Papers

Hydrographic and hydrochemical conditions in the Gotland Deep area between 1992 and 2003*

OCEANOLOGIA, 45 (4), 2003.
pp. 557–569.

KEYWORDS
Stagnation periods
Deep water renewal
Hydrography
Nutrient distribution
Nutrient pools

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Manuscript received 29 September 2003, reviewed 20 October 2003, accepted 12 November 2003.

In memory of Stig H. Fonselius (1921–2003), who studied the basic hydrographic-hydrochemical conditions in the Gotland Deep area during the 1960s.

Abstract

The paper describes the hydrographic-hydrochemical development in the eastern Gotland Basin between the major saltwater inflows into the Baltic Sea in 1993 and 2003. This period is characterised by only low inflow activity. The most important hydrographic events were the effects of the very strong inflow in 1993 and the weak inflows in 1993/1994 and 1997. The 1993/1994 inflows led to deep-water renewal, a steep fall in deep-water temperatures, and increasing salinity. The effects of the inflow of very warm, saline and oxygen-rich water in autumn 1997 were observed in the deep water in 1998, resulting in temperatures rising to 7°C. The recent renewal in spring 2003 is reflected in the decreasing temperature, higher salinity and improved ventilation of the bottom water.

* This paper was presented at the Baltic Sea Science Congress (BSSC) in August 2003 in Helsinki.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Changes in the redox conditions exert a considerable influence on the nutrient distribution. During stagnation periods, there is enrichment of phosphate and ammonium, while nitrate is absent. Thus, around 31 μmol l^{-1} ammonium and 7 μmol l^{-1} phosphate were measured prior to the water renewal in 2003. Deep-water ventilation results in lower phosphate concentrations of around 2 μmol l^{-1}, the nitrification of ammonium and the occurrence of nitrate.

For the observation period, an estimate of nutrients stored in the deep water was done for the eastern Gotland Basin. During the recent stagnation period, there was an increase of up to 150% in the phosphate pool below the halocline, whereas the pool of inorganic nitrogen compounds decreased to 80% compared with 1992 when the previous stagnation period had ended. Under specific circumstances, these unbalanced nutrients can be made available to the upper water layers and can induce large-scale blooms of algae, especially of cyanobacteria.

1. Introduction

Conditions of life in the deep basins of the Baltic Sea are strongly influenced by episodic inflows of larger volumes of highly saline, oxygen-rich water from the North Sea. Owing to their high density and their considerable oxygen content, these major Baltic inflows (MBIs) are the only mechanism by which the deep waters in the central basins can be replaced and significantly renewed. Whereas until the mid-1970s such events occurred relatively frequently (Matthäus & Franck 1992, Matthäus & Nausch 2003), they have since then taken place only seldom. Within the last 20 years, such events have happened only in 1983, 1993, and quite recently in January 2003 (Feistel et al. 2003b in this volume). Because of the low inflow activity since 1994 a pronounced period of stagnation persisted in the central Baltic Sea from 1995 until 2003. Of all the deep basins in the Baltic, the eastern Gotland Basin is the best area for investigating the problem of water renewal and subsequent stagnation.

In the present study, hydrographic conditions and their hydrochemical implications are described for the eastern Gotland Basin during the period between 1992, which characterises the end of the longest stagnation period observed so far, and 2003, when water renewal terminated a second, long stagnation period.

2. Material and methods

All the measurements presented in this paper were performed at the central station in the eastern Gotland Basin, the Gotland Deep (station BMP J1 = BY 15A) at 57°19.20′N and 20°03.00′E. They cover the period between 1992 and July 2003. In all, 254 CTD casts, 236 samples of phosphate and nitrate and 125 samples of ammonium, almost evenly distributed over the years, were included in the evaluation.

