Journal of Marine Systems 80 (2010) 71–89

Contents lists available at ScienceDirect

Journal of Marine Systems

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

On phosphate pumping into the surface layer of the eastern Gotland Basin by upwelling

Hans-Ulrich Lass *, Volker Mohrholz, Günther Nausch, Herbert Siegel

Leibniz Institute of Baltic Sea Research Warnemünde, Seestraße 15, 18119 Rostock-Warnemünde, Germany

ARTICLE INFO

Article history:
Received 30 April 2009
Received in revised form 4 October 2009
Accepted 10 October 2009
Available online 20 October 2009

Keywords:
Baltic Sea
Eastern Gotland Basin
Surface layer
Intermediate winter water
Mesoscale eddies
Upwelling
Vertical turbulent diffusion
Phosphate
Nitrate
Particulate phosphorus
Phytoplankton

ABSTRACT

Hydrographic, current, and nutrient measurements were performed on board of the R/V Poseidon in the eastern Gotland Basin from 12 to 21 July 2007, complemented by satellite measurements of sea surface temperature and chlorophyll-a and by measurements of turbulent dissipation. The main aim of the investigations was to elucidate the pathways of phosphate from the intermediate winter water into the surface mixed layer and how this phosphate flux fosters phytoplankto growth. The deep water of the Gotland Basin was exposed to an enduring stagnation phase resulting in a nitrogen to phosphorus ratio very much lower than the Redfield ratio. The intermediate winter water was completely depleted of nitrate but contained a phosphate pool of about 0.40 μM. The surface mixed layer had a mean depth of about 18 m and water temperature of 16 °C and was depleted of both nitrate and phosphate. The average of photosynthetically active radiation during the cruise was about 700 μE/(m²s) at the sea surface. Three pulses of westerly wind with maximum wind speed of about 15 m/s forced upwelling during the cruise at the east coast of Gotland and downwelling at the Latvian coast. The corresponding eastward Ekman offshore transport moved surface water within about three days through the coastal boundary layer and in roughly 50 days across the Gotland Basin. Two mesoscale eddies were observed off the south eastern coast of Gotland which supported upwelling filaments near the southern tip of this island.

Within the coastal boundary layer, the upwelling transported phosphate from the intermediate winter water into the surface layer off Gotland where it was mixed with the phosphate depleted surface water. Generally, the upwelled phosphate was taken up by the plankton community of the surface mixed layer already within the coastal boundary layer and transformed completely into the particulate and dissolved organic phase. However, at sites where upwelling filaments develop, dissolved phosphate is transported over a distance of about three times the internal Rossby radius in offshore direction. The phosphate transport into the surface mixed layer of the eastern Gotland Basin by upwelling exceeded the corresponding transport by turbulent mixing through the seasonal thermocline by about one order of magnitude during typical summerlike wind conditions.

1. Introduction

1.1. Estuarine circulation of the Baltic Sea

The Baltic Sea is located with its entire drainage basin (about $1.7 \times 10^6\,km^2$) in the humid temperate climate belt of the Northern Hemisphere. It is connected to the North Sea via the transition area consisting of the Kattegat and subsequently of three narrow Danish Straits (Little Belt, Great Belt and Sound). The Great Belt and the Sound are linked to the Arkona Sea by shallow sills, the Darss Sill being 18 m deep and the Drogden Sill being 8 m deep, respectively.

Like other landlocked sea areas in humid climate belts, the Baltic Sea is characterised by a fresh water surplus of 481 km^3 (HELCOM, 1986). The fresh water surplus [river runoff (428 km^3) + precipitation (237 km^3) − evaporation (184 km^3)] is dominated by river runoff because precipitation and evaporation almost balance each other. This water surplus determines the basic hydrographic and ecological properties of the Baltic Sea: The estuarine circulation, the deep water formation and ventilation, the stratification and the gross nutrient balance. Outflow of brackish surface water and inflow of saline water combined with upwelling and vertical mixing of saline bottom water with brackish surface water closes the estuarine circulation.

