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Vertical Mixing due to Ship Traffic and Consequences for the Baltic Sea
Brassages des eaux par les bateaux et conséquences pour la Baltique
Vertikale Verwirbelung durch Schiffsverkehr und deren Folgen für die Ostsee

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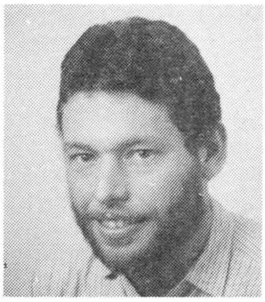

Carsten Jürgensen, born in 1958, received his Ph. D. from the Technical Univ. of Denmark. The subject of his Ph. D. research was: entrainment introduced by piers, dams, and ships. Carsten Jürgensen is now responsible for the hydrographic monitoring carried out by the county of Funen, which includes monitoring in the Great Belt.

SUMMARY
The entrainment by ships is studied in laboratory experiments and verified in two full scale experiments. The results are applied to the Great Belt and the Baltic Sea. Simulations of the surface salinity in the Baltic Sea indicate, that the ship traffic in the Great Belt has a greater impact on the Baltic hydrography than the planned bridge over the Great Belt, without compensational dredging.

Brassages des eaux par les bateaux et conséquences pour la Baltique

Résumé
La propulsion des bateaux est étudiée en laboratoire et vérifiée par par deux essais en vraie grandeur. Les résultats sont appliqués au Great Belt et à la Mer Baltique. La simulation de la salinité en surface de la Mer Baltique indique que le traffic des bateaux dans le Great Belt a un effet plus grand sur l'hydrographie de la Baltique qu'un pont sur le Great Belt, réalisé sans aucun dragage de compensation.

Vertikale Verwirbelung durch Schiffsverkehr und deren Folgen für die Ostsee

Zusammenfassung
Die Wasserturbulenz infolge Schiffsverkehr wurde in Laborexperimenten studiert und durch zwei Grossversuche überprüft. Die Ergebnisse wurden auf den Grossen Belt und die Ostsee übertragen. Simulationen des Oberflächensalzgehaltes in der Ostsee zeigen, dass der Schiffsverkehr im Grossen Belt grösseren Einfluss auf die Hydrographie der Ostsee hat als die geplante Brücke über den Grossen Belt, und zwar ohne Ausgleichsbaggerung.

1. INTRODUCTION

At the 11th Conference of Baltic Oceanographers in Rostock 1978 the first questions about the possible hydrographical consequences of a fixed Belt link were raised. From that time on there has been increasing concern about how a traffic link might influence the sensitive two layer flow in the Great Belt and the natural balance of the complicated hydrography of the Baltic Sea. The present construction plans do in fact include a broad range of investigations designed to estimate the consequences of different structures. The basic philosophy in these plans is, that as long as the structure does not change the average hydraulic parameters in the Great Belt, the hydrography in the adjacent waters and especially in the central Baltic will remain unchanged. This is often called the "zero effect solution".

One factor, however, has not until now been a point of concern, namely the mixing effect of the ship traffic in the Belt, i.e. the ship induced mixing or entrainment of dense saline water from the lower layer into the less dense water in the upper layer. The driving force behind vertical mixing is the amount of turbulence close to the interface. It is obvious that the turbulence from the entire ship traffic is large, but the following key questions have to be answered before any statement can be made on the possible hydrographical consequences:

1) Is the level of ship turbulence significant compared with the background level of turbulence?

2) How is the turbulent energy input of a sailing vessel physically tied to the upward entrainment?

3) What consequence does the ship induced entrainment in the Great Belt have on the salinity in the Baltic Sea?

4) What are the environmental consequences of ship induced entrainment compared to the consequences of the fixed link?

The answers to these questions are of general interest as they also give some insight into the response of the Baltic Sea to man-made changes, especially in view of the actual discussion about the Great Belt bridge.

2. ENERGY ANALYSIS

The significance of the ship induced energy input can be illustrated by an order of magnitude calculation, where the ship induced energy is compared with the other dominant causes of mixing in the Great Belt area (20 km x 100 km):

1) Contribution S of total ship traffic
2) Contribution W of the wind
3) Contribution C of the current

1) Ship induced contribution S:

The average ship traffic in the Belt area is roughly estimated to be seven ships (three ferries and four cargo vessels), each powered on average by a 10.000 kW engine, resulting in a contribution from ships S of approx.

