Papers

Transport and hydraulically-induced recycling of phosphorus in the North Sea–Baltic Sea transition zone*

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Abstract

Bottom-mounted acoustic Doppler current profiler measurements indicate that the net transport of water (844 m^3 s^{-1}) in the Little Belt makes up only 6% of the total transport between the Baltic Sea and the North Sea. This is a smaller percentage than the 9% commonly found in the literature. Owing to barotropic and tidal currents the gross transport is 5 times larger. The net transport is directed towards the North Sea mainly in the top 32 m of the water column but towards the Baltic Sea it occurs in the lower 5 m of the water column. The resulting transport of phosphorus is strongly affected by vertical mixing in an area of hydraulic control in the narrow part of the Little Belt. Comparisons of phosphorus profiles in stratified waters and in the mixing area indicate a yearly entrainment of 15 tonnes P from the bottom water to the surface layer. This vertical transport of P forms part of an internal loop in the general transport between the Baltic Sea and the North Sea. Compared to the transport observed 15–16 years ago, the present net phosphorus transport of 163 tonnes yr^{-1} from the Baltic Sea through the Little Belt is substantially lower.

1. Introduction

Many authors (e.g. Conley et al. 1993, Jørgensen & Richardson 1996) have pointed out that cultural eutrophication alters the relative availability of nutrients in coastal waters. A major factor in this respect is the influence of hydrography on local nutrient availability (Christiansen et al. 2004). The supply of nutrients to the Kattegat in the transition zone between the Baltic Sea and the North Sea caused by the general circulation has been shown to be much higher than the local terrestrial and atmospheric supply (Christensen et al. 1998). Areas of coastal marine fronts (Pedersen 1993), upwelling (Lund-Hansen & Vang 2003) and intrusion (Lund-Hansen & Vang 2004) are all known to have nutrient availability strongly influenced by circulation patterns.

It is becoming increasingly recognized that part of the mixing taking place in narrow marine straits with two-layer flows occurs by internal hydraulic control. Theoretical considerations (e.g. Nielsen et al. 2004), numerical modelling (Oguz 2005), *in situ* observations (MacDonald & Geyer 2005) and estimates of the strength of stratification in the form of Richardson numbers (Peters 2003) all suggest that vertical mixing across the pycnocline is enhanced downstream of channel contractions. Hydraulic control is also observed in the North Sea-Baltic Sea transition zone. Nielsen (2001) observed that two-layer flows in the Øresund were often hydraulically controlled. Recently, similar flow patterns have been observed in the Little Belt (Lund-Hansen et al. 2006). The majority of studies on hydraulic control have focused on the physical conditions leading to mixing across the pycnocline. Few publications exist on their possible biological effects in the form of (as examples) plankton variability (Lund-Hansen et al. 2006) and enhanced trophic coupling between plankton and fish (Roman et al. 2005), but knowledge of the resulting upward mixing of bottom water nutrients is limited.

The objective of the present study is to describe the exchange of water and phosphorus in a narrow transition area between the North Sea and the Baltic Sea (Little Belt area), and to discuss the role of local hydraulically-induced vertical mixing in this regional exchange. Local Danish county monitoring of the marine environment had shown a persistent plankton maximum in a part of the narrow strait. The present working hypothesis is that this plankton maximum was partly fed by the vertical mixing of nutrients.

2. Study area

The study area (Fig. 1) is situated in the transition zone between the high-saline North Sea and the low-saline Baltic Sea. The yearly fresh water surplus over the Baltic Sea catchments is 470 km^3 yr^{-1}, resulting in an average discharge of 15 000 m^3 s^{-1} of water through the Danish Belts (Jacobsen & Ottavi 1997, Christensen et al. 1998). Being one of the three straits making up this zone, the Little Belt has traditionally been considered as carrying about 9% of the water exchange between the North Sea and the Baltic Sea (e.g. Christensen et al. 1998). The area is microtidal with a tidal range of 0.4 m. However, owing to the large tidal prism passing the Little Belt, tide-induced current velocities are high and reach 0.8–1.0 m s^{-1}.

