

# Dynamics of Nutrients Pool in the Baltic Sea Using the Ecosystem Model 3D-CEMBS

L. Dzierzbicka-Głowacka and M. Janecki

**Abstract**—Seasonal variability of nutrients concentration in the Baltic Sea using the 3D ecosystem numerical model 3D-CEMBS has been investigated. Additionally this study shows horizontal and vertical distribution of nutrients in the Baltic Sea. Model domain is an extended Baltic Sea area divided into 600x640 horizontal grid cells. Aside from standard hydrodynamic parameters 3D-CEMBS produces modeled ecological variables such as: three types of phytoplankton, two detrital classes, dissolved oxygen and the nutrients (nitrate, ammonium, phosphate and silicate). The presented model allows prediction of parameters that describe distribution of nutrients concentration and phytoplankton biomass. 3D-CEMBS can be used to study the effect of different hydrodynamic and biogeochemical processes on distributions of these variables in a larger scale.

**Keywords**—Ecosystem model, nutrients, Baltic Sea.

## I. INTRODUCTION

THE Baltic Sea is a shallow, Mediterranean shelf sea. It is the youngest European sea and one of the youngest seas of the Atlantic with the area of about 415,000km<sup>2</sup>. It connects to the North Sea through a series of straits: the Danish Straits (The Sound, Little Belt and Great Belt), Kattegat and Skagerrak. Baltic Sea can be divided into regions with well-defined hydrographic parameters [1], [2], by taking into account the topography of the bottom. These are the Gulf of Bothnia, Bothnia Sea, Gulf of Finland, Gulf of Riga, the Baltic Proper (South), the Danish Straits and the Kattegat. The average depth of the Baltic Sea is 52 meters and there is no region with an average depth greater than 70 meters. Shallow area of The Sound and Belt Sea (average 38 meters depth) is a palpable threshold impending water exchange between the North Sea, Kattegat and the rest of Baltic. Despite the low average depth in general, Baltic Sea has water bodies with a maximum depth reaching several hundred meters.

The characteristic feature of the Baltic, compared to the waters of other seas and oceans, is its distinctly lower salinity. Salinity in surface level decreases from over 20 PSU in the region of Kattegat to around 2 PSU in the northern parts of Gulf of Bothnia and eastern parts of the Gulf of Finland. It is caused by the inflow of freshwater mainly by rivers and precipitation. Amount of water that flows into the Baltic Sea through rivers is ten times greater than the surplus of

precipitation over evaporation. The water level in the Baltic Sea is higher than the level in the North Sea. From around 10 cm higher in Kattegat, 18cm in the Baltic Proper up to 36cm in the Gulf of Bothnia. Differences in water level height cause a flow of water from the Baltic Sea to the North Sea, which is around two times greater than the average amount of water flowing in. Rivers take the biggest role in this processes being not only the main source of fresh water but also providing inflow of nutrients. Due to this, rivers have huge role in shaping the Mediterranean environment of Baltic Sea [3].

## II. 3D-CEMBS MODEL

### A. Configuration

3D-CEMBS (3D Coupled Ecosystem Model of Baltic Sea) is a coupled ice-ocean-ecosystem model that consists of four separate components with an additional central coupler CPL7, which controls time, exchange forces, domains, grids and other model data (Fig. 1). Model domain is extended Baltic Sea. Ocean (POP model, version 2.1) and ice (CICE model, version 4.0) models are forced by atmospheric data model (datm7). In addition, river inflow of freshwater and nutrient deposition is processed by land model (dlnd) [4]-[9]. All model forecasts are available on website [http://deep.iopan.gda.pl/CEMBaltic/new\\_lay/index.php](http://deep.iopan.gda.pl/CEMBaltic/new_lay/index.php).