$S = 70$ MW

2) Wind contribution W:

The wind effect calculation is based on a surface friction factor $fs/2 = 0.0026$ and on an average windspeed of 7.5 m/s.

The effect W of the wind blowing over the Belt area is found to be:

$W = 100$ MW

3) Current contribution C:

The effect C of the average current is roughly calculated on the basis of an average head loss over the Great Belt of 0,20 m, and the corresponding discharge of approx. 75.000 m**3/s. For these numbers the current contribution C is:

$C = 150$ MW

The order of magnitude analysis can now be done by comparing the estimated energies:

$S/(W+C) = 1/4$

Based on yearly average data the estimated total ship traffic contributes 1/4 of the natural energy input to the Great Belt mixing. This ratio is expected to be higher in summer and lower in winter due to the seasonal changes of the wind and current intensities.

3. EXPERIMENTAL PROCEDURE

An entrainment process is traditionally described in terms of the involved energies (1). Entrainment in a subcritical, quasi-stationary two-layer flow is characterized by a constant ratio between the potential energy gained (lifting of dense, saline water) and of the turbulent energy produced in the flow (turbulence production). This ratio can be regarded as an efficiency ratio for entrainment. The present work deals with the entrainment in flows around propeller-powered ships. This flow is not subcritical and non-stationary and therefore not covered by the existing theory.

The production of turbulence is a key parameter. Laboratory measurements will of course always be influenced by scaling and model effect and will not reproduce the correct ratio between the three major sources of turbulence involved:

1) boundary layer turbulence
2) ship wake turbulence
3) propeller jet turbulence

Since it is physically impossible to achieve the "natural" ratio between these sources in the laboratory, entrainment experiments are carried out with different ship hulls at a variety of speed and draft conditions and for different propeller jets. This way the magnitude and the sensitivity of the entrainment function to different types of sources of turbulence is determined.

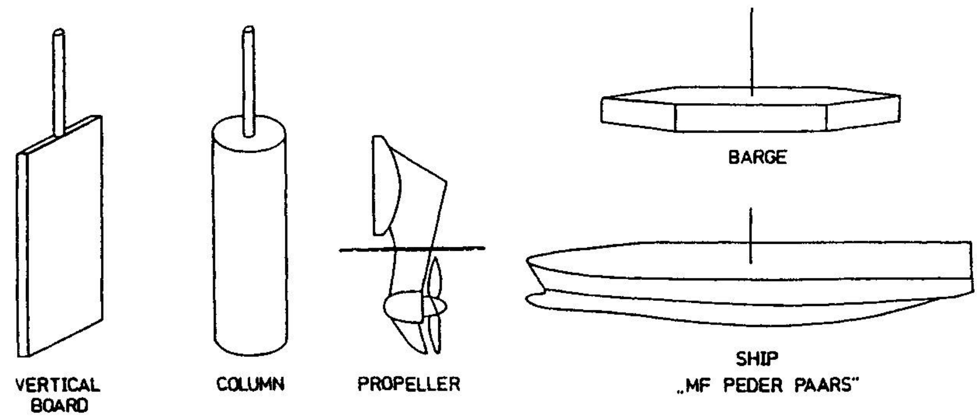

Fig. 1: Device used in entrainment experiments. The propeller is mounted on the different devices.