The data sources are as follows:

- Data collected within the framework of the Baltic Monitoring Programme (COMBINE) of the Helsinki Commission (HELCOM);
- Data collected as part of the German National Monitoring Programme, conducted by the Baltic Sea Research Institute (IOW) on behalf of the Bundesamt für Seeschifffahrt und Hydrographie (BSH);
- Special research programmes carried out by the IOW in the Gotland Deep area in all summers between 1993 and 2001 except for 1995;
- For recent years, data collected by the Swedish National Marine Monitoring Programme.

All the hydrographic and chemical variables studied and the methods used are based on the standard guidelines of the COMBINE programme of HELCOM (HELCOM 2002). Furthermore, a detailed description of the chemical analysis can be gleaned from Grasshoff et al. (1983).

In order to estimate the nutrient enrichment below the halocline in the eastern Gotland Basin, the water body between 70 m and the bottom was divided vertically into three depth regions (A, B and C in Table 1) on the basis of the seven box division used by Schneider et al. (2002). Their volumes were calculated based on the high-resolution grid topography of the Baltic Sea published by Seifert & Kayser (1995). The volumes of each box were multiplied by the corresponding averaged annual nutrient concentrations.

Table 1. Depth regions of the eastern Gotland Basin deep water: between the halocline and the bottom (A); between the redoxcline and the bottom (B); between the halocline and redoxcline (C). Depth regions are based on the box division used by Schneider et al. (2002)

Depth regions		Box	Depth [m]	Box area [km^2]	Box volume [km^3]
A	C	1	70–97	12 300	343
		2	98–117	9 050	169
		3	118–137	6 560	128
	B	4	138–157	4 150	85
		5	158–177	2 610	56
		6	178–197	1 070	23
		7	197–236	130	5

3. Results

During the first half of the 1990s, conditions in the central Baltic deep water were dominated by the late phase of the long stagnation period

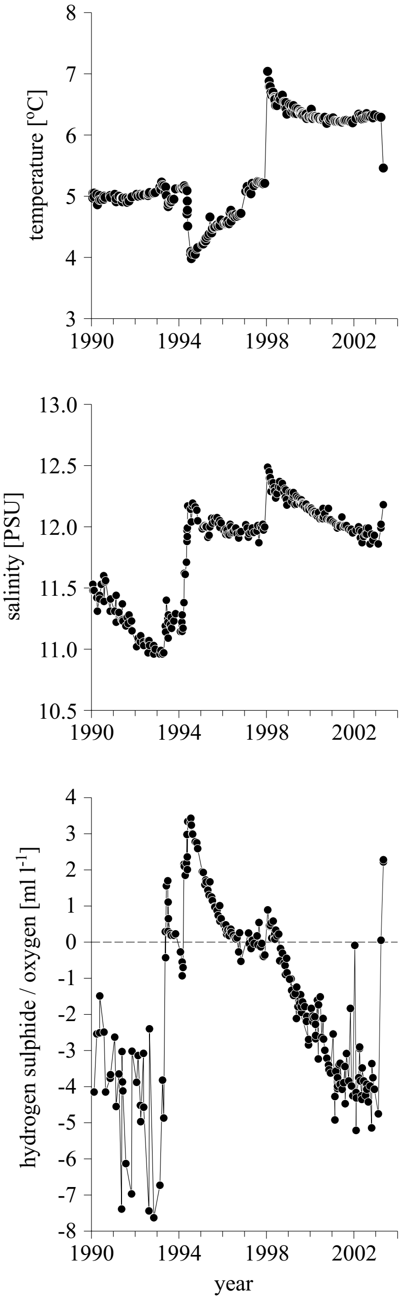

Fig. 1. Variations of temperature, salinity and oxygen/hydrogen sulphide concentrations in the deep water (200 m) of the Gotland Deep between 1990 and 2003 (H_2S converted into negative oxygen equivalents) (updated after Matthäus et al. 2001)

from 1977 to 1992 (Matthäus 1990, Nehring & Matthäus 1991, Nehring et al. 1993), with decreasing salinity, high hydrogen sulphide (cf. Fig. 1), phosphate and ammonium concentrations and no nitrate (cf. Fig. 2). The effects of the very strong inflow of saline and oxygen-rich water in January 1993 (Håkansson et al. 1993, Jakobsen 1995, Matthäus & Lass