The narrow central part of the Little Belt is incised into glacial deposits, and depths generally vary between 30 and 50 m. Locally, depths may reach 80 m. Because of the strong currents in the central part there is no recent deposition of fine-grained material. Point bars in this meandering strait indicate predominantly southward-flowing currents at the bottom. The morphology of the sand waves on the point bars also signifies southward-flowing currents at the bottom. The high current velocities in the narrow part of the Belt imply that the water column is generally well mixed (Lund-Hansen & Vang 2003). Both to the north and the south of the narrow part of the Little Belt, depths are shallower at about 16–20 m. Here current velocities are much smaller and fine-grained sediment deposition takes place from suspension. The high contents of organic matter in these deposits (Christiansen et al. 1997, Jansen et al. 2003) frequently cause oxygen deficits in the near-bottom water masses. Stratifications of the water masses both to the north and to the south of the narrow part (Lund-Hansen & Vang 2004) contribute to the oxygen deficits. The strong turbulence and mixing of the water masses in the narrow part of the Belt may cause advection of water masses of intermediate density, and also intrusion and subsequent subsurface algae blooms in the northern part of the Belt (Lund-Hansen

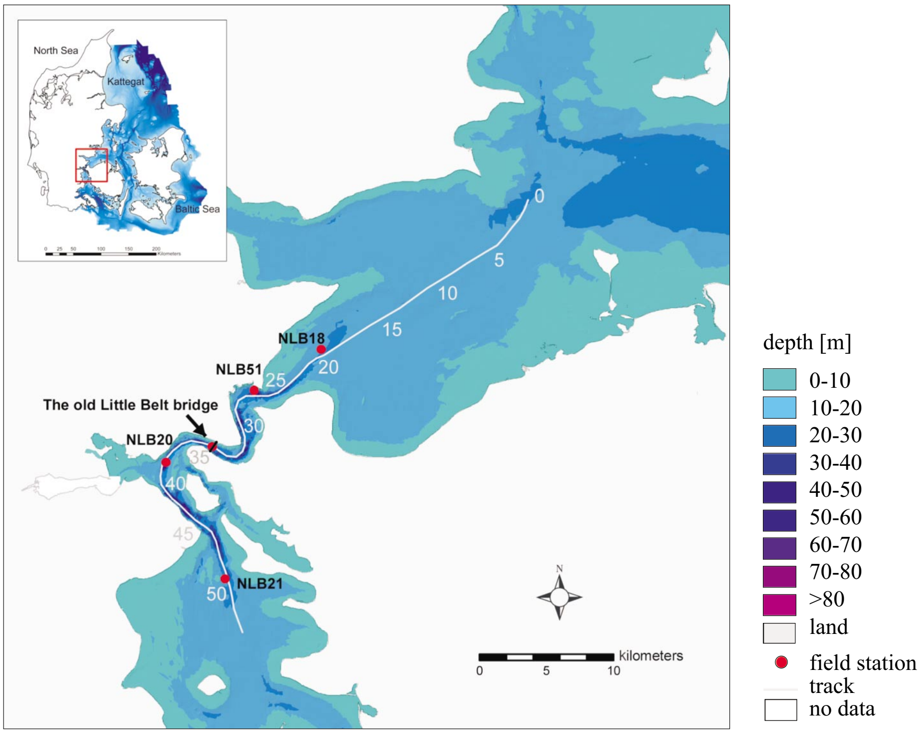

Fig. 1. Study area. The line through the study area shows the position of the transect presented in Fig. 4 (page 183)

& Vang 2004). Strongly contributing to mixing in the narrow part of the Little Belt is a subarea of hydraulic control. In this area primary production was measured to be 75–300 mgC m^{-2} d^{-1} higher than in the areas both to the south and to the north of the Little Belt (Lund-Hansen et al. 2006).

The main part of the nutrients transported through the Little Belt is derived from remote sources, and numerical modelling has shown that local reductions in the terrestrial supply of nutrients to the area have only marginal effects on the nutrient concentration in the water masses (Jürgensen et al. 1997).

3. Methods and data

The present study covers the period from August 1, 2003 to July 31, 2004. Current measurements with a vertical resolution of 5 m were performed with a bottom-mounted 300 kHz ADCP (acoustic Doppler current profiler – RD Instruments) every $\frac{1}{2}$ hour at position 55.5333°N, 9.7167°E near the old Little Belt Bridge (Fig. 1). These measurements were applied to equations developed by DHI Water & Environment (2001) to calculate the discharge. The equations used are linear regressions describing discharge based on depth-mean current velocities for situations with both mixed and stratified water columns. At the same position and with the same frequency as the current measurements, conductivity (salinity) and temperature were also measured at five depths ($-5, -10, -15, -20, -22.5$ m). These measurements were obtained with a self-recording CTD-string (GMI-Geological and Marine Instrumentations, Denmark).

