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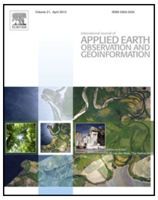

Satellite mapping of Baltic Sea Secchi depth with multiple regression models

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ABSTRACT

Secchi depth is a measure of water transparency. In the Baltic Sea region, Secchi depth maps are used to assess eutrophication and as input for habitat models. Due to their spatial and temporal coverage, satellite data would be the most suitable data source for such maps. But the Baltic Sea's optical properties are so different from the open ocean that globally calibrated standard models suffer from large errors. Regional predictive models that take the Baltic Sea's special optical properties into account are thus needed. This paper tests how accurately generalized linear models (GLMs) and generalized additive models (GAMs) with MODIS/Aqua and auxiliary data as inputs can predict Secchi depth at a regional scale. It uses cross-validation to test the prediction accuracy of hundreds of GAMs and GLMs with up to 5 input variables. A GAM with 3 input variables (chlorophyll a, remote sensing reflectance at 678 nm, and long-term mean salinity) made the most accurate predictions. Tested against field observations not used for model selection and calibration, the best model's mean absolute error (MAE) for daily predictions was 1.07 m (22%), more than 50% lower than for other publicly available Baltic Sea Secchi depth maps. The MAE for predicting monthly averages was 0.86 m (15%). Thus, the proposed model selection process was able to find a regional model with good prediction accuracy. It could be useful to find predictive models for environmental variables other than Secchi depth, using data from other satellite sensors, and for other regions where non-standard remote sensing models are needed for prediction and mapping. Annual and monthly mean Secchi depth maps for 2003–2012 come with this paper as Supplementary materials.

1. Introduction

Secchi depth is a measure of water transparency (Preisendorfer, 1986). There are at least two important applications of Secchi depth maps in the Baltic Sea. First, because Secchi depth is related to clear water, the Helsinki Commission (HELCOM, the international body for the environmental protection of the Baltic Sea) uses it as a core indicator of eutrophication (HELCOM, 2014). Eutrophication is one if the largest environmental problems in the Baltic Sea (HELCOM, 2009; Leppäranta and Myrberg, 2009) and may be spatially expanding (Fleming-Lehtinen et al., 2015). Second, Secchi depth is ecologically important because of its relationship to the euphotic depth (the depth down to which there is enough light for photosynthesis). It is related to the spatial distribution of benthic vegetation such as macroalgae: areas with higher Secchi depth tend to have more macroalgal cover at a given water depth (Krause-Jensen et al., 2009). Because Secchi depth data are cheaper to obtain, and because there is a large archive of historical Secchi depth measurements for the Baltic Sea (Aarup, 2002), they are often used as a proxy for direct measurements of euphotic depth (Luhtala and Tolvanen, 2013).

Due to their ability to cost-effectively cover large areas at high temporal resolution, satellite data would be the most suitable data source for regional-scale Secchi depth maps (Kahru 1997; Kerr and Ostrovsky, 2003; Kratzer et al., 2014). However, globally calibrated standard models that predict environmental variables of interest based on satellite data do not work well in the Baltic Sea because of its unusual optical properties (Darecki and Stramski 2004; Siegel and Gerth, 2008; Kowalczuk et al., 2010; Kratzer et al., 2011). The Baltic Sea is semi-enclosed and only connected to the open Atlantic Ocean through the narrow and shallow Danish Straits. There is high freshwater input from rivers: Including the Kattegat about 480 $km^3 y^{-1}$, most of which enters the northern and eastern parts of the Baltic Sea. Thus, the further one moves away from the Baltic Sea's connection to the Atlantic Ocean, the lower is surface salinity: from 18–26‰ in the Kattegat to 2–3.8‰ in the Bay of

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Abbreviations: GLM, generalized linear model; GAM, generalized additive model; RMSE, root mean square error; MAE, mean absolute error; MNB, mean normalized bias.

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Bothnia, the northernmost sub-basin of the Baltic Sea (Leppäranta and Myrberg, 2009). Many rivers carry high amounts of colored dissolved organic matter (CDOM), which is the optically dominant water constituent in the Baltic Sea (Kratzer et al., 2011). CDOM concentrations are thus inversely related to salinity (Kratzer et al., 2003; Kratzer and Tett, 2009). Riverine discharge is highest during the spring snow melt and lowest in winter (Hansson et al., 2011), and the CDOM concentration in river water changes seasonally (Kowalczuk et al., 2006). Also suspended particulate matter (SPM) enters the sea via rivers, originates from primary production and re-suspension, and is transported mostly by coastal currents (Håkanson and Eckhéll, 2005). There are frequent phytoplankton blooms in the spring and summer (Hansson and Håkansson, 2007; Siegel and Gerth, 2008). Thus, the optical properties of the Baltic Sea tend to differ much between different locations and seasons (Siegel et al., 2005). This spatial and temporal variability, as well as difficulties with atmospheric correction, make many satellite remote sensing applications at the regional scale difficult (Siegel and Gerth, 2008; Kratzer et al., 2011). Indeed, for the southern Baltic Sea Darecki and Stramski (2004) found that systematic and random errors in standard MODIS pigment algorithms consistently exceeded 150%.

