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Archipelago
Research Institute

Transfer-function modelling from climate and runoff to nutrient loading and concentrations in the Baltic Sea

Jari Hänninen & Ilppo Vuorinen
Archipelago Research Institute, University of Turku, Finland

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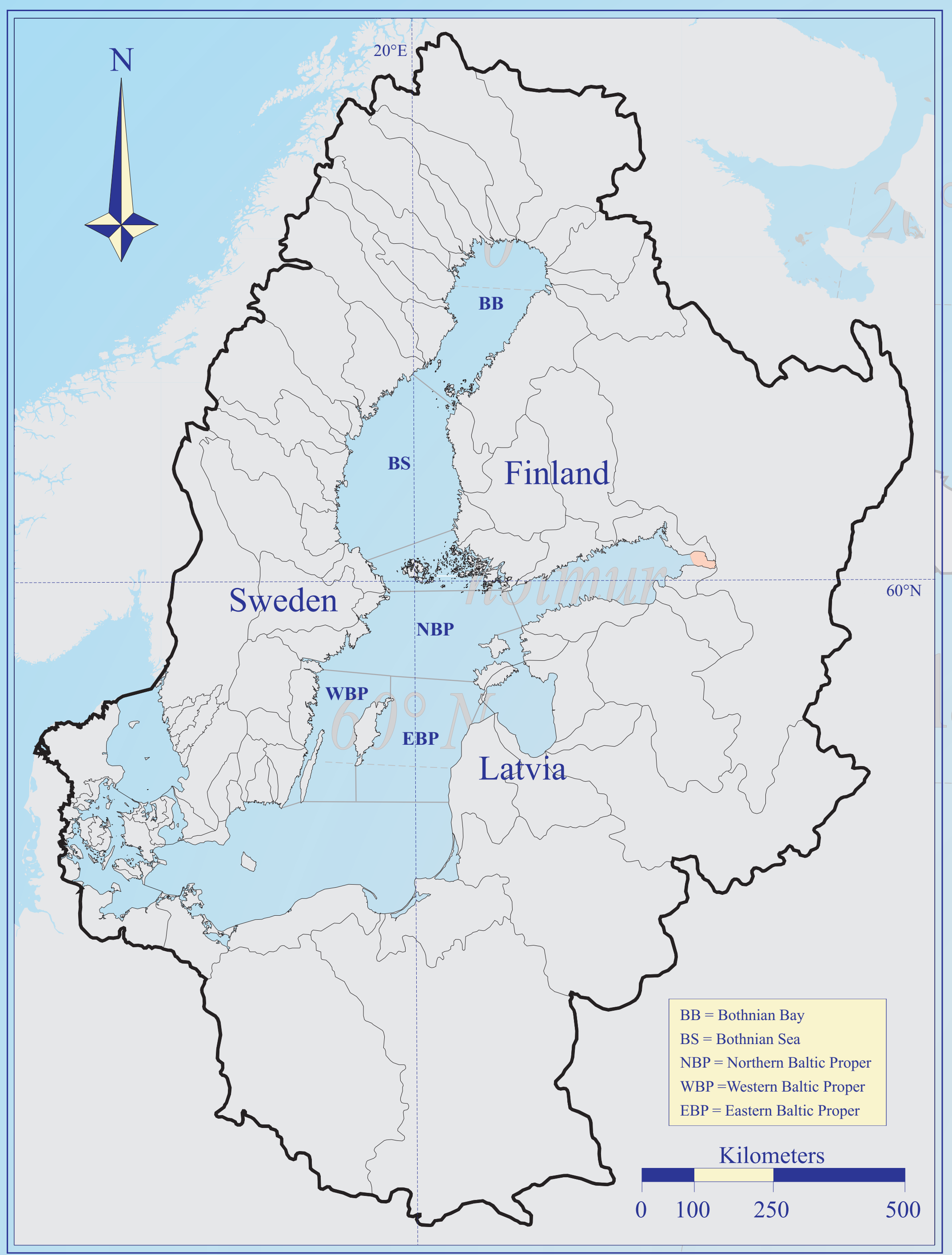

Fig.1. The total Baltic Sea with catchment area (thick line) and used subdivisions in modelling exercises. BB = Bothnian Bay, BS = Bothnian Sea (hereby = Gulf of Bothnia) and NBP = northern Baltic Proper, WBP = western Baltic Proper, EBP = eastern Baltic Proper (hereby = central Baltic Sea).