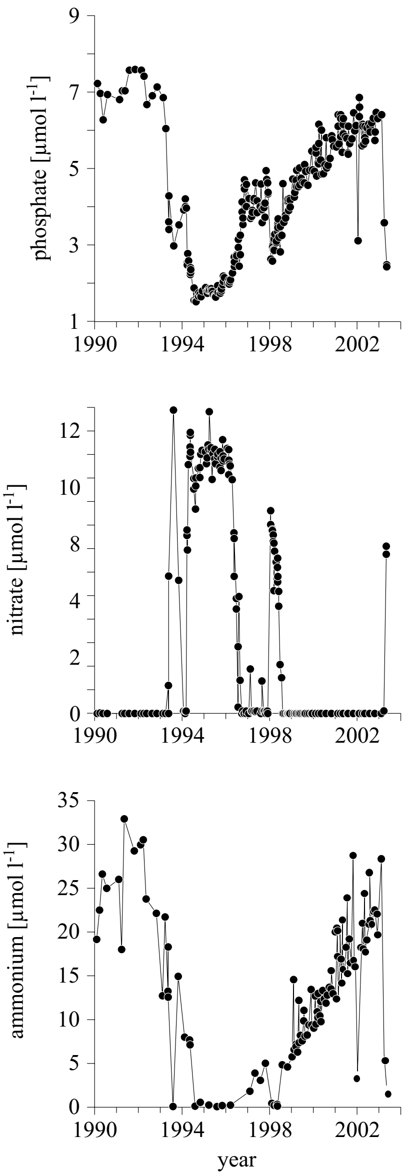

Fig. 2. Variations of phosphate, nitrate and ammonium concentrations in the deep water (200 m) of the Gotland Deep between 1990 and 2003 (supplemented and updated after Matthäus et al. 2001)

1995) and the subsequent inflow events in December 1993 and March 1994 are also clearly reflected by all the parameters. The summer of 1997 was characterised by exceptionally high surface temperatures in the whole Baltic Sea (Matthäus et al. 1998). An inflow in September and early October of that year led to an unusual increase in deep-water temperatures, which were detectable in the Arkona and Bornholm Basins already at the end of October 1997. The effects of this inflow could be seen in the Gotland Deep in spring 1998 (cf. Figs 1 and 2). However, this inflow only briefly interrupted the stagnation period that had begun in 1995 (Nehring et al. 1995b). The same applies to the medium-sized inflow in autumn 2001 (Feistel et al. 2003a). This stagnation period was finally brought to an end by the strong MBI of January 2003 (Feistel et al. 2003b in this volume).

All these events can be followed in detail by examining the variations in the hydrographic and hydrochemical conditions in the Gotland Deep (Figs 1 and 2). For the purpose of interpretation, the individual measurements were used in part to identify the date of occurrence of the different events. The January 1993 MBI can be thought of as a prerequisite for water renewal in the Gotland Basin area. While it filled the Bornholm Basin with highly saline, oxygen-rich water (for more details on the role of the Bornholm Basin, cf. Matthäus et al. 2001), the effects in the Gotland Deep remained relatively small (Nehring et al. 1994). The temperature decreased and the salinity rose only slightly (Fig. 1). It was in April 1993 that the first signs of renewal were observed, as a result of which the oxygen content at 200 m depth rose to nearly 2 ml l^{-1} (Fig. 1). However, anoxic conditions were very soon restored. Even though the inflow events of December 1993 and March 1994 did not fulfil the criteria of MBIs (Matthäus & Franck 1992), their effects on the central Baltic deep water were strongly felt. Since the Bornholm Basin was already filled with dense water, the new water masses were able to propagate quickly in a relatively undisturbed manner, without significant losses being sustained. The temperature dropped from $> 5°C$ at the beginning of the year to around 4°C in May 1994 (Fig. 1). These temperatures are among the lowest values observed since recordings started (Matthäus & Nausch 2003). The salinity increased by 1 PSU at 200 m and oxygen reached concentrations of 3.0–3.8 ml l^{-1} between 170 m and the bottom, the highest values since the 1930s (Matthäus 1990). As a result of the January 1993 MBI and the subsequent smaller inflows, the deep water of the whole Baltic Sea was free of hydrogen sulphide by May 1994.

