Construction of models with reference to HABs

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The overall scientific goal of GEOHAB is to:

Improve **prediction of HABs** by determining the ecological and oceanographic mechanisms underlying their population dynamics, integrating biological, chemical, and physical studies supported by enhanced observation and **modelling** techniques.

SP 2001, IP 2003

http://www.jhu.edu/scor/GEOHABfront.htm

Good news:

Physical-chemical-biological processes can be described by models (ode's)

Not everything.

Ask the right questions!

Bad news:

Modeling is not free, one has to deal with a certain amount of mathematics and computing

Example:
one can start to work with box models and use MATLAB.

This helps to interact and communicate with modelers, to implement full 3d-model systems

More good news:

There is an increasing number of 3d physical-chemical-biological models available.

Potential for partnership, networking and cooperation (do not reinvent the wheel!)

‘Harmfulness’ is a societal, not a scientific, term.
(i.e. it does not help to design or scale models)

‘Harmfulness’ points to

- species of interest and
- locations where HABs occur
- toxicity (may have an ecological function relevant for modeling)

How to model HABs?

- As continuous distributions, [aggregating many individuals in a state variable]?

- As individual particles, [individual based models, IBM's] ?

Elements of chemical biological models:

State variables

Concentration or number of individuals per volume
It consists of a number and a unit.

Process rates

Describing the rate of change of state variable,
may depend on other state variables and abiotic quantities,
such as T, O_2, S, etc.
Unit → 1/time

Dynamics means: change over time driven by fluxes

$$\frac{d}{dt}S = r^{gain}S - r^{loss}S$$

Process **rates** are not a result of the model, rates are needed to implement a working model.

Interface between modeling and experimental work. Rates must be provided by observations (Field or lab).

Most important:

- Growth-rate (division or birth rates)
- Mortality (difficult to measure, truncation of HTL's)
- Vital functions (respiration, excretion etc.)
- Toxicity (if it has a relevant ecological role)

Life cycles and size classes

Phytoplankton, cells cycle between two levels of mass
→mass levels before and after division, (about factor 2)

Zooplankton of fish mass vary by several orders of magnitude

Biomass B= m N.
(m- individual mass, N – number of ind.)

$$\frac{d}{dt}B \approx m\frac{d}{dt}N,$$

phytoplankton

$$\frac{d}{dt}B = m\frac{d}{dt}N + N\frac{d}{dt}m.$$

zooplankton and fish

This implies for phytoplankton biomass and numbers the equations:

$$\frac{d}{dt}B = (r^{gain} - r^{loss})B;$$

$$\frac{d}{dt}N = (r^{birth} - r^{death})N.$$

Note that: $r^{loss} \neq r^{death}$ Loss rates involve biochemical transformations!

Example systems

Gulf of Main

(e.g. Anderson et al., 2000; McGillicuddy et al., 2003)

Alexandrium fundyense

Low abundance, advection of cells important,
Weak interaction within the food web,
Life cycle: cysts formation important,
Two state variables,
nutrient fields prescribed by climatological data
3d circulation models.

Baltic Sea

(e.g.Kononen 2001; Neumann et al., 2002)

Cyanobacteria: *Nodularia & Aphanizomenon*

Near sea-surface accumulation of biomass
Strong interaction within the food web
Seasonal succession,
Competition for nutrients,
Many state variables are needed,
3d physical-chemical-biological-model.

If r^{gain} depends on another state variable,
e.g. growth of P depends on nutrients,

$$\frac{d}{dt}P = (r^{gain}(NO_3) - r^{loss})P,$$

Two options:
If the action of P on the nutrients is weak, then the changes of NO_3 may be described by climatological values or so.
If the action of P on the nutrients is strong, then a dynamical equation for NO_3 is needed.

$$\frac{d}{dt}NO_3 \approx -r^{gain}(NO_3)P.$$

If recycling of detritus, (D), is important, then an equation for Detritus is needed:

$$\frac{d}{dt}P = (r^{gain}(NO_3) - r^{loss})P,$$

$$\frac{d}{dt}NO_3 \approx -r^{gain}(NO_3)P + L_{DN}D,$$

$$\frac{d}{dt}D \approx -L_{DN}D + r^{loss}P$$

If for the loss of P grazing of zooplankton, (Z), is important, then an equation for Z is needed:

$$\frac{d}{dt}P = r^{gain}(NO_3)P - r^{loss}P - g(P)Z,$$

$$\frac{d}{dt}NO_3 \approx -r^{gain}(NO_3)P + L_{DN}D,$$

$$\frac{d}{dt}Z \approx g(P)Z - L_{ZD}Z,$$

$$\frac{d}{dt}D \approx L_{ZD}Z - L_{DN}D + r^{loss}P$$

Examples for rates:

$$Y(\alpha, x) = \frac{x^2}{\alpha^2 + x^2}$$

$$L_{\mathrm{DA}} = l_{\mathrm{DA}}(1 + \beta_{\mathrm{DA}} Y(T_{\mathrm{DA}}, T))$$

$$R_2 = r_2^{\max}\left(1 + \frac{1}{1 + e^{\beta_{\mathrm{fl}}(T_{\mathrm{fl}} - T)}}\right)\min[Y(\alpha_2, A + N), Y(S_{\mathrm{Redfield}}\alpha_2, PO)]$$

$$R_3 = r_3^{\max}\frac{1}{1 + e^{\beta_{cy}(T_{cy} - T)}}Y(S_{\mathrm{Redfield}}\alpha_3, PO)$$

Truncation issue

UTL (upper trophic level, i.e. fish)

Considered as part of zooplankton mortality,
assuming that variations in fish biomass or abundance can be ignored or qualitatively prescribed (forcing).

Level below phytoplankton, i.e. bacteria

Bacteria are assumed to be present to carry out mineralization processes, the dynamic interaction can be ignored.

Spatial dimension (advection, turbulent mixing, sinking etc)

Models range from simple biogeochemical box models or Particle tracking (’individual based models’)

(first step for development, easy to understand and to use, provide forum for the interdisciplinary dialogue)

to

3D coupled physical chemical biological model systems
(require super-computers, educated modeller)

Linkage of physics and biology in models

Advection diffusion equations

(for fixed volume element)

$$\frac{\partial}{\partial t} S_i + \nabla \cdot \vec{v} S_i - \nabla A \cdot \nabla S_i = (r^{gain} - r^{loss}) S_i + Q^{extern}.$$

change through advection

changes by chemical and biological processes

rate of time change

rate of change due to turbulent mixing

external loads

Dynamics of a state variable = change in time driven by fluxes
(in a parcel of water)

$$\frac{d}{dt} S_i = (gain(S_j) - loss(S_j)) S_i + Q^{extern},$$

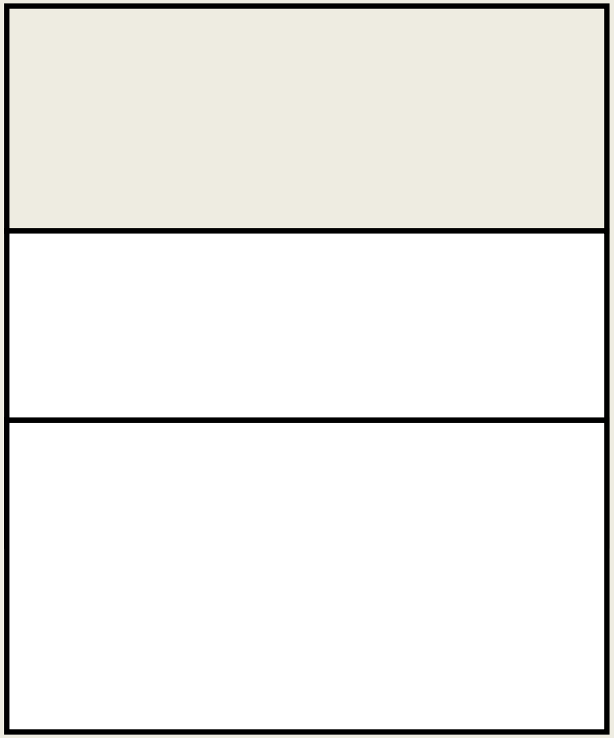
Formal integration illuminates the predictive potential

$$S_i(t) = S_i(0) + \int_0^t dt' \{(gain(t') - loss(t')) S_i(t') + Q^{extern}(t')\}$$

integral over the history of the processes

initial conditions

Box model means integration (average) over a part of the ocean e.g.
→ average concentrations of plankton consume averaged concentrations of nutrients