There are several textbooks describing the general oceanography of the Baltic Sea, e.g. Voipio (1981). The most recent textbook on the physical oceanography of the Baltic Sea is given by Läpparanta and Myrberg (2009). The inflow of saline water from the Kattegat is responsible for the permanent stratification of the central Baltic water body consisting of an upper layer of brackish water with salinities of about 6–8 PSU and a more saline deep water layer of about 10–14 PSU. The resulting permanent halocline at about 70 m depth

* Corresponding author. Tel.: +493815197120.
E-mail address: uli.lass@io-warnemuende.de (H.-U. Lass).

0924-7963/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmarsys.2009.10.002

prevents the ventilation of the bottom layer by vertical convection and wind mixing during the winter season. Additionally, heating of the surface water during the summer forms a strong seasonal thermocline at about 20 m depth which separates the warm surface water from the cold intermediate winter water. The strong seasonal thermocline shelters the intermediate winter water, located between halocline and seasonal thermocline, from mixing with the warm surface water.

The deep water of the Baltic Proper can therefore be ventilated only by inflowing dense water from the Kattegat. There are two types of inflowing dense water. The frequent medium size inflow of small amounts (a few 10 km³) of dense water mostly through the Sound, Sellschopp et al. (2006), Burchard et al. (2009). These inflows are generally not sufficient to replace the bottom water or to change oceanographic conditions in the Baltic deep basins significantly. However, this water interleaves just beneath the permanent halocline and ventilates the upper parts of the bottom water. The other type is the episodic barotropic major Baltic inflow with large volumes (100–250 km^3) of highly saline (17–25 PSU) and oxygenated water which occurs mostly during the winter season representing the most important mechanism by which the Baltic deep water is refreshed to a significant degree with respect to salinity and oxygen, Matthäus and Frank (1992). These inflows occur through both the Great Belt and the Sound, Fischer and Matthaus (1996). A recent review of the mechanisms and the impact of these inflows on the deep water properties in the Baltic Proper is given by Matthäus et al. (2008). Due to the shallow sills of the Baltic Sea transition area the inflowing water originates mainly from the Kattegat surface water. The nutrient concentrations in the surface layer of both the Kattegat and the Baltic Sea have no substantial differences. Therefore, the net nutrient transport by the estuarine circulation from the Kattegat into the Baltic Sea is quite low in contrast to semi-enclosed seas in humid climate belts with deep sills where nutrient enriched deep water flows into the semi-enclosed seas. This implies that the nutrient balance of the Baltic Sea is mainly determined by the input from the rivers and the atmosphere, by the pelagic biochemical cycles, and by the sedimentation of particulate organic matter. The exchange between the nutrient enriched deep water and the nutrient depleted surface water is mainly controlled by turbulent mixing, see Reissmann et al. (2009) for a review, and upwelling.

The vertical transport of nutrients into the surface layer by turbulent diffusion is impeded by the very stable three layer stratification of the Baltic Sea during the summer season. However, upwelling of cold water from the intermediate winter water layer occurs frequently in particular within narrow coastal belts. The location and the frequency of upwelling events depend on the coastal topography and the direction and duration of the wind blowing at the coast. Reviews on upwelling in the Baltic Sea are given by Lehmann et al. (2002), Myrberg and Andrejev (2003), and Lehmann and Myrberg (2008). The intermediate winter water of the Baltic Proper contains almost exclusively dissolved inorganic phosphate, but only traces of inorganic nitrogen compounds. This water may be transported by upwelling into the surface layer of a coastal belt and subsequently transported by the Ekman transport toward the inner parts of a basin. The upwelled phosphate and the traces of nitrate can be taken up by the plankton community and foster the primary productivity in the surface layer during summer.