With a frequency of about 14 days and a vertical resolution of 0.2 m 24 profiles of salinity and temperature were obtained with a GMI CTD (model: AROP 2000) at position NLB51 (Fig. 1). Salinity and temperature transects through the study area were measured occasionally using a GMI Scan Fish CTD, a towed CTD that moves automatically between the water surface and the sea floor. At position NLB51 oxygen concentrations were measured 27 times – by Winkler titration (Grasshoff et al. 1983) – during the study, near the sediment surface and at a depth of 1 m. Phosphorus concentrations were measured by standard procedures (Grasshoff et al. 1983) on water samples collected with Niskin bottles. The samples were kept in the dark and at a low temperature, and analyzed within a few hours. Analysis of orthophosphate (filtered) and total phosphorus (non-filtered) were performed with a precision of 1%. The respective reproducibilities were 98% and 95%. The samples at station NLB51 and NLB21 (Fig. 1) were taken 25 times during the year at the same depths in the same way as the samples for oxygen concentrations. At position NLB18 and NLB20 (Fig. 1) salinity and temperature obtained by a CTD and phosphorus samples were taken 7 times in the period between January and May 2004 with a vertical resolution of 5 m. Wind speed and direction were obtained from the old Little Belt Bridge every three hours.

The net phosphorus transport in the upper 32 m of the water column and the net phosphorus transport near the bottom were determined for the study period. They were calculated as the product of the cross-section, mean current velocity and phosphorus concentration. For north- and south-flowing currents, measurements from station NLB21 and NLB51, respectively, were used. Each phosphorus sample was assumed to represent a period of about two weeks depending on the hydrographical conditions. For the upper water column a mixing surplus was added to the product. The average phosphorus concentration during northward currents was higher at NLB20 (in the mixing area) than at NLB21 (just south of the mixing area). It is assumed that this higher concentration reflects the amount contributed by mixing. The phosphorus surplus was therefore calculated as the percentage by which the phosphorus concentration at NLB20 was on average higher than the corresponding concentration at NLB21 (Fig. 1). The cross-sections were calculated at 16 328 m^2 and 816 m^2 respectively.

4. Results

4.1. Hydrography

The flow pattern in the Northern Little Belt is strongly affected by the semidiurnal tide. The current speed changes according to the tide (Fig. 2a) and is superimposed on variations reflecting the wind conditions. Tide-induced current velocity variations prevail for about 30% of the year with velocities varying between ± 1 m s^{-1}, changing direction every 6 hours. Wind-induced current velocity variations are very common, and 65% of the

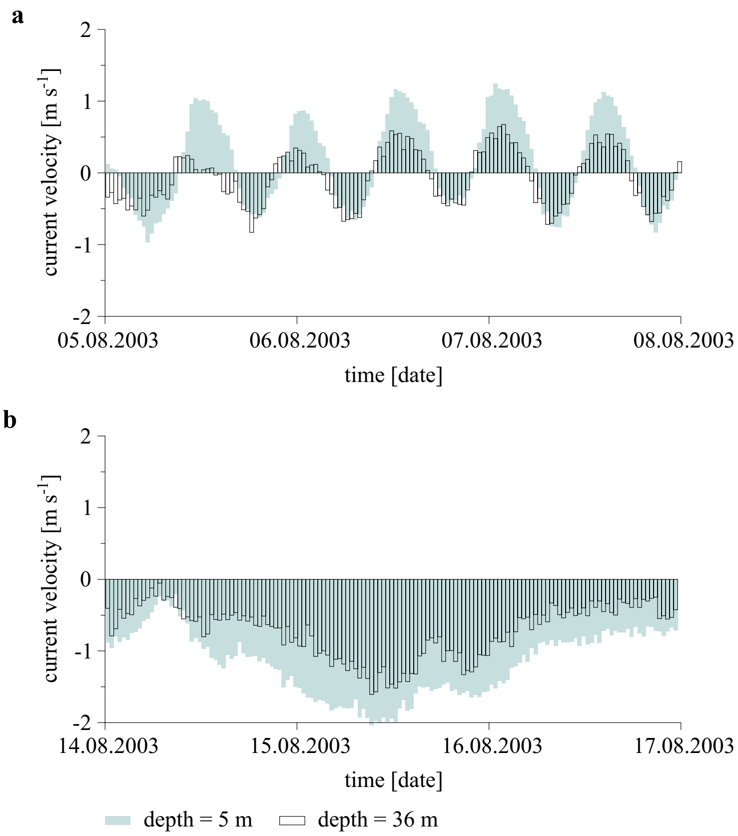

Fig. 2. Current velocities at 5 and 36 m depth obtained at the old Little Belt Bridge measured with an ADCP. Northward (outflow) current velocity is marked as positive values, and southward (inflow) velocity is negative. Current velocity varying with the tide (a). Current velocity during a westerly wind episode with wind speeds around 13 m s^{-1} (b)

study period was strongly affected by the wind. Current velocities as high as 2.3 m s^{-1} were recorded in situations of high wind speeds.