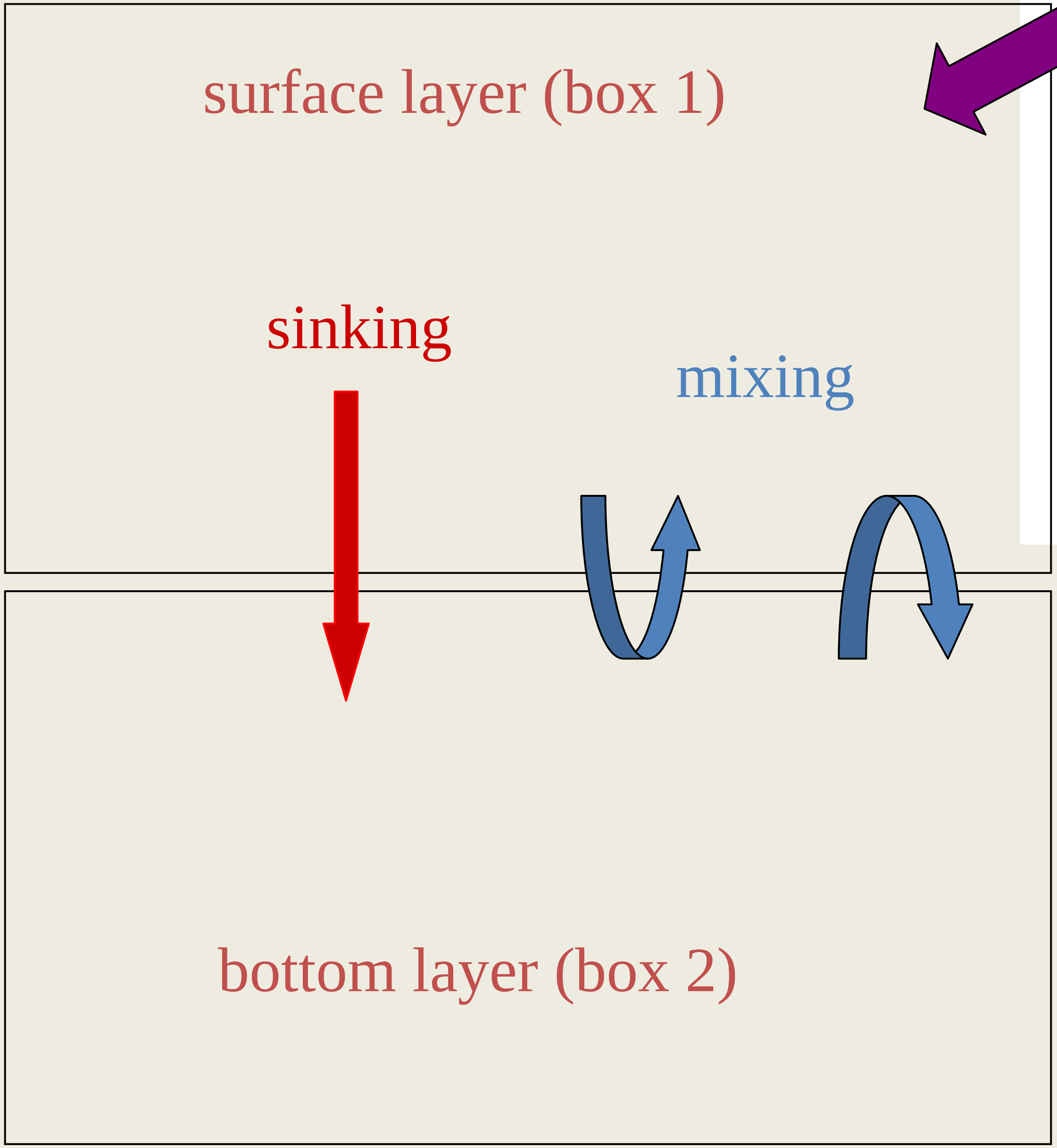


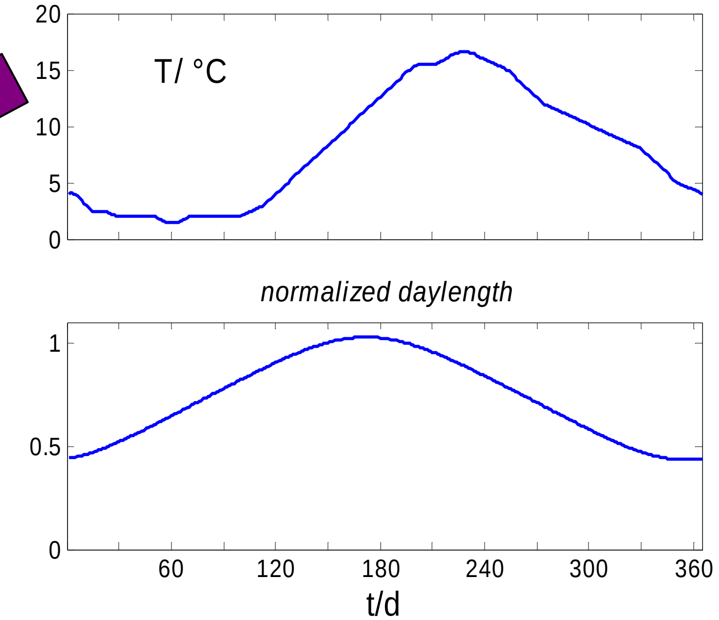
Include vertical stratification
Stacked boxes, (two or more)
integrated (averaged) over vertical segments of a part of the ocean
→ average concentrations of plankton consume averaged concentrations of nutrients, but vertical variations are resolved

Fluxes through the box faces must be prescribed

Similar to a 1d model, where fluxes are dynamical computed with turbulence models and external driven by wind and buoyancy forcing.
Note; the chemical biological variables are assumed to be homogenous (horizontally).

