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MERIS observations of phytoplankton phenology in the Baltic Sea

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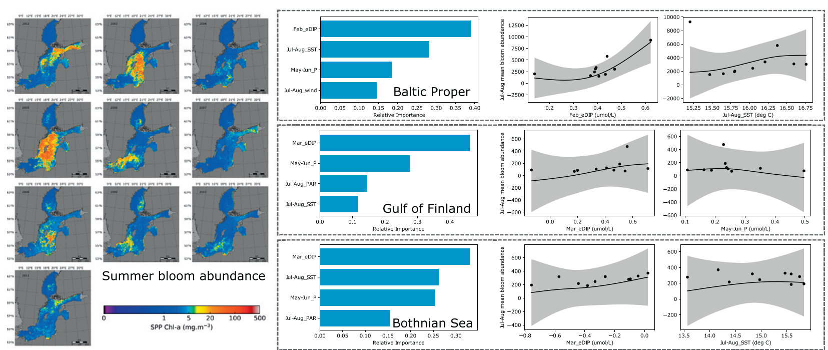
HIGHLIGHTS

- 10-year MERIS data archive was explored for studying phytoplankton phenology.
- Chl-a concentration of ~6 mg m^{-3} was determined statistically for bloom detections.
- BRTs showed spring eDIP had the highest variable importance on summer bloom abundance.
- GAM indicated the relationship between bloom abundance and each predictor variables.

GRAPHICAL ABSTRACT



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ABSTRACT

The historical data from the MEdium Resolution Imaging Spectrometer (MERIS) is an invaluable archive for studying global waters from inland lakes to open oceans. Although the MERIS sensor ceased to operate in April 2012, the data capacities are now re-established through the recently launched Sentinel-3 Ocean and Land Colour Instrument (OLCI). The development of a consistent time series for investigating phytoplankton phenology features is crucial if the potential of MERIS and OLCI data is to be fully exploited for inland water monitoring. This study presents a time series of phytoplankton abundance and bloom spatial extent for the highly eutrophic inland water of the Baltic Sea using the 10-year MERIS archive (2002–2011) and a chlorophyll-a based Summed Positive Peaks (SPP) algorithm. A gradient approach in conjunction with the histogram analysis was used to determine a global threshold from the entire collection of SPP images for identifying phytoplankton blooms. This allows spatio-temporal dynamics of daily bloom coverage, timing, phytoplankton abundance and spatial extent to be investigated for each Baltic basin. Furthermore, a number of meteorological and hydrological variables, including spring excess phosphate, summer sea surface temperature and photosynthetically active radiation, were explored using boosted regression trees and generalised additive models to understand the ecological response of phytoplankton assemblages to environmental perturbations and potential predictor variables of summer blooms. The results indicate that the surface layer excess phosphate available in February and March had paramount importance over all other variables considered in governing summer bloom abundance in the major Baltic basins. This finding allows new insights into the development of early warning systems for summer phytoplankton blooms in the Baltic Sea and elsewhere.

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1. Introduction

Over the last few decades, coastal eutrophication has been considered as a serious threat to marine ecosystems (Paerl, 1997; Smith, 2003; Lundberg et al., 2005; Andersen et al., 2010; Fleming-Lehtinen et al., 2015). Dense algal blooms limit light availability in the water column, restricting growth and causing the death of submerged aquatic vegetation in coastal zones (Chislock et al., 2013). Nuisance algal blooms taint water resources, causing purification difficulties for drinking water supplies and disrupting recreational and tourism activities. Additionally, poisonous substances produced by toxic algal blooms pose a health hazard to the public (Hunter, 1998; Backer et al., 2010a).

To address eutrophication and its associated adverse effects on the environment, extensive efforts have been made by government agencies and environmental organisations. Subsequently, conventions and directives were put in place to define strategies for eutrophication assessment and management. For instance, the Oslo-Paris Convention for the Protection of the North-East Atlantic (known as the OSPAR Convention) entered into force in 1998. To achieve the primary objective of maintaining a healthy marine environment without eutrophication, the Ecological Quality (EcoQ) elements and Ecological Quality Objectives (EcoQOs) incorporating the most severe effects of water quality (e.g. toxic algal blooms, the loss of submerged vegetation etc.) were proposed to monitor and assess biological responses to nutrient enrichment. Evaluation of the EcoQOs involves a comparison between the region-specific reference levels and monitoring data collected routinely for each EcoQ indicator, including chlorophyll-a (Chl-a), winter nutrient concentrations and oxygen deficiency levels (OSPAR, 2005, 2008). A similar scheme was adopted by the Baltic Sea Action Plan: BSAP (HELCOM, 2007) for the eutrophication assessment in the Baltic Sea. One of the crucial steps in implementing these programmes is to set a suitable reference level as an objective. Within the OSPAR Convention, the reference level is determined by the analysis of long-term historical monitoring data to derive the ‘ pristine’ condition. However, for most water bodies, historical monitoring records are either unavailable or insufficient (Painting et al., 2005). Although BSAP adopted an alternative approach to use both historical data and modelling, this is still challenging for several water monitoring programmes due to the limited technical supports (HELCOM, 2009; Backer et al., 2010b). Another factor hampering the establishment of reliable eutrophication assessments is the restricted spatial coverage and limited temporal frequency of *in situ* sampling programmes; the spatial distribution of algal blooms is usually both patchy and transient. Sampling at a few pre-defined stations (e.g. 42 stations under BSAP) at monthly, seasonal or even annual frequency (Ferreira et al., 2011) is generally insufficient. Therefore, alternative monitoring methods are needed.