One result of high wind speeds and/or a persistent wind direction is the difference in water level in the inner Danish waters, which causes barotropic flow. Sequences of barotropic flow often occur as a consequence of cyclone passages over Denmark, and they cause southward and subsequent northward flow in the entire water column. An example of barotropic flow is seen between August 14 and August 17, 2003 (Fig. 2b). This situation is the result of westerly winds exceeding 10 m s^{-1} which cause a southward current of more than -2 m s^{-1}.

Baroclinic flow is observed as well. The flow direction near the bottom is opposite to that of the surface flow for 10% of the time. However, about half of the time with opposing flow occurs around the time of current direction changes. Very often the direction in the lower water layer changes prior to the direction change in the upper layer (Fig. 2a). The duration of these periods around the direction change is only a few hours. Contrary to this are long periods with opposing current directions in the two layers, which make up the other half of the time. These periods are observed predominately in late spring (Fig. 3) with the northward current in the upper water column and the southward current in the lower water column. They often occur during westerly winds, when heavy, highly saline water is forced underneath the low-saline upper layer.

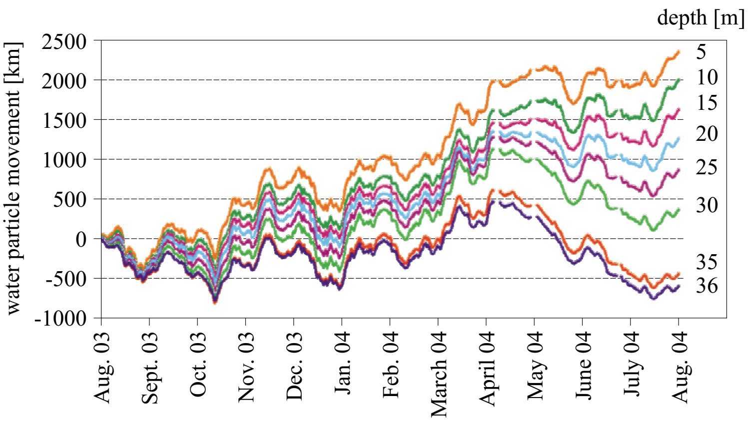

Fig. 3. Summed current velocity measured with an ADCP at 8 different water depths obtained at the old Little Belt Bridge showing the flow distance of a water particle during the campaign, assuming that the velocity remains the same as that measured at the bridge

The northward flow in the upper water column is also a result of the fresh water discharge to the Baltic Sea, which proceeds towards the

North Sea. The northward flow of low-saline water in the upper layer leads to a compensatory southward flow of high-saline water in the lower layer. This major difference in flow patterns combined with the minor differences around the flow direction change and vertical velocity differences in the water column results in a yearly difference of 3000 km between the movement of a particle in the surface water and in the bottom water (Fig. 3).

Even though the weather conditions with prevailing westerly winds over Denmark favour southward flows in the Belt area, the measurements show that the net discharge through Little Belt flows north as a result of the freshwater runoff to the Baltic Sea. In this study the net discharge was calculated at 844 m^3 s^{-1}, which is equal to 26.7 km^3 yr^{-1}. The discharge through the Little Belt during the study period comprised 6% of the freshwater discharge to the Baltic Sea, which on average amounts to 470 km^3 yr^{-1} (Christensen et al. 1998). Because of the tides, the gross discharges in the northward and southward directions are respectively 5 and 4 times larger than the net discharge.

The current is also strongly affected by the bathymetry of the narrow passage. As a result of the change in cross-sectional area, the flow changes from sub-critical to critical and hydraulic control occurs (see Lund-Hansen et al. (2006) for details on the hydraulics involved). This change in flow pattern is a contributory factor to the mixing of the water column. The most intense mixing is found in the area just west of the old Little Belt Bridge, whereas the northernmost area is stratified. This is exemplified by the situation on September 3, 2003, seen in Fig. 4, which shows the strongest stratification at the beginning of the track in the north with a salinity difference of 5 between surface and bottom. The most pronounced mixing occurs at kilometres 30–37 on the track in Fig. 1 in the narrowest part of the strait around the old Little Belt Bridge.