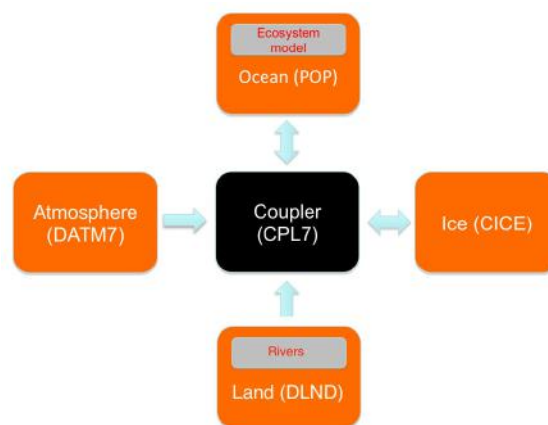


Fig. 1 3D-CEMBS configuration

- Horizontal resolution of approximately 2km (1/48°)
- Bathymetry (based on ETOPO1 1 arc-minute global relief model) represented as 21 vertical levels.
- Thickness of the first four surface layers is 5 meters.
- Model domain based on stereographic coordinates with equator in the center of the Baltic Sea.

L. Dzierzbicka-Głowacka is with the Institute of Oceanology, Polish Academy of Sciences, 81-712 Sopot, Poland (phone: +48-58-7311912; e-mail: [dzierzb@iopan.gda.pl](mailto:dzierzb@iopan.gda.pl)).

M. Janecki is with the Institute of Oceanology, Polish Academy of Sciences, 81-712 Sopot, Poland (phone: +48-58-7311915; e-mail: [mjanecki@iopan.gda.pl](mailto:mjanecki@iopan.gda.pl)).

- Driver and coupling time step is 1440 seconds. Ocean model time step is 480 seconds (8 minutes).
- POP modeled variables: temperature, salinity, currents and sea surface height.
- CICE modeled variables: ice area cover and ice thickness.
- 48-hour atmospheric forcing data from ICM-UM model (University of Warsaw)

### B. Ecosystem Model

Ecosystem model is based on an intermediate complexity marine ecosystem model for the global domain [10] and consists of 11 main components: zooplankton, small phytoplankton, diatoms, cyanobacteria, two detrital classes, dissolved oxygen and the nutrients nitrate, ammonium, phosphate and silicate. Data from 78 main rivers of Baltic Sea is taken to provide nutrient deposition from rivers.

In the 3D-CEMBS model, there is a second order advection-diffusion partial differential equation, similar to the conservation equations for temperature and salinity in the ocean model for each compartment in the ecosystem model:

$$\frac{\partial S}{\partial t} + (V + w_s) \cdot \nabla S = \frac{\partial}{\partial z} \left( K_z \frac{\partial S}{\partial z} \right) + \sum_{i=1}^2 \frac{\partial}{\partial x_i} \left( K_{x_i} \frac{\partial S}{\partial x_i} \right) + F_S \quad (1)$$

where:

- $S$  –each model variable
- $V$  –velocity vector,
- $w_s$  –sinking velocity of phytoplankton or pelagic detritus,
- $K_z, K_x$  –vertical and horizontal turbulent diffusion coefficients,
- $F_S$  –biogeochemical source-sink term

The model is based on comparatively simple trophic interactions among variables. The structural relationships between the different variables are presented in (Fig. 2). In this study only the general forms of the time rate of change equations for nutrients are presented in Appendix A.