Table 1. Identified transfer function models for A) general runoff regulation by climate and B) riverine nutrient loading processes. Models indicate initial estimates of the parameters with standard errors and *t*-values with *p*-values. Coefficients of determination for the models are calculated with $r^2 = 1 - [(n-1)/(n-p)][(\text{sum of squares}_{\text{resid.}})/(\text{sum of squares}_{\text{total}})]$, where n = number of observations and p = number of estimated parameters. All presented time series are monthly means. For more detailed description see Hänninen *et al*. 2000.

A. Climate indices models

I. total Baltic Sea Runoff vs. NAO	$r^2 = 0.71, n = 359$ $(1-B^{12})Runoff_t = (\omega_0+\omega_1 B^1)(1-B^{12})NAO_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	1.10	0.76	0.83	0.61
S.E.	0.18	0.18	0.03	0.04
t-value	6.00	4.19	25.88	14.38
p-value	<0.001	<0.001	<0.001	<0.001
II. total Baltic Sea Runoff vs. AO	$r^2 = 0.68, n = 359$ $(1-B^{12})Runoff_t = (\omega_7 B^7)(1-B^{12})AO_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	-0.55		0.81	0.60
S.E.	0.26		0.03	0.04
t-value	-2.12		25.20	13.88
p-value	0.035		<0.001	<0.001
III. total Baltic Sea Runoff vs. Iceland SLP	$r^2 = 0.69, n = 359$ $(1-B^{12})Runoff_t = (\omega_0+\omega_1 B^1)(1-B^{12})Iceland\ SLP_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	-0.17	-0.15	0.81	0.62
S.E.	0.05	0.05	0.03	0.04
t-value	-3.45	-3.02	25.01	14.40
p-value	<0.001	0.003	<0.001	<0.001
IV. total Baltic Sea Runoff vs. Hoburg Winds	$r^2 = 0.70, n = 359$ $(1-B^{12})Runoff_t = (\omega_0+\omega_1 B^1)(1-B^{12})Wind_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	1.64	1.86	0.78	0.64
S.E.	0.38	0.37	0.03	0.04
t-value	4.37	4.97	22.96	15.35
p-value	<0.001	<0.001	<0.001	<0.001

B. Nutrient loading models

I. total Baltic Sea tot-N loading vs. Runoff	$r^2 = 0.88, n = 359$ $(1-B^{12})tot\text{-}N_t = \omega_0(1-B^{12})Runoff_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	1614.46		0.81	0.50
S.E.	71.86		0.03	0.05
t-value	22.47		26.77	10.38
p-value	<0.001		<0.001	<0.001
II. total Baltic Sea NH4-N loading vs. Runoff	$r^2 = 0.82, n = 359$ $(1-B^{12})NH4\text{-}N_t = -C + \omega_0(1-B^{12})Runoff_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	-208.09	108.81	0.76	0.50
S.E.	41.11	11.10	0.04	0.05
t-value	-5.06	9.81	21.51	10.55
p-value	<0.001	<0.001	<0.001	<0.001
III. total Baltic Sea NO23-N loading vs. Runoff	$r^2 = 0.82, n = 359$ $(1-B^{12})NO23\text{-}N_t = \omega_0(1-B^{12})Runoff_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	977.26		0.75	0.37
S.E.	56.87		0.04	0.05
t-value	17.18		19.75	7.24
p-value	<0.001		<0.001	<0.001
IV. total Baltic Sea tot-P loading vs. Runoff	$r^2 = 0.84, n = 359$ $(1-B^{12})tot\text{-}P_t = \omega_0(1-B^{12})Runoff_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	69.15		0.85	0.55
S.E.	2.77		0.03	0.05
t-value	25.00		28.08	12.11
p-value	<0.001		<0.001	<0.001
IV. total Baltic Sea PO4-P loading vs. Runoff	$r^2 = 0.77, n = 359$ $(1-B^{12})PO4\text{-}P_t = \omega_0(1-B^{12})Runoff_t + (1-\Theta_{12}B^{12})/(1-\phi_1 B)a_t$			
Estimate	34.07		0.87	0.44
S.E.	1.47		0.03	0.05
t-value	23.18		30.69	8.84
p-value	<0.001		<0.001	<0.001