Because of these problems, regional-scale habitat mapping and eutrophication assessments have so far relied on calculating sub-regional averages or interpolating between field observations of Secchi depth (e.g., Fleming-Lehtinen and Laamanen, 2012; Cameron and Askew, 2011, notably using satellite data to map euphotic depth for all parts of their study area except the Baltic Sea). Such interpolated maps can show broad-scale regional patterns, but they miss important temporal and fine-scale spatial patterns. They could also be affected by spatial and temporal biases in field data collection (for example, if more field data were collected during plankton blooms). Cameron and Askew's (2011) benthic habitat maps, in turn, were inputs for later modeling efforts, e.g., an assessment of potential human impacts on seabed habitats (Korpinen et al., 2013). Thus, more accurate Secchi depth maps for the Baltic Sea could improve the accuracy of various environmental assessments that directly or indirectly incorporate water transparency data.

Developing a regional model for the Baltic Sea that can accurately predict Secchi depth based on satellite data, and making the resulting Secchi depth maps publicly available, would therefore be an important contribution to environmental management and science in the Baltic Sea. There have so far been two initiatives to map Baltic Sea Secchi depth from satellite data: the work by Kratzer et al. (2003, 2008), and the Baltic Sea Ocean color optics (in the following BSO) data available online at the European Union's MyOcean portal (http://www.myocean.eu/, data downloaded on 05/30/2013). According to the BSO data's Quality Information Document (Saulquin, 2013), they were calibrated and tested on a *global* field observation data set. Given the Baltic Sea's special optical conditions, it would be surprising if globally calibrated models worked well for the Baltic Sea. Kratzer et al. in contrast, calibrated and tested their models at a *local* scale. Kratzer et al. (2003, 2011) show a regional Secchi depth map for the whole Baltic Sea based on their local model, but do not provide quantitative accuracy estimates for their regional map. While their models worked well locally, given the high spatial and temporal variability of optical conditions in the Baltic Sea it would be surprising if such models worked well for the whole region. This paper thus presents the first published attempt to map Secchi depth in the Baltic Sea based on satellite data using a model that was selected, calibrated and tested at the *regional* scale.

2. Data and methods

Fig. 1 shows an overview of this paper's data and methods.

2.1. Data sources

2.1.1. Secchi depth field observations

HELCOM oceanographic data were downloaded from the ICES website (http://ocean.ices.dk/Helcom/Helcom.aspx?Mode=1, downloaded on June 10, 2013). All Secchi depth field observations for days 60–305 of the years 2003–2012 were extracted. To avoid problems with stray light or the effects of small islands, all field observations from within 3 km of GSHHG full-resolution shorelines (http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html, downloaded on July 30, 2013) were excluded.

2.1.2. Satellite and static data

MODIS/Aqua Level 2 data products were obtained from NASA's Ocean Color Website (http://oceancolor.gsfc.nasa.gov/, all data downloaded in May 2013):

- Remote sensing reflectance at all available wavelengths (Rrs_*x*, where *x* is wavelength) with the exception of Rrs_412 (because of data gaps).
- Spectral attenuation coefficient at 490 nm (Kd_490).

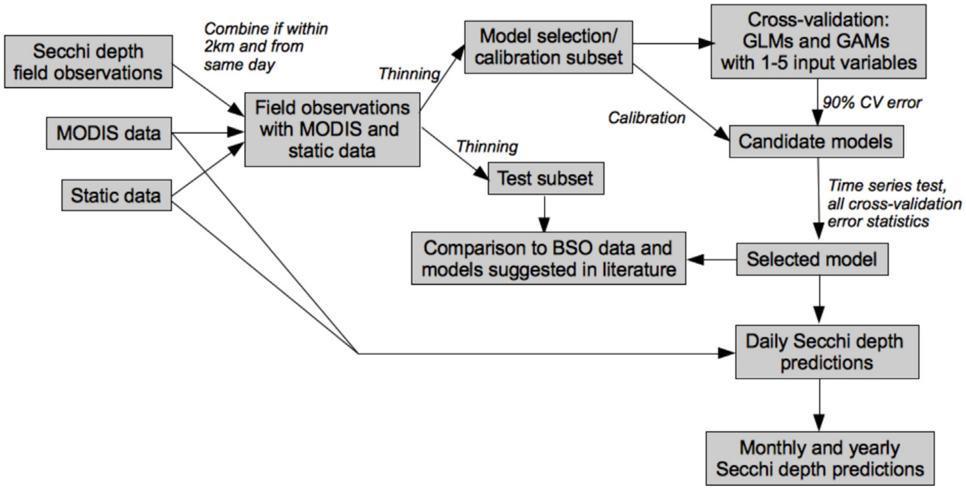

Fig. 1. This paper's process to find and test a regional model that accurately predicted Secchi depth based on satellite and static spatial data, and to create Secchi depth maps with this model.