simple model - two boxes

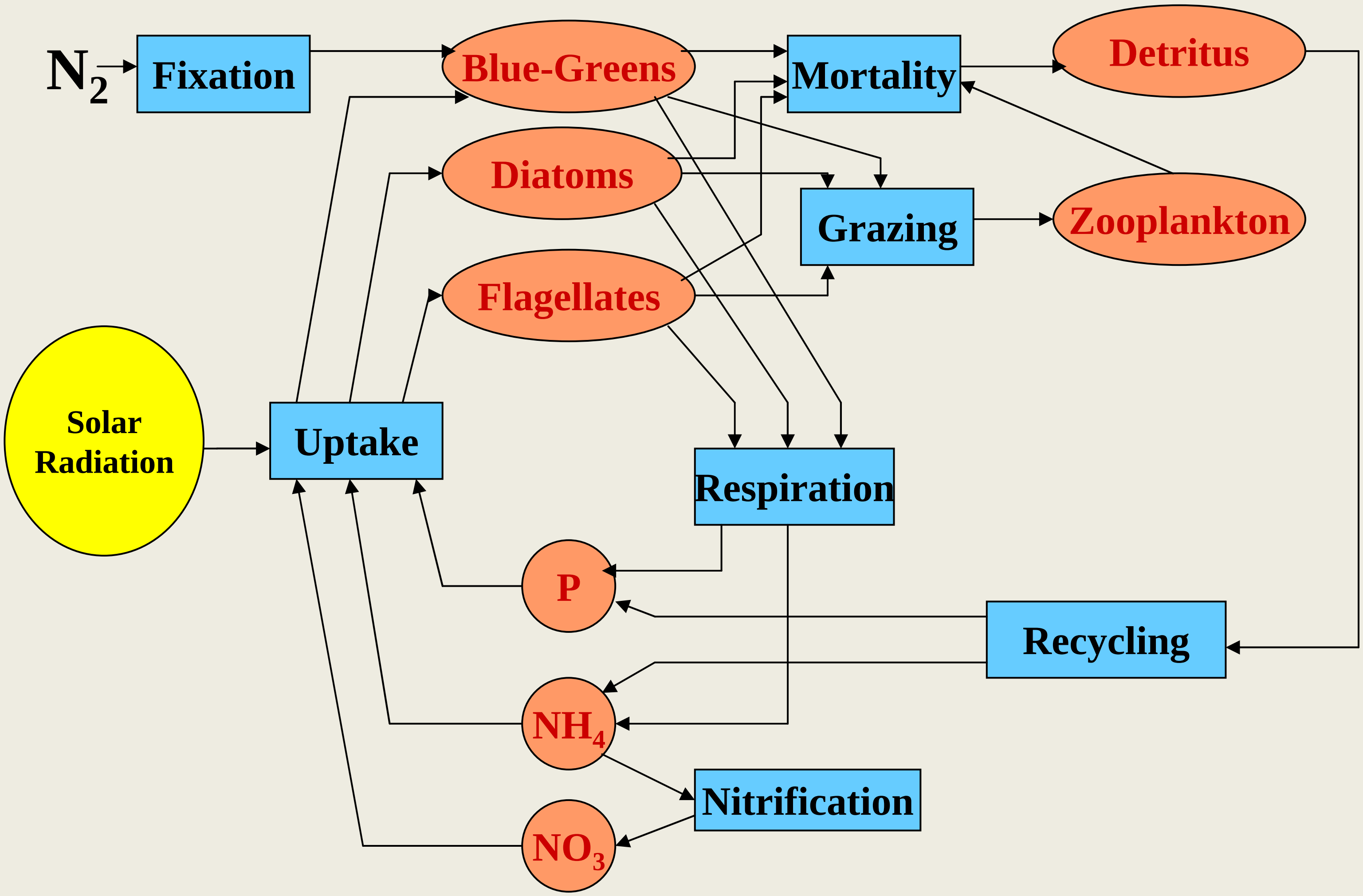




T = const

no light

state variables and processes (two stacked boxes)



equations (box 1)

$$\frac{d}{dt}A^{(1)} = -\Pi_A(R_1P_1^{(1)} + R_2P_2^{(1)}) + l_{P_1A}(P_1^{(1)} - P_o) + l_{P_2A}(P_2^{(1)} - P_o) + l_{P_3A}(P_3^{(1)} - P_o)$$
$$+ l_{ZA}(Z^{(1)} - Z_0) - L_{AN}A^{(1)} + L_{DA}D^{(1)},$$

$$\frac{d}{dt}N^{(1)} = -\Pi_N(R_1P_1^{(1)} + R_2P_2^{(1)}) + L_{AN}A^{(1)} - A_{mix}(N^{(1)} - N^{(2)}) + Q_N^{ext},$$

$$\frac{d}{dt}PO^{(1)} = s_{\text{Redfield}}\{-\sum_{i=1}^{3}R_iP_i^{(1)} + l_{P_1A}(P_1^{(1)} - P_o) + l_{P_2A}(P_2^{(1)} - P_o) + l_{P_3A}(P_3^{(1)} - P_o)$$
$$+ l_{ZA}(Z^{(1)} - Z_0) + L_{DA}D^{(1)}\} - A_{mix}(PO^{(1)} - PO^{(2)}) + Q_{PO}^{ext}.$$

Nutrients
$A=NH_4$,
$N=NO_3$,
$PO=PO_4$

$$\frac{d}{dt}P_1^{(1)} = R_1P_1^{(1)} - l_{P_1A}(P_1^{(1)} - P_0) - G_1Z^{(1)} - w_1^{\sin k}(P_1^{(1)} - P_0)$$

$$\frac{d}{dt}P_2^{(1)} = R_2P_2^{(1)} - (l_{P_2A} + l_{P_2D})(P_2^{(1)} - P_0) - G_2Z^{(1)}$$

$$\frac{d}{dt}P_3^{(1)} = R_3P_3^{(1)} - (l_{P_3A} + l_{P_3D})(P_3^{(1)} - P_0) - G_3Z^{(1)}$$

Phytoplankton
P_1=diatoms
P_2=flagellates
P_3=cyanobacteria

$$\frac{d}{dt}D^{(1)} = l_{P_2D}(P_2^{(1)} - P_0) + l_{P_3D}(P_3^{(1)} - P_0) + l_{ZD}(Z^{(1)} - Z_0) - L_{DA}D^{(1)} - G_{D^{(1)}}Z - w_D^{\sin k}D^{(1)},$$

$$\frac{d}{dt}Z^{(1)} = (G_1 + G_2 + G_3 + G_{D^{(1)}})Z^{(1)} - (l_{ZA} + l_{ZD})(Z^{(1)} - Z_0).$$

D=bulk detritus
Z=bulk zooplankton

equations (box 2)

$$\frac{d}{dt}A^{(2)} = +l_{ZA}(Z^{(2)} - Z_0) - L_{AN}A^{(2)} + L_{DA}D^{(2)},$$

$$\frac{d}{dt}N^{(2)} = L_{AN}A^{(1)} - A_{mix}(N^{(1)} - N^{(2)}),$$

$$\frac{d}{dt}PO^{(2)} = s_{\text{Redfield}}\{l_{ZA}(Z^{(2)} - Z_0) + L_{DA}D^{(2)}\} - A_{mix}(PO^{(1)} - PO^{(2)}).$$

Nutrients
$A=NH_4$,
$N=NO_3$,
$PO=PO_4$

$$\frac{d}{dt}P_1^{(2)} = -l_{P_1D}(P_1^{(2)} - P_0) - G_1Z^{(2)} + w_1^{\text{sink}}(P_1^{(1)} - P_0)$$

$$\frac{d}{dt}P_2^{(2)} = 0,$$

$$\frac{d}{dt}P_3^{(2)} = 0.$$

Phytoplankton
P_1=diatoms
P_2=flagellates
P_3=cyanobacteria

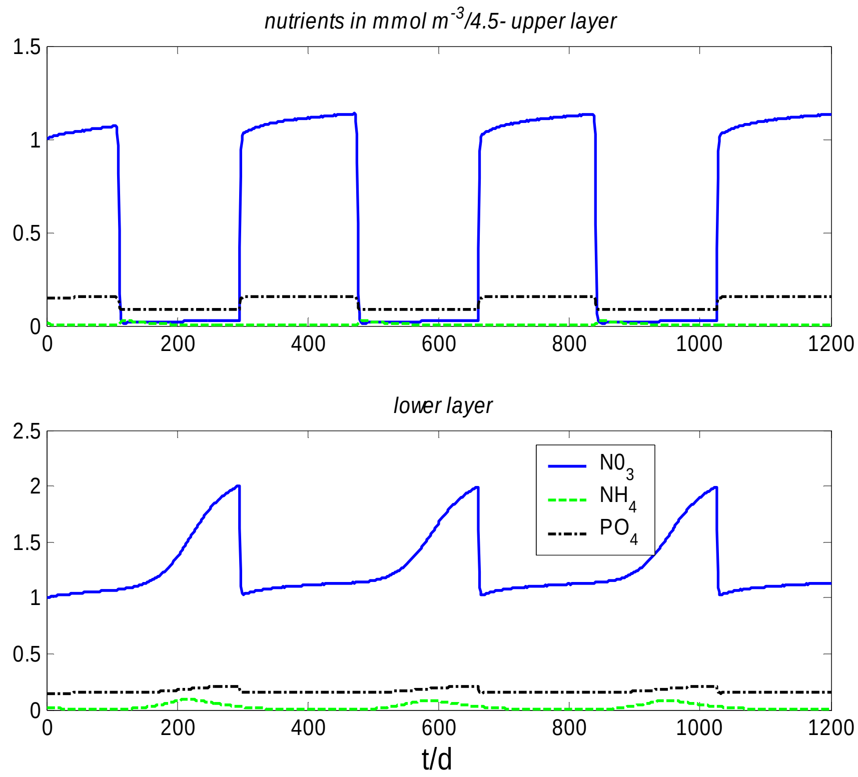
$$\frac{d}{dt}D^{(2)} = l_{P_1D}(P_1^{(2)} - P_0) + l_{ZD}(Z^{(2)} - Z_0) - L_{DA}D^{(1)} - G_{D^{(1)}}Z + w_D^{\text{sink}}D^{(1)},$$