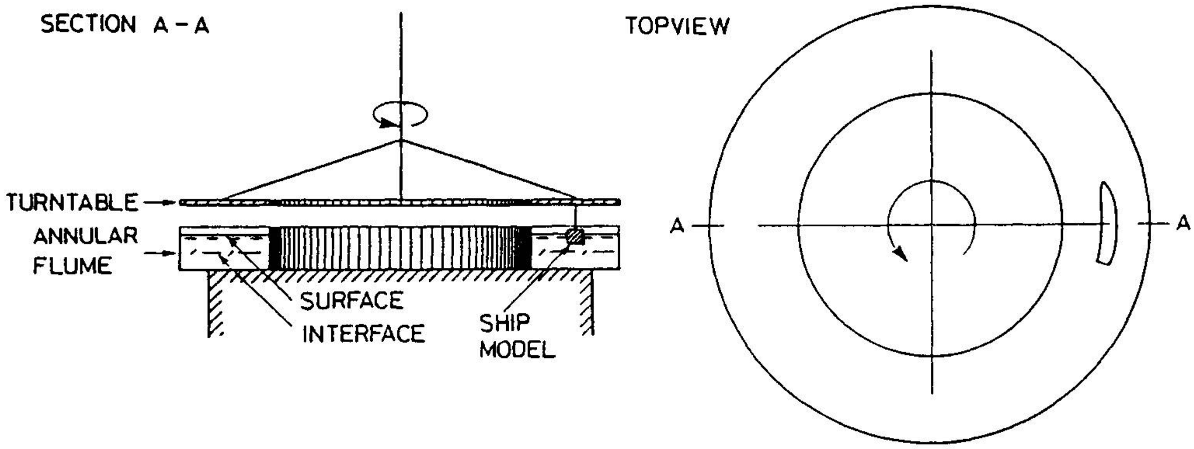

Fig. 2: Sketch of the experimental setup.

The experiments are conducted in an annular two layer flume, with an outer diameter of 1.00 m, two different widths of 0.2 m and 0.4 m, respectively and a total depth of approx 0.2 m. The stratification is achieved by salinity differences close to those found in the Great Belt. The devices are fixed to a turn-table and towed through the flume by the turn-table, see fig. 2.

The energy production is determined by:

$$PROD = (|Fdrag| + |Fprop|) * Vdrag$$

The gain of potential energy is found by measuring the density profiles at adequate time intervals.

4. RESULTS

The experimental measurements gave the following results:

1) A very clear relation between the relative draft D/Y and the entrainment efficiency POT/PROD was found, see fig. 3. The entrainment function is close to zero for very small D/Y-values (interface is far below the device) and close to zero for very large D/Y-values (the interface is much higher than the draft of the device). For intermediate D/Y-values there is an

efficiency maximum. The maximum efficiency is of the same order as the efficiency found in stationary, subcritical flows, which is 3-5%.

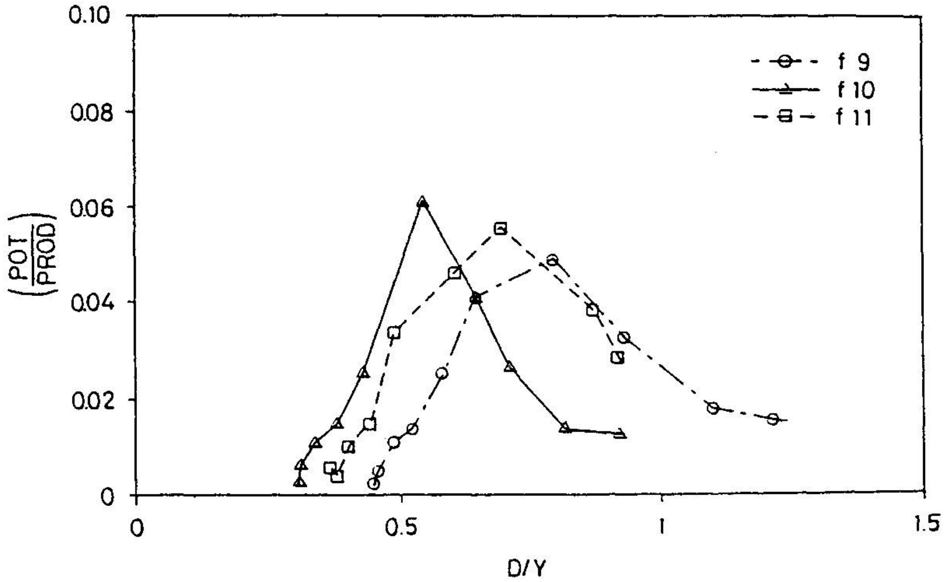

Fig. 3 Measured entrainment efficiency ratio in three experiments. The actual device is a barge without a propeller attached. Each experiment starts with high D/Y values. As the mixing takes place, the interface moves downward and the D/Y values become smaller.

2) The entrainment efficiency is not found to be sensitive to the densimetric Froude Number within the applied range, i.e. $20 < F^2 < 120$, F^2 nature = 100.

3) The entrainment does not depend on the shape of the density profile, i.e. whether it is a sharp pycnocline or not.

4) The shape of the different "ships" have only a minor influence on the entrainment. The advantage of testing a very broad range of ship hulls is now evident, since dramatic changes in the form of the hull only give minor changes in the entrainment function.