1. Introduction

The Baltic Sea supports the economy and receives the impact of some 85 million people in nine coastal nations. Discussion around Baltic environmental change has focused on two closely combined topics, i.e. climate change and eutrophication. According to IPCC the northern Europe will experience increased rainfall in near future (Alcamo *et al.* 2007) which increases leaching of nutrients (e.g. Justić *et al.* 2003, Graham 2004) and accelerates eutrophication of sea (BACC author team 2008). Although Baltic countries are financing extensive monitoring programmes, there are only few studies done between climate regulation, runoffs, nutrient loadings and nutrient enrichment into the seawater (BACC author team 2008).

We have earlier presented a chain-of-events between changes in the North Atlantic weather patterns and subsequent changes in the Baltic Sea runoff and salinity and, finally, in Baltic biota (e.g. Hänninen *et al.* 2000, Hänninen *et al*. 2003, Vuorinen *et al*. 2004). The same reasoning is here extended to general Baltic system regulation and actual nutrient enrichment processes in the sea. The study is divided into three main questions:

1. Will increasing the number of climate predictors in modelling improve our understanding of the Baltic Sea system regulation?
2. Is it possible to model Baltic nutrient loading only on the basis of runoff and nutrient concentrations in the incoming water masses?
3. Is it possible to model nutrient concentrations in seawater using loading as the predictor?

2. Materials and methods

We modelled various weather indices to describe climatic regulation effects. NAO (North Atlantic Oscillation) was defined as normalised air pressure difference between Azores and Iceland. AO (Artic Oscillation) were 1000mb height anomalies poleward of 20°N. SLP described sea level air pressures in Iceland. Finally, we used wind speed data from Gotland's Hoburg (56°92'22N, 18°14'71E). The runoff data were monthly values (km^3) of total freshwater discharges from the catchment area into the Baltic Sea divided according to HELCOM Baltic sub-drainage basins (Fig.1), and comprising both monitored river runoffs and estimates of non-monitored runoffs. Nutrient data were downloaded from MARE's *Nest* (*http://nest.su.se/nest*), which holds reviewed Baltic Sea monitoring records, gathered by surrounding Baltic countries, and stored as databank according to the protocols of HELCOM (Anonymous 2005). We averaged data sets over HELCOM sub-basins and pooled it into three vertical water layers: 0-21m, 21-70m and below 70m, representing the vertical environmental gradient typical for the Baltic Sea.

In the statistical analysis we applied Transfer Function models, also called dynamic regressions (Box & Jenkins 1976, Pankratz 1991), using the Scientific Computing Associates (SCA) software (Liu & Lattyak 207). Transfer functions are able to relate the response of one series not only to its own past values, but also to the past and present values of the other related time series. In practice this is realized by merging the basic concepts of the general regression model with that of traditional ARIMA models. The analysis was conducted for the period 1970-2000.

3. Results and discussion

Resulting Transfer Function models fit well with the observed series (Tables 1&2). All the substantial parameters showed statistical significance, and coefficient of determination (r^2) values varied between 0.49 and 0.88, which are considered satisfactory in statistical time series analysis.

General runoff regulation

All indices had specific influence in the Baltic freshwater runoff regulation. The most obvious difference between models could be detected in observed time lags (Table 1A). Larger geographical area, in general, meant longer regulation effect, i.e. delayed response from weather effect to a response of runoff into the sea. In north-south direction, the northern areas showed lagged response indicating stronger winter effect in north and east. NAO was evidently the best index to explain general runoff regulation. AO showed inverse and much longer regulation response. Iceland SLP indicated weaker but very similar kind of regulation as NAO, but inversely. Also Hoburg's wind speeds resembled very much the NAO regulation.