The mixing has an impact on the salinity profile measured at the old Little Belt Bridge. Fig. 5 shows the salinity difference between 5 and 22.5 m depth at the bridge. During the first eight months of the study year the water column was mostly well mixed. On April 18 the characteristics of the water column changed dramatically within a few days. The stratification generally became stronger and very variable. On April 23 the most distinct salinity difference occurred, with a difference of 10.3 between the two depths. This change in stratification occurred when the baroclinic current was most distinct. At that time, spring freshwater runoff was still giving rise to differences in salinity. On April 18 the wind backed from easterly to westerly, and highly saline water was forced into the Little Belt, thus initiating baroclinic current conditions. On the following days the wind veered easterly again, and northward currents and a mixed water column were recorded.

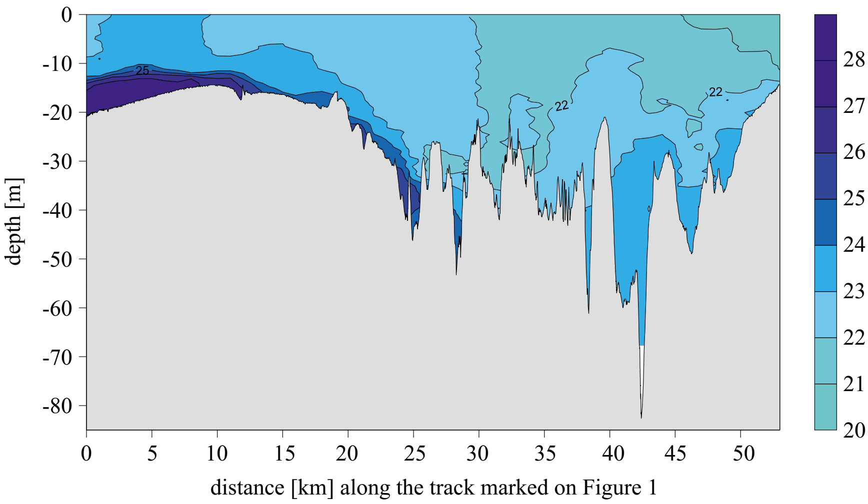

Fig. 4. Vertical salinity transect on September 3, 2003 through the northern Little Belt obtained by a Scan Fish (GMI). The track is shown in Fig. 1 (page 178)

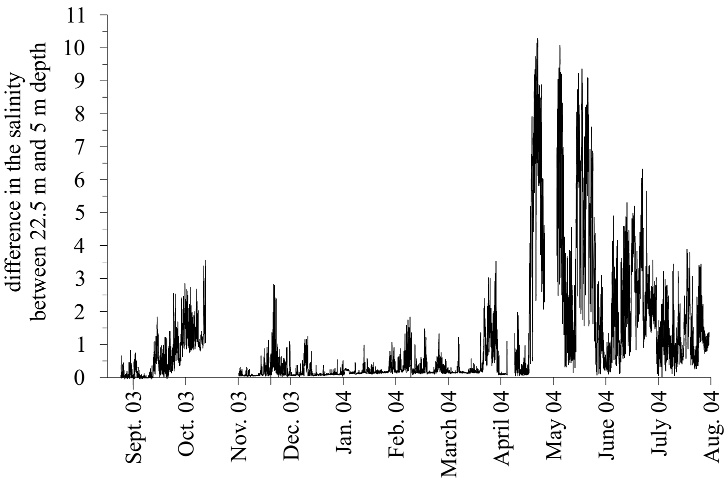

Fig. 5. Salinity difference between 22.5 and 5 m water depth obtained at the old Little Belt Bridge

In the subsequent period until the end of the study, several peaks in salinity difference occurred, the most distinct ones on May 6 and May 19.

5. Water chemistry

At the beginning of the study period, late-summer oxygen concentrations at NLB51 were low at approximately 2 mg dm^{-3}. In the following months until early spring, overall concentrations increased, reaching values of 13 mg dm^{-3}. Thereafter, oxygen concentrations mainly decreased, reaching a concentration of about 5 mg dm^{-3} at the end of the campaign, as shown in Fig. 6. The lowest (2.1 mg dm^{-3}) and highest (13.3 mg dm^{-3}) concentrations were measured on August 12 and March 9 respectively.

