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Vernal phytoplankton bloom in the Baltic Sea: Intensity and relation to nutrient regime

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ABSTRACT

The intensity of the vernal phytoplankton bloom (VPB) was quantified in the Baltic Sea in 1993–2012, and its relation to the wintertime growth-limiting nutrient pool (the dissolved inorganic nitrogen, DIN, in our case) was assessed. The intensity of the VPB (I_{VPB}, μg/l of Chl *a*) was based on the integration of the measured chlorophyll *a* (Chl *a*) concentration over time and was estimated for the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin, the Northern Gotland Basin and the western Gulf of Finland. The conventional research vessel based monitoring supplemented with the ship-of-opportunity data provided a close insight into the VPB dynamics. The highly variable climatic forcing in the Baltic Sea area produces large inter-annual variation in how the VPB progresses during the spring within the frames set by available DIN. As a result, the I_{VPB} exhibited an 8-fold variation when all the sub-regions were taken into account (3 to 24 μg/l of Chl *a*), compared to a 5-fold corresponding variation in DIN (2.1 to 9.7 μmol/l). Consequently, the inter-annual variation in the wintertime DIN pool explained the inter-annual variation in the I_{VPB} well only in the Bornholm Basin (regression: $p < .001$), fairly in the Arkona Basin (regression: $p < .05$), and for the other basins no relation was detected. The quantitative relation between the I_{VPB} and the wintertime DIN pool varies largely within the frames provided by the progress of the physical environment over the winter and spring. The performance and applicability of a trophic index which has its foundation in the intensity of seasonal phytoplankton blooms is discussed.

1. Introduction

The Baltic Sea (BS) has a long history of being subject to a large-scale anthropogenic pressure that has gradually deteriorated its environmental state. Consequently, the BS is subject to marine management stipulated by the EU Marine Strategy Framework Directive (MSFD; EU, 2008) that aims at restoring the good environmental state of the BS (HELCOM, 2007). The land-based nutrient load has had the most conspicuous fingerprint on the environmental state of the BS by leading to pronounced eutrophication (Cederwall and Elmgren, 1990; Wulff et al., 1990) – the condition that has been exacerbated by the changes in the community-wide pelagic trophic cascade (Casini et al., 2008). With regard to tackling eutrophication, a series of trophic indices have been built to facilitate assessment of the trophic state of the BS and its recent changes (HELCOM, 2017b).

The wintertime surface nutrient inventory is the most widely-employed aquatic trophic index (e.g., HELCOM, 2009; OSPAR, 2009), because it represents the annual maximum of the readily-available nutrient stock for phytoplankton growth. This inventory – in a form of the dissolved inorganic nitrogen (DIN) and the dissolved inorganic phosphorus (DIP) – for the BS is large, reflecting the basic problem of a small semi-enclosed sea in the midst of heavily-populated areas; high land-based nutrient load received by a small volume of water, which in turn exchanges slowly with the Atlantic. The wintertime nutrient concentration level in the Gotland Basin, the central basin of the BS, is about 4 and 0.6 μmol/ l for DIN and DIP, respectively (1990–2015 average; HELCOM, 2017d). The corresponding values for the Gulf of Finland, the most eutrophied basin in the BS, are 10 and 1.0 μmol/ l. Despite the high ambient nutrient concentrations, the vernal phytoplankton bloom (VPB) constantly exhausts DIN and consumes about half of DIP in these basins (Raateoja et al., 2011).

The VPB is the most conspicuous seasonal phytoplankton bloom event in the temperate BS in terms of phytoplankton biomass (Andersson et al., 2017; Wasmund et al., 1998). There is a causal link between the wintertime nutrient stock and the intensity of the VPB due to low wintertime grazing pressure (Lignell et al., 1993; Witek, 1986), and the intensity of the VPB is in principle solely limited by the wintertime surface nutrient inventory within the frames set by the physical environment.

The intensity of the VPB is best described by the build-up of vernal

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phytoplankton biomass. Being a first-order proxy for phytoplankton biomass, chlorophyll *a* (Chl *a*) concentration is the most effective descriptor for this intensity for routine monitoring purposes. Chl *a* is currently included in the EU MSFD as an environmental metric for Descriptor 5 (eutrophication) with stipulated criteria for a good environmental status (GES; (EU, 2010)). HELCOM (the Baltic Marine Environment Protection Commission), established to protect the BS marine environment through inter-governmental collaboration, has employed Chl *a* as one of its core indicators of eutrophication (HELCOM, 2017a). From this point of view, the magnitude of the VPB, that approaches trophic development through the build-up of phytoplankton biomass in the form of Chl *a* concentration, could also be employed as a trophic metric.

We assessed the variation of the VPB in the sub-basins of the BS utilizing extensive datasets, one collected with the ship-of-opportunity (SOOP) monitoring, and the other two collected within the framework of the national COMBINE coordinated monitoring programmes (HELCOM, 2017c). Although providing a rather scarce spatio-temporal monitoring network, conventional monitoring yields insight into the water column nutrient regime and thus provides a new dimension to the high-frequency surface layer data provided by the SOOP. We wanted to find out whether the most comprehensive dataset available in the BS – built on various monitoring and data collection approaches, each having their own virtues – can reveal a causal link between the wintertime nutrient stock and the intensity of the VPB.

