used as a proxy for underwater light conditions in habitat modelling. Turbidity as such is not always included in ocean colour data products, whereas SPM is assessed by all the above-mentioned processors—MEGS, FUB/WeW, C2R and CC L2W. We used turbidity rather than SPM because we needed extensive in situ measures to evaluate our methodology, and SPM measurements are seldom available for the Archipelago Sea.

2. Material and methods

2.1. The Archipelago Sea

The Baltic Sea is a marginal sea, with limited water exchange with the ocean to the south-west. Since the Baltic is located at high latitudes, between 54°N and 66°N, it experiences a wide annual cycles of temperature, available light and consequently multiple physical, chemical and biological features. During the winters the basin is at least partly ice-covered (Leppäranta and Myrberg, 2009), while in the summer months water temperatures rise to 15–20 °C. In the open sea the optical properties are dominated by CDOM (Kratzer et al., 2008), originating both from autochthonous biological production and from allochthonous sources. Near the coast, river loads increase further the concentrations of CDOM (Asmala et al., 2012; Kowalczuk et al., 2006) and inorganic suspended matter. Algal blooms are frequent (HELCOM, 2009; Kahru et al., 2007; Rantajärvi et al., 1998), notably affecting on optical properties of seawater typically in late summer.

Our study area, the Archipelago Sea, is located in an area where the three major basins of the Baltic Sea meet: the Baltic Proper in the south, the Gulf of Finland in the south-east and the Gulf of Bothnia in the north (Fig. 1). The sea area consists of 25 000 islands exceeding 500 m^2 and 14 400 km of shoreline in an area of approximately 10 000 km^2 (Granö et al., 1999). The area is structured by fragmental bedrock that has an elevation range of about two hundred meters. The bedrock is partly covered with till, glaciofluvial deposits and marine sediments. The depth of the Archipelago Sea is typically ranging from 0 to 50 m, with some deeps and fault lines exceeding 100 m. Islands and underwater sills form numerous local sea basins at various scales, resulting in a complex transitional system where the fresh water runoff mixes with the brackish sea water of the adjacent main basins. At a broader scale there is a counter-clockwise upper layer circulation pattern in the Baltic Sea basin, seen as a net flow from south to north through the Archipelago Sea and a southward flow along the Swedish coast and in the upper layer of Åland Sea (Hietala et al., 2007; Myrberg and Andrejev, 2006).

Almost one third of the continental drainage area of the Archipelago Sea consists of arable fields, with the rest consisting mainly of forest; the fluvial waters are therefore rich in SPM and