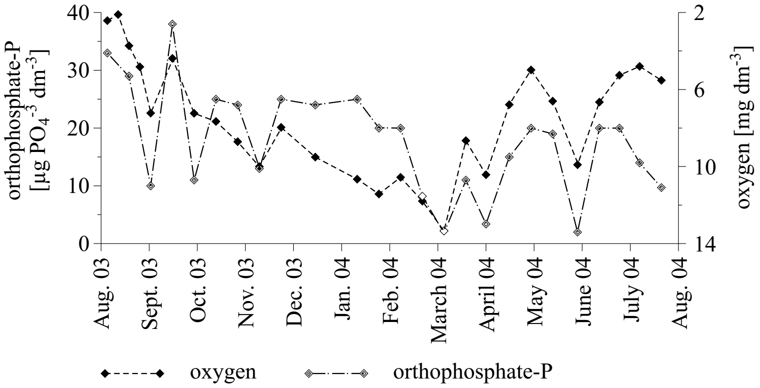

Fig. 6. Orthophosphate-P and oxygen concentrations near the bottom of the water column at NLB51. Note that the oxygen axis is inverted

The near-bottom PO_4^{-3}-P concentrations are on average characterized by low spring and high autumn concentrations. This is exemplified in Fig. 6, which shows the concentrations in the study period. These vary between 2 and 38 μg $PO_4{}^{-3}$-P dm^{-3}. The general trend is interrupted by concentration peaks which occur in the warmer season. In late summer and early autumn the PO_4^{-3} peaks become very pronounced: the maximum concentration of 38 μg PO_4^{-3}-P dm^{-3} was recorded on September 16.

Comparisons between orthophosphate and oxygen concentrations at NLB51 show counter-phase variations, especially from spring to autumn. One explanation for the observations may be found in the phosphorus recycling. Winter storms supply oxygen to the water column and low biological activity gives rise to a phosphorus build-up. A reduction in oxygen levels caused by mineralization of organic material and phosphorus consumption by algae characterizes the warmer part of the year. In late summer, oxygen concentrations close to depletion result in the release of iron-bound PO_4^{-3} (Emeis et al. 2000). The release of phosphorus from the seafloor in the mixing area, near NLB51 is, however, unlikely since the bottom is mostly erosional or composed of point bars. In situ transformations and quantities of river-supplied phosphorus are too small to cause these variations (Skyum et al. 1994). More likely are advection-induced concentration variations (Christiansen et al. 1997) with high phosphorus and low oxygen concentrations originating from the fine-grained deposits north or south of the narrow part of the Little Belt.

Hydrography has a significant influence on phosphorus concentrations in the central Little Belt. NLB20 and NLB18 are typical examples of stations in the mixed and stratified areas, respectively. Fig. 7 shows characteristic salinity and orthophosphate-P profiles at these two stations. It can be seen how the stratification influences the phosphorus concentration. The orthophosphate-P concentration at NLB20 is almost the same, c. 12 μg PO_4^{-3}P dm^{-3}, in the entire water column, whereas the concentration at NLB18 increases significantly at the halocline, reaching more than 15 μg $PO_4{}^{-3}$-P dm^{-3}. Since the salinity characteristics depend on the current direction and a strong relationship between stratification and phosphorus concentration can be observed, it is likely that current direction and phosphorus concentrations are interconnected.

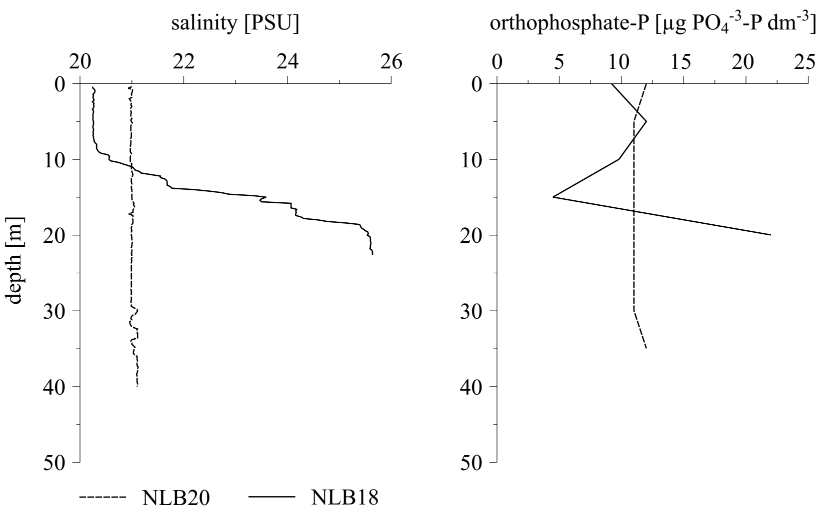

Fig. 7. Salinity and orthophosphate-P profiles on February 23, 2004 at NLB18, a stratified station, and at NLB20, a mixed station

Comparing salinity and temperature profiles with phosphorus and oxygen concentrations at NLB51 the following trend can be recognized: high phosphorus concentrations and low oxygen concentrations, especially near the bottom, are typically produced by a more stratified water column. Furthermore, observations suggest mostly southward currents (measured at the old Little Belt Bridge) in these situations. Northward currents mainly show a well-mixed water column and high oxygen concentrations. This indicates that the water chemistry in the narrow part of the Little Belt is strongly influenced by both stratification in the wider area further to the north and mixing further to the south.