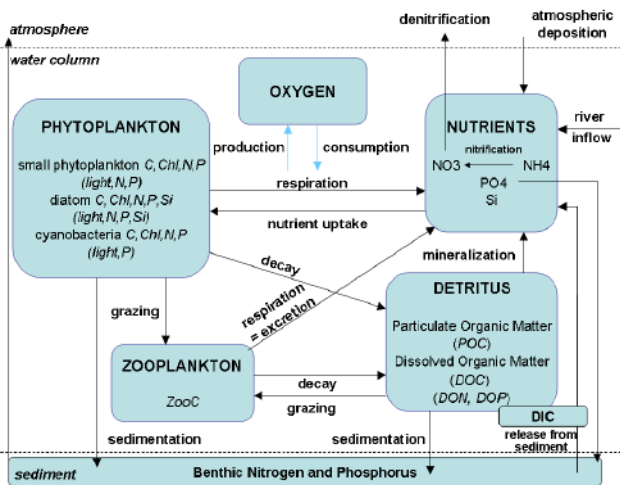


Fig. 2 Structure of the ecosystem model

### III. RESULTS

Nutrients are an indispensable part of the ecosystem, and their absence causes inhibition of growth and development of plants. Excessive or unbalanced concentrations of one of the basic elements or compounds affect biogenic balance in the ecosystem. Most of the Baltic areas are characterized by surplus phosphorus; therefore nitrogen is the factor limiting growth of algae and vascular plants. Some blue-green algae can compensate for the lack of dissolved inorganic nitrogen compounds in water by absorbing molecular nitrogen from the atmosphere, and grow very well in these conditions. Phosphorus limitation plays a very important role in the northern part of Gulf of Bothnia and the eastern part of Gulf of Riga and locally in other areas. Silicon is not a factor limiting primary production, although it is widely depleted during intense spring blooms of diatoms. Horizontal distribution of nutrients in the euphotic layer during winter (before beginning of the spring blooms) is uneven (Fig. 3). The nitrogen concentration drops from 6-8mmol N m<sup>-3</sup> in Kattegat to around 5mmol N m<sup>-3</sup> along the Bornholm Deep and Gotland Basin, while the concentration of phosphorus is ranging from 0.1-0.6mmol P m<sup>-3</sup>. The highest concentration of nutrients is observed in the estuarine coastal waters

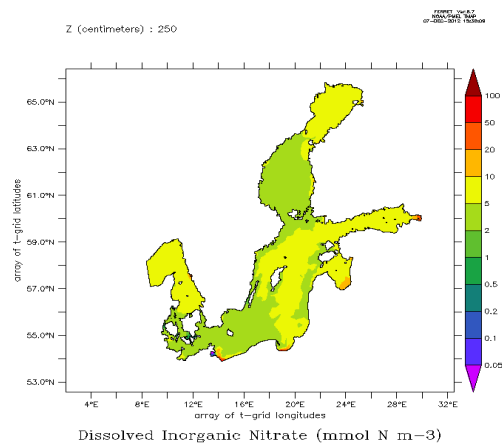


Fig. 3 (a) Horizontal distribution of nitrate surface concentration for 17<sup>th</sup> January 2011

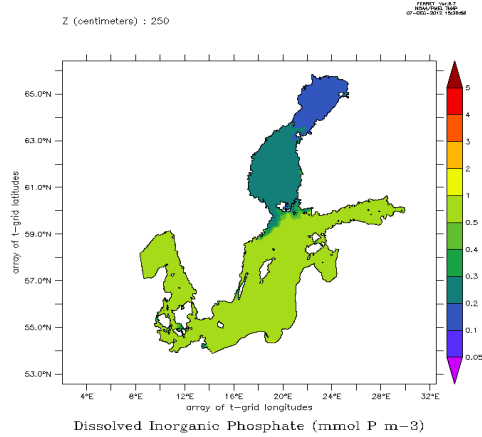


Fig. 3 (b) Horizontal distribution of phosphate surface concentration for 17<sup>th</sup> January 2011

Vertical nutrient distribution depends on the regional hydrology conditions. Generally, halocline separates the surface layers with a lower nutrient concentration from bottom waters rich in these substances (Fig. 4). Taking into account that decomposition and mineralization of a large part of the matter, run mainly in deeper water and bottom sediment layers, those environments constitute a reservoir of nutrients

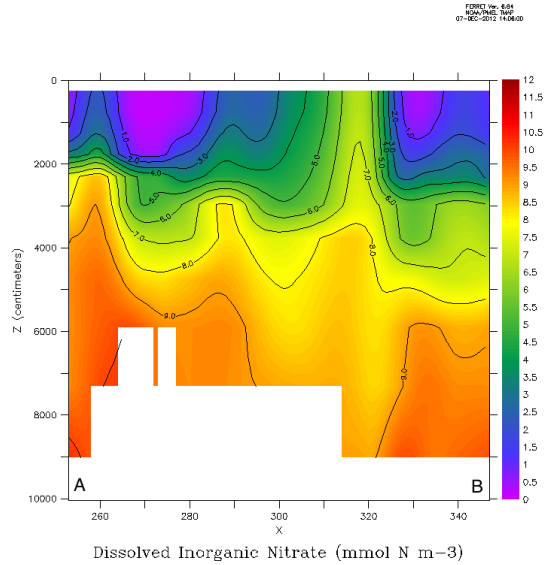


Fig. 4 (b) NO<sub>3</sub> concentration for 16<sup>th</sup> May 2011 at selected section AB

Seasonal nutrient concentrations differences, determines the annual cycle of phytoplankton development growth. Phytoplankton growth stages are similar throughout the Baltic Sea. It is characterized by an intense, but short spring diatom bloom, followed by other algae blooms (starting around mid-summer until the autumn). Nutrient concentration decreases significantly after the spring bloom. Weak vertical water movements cause low nutrient concentration in summer that lasts until autumn. Thanks to autumn intense water mixing, nutrients reclaimed from bottom layers enrich euphotic zone. This influx is so large, that even less intense (compared to spring) primary production does not cause nutrients depletion. Winter inhibition of the primary production (not enough light and too low temperature) allows full regeneration of nutrient supply in the euphotic zone (Fig. 5).