No further MBIs occurred after January 1993 and the smaller inflows in 1993 and 1994. Thus, oxygen concentrations started to fall again and anoxic conditions developed in the near-bottom layer of the Gotland Deep in February 1996 (Fig. 3). The stagnation period from 1996 until 1998 displayed some peculiarities. Anoxic conditions were interrupted every winter and spring by the occurrence of low oxygen concentrations as a result of weak inflows of saline and oxygen-rich water entering the Gotland Deep after having overflowed from the Bornholm Basin (Matthäus et al. 1997, 1998, 1999). However, these small amounts of oxygen were rapidly consumed and in the second half of these years the anoxic zone extended from the bottom up to a depth of 150 m. These changes are discussed in conjunction with changes in the nutrient regime (cf. Fig. 3).

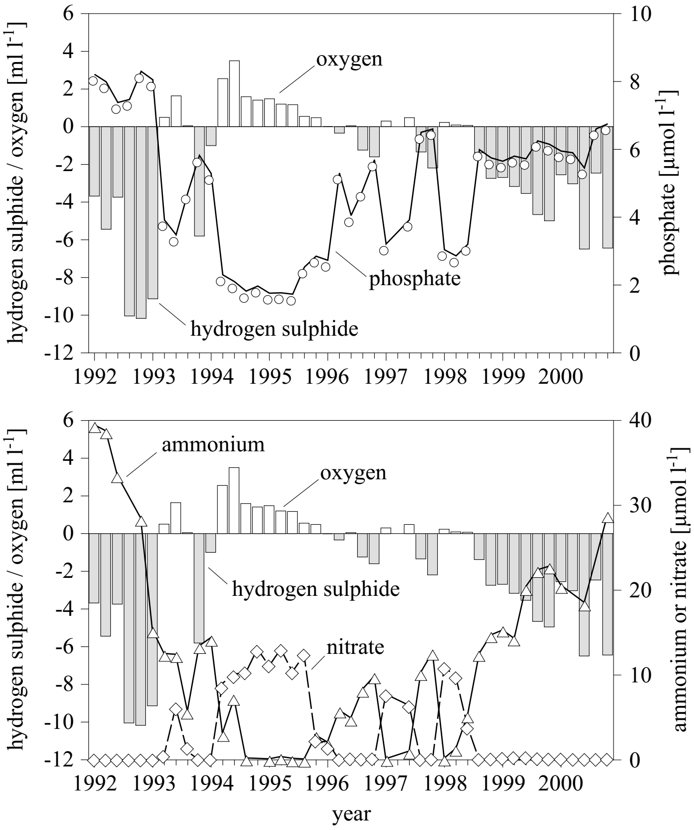

Fig. 3. Development of oxygen/hydrogen sulphide and the influence on phosphate or nitrate and ammonium distribution in the near-bottom layer of the Gotland Deep between 1992 and 2000 (H_2S converted into negative oxygen equivalents) (redrawn and supplemented after Nehring et al. 1995b)

The next of these inflow events during the period under discussion was the intrusion of extremely warm, saline and oxygen-rich water resulting from the exceptionally warm summer of 1997 (Matthäus et al. 1998). The inflow reached the Gotland Deep in spring 1998 and led to an increase in temperature and salinity to $> 7°$C and 12.7 PSU respectively (Fig. 1). The inflow process came to an end in May 1998 (Hagen & Feistel 2001). The inflow in autumn 2001 reached the Gotland Deep in the first half of January 2002 (Fig. 1). The effects could be traced until summer 2002, although with rapidly fading magnitude (Feistel et al. 2003a). Thus, the stagnation period continued in general until spring 2003, when the effects of the new MBI became detectable (Feistel et al. 2003b in this volume). Clear indications of this major inflow could be measured in the Gotland Deep in May 2003, as can be seen by the steep decrease in temperature, the elevated salinity and the considerable increase in oxygen concentrations (Fig. 1). In the near-bottom layer up to 4 ml l^{-1} oxygen were measured. Similar amounts of oxygen had been recorded on only two previous occasions, in the 1930s and in May 1994 (Nehring et al. 1995a).