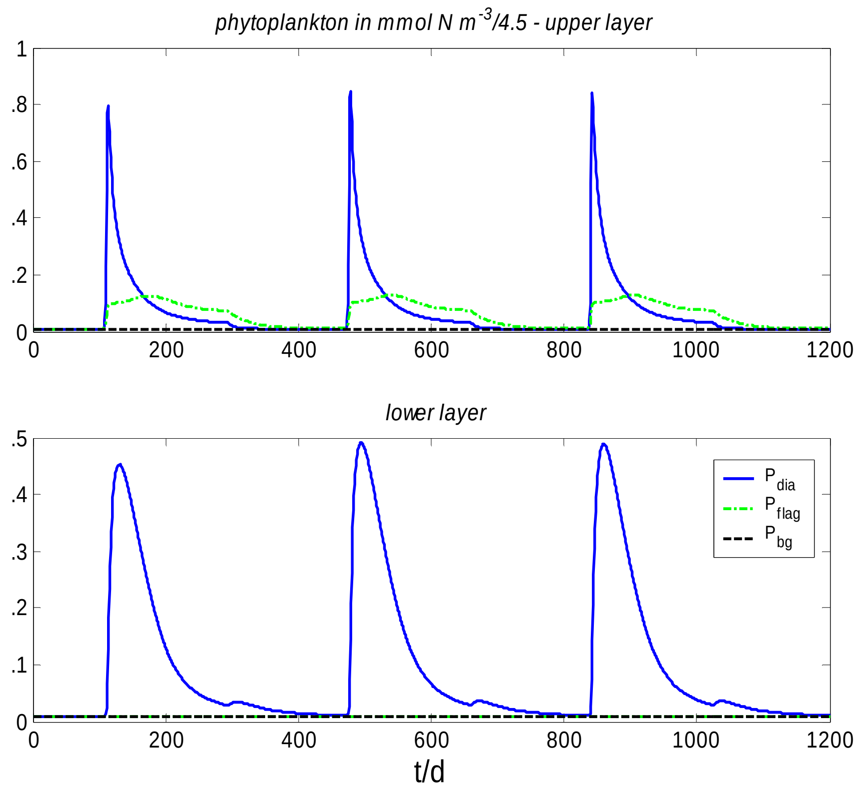
$$\frac{d}{dt}Z^{(2)} = (G_1 + G_{D^{(1)}})Z^{(1)} - (l_{ZA} + l_{ZD})(Z^{(2)} - Z_0).$$

D=bulk detritus
Z=bulk zooplankton

Experiment 1

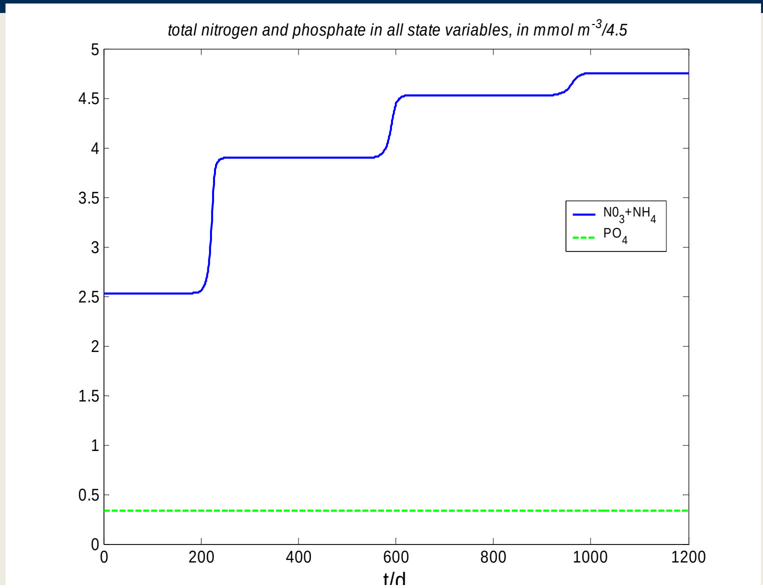
no external loads,
no active blue greens