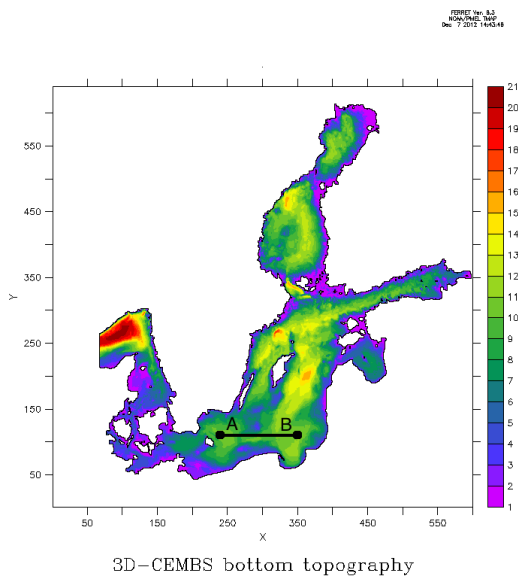


Fig. 4 (a) Section AB for NO<sub>3</sub> concentration

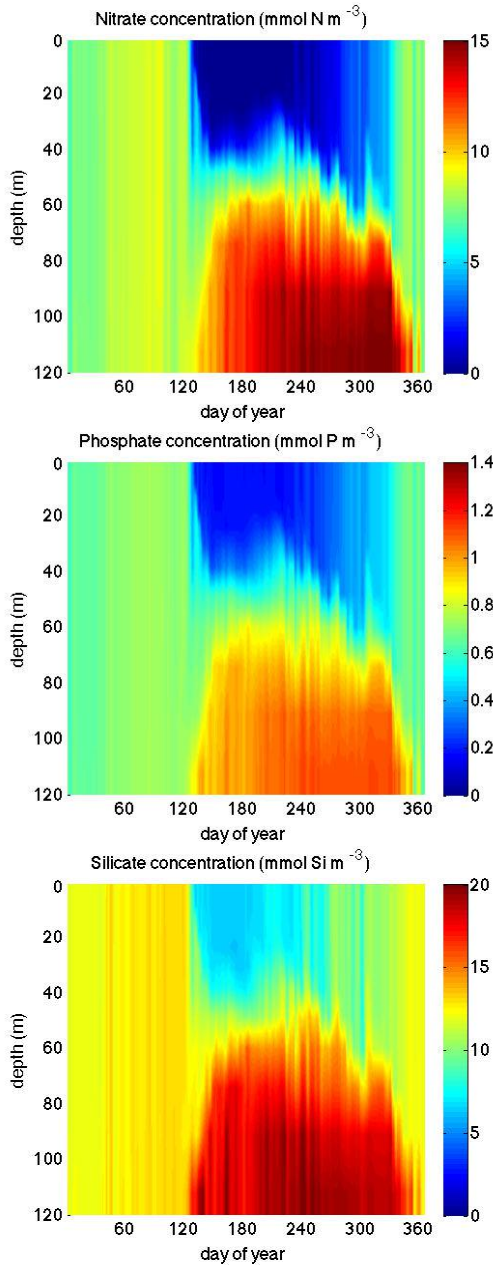


Fig. 5 (a) The annual cycle of nutrient concentration ( $\text{NO}_3$ ,  $\text{PO}_4$ ,  $\text{SiO}_3$ ) at Gdansk Deep during year 2011