Since the launch of the first ocean colour sensor, the Coastal Zone Color Scanner (CZCS) in 1978, satellite remote sensing techniques have been widely applied to various environmental programmes. It is now one of the most effective means to acquire spatially and temporally cohesive daily information on global waters. The cost effective accessibility and long-term availability have made it a vital and practical tool in aquatic studies (Brando and Dekker, 2003; Hu et al., 2004; Platt etal., 2009; Matthews et al., 2010; Zhang et al., 2015; Alikas and Kratzer, 2017), including retrieving phytoplankton pigments (Kutser, 2004; Simis et al., 2005; Gitelson et al., 2009; Moses et al., 2009; Al-Naimi et al., 2017), estimating Coloured Dissolved Organic Matter (CDOM) (Dall'Olmo et al., 2017) and Total Suspended Solids (TSS) (Chen et al., 2007a; Chen et al., 2007b). To detect and map phytoplankton blooms in optically complex inland and coastal waters, ocean colour indices have been demonstrated as one promising approach (Gower et al., 2005; Gower et al., 2006; Hu, 2009; Hu et al., 2010; Matthews et al., 2012; Matthews, 2014; Palmer et al., 2015; Hu and Feng, 2017). These approaches generally take advantage of the red-NIR reflectance peaks measured in Bottom of Rayleigh Reflectance (BRR) for estimating phytoplankton abundances and bloom distributions. In particular, the Floating Algae Index (FAI, Hu, 2009) was proposed to study the time series of floating algal blooms in eutrophic lakes in China (Hu et al., 2010; Zhang et al., 2015). The Maximum Peak Height algorithm (MPH, Matthews et al., 2012) was applied to South African inland waters for investigating the long-term trend of cyanobacterial blooms (Matthews, 2014). In the Baltic Sea, however, both FAI and MPH approaches have been shown to be inapplicable to the general bloom case where the surface biomass can be relatively low (Hu, 2009; Matthews et al., 2012). Although an alternative thresholding method was adopted to establish a long-term bloom record for the Baltic region (Kahru et al., 2007; Kahru and Elmgren, 2014), the bias related to the arbitrarily defined bloom threshold is difficult to identify.

The Summed Positive Peaks (SPP) algorithm, originally developed for estimating phytoplankton abundances (Chl-a) (see Zhang et al., 2017), provides an insight into the study of phytoplankton dynamics in the Baltic Sea. The SPP approach uses MERIS BRR that is corrected for gaseous absorption and Rayleigh scattering, avoiding complicated and error-prone atmospheric aerosol correction procedures. In addition, summation of the positive reflectance line heights makes it sensitive and applicable to the general bloom case in the Baltic Sea. Despite the fact that the MERIS data is no longer actively acquired, the data continuity is now re-established by recently launched OLCI operated on the European Space Agency's (ESA) Sentinel-3 satellites. Hence, it is of key importance to investigate spatio-temporal dynamics of phytoplankton abundance if the potential of MERIS and OLCI data is to be fully exploited.

In this paper, we apply the SPP approach to the Baltic Sea to establish a time series of phytoplankton phenology (intensity, timing and bloom extent) using the 10-year MERIS data archive (2002 to 2011), aiming to understand phytoplankton dynamics and their ecological responses to environmental perturbations. Specifically, our objectives are to (1) quantify the seasonal and interannual variability of phytoplankton assemblages within the major Baltic basins, alongside the bloom spatial extents; (2) determine the relationship between summer phytoplankton abundance and hydrological, meteorological factors, in an attempt to develop ecological models for estimating summer blooms in the Baltic Sea.

2. Materials and methods

2.1. Study site

Being a semi-enclosed shallow brackish water body located in northern Europe, the Baltic Sea has been considered as one of the largest inland seas affected by eutrophication (HELCOM, 2009; Pyhälä et al., 2013). It receives hazardous compounds from various sources, including industry, agriculture, shipping and recreational activities (Lotze et al., 2006). The Baltic Sea can be partitioned into several sub-regions by its shallow sills. For instance, the Danish Straits are separated from the major part of the sea by two shallow sills: the Darss Sill and the Drodgen Sill (Daewel and Schrum, 2013). The remaining section of the Sea is divided into a number of basins, including the Baltic Proper (BoP), Gulf of Riga (GoR), Gulf of Finland (GoF) and Gulf of Bothnia (GoB), where BoP can be further separated into the Southern and Northern Baltic Proper (SBP and NBP) alongside Western and Eastern Gotland Basin (WGB and EGB). GoB consists of the Bothnian Sea (BoS) and Bothnian Bay (BoB), see Fig. 1. All these basins are separated from the adjacent regions by shallow sills, except GoF.

The Baltic Sea is a unique and complex brackish water ecosystem, acting as the indispensable habitat for various species such as macro-algae, marine mammals and sea birds; it also produces