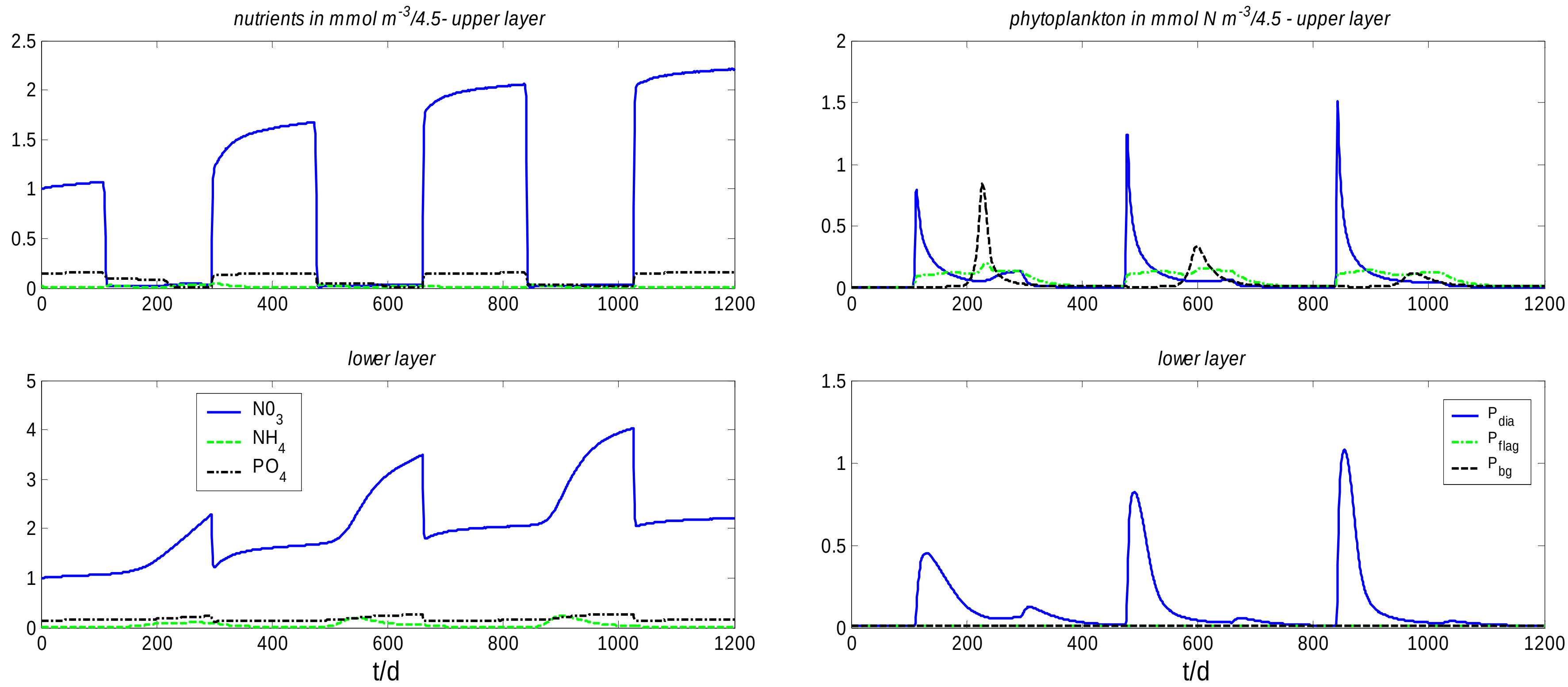




Experiment 2

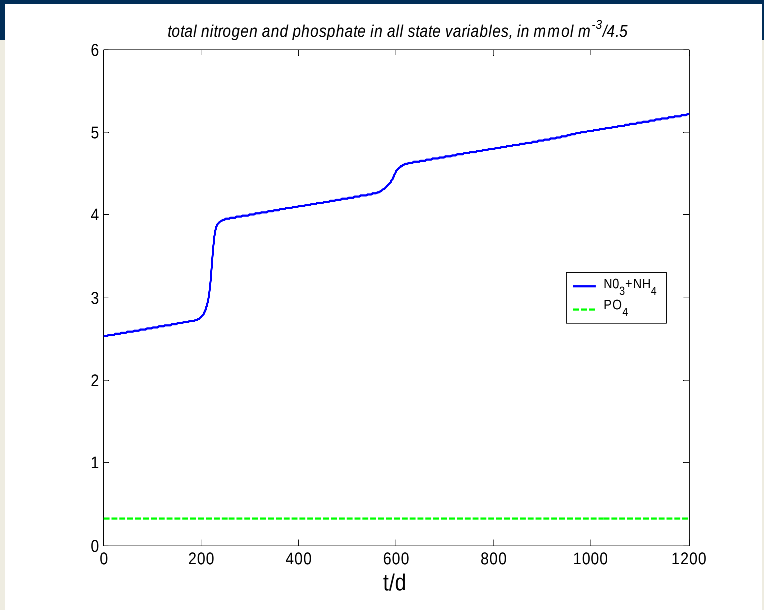
no external loads, active blue greens

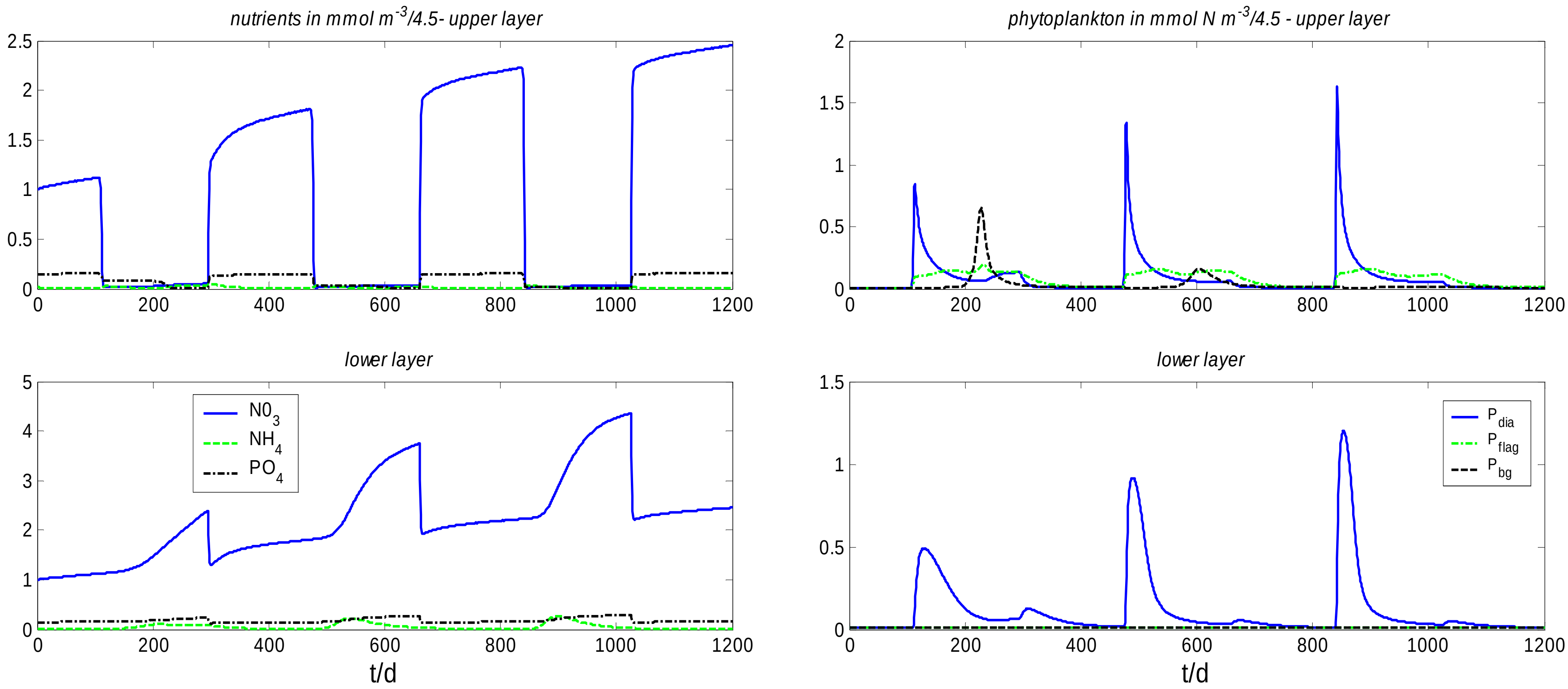




Experiment 3

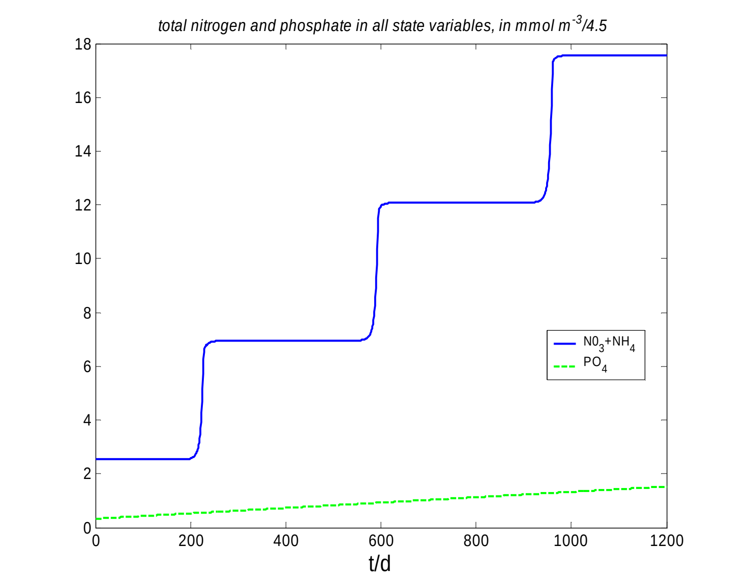
external NO_3 – loads, active blue greens

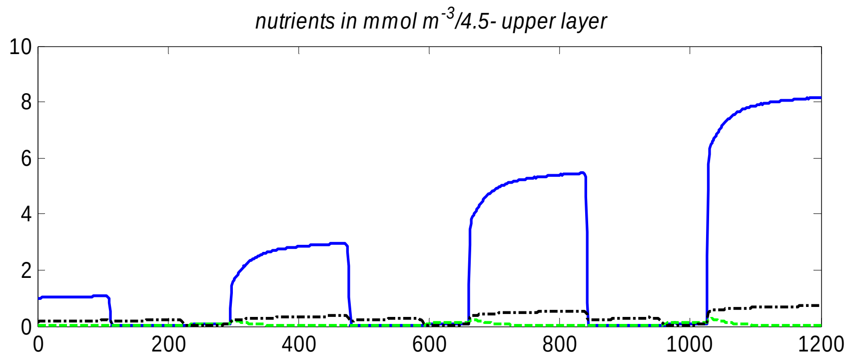


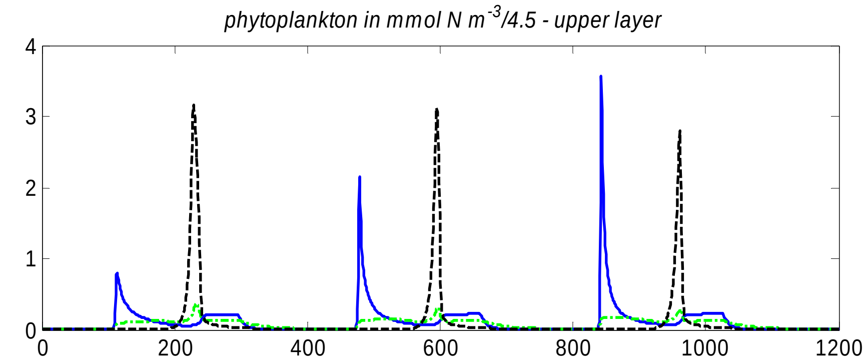


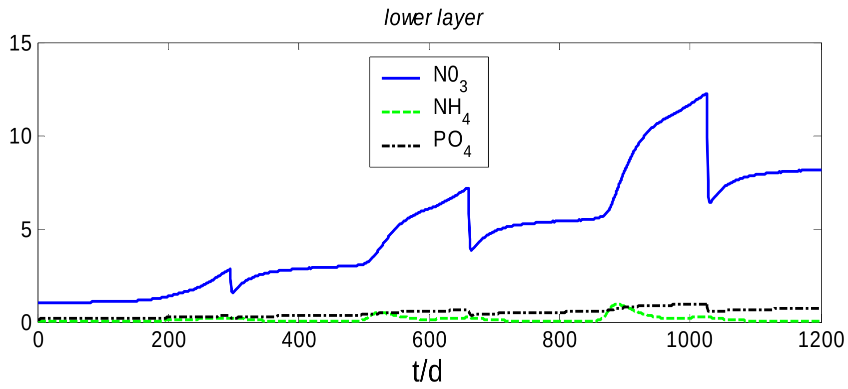
Experiment 4

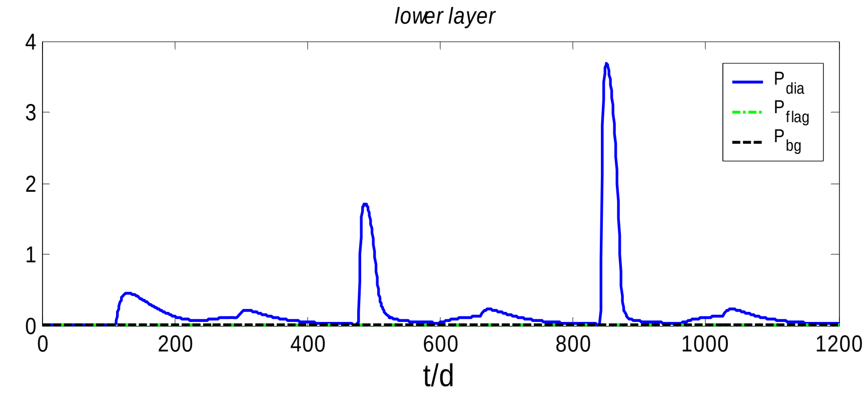
external PO_4 - loads and active blue greens