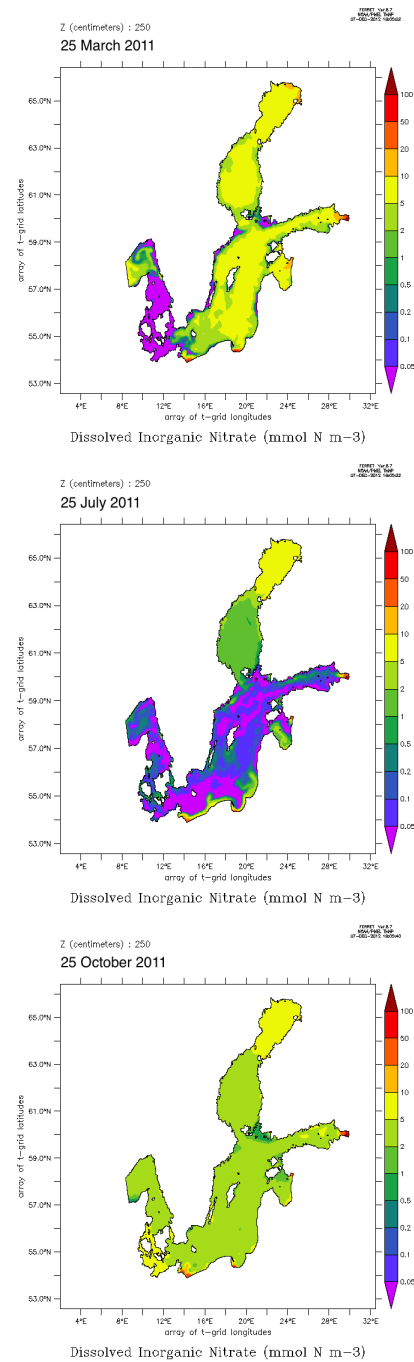


Fig. 5 (b) Horizontal nitrate concentration differences in surface layer between spring, summer and autumn. Depth values are from the centre of each vertical model level

#### IV. SUMMARY

About half of the total amount of nitrogen and about 10% of the phosphorus gets into the sea from the atmosphere, and the remaining part is possessed by the waterway [11]. It has been estimated that the nitrogen concentration is four and phosphorus about eight times higher than 100 years ago. This increase starts probably around 1950 [3]. In the current century, the increased amount of nutrients in the Baltic Sea is caused mainly by excessive:

- application of fertilizers
- use of detergents
- combustion of fossil fuels (coal, oil, gas, wood)

This knowledge, combined with a synthesis of the available experimental data and numerical ecosystem models of Baltic Sea 3D-CEMBS (i) may be used in studies over the clinical impact of human activity on the dynamics of the nutrient concentration. Secondly, it can be used to estimate the impact of climate change on abiotic factors, which affect the processes occurring in the food chain, and (ii) to give hypothetical predictions for the negative or positive effects of on-going changes in the marine environment.

#### APPENDIX

##### A.1. Nitrogen

$$\frac{d(NO_3)}{dt} = NITRIF - DENITRIF - upNO_3sp - upNO_3diat - upNO_3diaz \quad (A-1)$$

where:

- NITRIF* – nitrification ( $NH_4 \rightarrow NO_3$ )  
*DENITRIF* – denitrification ( $NO_3 \rightarrow N_2$ )  
*upNO<sub>3</sub>* – nitrate uptake by small phytoplankton / diatoms / diazotrophs

##### A.2. Ammonia

$$\frac{d(NH_4)}{dt} = Q \cdot \left( \begin{array}{l} lossDICsp + lossDICdiat + \\ lossDICdiaz + lossDICzoo + \\ grazeDICsp + grazeDICdiat + \\ grazeDICdiaz \end{array} \right) + reminDON + diazNex - NITRIF - upNH_4sp - upNH_4diat - upNH_4diaz \quad (A-2)$$

where:

- Q* – nitrogen/carbon ratio of phytoplankton & zooplankton  
*lossDIC* – non-grazing mortality of small phytoplankton / diatoms / diazotrophs / zooplankton routed to Dissolved Inorganic Carbon  
*grazeDIC* – grazing rate on small phytoplankton / diatoms / diazotrophs routed to Dissolved Inorganic Carbon  
*NITRIF* – nitrification ( $NH_4 \rightarrow NO_3$ )  
*upNH<sub>4</sub>* – ammonium uptake by small phytoplankton / diatoms / diazotrophs  
*reminDON* – portion of Dissolved Organic Nitrogen remineralized  
*diazNex* – diazotroph fixed nitrogen excretion