Fig. 8 illustrates the link between current direction and oxygen concentrations measured near the bottom at the old Little Belt Bridge and at NLB51 respectively. The current is very variable and can shift direction several times within a comparatively short time. This can cause the water chemistry to reflect past, more substantial events, rather than the current, instantaneous situation. To eliminate this phenomenon the current velocity has been summed, which evens out short-term variations. Overall, a northward current characterizes situations with high oxygen concentrations, whereas low oxygen levels are measured when the net current flows south.

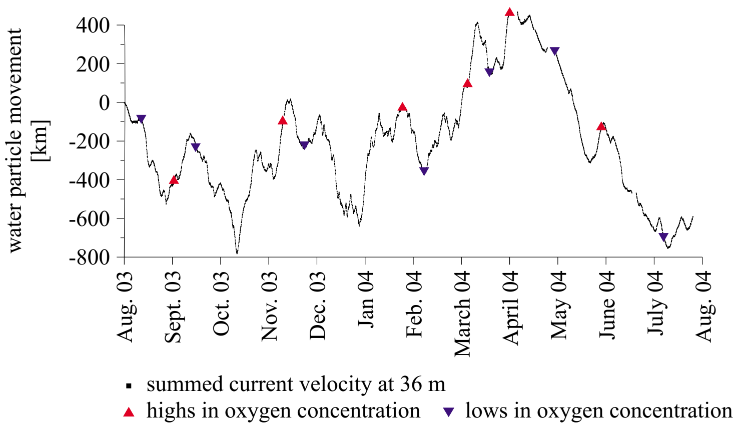

Fig. 8. Summed particle travel distance at 36 m water depth measured with an ADCP at the old Little Belt Bridge station. Increasing values result from outflow and decreasing values from inflow. Highs and lows in oxygen concentration near the bottom of NLB51 are also shown

5.1. Phosphorus cycling

The observations described in the previous sections indicate the existence of a phosphorus cycle in the northern Little Belt, exemplified in Fig. 9. One component of the cycle is the release of phosphorus from the bottom in the wider area in the northernmost part of the Little Belt (A). From here, the phosphorus-rich bottom water is transported southwards by advection into the narrower part of the Little Belt (B). Turbulence and mixing at this location break up the stratification and raise the phosphorus-rich bottom water to the photic zone, where phosphorus uptake by algae occurs (C). The algae are then transported to the wider northern area by the

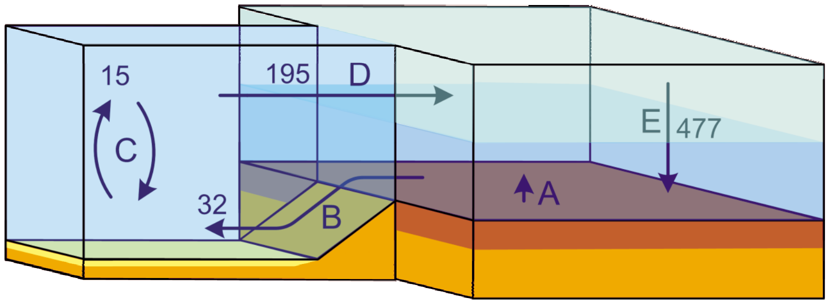

Fig. 9. A sketch of the phosphorus cycle in the northern Little Belt based on net calculations of one year of data. The process components of the phosphorus cycle are: A: Nutrient release, B: Advection, C: Mixing, D: Advection (also in the form of transport of algae) and E: settling and deposition (sedimentation data from Christiansen et al. 1997). Numbers on the sketch are in tonnes P per year

net northward current in the upper water column (D). This northern area is calmer, supporting the settling and deposition of organic material (E). This material is then decomposed by bacteria and a new cycle is initiated with phosphorus release from the bottom (A).

Fig. 3 shows a net northward current in the upper 30 m of the water column and a southward current near the bottom. Based on this division the net total phosphorus transports along the bottom to the south and in the upper water column to the north have been calculated at 32 and 195 tonnes, respectively. The amount of phosphorus raised to the upper water column through mixing has been calculated at 15 tonnes.

Gross phosphorus transports in the upper water column in the northward and southward directions are 17 and 16 times larger, respectively, than the net transport. In the lower water column the gross transport is 5 and 6 times higher than the net transport in the northward and southward directions, respectively. Strong tide-induced currents and barotropic flow are the main reasons for the large difference between the gross and the net phosphorus transport.