Nutrient conditions strongly reflect the alternation between inflow and stagnation periods. In the presence of oxygen, phosphate is partly bound in the sediment and onto sedimenting particles in the form of an iron-III-hydroxophosphate complex. If the system becomes anoxic, this complex is reduced by hydrogen sulphide, and phosphate and iron(II) ions are liberated. Moreover, inorganic nitrogen compounds are affected by the interplay between oxygen and hydrogen sulphide. Under oxic conditions, they are present almost exclusively in the oxidised form as nitrate. Under anoxic conditions, however, the available nitrate is denitrified to dinitrogen gas. On the other hand, ammonium, liberated during mineralisation processes, cannot be oxidised and is enriched. This interplay is perfectly clear from Fig. 2. At the end of the previous stagnation period in the early 1990s, high concentrations of phosphate and ammonium were observed – c. 7 μmol l^{-1} and 20–35 μmol l^{-1} respectively. Nitrate was absent. In 1993, the system reacted distinctly to the changes in the redox regime, despite the fact that the January 1993 inflow had little impact on the central Baltic Sea. Phosphate decreased to 3 μmol l^{-1}, ammonium was not detectable, and nitrate reached concentrations up to 13 μmol l^{-1} (cf. also Nausch & Nehring 1994, Nehring et al. 1994). Nevertheless, in November 1993 the layer between 200 m depth and the bottom again became anoxic (cf. Fig. 3), with the consequent reversal of nutrient concentrations. Only the weak inflows in December 1993 and March 1994 brought about a longer improvement of the oxic conditions in the eastern Gotland Basin. As a result, the lowest phosphate and ammonium concentrations but the highest nitrate values of the whole investigation period were recorded in 1995 before the new stagnation period started (Figs 2 and 3, and Nehring et al. 1995b).

On the basis of measurements performed every February, March, May, July and October/November between 1992 and 2000, changes in oxygen/hydrogen sulphide and nutrient concentrations during the course of the year can be seen in greater detail for the near-bottom layer between 230 m and 240 m depth (Fig. 3). During 1996, 1997 and 1998, when anoxic conditions were interrupted every winter and spring by the occurrence of low oxygen concentrations, the nutrient regime reacted promptly. Traces of oxygen caused a decrease in phosphate concentrations and raised the nitrate content. The occurrence of hydrogen sulphide resulted in an immediate increase in phosphate due to liberation processes, the denitrification of nitrate, which finally disappeared, and the enrichment of ammonium (Fig. 3

and Matthäus et al. 1999). From mid-1998 onwards, when permanent anoxic conditions prevailed, nitrate could not be detected, and phosphate and ammonium concentrations were on the increase (Fig. 3). In 2001 and 2002, phosphate and ammonium concentrations were comparable with the high values measured at the end of the 1977–1992 stagnation period (Fig. 2 and Nausch et al. 2002, 2003). Consequently, nitrate was not found after mid-1998.

4. Discussion

The following question arises: What implications can these changes in the nutrient concentrations in the deep waters have for nutrient pool sizes? The dense vertical nutrient profiles observed at the central Gotland Deep station BMP J1 during monitoring cruises as well as during special programmes in the 1990s permit a rough estimate of nutrient enrichment below the halocline (Nausch et al. 2002). Nutrient enrichment was assessed for three depth regions (cf. Table 1) based on seven levels between 70 m and 236 m water depth. The box area in the eastern Gotland Basin below 70 m is 12 300 km^2 with a volume of 343 km^3. In the south and north, the box is bounded by approximately 56.7°N and 58.0°N respectively.