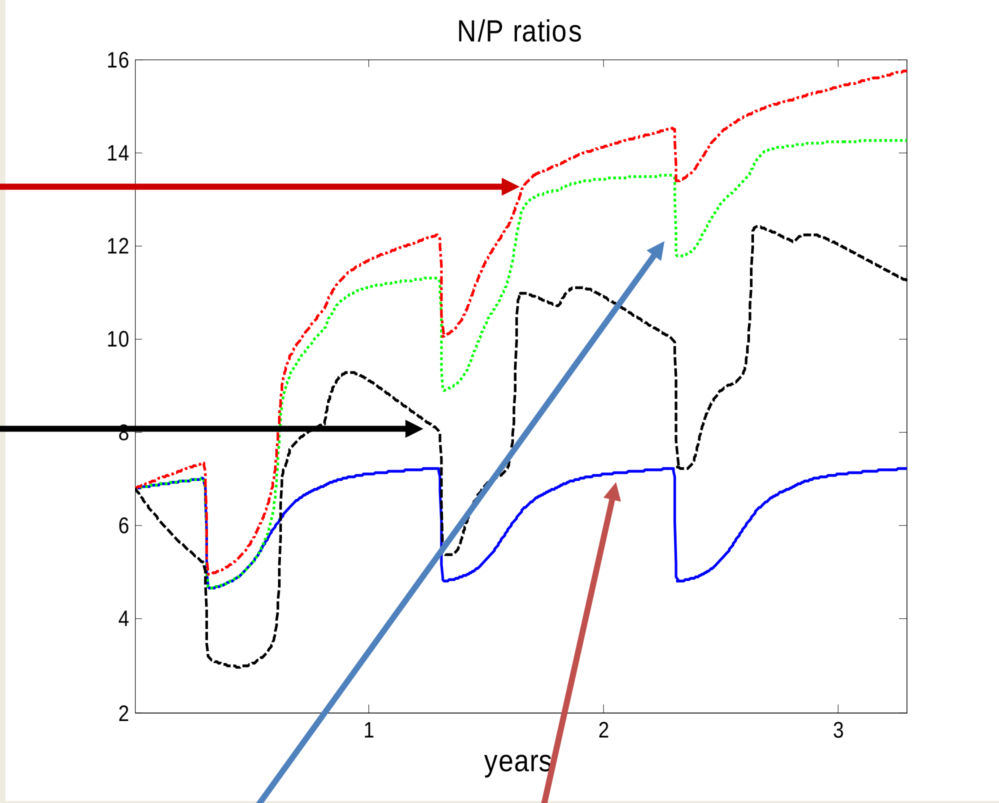








Nutrients - N/P ratio



N-loads and blue greens

P-loads and blue greens

No loads and blue greens

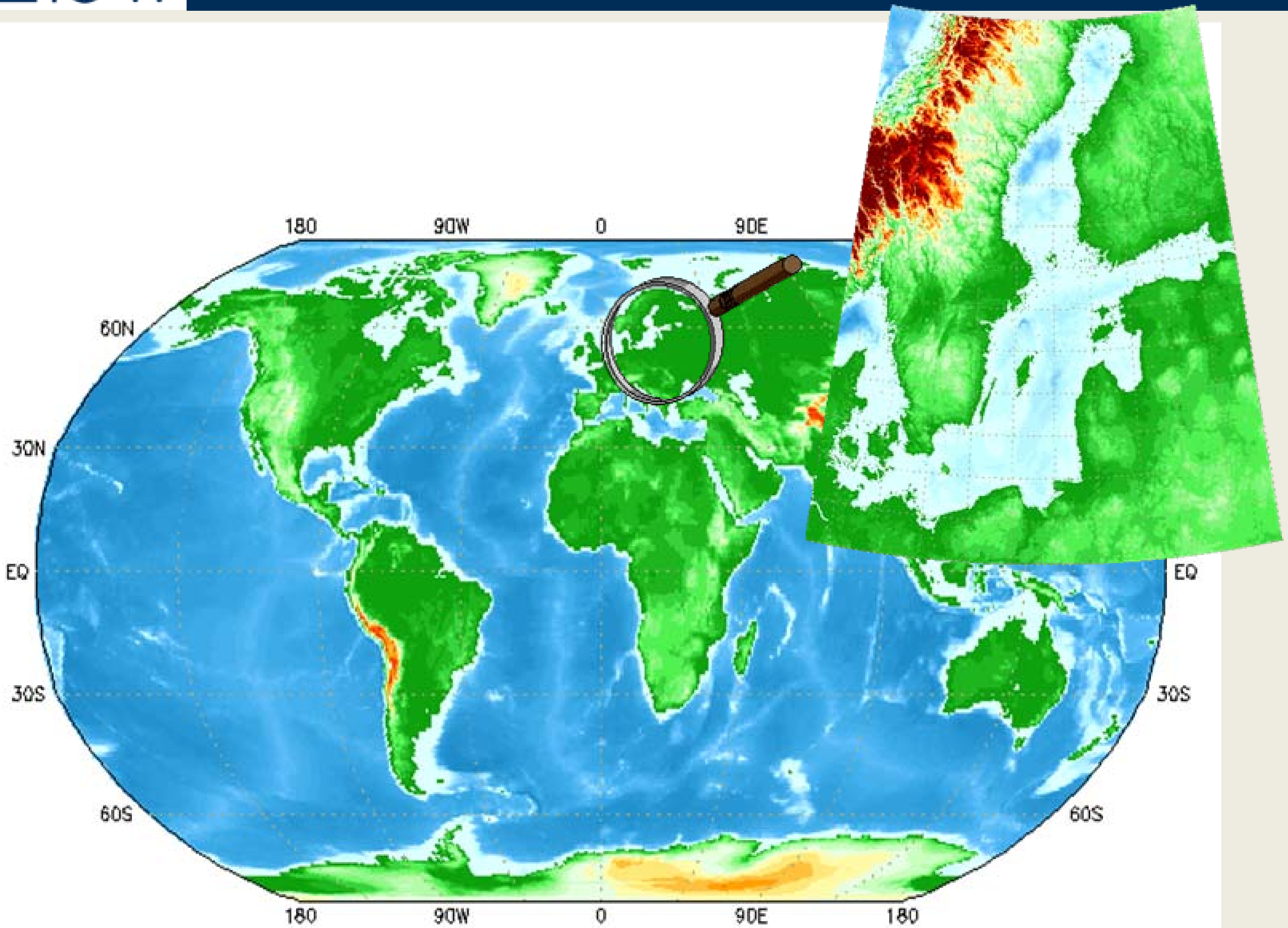
No loads no blue greens

What is missing?