Nutrient loading processes

Nutrient loading models indicated very strong coupling between nutrient loading and freshwater runoff (Table 1B). All models showed that loading had instant response to runoffs in every geographical area studied. NH4-N showed decreasing trend during study period.

Nutrient concentrations in seawater

The effect of phosphorus loading can been seen in tot-P concentrations in upper and middle seawater layers (Fig.2), with a lag of about one year in the central Baltic Sea, and a bit longer in the Gulf of Bothnia (Table 2). None of our models for nitrogen manifested any connection between the nitrogen loading and concentrations in seawater, regardless of the chemical form (organic/inorganic) of the substance.

Table 2. Identified transfer function models for C) nutrient enrichment processes in seawater, initial estimates of the parameters with standard errors, *t*-values and *p*-values. For practicality, only significant models are presented. Coefficients of determination for the models are calculated with $r^2 = 1 - [(n-1)/(n-p)][(\text{sum of squares}_{\text{resid.}})/(\text{sum of squares}_{\text{total}})]$, where n = number of observations and p = number of estimated parameters. The central Baltic Sea series were monthly series but quarterly in the Gulf of Bothnia. For more detailed description see Hänninen *et al*. 2000.

C. Nutrient concentration models

I. Gulf of Bothnia Upper layer (0-21m) tot-P concentration vs. tot-P loading	$r^2 = 0.49, n = 113$ $(1-B^4)tot\text{-}P_{(conc.)_t} = (\omega_6 B^6)(1-B^4)tot\text{-}P_{(load.)_t} + (1-\Theta_4 B^4)a_t$			
Estimate	0.73	0.80		
S.E.	0.28	0.06		
t-value	2.64	13.72		
p-value	0.009	<0.001		
II. Gulf of Bothnia Middle layer (21-70m) tot-P concentration vs. tot-P loading	$r^2 = 0.57, n = 111$ $(1-B^4)tot\text{-}P_{(conc.)_t} = (\omega_6 B^6)(1-B^4)tot\text{-}P_{(load.)_t} + (1-\Theta_4 B^4)/(1-\phi_3 B^3)a_t$			
Estimate	0.73	0.80	0.37	
S.E.	0.28	0.06	0.09	
t-value	2.64	12.30	4.16	
p-value	0.009	<0.001	<0.001	
III. central Baltic Sea Upper layer (0-21m) tot-P concentration vs. tot-P loading	$r^2 = 0.82, n = 343$ $(1-B^{12})tot\text{-}P_{(conc.)_t} = (\omega_{15} B^{15})(1-B^{12})tot\text{-}P_{(load.)_t} + (1-\Theta_{12} B^{12})/(1-\phi_1 B^1)(1-\phi_2 B^2)a_t$			
Estimate	0.30	0.68	0.36	0.22
S.E.	0.13	0.04	0.06	0.06
t-value	2.26	15.77	6.42	3.98
p-value	0.024	<0.001	<0.001	<0.001
IV. central Baltic Sea Middle layer (21-70m) tot-P concentration vs. tot-P loading	$r^2 = 0.66, n = 343$ $(1-B^{12})tot\text{-}P_{(conc.)_t} = (\omega_{16} B^{16})(1-B^{12})tot\text{-}P_{(load.)_t} + (1-\Theta_{12} B^{12})/(1-\phi_1 B^1)(1-\phi_2 B^2)a_t$			
Estimate	0.40	0.60	0.23	0.21
S.E.	0.20	0.05	0.06	0.05
t-value	2.40	13.04	4.21	3.84
p-value	0.017	<0.001	<0.001	<0.001