Fig. 4 summarises the amounts of phosphate and inorganic nitrogen compounds for three different depth regions: between the halocline and the bottom (A), between the redoxcline and the bottom (B), and between the halocline and the redoxcline (C). With the beginning of the stagnation period in 1995 (Nehring et al. 1995b) the amount of phosphate stored below the halocline increased continuously and reached a nearly stable level from 2000 onwards (Fig. 4 (A)). Probably, the particle-bound phosphate supply had become exhausted or an equilibrium between liberation from the sediment and transport processes had become established. A similar plateau phase with regard to phosphate concentration was observed at the end of the stagnation period 1977–1992. Most remarkable, however, was the fact that the 1993 MBI and the subsequent inflow events in 1994 caused only a comparatively small decrease in the amount of phosphate stored (Fig. 4 (A)). Nevertheless, if we examine this phenomenon in greater detail, the differences become more obvious. Below the redoxcline, water renewal led to a considerable drop in phosphate stored until 1995 (Fig. 4 (B)). Phosphate was bound to particles and accumulated in the sediment. Following the restoration of anoxic conditions, phosphate was redissolved and continuously enriched until 2001. However, owing to the relatively small water volume below the redoxcline (Table 1) these changes did not influence the total

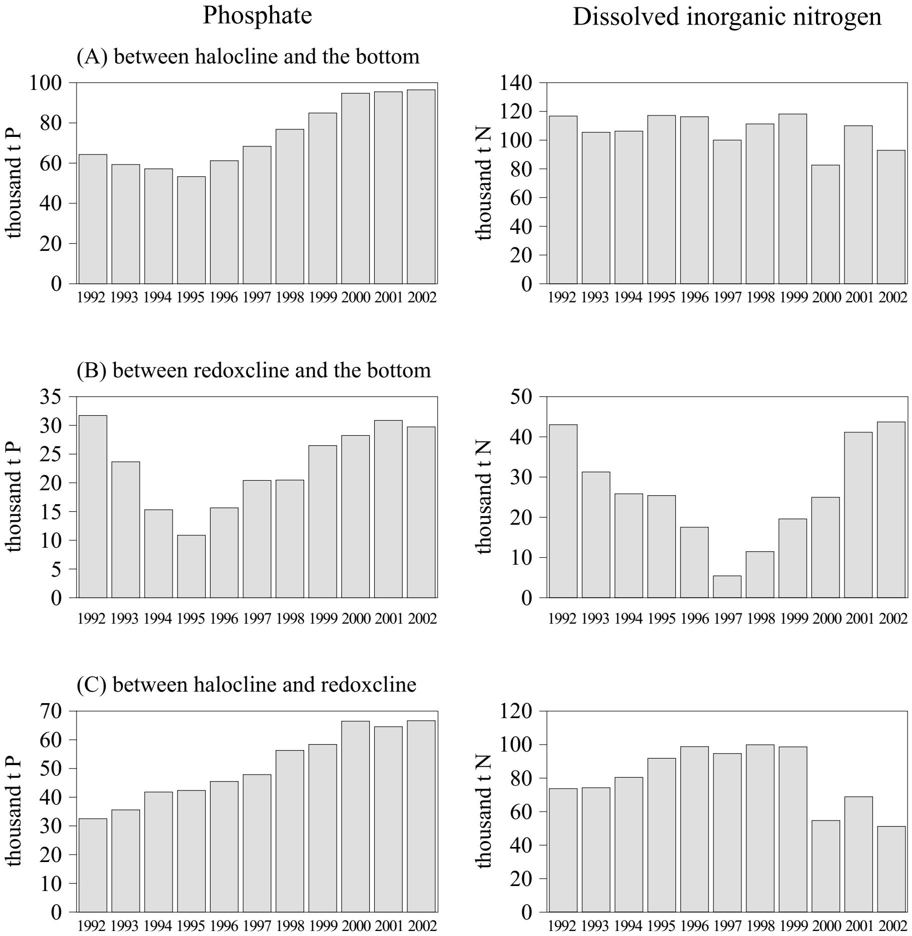

Fig. 4. Phosphate and inorganic nitrogen pools between 1992 and 2002 in a deep water box in the eastern Gotland Basin: between the halocline and the bottom (A); between the redoxcline and the bottom (B); between the halocline and redoxcline (C) (supplemented and updated after Nausch et al. 2003)