6. Discussion

6.1. Transport

Fresh water discharge from the Baltic Sea passing through the inner Danish waters is on average expected to be divided into Great Belt : Øresund : Little Belt in proportions of 7 : 3 : 1 (Jakobsen & Ottavi 1997). This means that 9% of the discharge runs through the Little Belt. The present study indicates, however, that this amount is smaller – about 6%. The reason for this discrepancy might have been a smaller-than-average fresh water discharge to the Baltic Sea catchments in the study year, but this was not the case. During the study, precipitation in the catchment area was close to the average of the period 1961–90 (www.dmi.dk). The finding of a smaller transport in the Little Belt seems to corroborate the findings of Jakobsen (1995). This author showed that transport of highly saline water through the Øresund during the inflow period was higher than the generally accepted 3/11 of the total transport in the Belt areas.

In the 1980s the net phosphorus transport from the Baltic Sea to the North Sea was 9500 tonnes P (Christensen et al. 1998). Therefore, the amount of phosphorus passing through the Little Belt was 570 tonnes, assuming that the percentage of phosphorus equals the percentage of water running through the Little Belt (6%). The net phosphorus transport calculated in the present study is only 163 tonnes (195 tonnes – 32 tonnes). Since the difference is not caused by precipitation differences between these periods, it is likely that the terrestrial supply of phosphorus in the intervening period has fallen. Since the 1980s, countries in the catchment areas have encouraged the reduction in phosphorus supply to marine areas. In Denmark the local supply to the Little Belt was reduced by 70% (Lillebæltsamarbejdet 2004). In contrast, the present transport of nitrogen through the Little Belt is similar to its transport 15 years ago (Kepp & Struve 2005).

The present observations of higher phosphorus concentrations in the water originating from the north and lower concentrations transported from the south are in agreement with other findings. Rasmussen & Gustafsson (2003) and Rasmussen et al. (2003) showed higher nutrient concentrations in the Kattegat than in either the North Sea or the Baltic Sea. In 2003 the local terrestrial phosphorus supply to the Little Belt was 180 tonnes (Lillebæltsamarbejdet 2004), which is of the same order as the net transport in the upper water column. However, compared to the gross P transport, the local terrestrial supply has only a slight influence on P concentrations in the Little Belt.

6.2. Phosphorus cycling

The observed phosphorus cycle in the northern Little Belt is not a closed system and therefore not as simple as sketched in Fig. 9. There are several different phosphorus sources contributing externally to the cycle. Values of inorganic phosphorus exchange with the sediment in the depositional northern part of the study area are not shown in Fig. 9. These values are highly variable and depend directly on the degree of oxygen deficit in the water column and thereby indirectly on stratification and meteorological conditions. Laima et al. (1995) have presented laboratory results indicating that the sediment-to-water fluxes in the study area may range between a yearly release from the sediment of 4210 tonnes to a yearly uptake of 2178 tonnes, depending on weather conditions. When recalculated to yearly fluxes these laboratory estimates indicate only potential ranges: they do not take into account variations on a daily and seasonal scale. Also, wave-induced resuspension of fine-grained sediments and their associated nutrients in the shallow northern part of the study area occur episodically. Christiansen et al. (1997) showed that the yearly resuspension rates were 17 times higher than the net deposition rate.

The recycling mechanism creates a coupling between the benthic and the pelagic ecosystems. The resulting fertilization of the surface waters may become increasingly important for primary production in the future when the terrestrial supply of phosphorus is cut as a result of better wastewater treatment and other amelioration procedures (e.g. change in agricultural and fish farming methods). At present the mixing area is shown to coincide with an area of a 75–300 mgC m^{-2} d^{-1} higher primary production than further to the north and to the south in the Little Belt (Lund-Hansen et al. 2006). Assuming a Redfield C/P ratio of 106 and that all the entrained P is consumed by primary production in the 25 km $\times$ 1.5 km mixing area, this would allow for an average production of 116 mgC m^{-2} d^{-1}. This is inside the measured yearly range of extra production in the mixing area.

The present estimates of a yearly entrainment of 15 tonnes P to the surface layers depend on measurements of P concentrations in the water column every 14 days, assuming stable concentrations between the measurements, and on current measurements with a high time resolution. Since the present measurements showed strong variations on short time scales, future modelling of transport processes in the Little Belt may show that a full understanding of the effects of the loop in P transport requires water column measurements of P at shorter time intervals than are presently done.

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