- sedimentary processes
- oxygen depletion
- denitrification

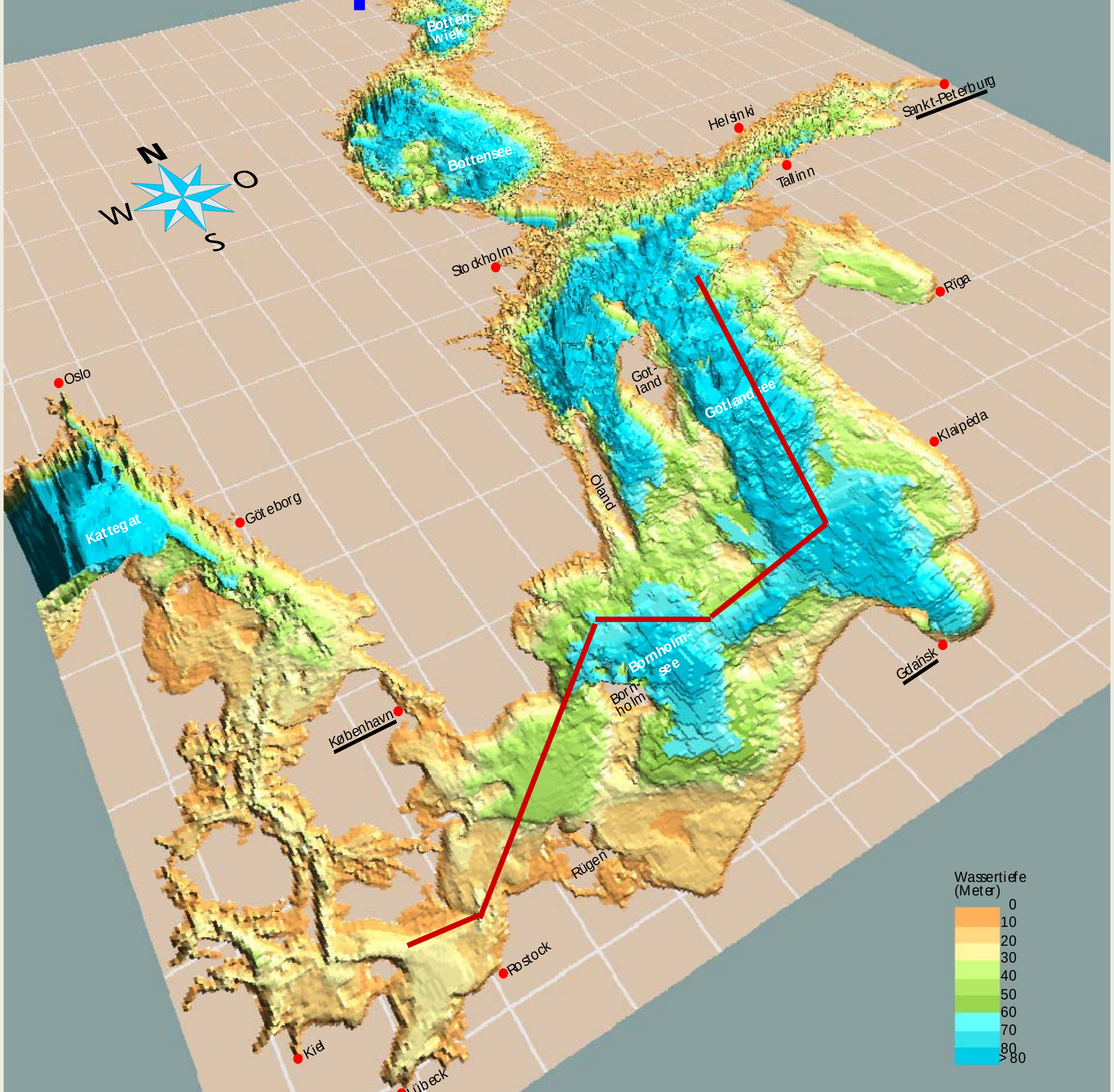
- horizontal gradients
- coastal zones - deep basins