##### A.3. Phosphate

$$\frac{d(PO_4)}{dt} = Qp \cdot \left( \begin{array}{l} lossDICsp + lossDICdiat + \\ lossDICzoo + grazeDICsp + \\ grazeDICdiat - photoCdiat \end{array} \right) + reminDOP + lossDIPdiaz - upPO_4sp - upPO_4diaz \quad (A-3)$$

where:

- Qp* –phosphate / carbon ratio of small phytoplankton, diatom & zooplankton  
*lossDIC* – non-grazing mortality of small phytoplankton / diatoms / zooplankton routed to Dissolved Inorganic Carbon  
*grazeDIC* –grazing rate on small phytoplankton/diatoms  
*photoCdiat* –diatom carbon fixation  
*reminDOP* –portion of Dissolved Organic Phosphate remineralized  
*lossDIP* –phosphate from mortality routed to remineralization  
*upNH<sub>4</sub>* – ammonium uptake by small phytoplankton / diatoms

##### A.4. Silicate

$$\frac{d(SiO_3)}{dt} = Qsi \cdot \left( \begin{array}{l} grazeSiremin \cdot grazeDiat + \\ lossDCdiat \cdot lossDiat \\ - photoSldiat \end{array} \right) \quad (A-4)$$

where:

- Qsi* – diatom initial silicate / carbon ratio  
*grazeSiremin* – fraction of diatom silicate grazing, which is remineralized  
*grazeDiat* – grazing rate on diatoms  
*lossDCdiat* – fraction diatom loss to Dissolved Organic Carbon  
*photoSldiat* – diatom carbon fixation  
*lossDiat* – diatom non-grazing mortality

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#### REFERENCES

- [1] SH. Fosnelius, *Hydrography of the Baltic Deep Basins. III. Fishery Board of Sweden*. Series Hydrography. Report 1969, 23:1-97

- [2] A. Omstedt, *Modelling the Baltic Sea as thirteen sub-basins with vertical resolution*. Tellus Series A: Dynamics Meteorology and Oceanography; 1990, vol. 42, 2:286-301
- [3] E. Andrulewicz, M. Szymelfenig, J. Urbański, J. M. Węslawski, S. Węslawski, *Morze Bałtyckie – o tym warto wiedzieć*. Polski Klub Ekologiczny, Okręg Wschodnio-Pomorski, 2008, ISBN 83-903702-2-0: 115 (in Polish).
- [4] L. Dzierzbicka-Głowacka, J. Jakacki, M. Janecki, A. Nowicki, *Variability in the distribution of phytoplankton as affected by changes to the main physical parameters in the Baltic Sea*. Oceanologia; 2011b, 53 (1-TI): 449-470
- [5] L. Dzierzbicka-Głowacka, J. Jakacki, M. Janecki, A. Nowicki, *The Baltic Sea coupled ice-ocean model*, Chaotic Modeling and Simulation (CMSIM); 2012, 4, 679-686.
- [6] L. Dzierzbicka-Głowacka, J. Jakacki, M. Janecki, A. Nowicki, *Activation of the operational ecohydrodynamic model (3D CEMBS) – the hydrodynamic part*. Oceanologia 55; 2013, (in press)
- [7] L. Dzierzbicka-Głowacka, M. Janecki, A. Nowicki, J. Jakacki, *A new marine ecosystem 3D CEMBS model (version 2) for the Baltic Sea*, Proceedings of 2012 International Conference on Complex Systems, ICCS; 2012, art. No 6458601.
- [8] L. Dzierzbicka-Głowacka, M. Janecki, A. Nowicki, J. Jakacki, *Activation of the operational ecohydrodynamic model (3D CEMBS) – the ecosystem module*. Oceanologia 55; 2013, (in press)
- [9] L. Dzierzbicka-Głowacka, M. Janecki, *Dynamics of Phytoplankton Blooms in the Baltic Sea – Numerical Simulations*. World Academy of Science, Engineering and Technology, Issue 73; 2013, 1232-1238
- [10] J. K. Moore, S. C. Doney, J. A. Kleypas, D. M. Glover, I. Y. Fung, *An intermediate complexity marine ecosystem model for the global domain*, Deep-Sea Res. II, vol. 49; 2002, 403-462
- [11] HELCOM. Second Baltic Sea Pollution Load Compilation. Balt. Sea Environ; 1993, Proc. No. 45