5) The entrainment efficiency of different propeller forces is found to be between 1% and 6%.

The magnitude and the variability of the propeller dominated entrainment efficiency is of the same order as the hull entrainment efficiency. This is a very important finding with regard to the entrainment associated with the local, non-stationary and supercritical flow of the propeller jet.

6) Full scale verification.

6.1) The laboratory results are compared with independent full scale measurements conducted in The Netherlands (2). The results are based on experiments with a motor vessel of 13.5m Lpp sailing in a stratified lock chamber of 350 m in length. The Dutch results are plotted along with the laboratory results in fig. 4.

6.2) A full scale experiment measuring the entrainment of ferries (3) has also been carried out in Nyborg Fjord, Denmark. Nyborg Fjord is approx. 5 km long, 0-3 km wide and 10-20 m deep. The ferries are 125 m long, 25 m wide and 6 m deep, and are powered by 10.000 kW engines. The result is shown in fig. 4.

Fig. 4 presents the main result of the experimental investigations. It shows the variation of the entrainment efficiency of a sailing vessel for different values of the parameter D/Y.

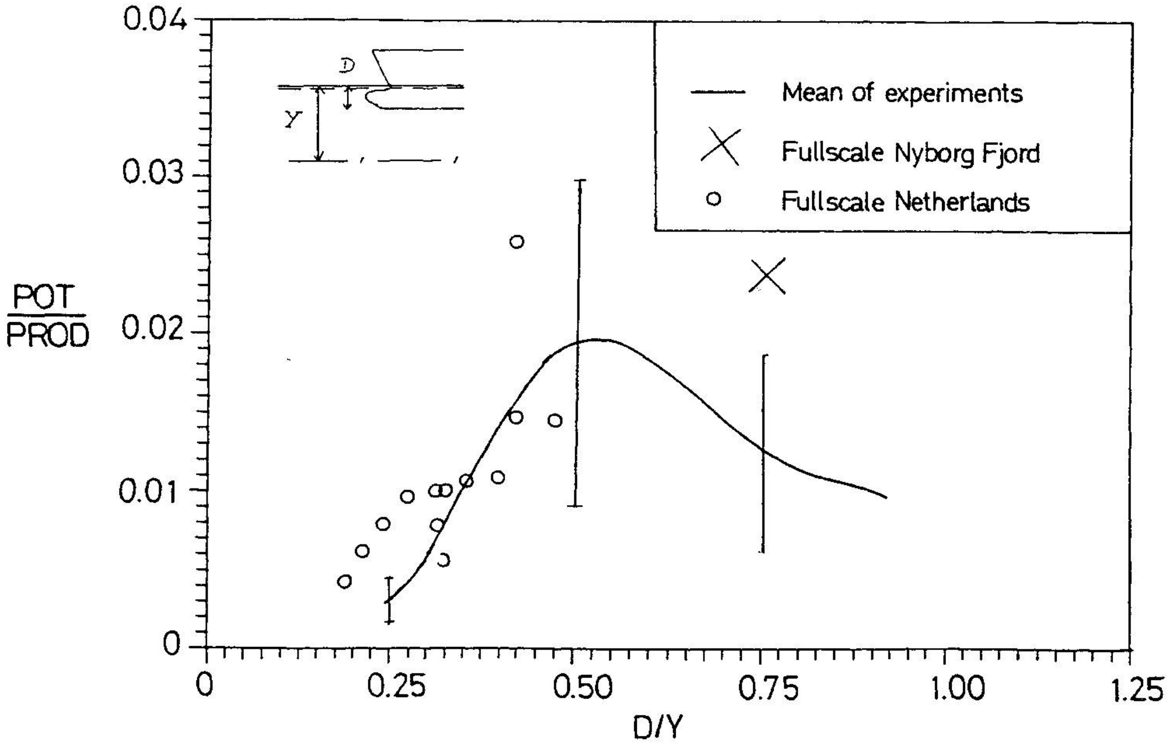

Fig. 4: Entrainment efficiency measurements POT/PROD as function of D/Y for a propeller-powered ship in force balance, i.e. |Fprop| = |Fdrag|. The line indicates the mean value and the error bars the standard deviation of the laboratory experiments. Results from full scale measurements are plotted for comparison.