2. Study area

The BS is located between the marine temperate and continental sub-arctic climate zones, so both the North Atlantic marine air mass and the continental air mass affect the climate in the area (Leppäranta and Myrberg, 2009). The BS is located within the North Atlantic storm track; low pressure systems frequently bring warm air masses into the area. The westerlies and the polar front, varying in their strength and location, express considerable variation on the climate. As a temperate sea, the BS has a distinct seasonality which is accentuated by the small water volume that causes the state of the BS surface waters to be largely determined by atmospheric conditions (Stigebrandt and Gustafsson, 2003).

The BS is a semi-enclosed and estuarine-like sea, which is reflected in its brackish nature and a pronounced salinity variation both horizontally and vertically. The voluminous riverine input leads to gradually freshening waters towards the N-E, that is, to the tips of the Gulf of Finland and the Gulf of Bothnia. The riverine input and restricted inflow of oceanic water along with topography sustain a vertical salinity gradient. The most distinct part of this gradient, the halocline, is a constant feature of the BS (Leppäranta and Myrberg, 2009), being quite stable both in time and in place in all the studied sub-regions, except for the western Gulf of Finland (Elken et al., 2014; Lips et al., 2011). Above the halocline, the BS is basically a dimictic water body.

The salinity regime of the BS plays a central role for the initiation of the VPB. According to the commonly-accepted paradigm the VPB commences once the vernal phytoplankton community circulates down to depths shallower than the critical depth (sensu Svedrup, 1953). The wintertime temperature of the BS is typically below the temperature of maximum density of these brackish waters and initial warming of surface waters leads to convective mixing, thus actually destabilizing the water column (Kahru and Nõmmann, 1990). It is thus the salinity gradient that typically restrains the vertical mixing from stretching down to the critical depth due to lateral advection of fresher waters (Kahru and Nõmmann, 1990; Stipa, 2004). The VPB peaks in the southern BS in late March, and progresses northwards so that it peaks in the Gulf of Finland in late April (Raateoja et al., 2011).

The VPB frequently starts in a mosaic of surface water masses offering a range of vertical stability (Kahru and Nõmmann, 1990). This set-up is still easily shaped or even broken by wind stress, thus degrading the average light environment for the vernal phytoplankton. The opposite occurs in the context of meso-scale structures such as eddies and quasi-permanent fronts that offer production hot-spots by restricting the extent of vertical mixing (Kahru et al., 1990; Pavelson et al., 1997).

Whenever a favorable physical set-up for the VPB is in place, the duration and the intensity of the VPB are dictated by the growth-limiting nutrient pool. The vernal phytoplankton is limited by DIN for their growth in the study area (Tamminen and Andersen, 2007). The January–February molar ratio of DIN to DIP varies from 5 to 15 in the study area with a long-term average of > 10 in the WGOF and < 10 in the other studied sub-regions (Fleming-Lehtinen et al., 2008; Raateoja et al., 2011), while the critical ratio reflecting the transition from DIN limitation to co-limitation of DIN and DIP, and eventually to DIP limitation lies in the range of 15 to 30 (Geider and La Roche, 2002; Ptacnik et al., 2010). The VPB can be co-limited or exclusively limited by DIP in the Bothnian Bay and the inner coastal areas of the BS (Lignell et al., 1992; Tamminen and Andersen, 2007). Even though silica occasionally was almost exhausted during the extensive VPBs in the 1980's, more recent studies suggest that silica does not limit the VPB in the BS (Wasmund et al., 2017; Wasmund et al., 2013), and consequently, HELCOM has not employed silica concentration as a core trophic indicator (HELCOM, 2017b).

The aquatic and atmospheric physics during the winter and spring are decisive for the mutual occurrence of the dominant vernal bloom phytoplankton groups. The dominance of either diatoms as r-strategists or dinoflagellates as K-strategists is dictated by a progress of hydrographic events controlling the timing and rate of growth of these groups (Klais et al., 2011; Kremp et al., 2008; Lips et al., 2014). The vernal dominance of either of the groups leads to profoundly different footprints for nutrient cycling during the subsequent growth season (Heiskanen, 1998; Spilling et al., 2014).

3. Materials and methods

3.1. Sub-regions

The dataset was divided into offshore sub-regions in order to avoid the possible bias in the results stemming from the latitudinal variation in the timing of the VPB (Raateoja et al., 2011; Wasmund et al., 2017). The sub-regions – according to geographical frames set by Fonselius (1995) – are the Arkona Basin (AB), the Bornholm Basin (BB), the Eastern Gotland Basin (EGB), the Northern Gotland Basin (NGB), and the western Gulf of Finland (WGOF, Fig. 1).

3.2. Data sources

3.2.1. Ship-of-opportunity data

The SOOP water samples for DIN [nitrite (NO_2) + nitrate (NO_3)], DIP [phosphate (PO_4)], silica and Chl *a* measurements were collected on board the merchant ships GTS "Finnjet" (Silja Line, currently Tallink Silja Line) in 1993–1997, the MS "Finnpartner" (Finnlines) in 1998–2006, and the MS "Finnmaid" (Finnlines) in 2007–2012 on their voyages on-route Helsinki (FIN) – Travemünde (GER) as part of the Alg@line project (Fig. 1, Table 1).

The 900-ml SOOP samples were taken every eighth day at 5 m depth at the sampling points along the route that have been stable throughout the study. Each part of the ferry route that were chosen to represent the sub-regions included at least two SOOP sampling points. Water temperature was measured at the water flow close to the water intake point in the hull. The Alg@line SOOP data recording and sampling approach is described in detail elsewhere (Raateoja et al., 2011; Ruokanen et al., 2003). This dataset is henceforth referred to as "SOOP".

3.2.2. Conventional monitoring data: SAMPLE and POOLED

For the two datasets below, we assumed that the wintertime mixing