1.2. Biogeochemical cycle

Reviews on the biogeochemical cycle in the Baltic Sea are given e.g. by Voipio (1981), Rheinheimer (1996), and Vahtera et al. (2007). The inflow of saline surface water from the Kattegat has not much influence on the net nutrient import into the Baltic Sea. However, it has a large impact on the biogeochemical cycle by providing oxygen to the deep water after major Baltic inflows. Oxygen is consumed permanently in the deep water and the sediment by bacterial degradation of organic matter whose downward flux has a yearly cycle with at least two maxima. The first maximum occurs in April and is associated with the spring bloom of phytoplankton. The second maximum occurs after the bloom of the diazotrophic cyanobacteria in August. The sedimentary carbon supply is dominated by the sedimentation of the blooms, Leipe et al. (2008). The downward carbon flux results in a permanent decline of oxygen concentration of the ventilated deep water after a major inflow and the formation of hydrogen sulfide after the depletion of oxygen until a new major Baltic inflow ventilates the deep water again after a decade, e.g. Matthäus et al. (2008). This change between oxygenated and hydrogen sulfide containing deep water controls the relation between dissolved inorganic phosphate (DIP) and dissolved inorganic nitrogen compounds (DIN). In periods when the deep water contains oxygen lower DIP and higher DIN concentrations, especially nitrate, are observed in deep waters. The opposite occurs during stagnation periods when hypoxia/anoxia reaches higher into the deep water column. DIP concentrations tend to be high whereas nitrate concentrations are lower or zero, Vahtera et al. (2007). Denitrification of nitrate occurs by denitrifying bacteria in the sediment and the pelagic near the redoxcline when oxygen concentration sinks below 0.1–0.3 ml/l, Goering (1968). Phosphate dissolves from sediments where it is bounded as iron (III) phosphate at low redox values as it is given in the Baltic Sea sediments when the pore water contains hydrogen sulfide, Hallberg et al. (1972).

In the Baltic Proper the net community production above the halocline is zero or negative from October to March in average, Vahtera et al. (2007). During this phase of the yearly cycle depleted DIP in the surface layer is regenerated to 40% by bacterial degradation of sinking organic phophorus and the remaining 60% by vertical transport from the deep water in particular in January and February. For DIN the internal sources have a similar relation, whereas an additional input from atmospheric sources during October to March constitutes 35% of the wintertime total increase, Vahtera et al. (2007). The resulting nitrogen to phosphorus (N/P) ratio of the winter surface water of the central Baltic Sea varied during the recent decades between about 6 and 8, see Nausch et al. (2008a,b) which is much lower than the Redfield ratio (N:P = 16, Redfield et al., 1963).

The phytoplankton spring bloom starts in the surface water of the Baltic Proper with the improvement of light conditions in April. A stabilization of the water column is required to trap phytoplankton in the well-lit upper water layers. When the upper mixed layer becomes shallower than the euphotic zone, the phytoplankton receives regularly enough light for growth, Kaiser and Schulz (1978), Smetacek and Passow (1990). An early weak stratification may be caused by overlay of low-saline water (Kahru and Nômmann, 1990) or by the warming of the upper water layers which occurs by positive heat flow when the sea surface temperature is above the temperature of the density maximum already long before the establishment of the seasonal thermocline (Lignell et al., 1993; Wasmund et al., 1998). Since the DIN:DIP ratio in the winter water of the Baltic Proper is much lower than the Redfield ratio, the nitrogen is used up by the plankton community first in the whole brackish layer, Nausch et al. (2005), and limits further growth (Bodungen et al., 1981; Schulz et al., 1984). Thus, the spring bloom is terminated by nitrogen limitation and disappears by quick sedimentation, see Bodungen et al. (1981).

Significant amounts of phosphate are still available after the spring bloom in the open Baltic Proper above the halocline (Nausch et al., 2005). This condition favors the growth of nitrogen-fixing cyanobacteria. Indeed, they develop just in the areas of the lowest N:P ratios (Niemi, 1979). But they do not follow immediately after the spring bloom, perhaps because of their low specific growth rates at low temperature.

A stable thermocline develops in mid May in the southern and central Baltic Proper. This ultimately blocks an upwards transport of nutrients between the intermediate winter water and the surface