budget so prominently. The remarkable increase from 64 000 t P in 1992 to 96 500 t P in 2002 (Fig. 4 (A)) was due mainly to the changes taking place between the halocline and the redoxcline (Fig. 4 (C)). At the end of the previous stagnation period in 1992, the water body between 80 m and 125 m water depth was relatively well supplied with oxygen (cf. Nehring et al. 1993). Phosphate concentrations were therefore comparatively low. Water renewal initially caused oxygen-poor water layers with high phosphate concentrations to be raised. Thus, no decrease between 1992 and 1995 could be observed. During the stagnation period from 1995 onwards, the water layers below the halocline remained extremely poor in oxygen, with the result that enormous amounts of phosphate had enriched this layer (Fig. 4 (C)).

The development in pool sizes with respect to inorganic nitrogen compounds in the same period is quite different. Below the halocline (Fig. 4 (A)) no obvious changes can be observed between the end of the previous stagnation period and the present one. In contrast to the increase in stored phosphate, a slight decrease in the inorganic nitrogen content has probably occurred in recent years. Below the redoxcline, the MBI of 1993 and the inflow events in 1994 caused a steep fall in the amount of available nitrogen until 1997 (Fig. 4 (B)). The huge amounts of ammonium found in 1992 (cf. Fig. 2) were nitrified, then partly denitrified and thus eliminated from the system. The re-establishment of anoxic conditions in 1996 at first caused nitrate concentrations to decrease further because of denitrification, with the result that in 1997 only about 5500 t N were stored between 138 m depth and the bottom. Owing to the stable stagnation conditions from 1998 onwards, nitrate was not present at all and ammonium was enriched. In 2002, the nitrogen pool was again comparable with the situation at the end of the previous stagnation period in 1992 (Fig. 4 (B)). Between the halocline and the redoxcline there was at first a slight increase (Fig. 4 (C)). After the water renewal of 1993/1994, nitrification occurred and a broad nitrate maximum was able to develop. As the stagnation continued and in conjunction with the very poor oxygen conditions in this depth zone, denitrification followed and only a small nitrate maximum remained. Consequently, the nitrogen pool was becoming depleted from 1999 onwards.

Summing up, the last stagnation period brought about an increase in the phosphate pool below the halocline of up to 150%, whereas the pool of inorganic nitrogen compounds decreased to 80% as compared with 1992 when the previous stagnation period had ended. These changes are more abrupt if only the water layer between the halocline and the redoxcline is considered. For the same period 1992–2002, there was an increase in stored phosphate up to 205%, in contrast to the reduction in the inorganic nitrogen pool to 69%. This development is especially problematic with respect to eutrophication processes. Directly below the halocline, an enormous amount of phosphate is stored. Under given circumstances, such as extraordinarily deep vertical convection in winter or local upwelling processes, phosphate can be supplied to the surface layer where it can enhance primary production. Because the parallel supply of nitrate or ammonium is comparatively low, large-scale blooms of algae, especially of cyanobacteria, can be induced.

Acknowledgements

The German part of the Baltic Monitoring Programme (COMBINE) of HELCOM is conducted by IOW on behalf of the BSH, financed by the Bundesministerium für Verkehr (BMV).The authors thank Jan Szaron, Oceanographic Laboratory of Swedish Meteorological and Hydrological Institute (SMHI), Gothenburg, for providing hydrographic-hydrochemical observations from the Swedish Ocean Archive SHARK, obtained within the framework of the Swedish monitoring programme.

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