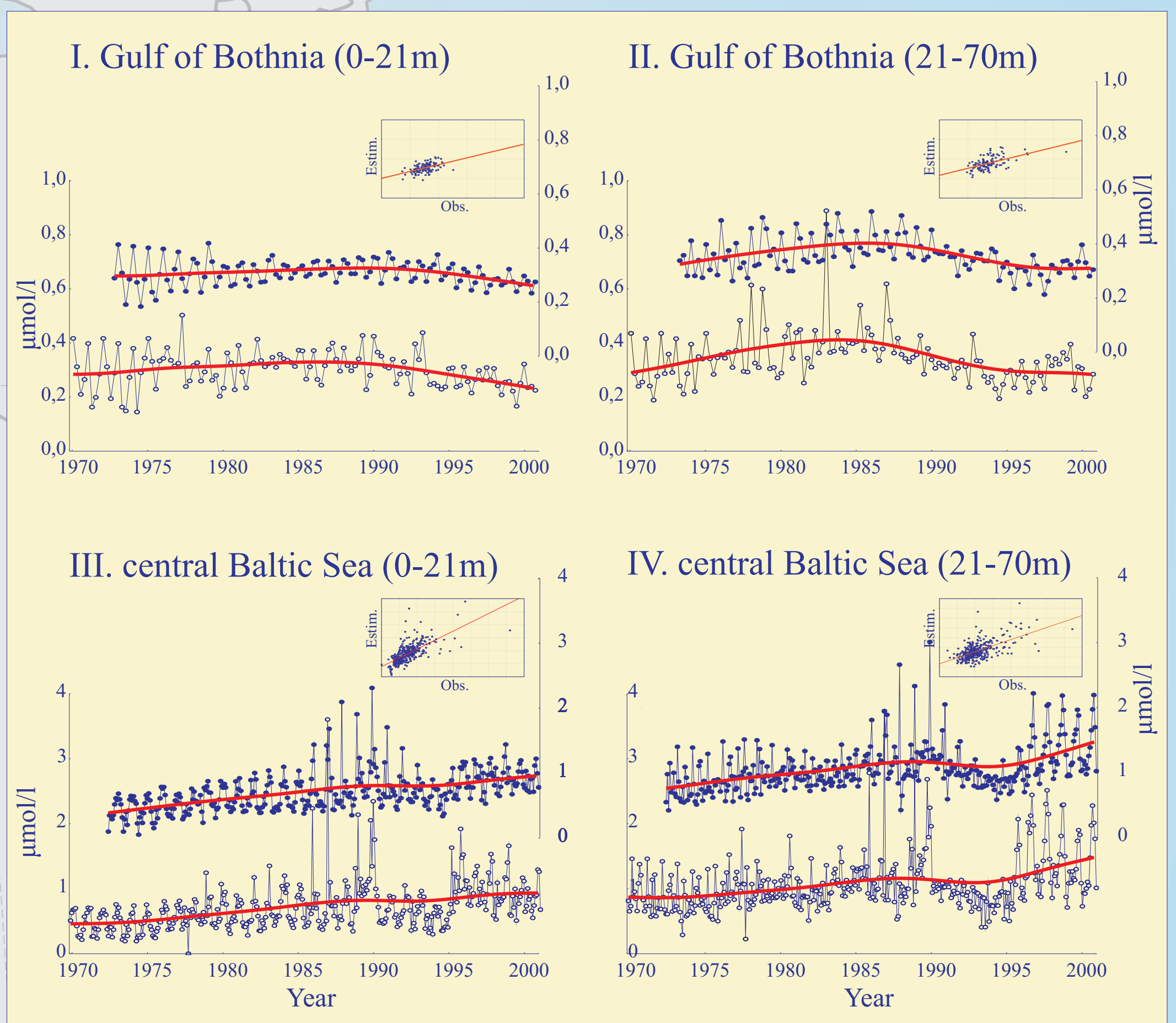

Fig.2. Models for tot-P concentrations in seawater on the basis of loadings. On each panel modeled (spots) and observed changes (open circles) of the time series are based on the identified TF -models. Letter next to topic refers to corresponding model in Table 2. Smooth red lines are drawn with distance-weighted least squares method. On small boxes of each panel are presented model fit scatterplots (observed values in X-axis, estimated values in Y-axis).

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