5. APPLICATION TO A BALTIC SEA MODEL

The present findings are now applied to a simple, stationary box model of the Baltic Sea (2). The theory of a linear reservoir is used in order to create a dynamic model.

The two layer model is based on the linearized governing equations for the different regions of the Baltic Sea. This linearization requires that changes in the parameters are small. The model therefore works with relative parameters. The equations are solved with respect to the upward entrainment in the Great Belt.

Four normalized input time series are needed:

1) The freshwater runoff R into the Baltic Sea

2) The major salt water inflows Qe

3) The wind intensities W

4) The ship energy S

The model is solved for each year, and the solutions are convoluted in time in order to give a salinity time series for the upper Baltic which can be compared with measurements from the central Baltic and from the island of Christiansoe, north of Bornholm. Similar time series are found in all regions of the Baltic (2).

Fig. 5 shows the observed salinity time series and the computed salinites ind the upper Baltic. The line marked "OS" simulates a situation where shipping is not taken into account and where fresh water runoff and the major salt water inflows are the only parameters that have changed since 1900. The applied time constant is 10 years. The observations and the calculations are almost identical from 1900 until about 1945. This shows that the model works very well for this period and it suggests that there were no major changes in wind or ship induced mixing in that period. For the time after 1945 an increasing deviation between observations and calculations indicates that a model based on runoff and major salt water inflows alone, is not sufficient.

An important factor for mixing is the wind effect. Wind intensities based on "historical" observations had to be rejected, partly because they are visual judgements, and partly because they comprise observations from a large number of individual observers. Better data are computed on the basis of air pressure measurements. The monthly peak-to-peak values are used to compute a time series of the relative wind intensity. This "pseudo-geostrophical" wind indicates a constant or a slightly decreasing intensity. Taking all this into account the best estimate of the wind is obtained by assuming constant mean wind intensity since 1900.

The effect of the ship traffic is included in the line marked "1S", which means that the applied ship induced mixing corresponds to the ship-induced entrainment outlined above. The applied time series for the shipping intensities is based on the actual fuel consumption for the ferries at Nyborg-Korsoer and Halskov-Knudshoved from 1970 til 1988 and an extrapolation of these intensities for the period before 1970. The intensity of the total ship traffic was insignificant before aprox. 1945 and has increased almost linearly since. The mathematical model is applied with a convolution time constant of 10 years, which is a typical time scale for the upper Baltic. The model was not found to be very sensitive to the choice of the time scale. There is convincing agreement between the calculations and the observations. The typical increase of the salinity after 1960 is clearly shown in this case. Obviously an additional mixing mechanism like the one introduced by ships is neccessary to explain the increasing surface salinity in the Baltic Sea.

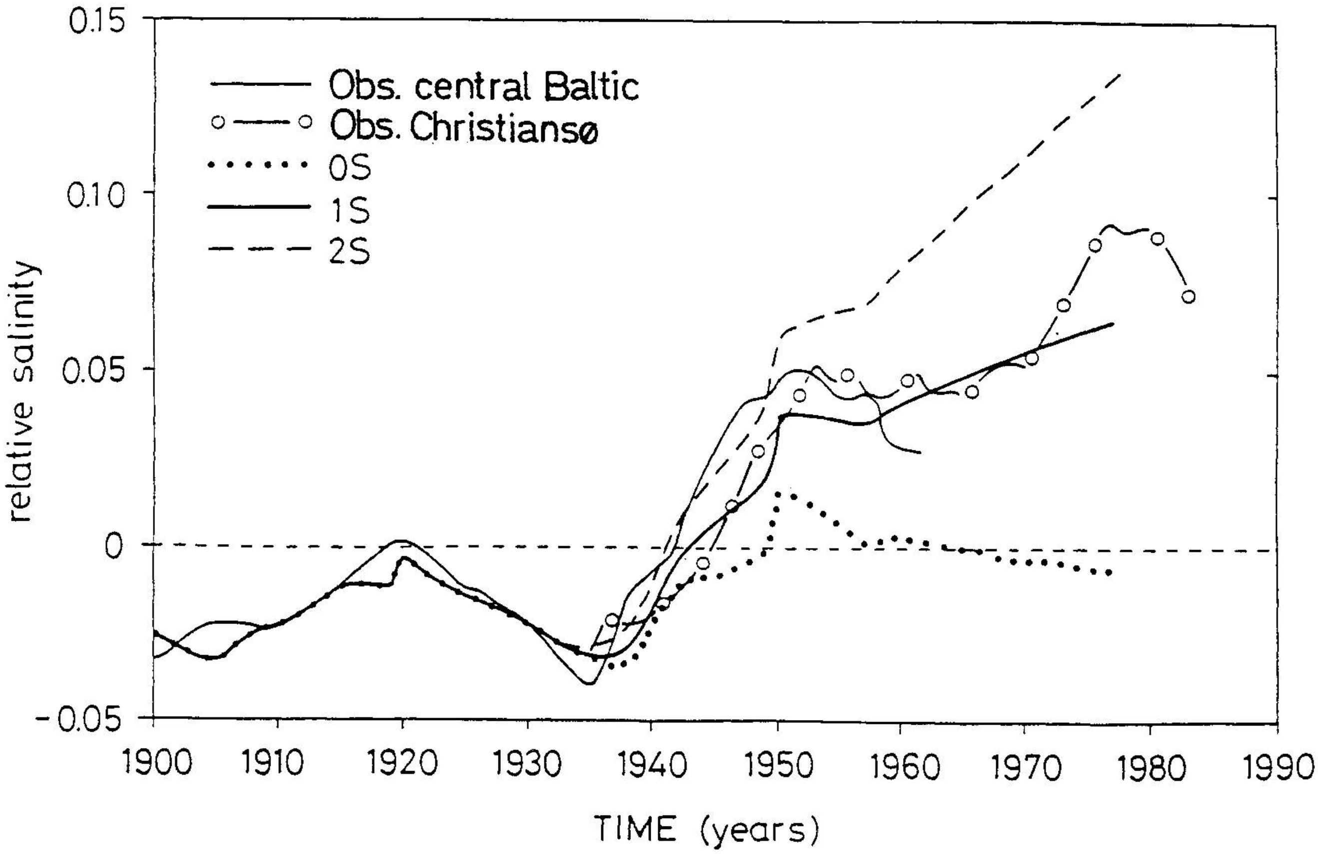

Fig. 5: Relative salinity time series in the upper Baltic:
Surface observations from the Baltic, 9 year sliding means.
Computations are made with a convolution time scale of 10 years:
Line "0S": No ship induced entrainment.
Line "1S": Including ship induced entrainment.
Line "2S": Including twice the calculated ship induced entrainment (sensitivity study).

The sensitivity of the results with respect to the importance of the effect of ships is shown with the line marked "2S". Here the shipping intensity is twice as high as estimated in the above energy analysis, based on the fuel consumption. The results indicate that the "central" estimate of the shipping intensities is in much better agreement with the salinity observations. It also shows that the Baltic is sinificantly sensitive to the mixing conditions in the Great Belt.

These simulations indicate, that the ship traffic in the Great Belt can be responsible for a salinity increase in the upper layer of the southern Baltic Sea of 0,6 $^{o}/oo$ (compared to an average of 7 $^{o}/oo$) over the last 50 years. The current plans for the fixed link without compensational dredging will cause a maximum salinity decrease of 0,1 $^{o}/oo$ over the next 10 years. The compensation dredging, nowever, will reduce this effect.

After completion of the fixed link the ferry traffic across the Great Belt will stop and the total ship induced entrainment will be reduced by approx. one half. This reduction can cause a salinity decrease in the upper layers of the Baltic Sea of 0,2 to 0,4 $^{o}/oo$ during the next 10 years, as long as the general ship traffic through the Great Belt keeps constant. The secondary effect of the Great Belt bridge (reduced shipping intensity) has therefore greater impact on the Baltic Sea than the primary effect of the bridge (piers and dams).

The ship entrainment mechanism shows three interesting new points with respect to the "zero effect solution":

1) It gives an unique engineering opportunity to relate and compare the effect of compensation dredging and ship traffic.

2) It illustrates how much man already does interfere with the state of the Baltic Sea.

3) Despite the uncertanties it seems evident, that the secondary consequences of the fixed link have a greater impact on the Baltic Sea than the primary consequences.

This illustrates some of the problems connected to the principle of the "zero effect solution". It should be noted, however, that the impact of ship traffic is an anthropogenic effect and that any reduction of this interference with nature is desirable from an environmental point of view.

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