→ **3d -modeling**



The Baltic Sea

The example of the Baltic Sea



F. Tauber, T. Seifert, B. Kayser, Institut für Ostseeforschung Warnemünde

P-E>0
(60 km³/y)
River discharge
480 km³/y

Mean depth = 50 m
Sill depth = 18 m
Vol.= 21 700 km³

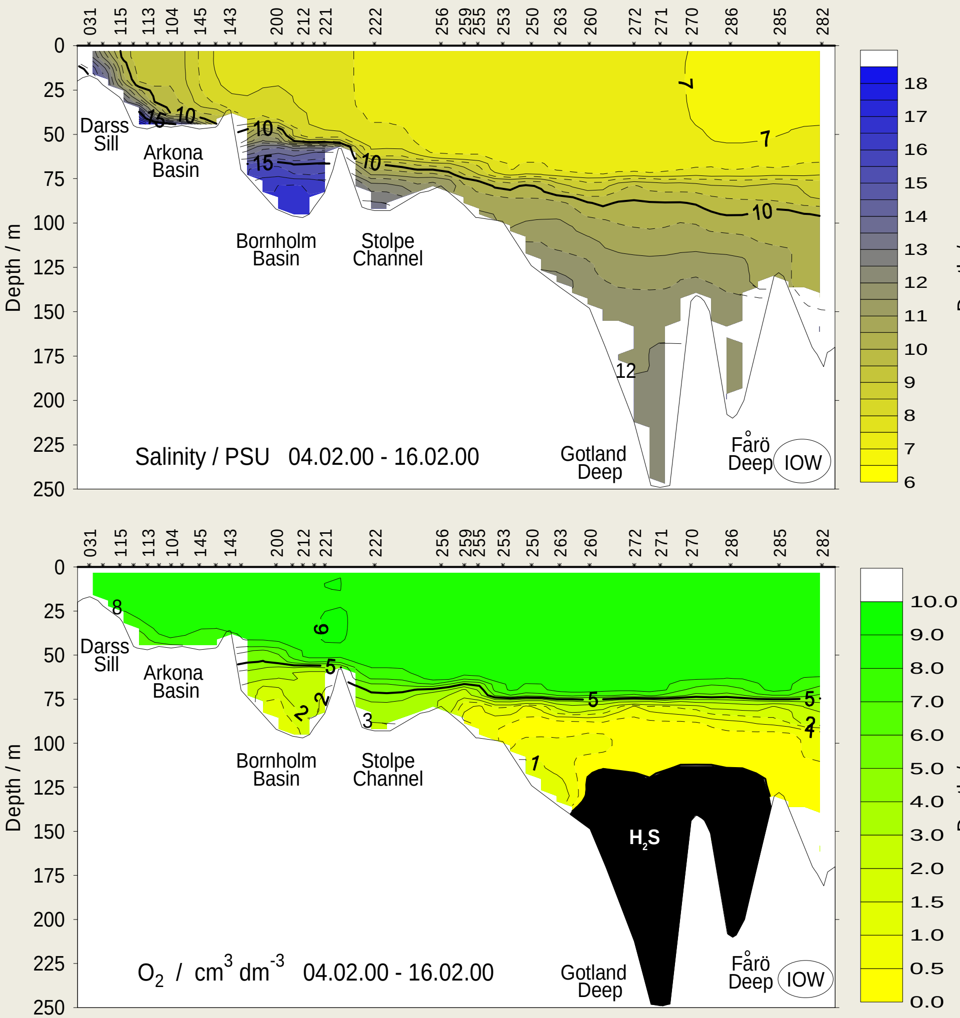
Monitoring

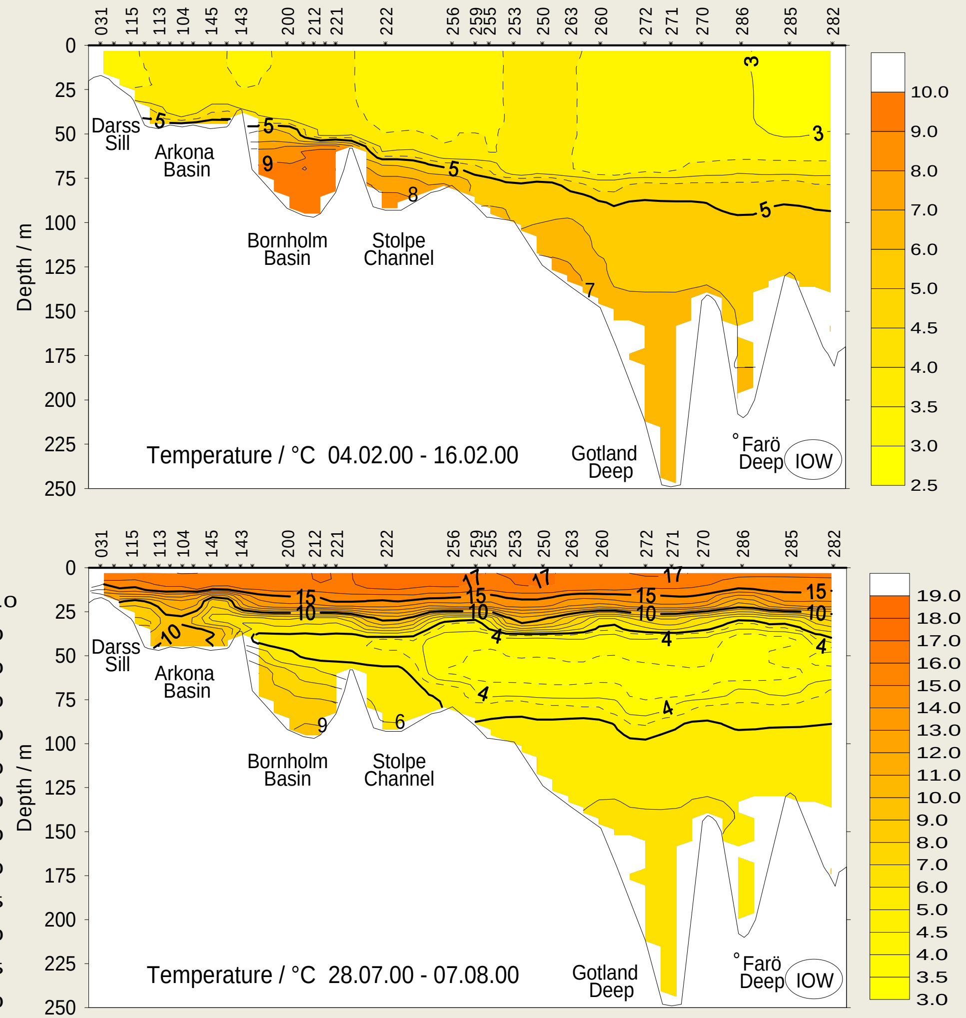
5 times a year

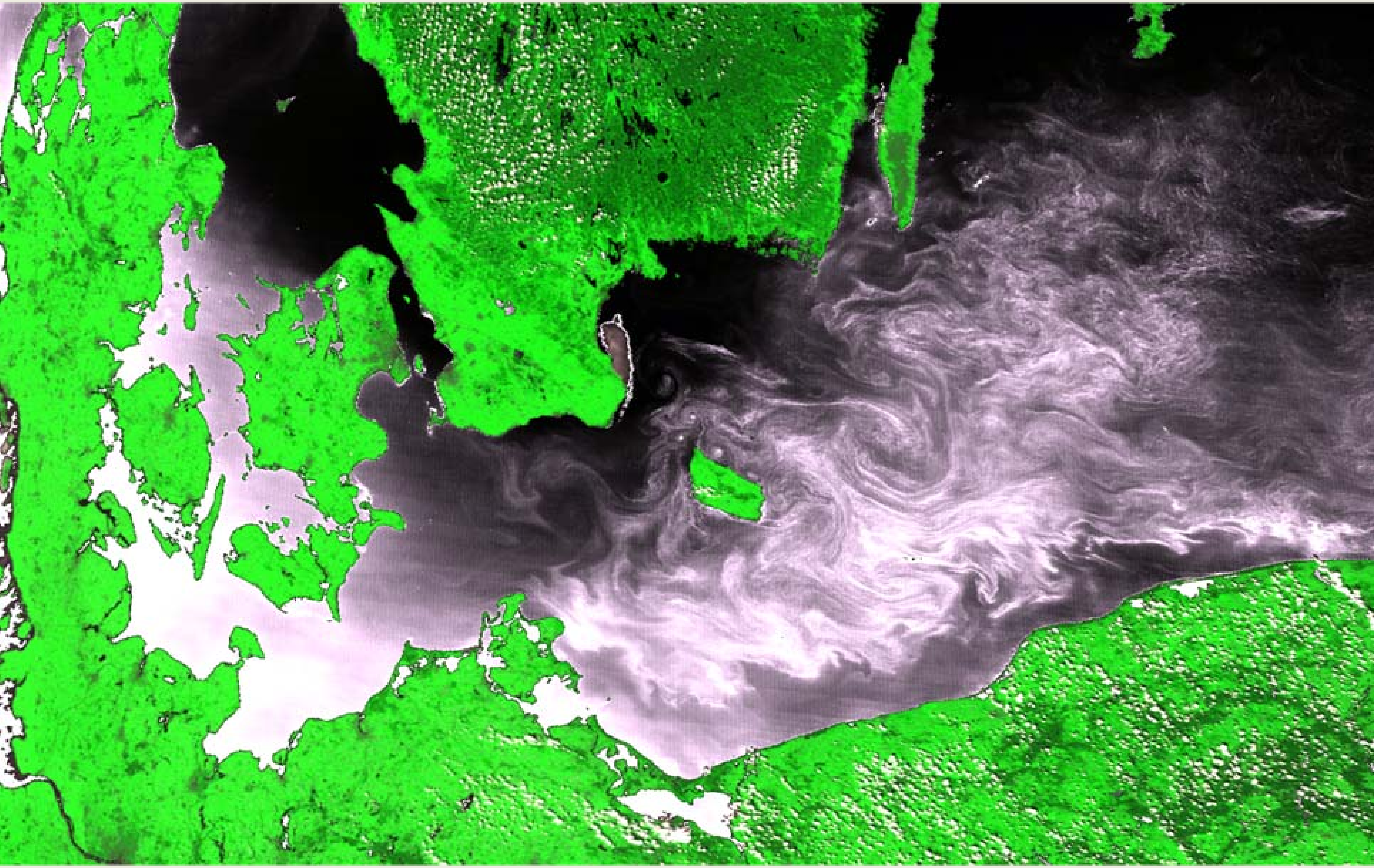
along the 'Talweg'

Salinity and oxygen

Temperature (winter/summer)



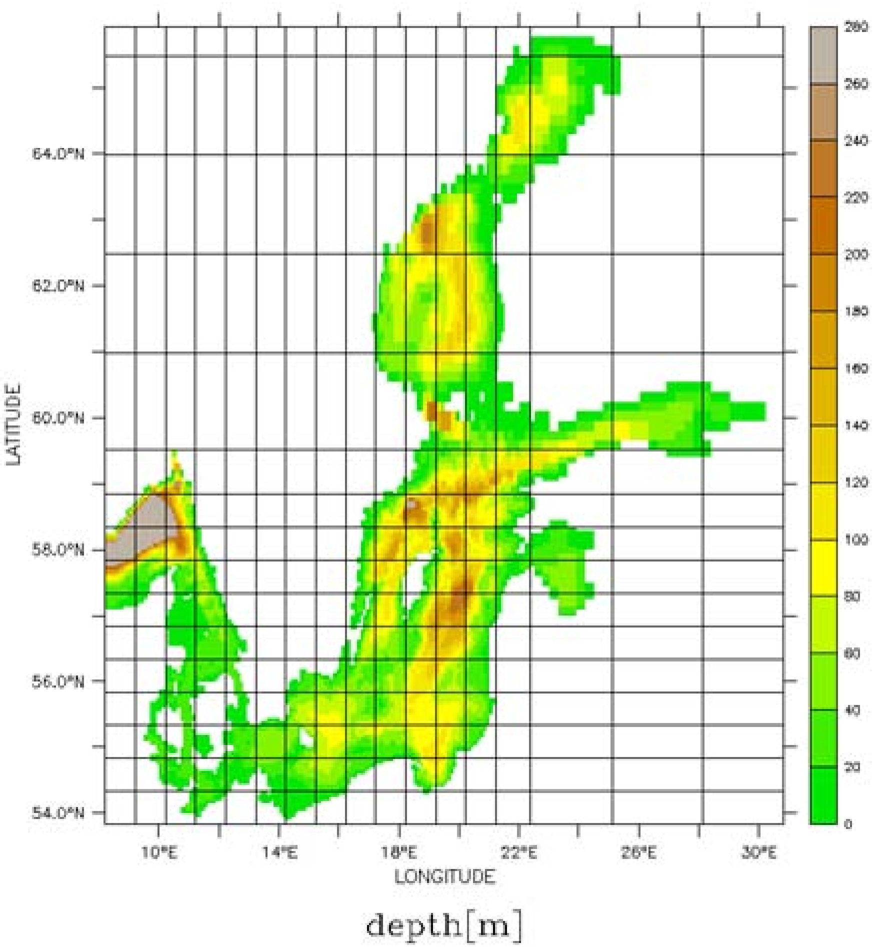


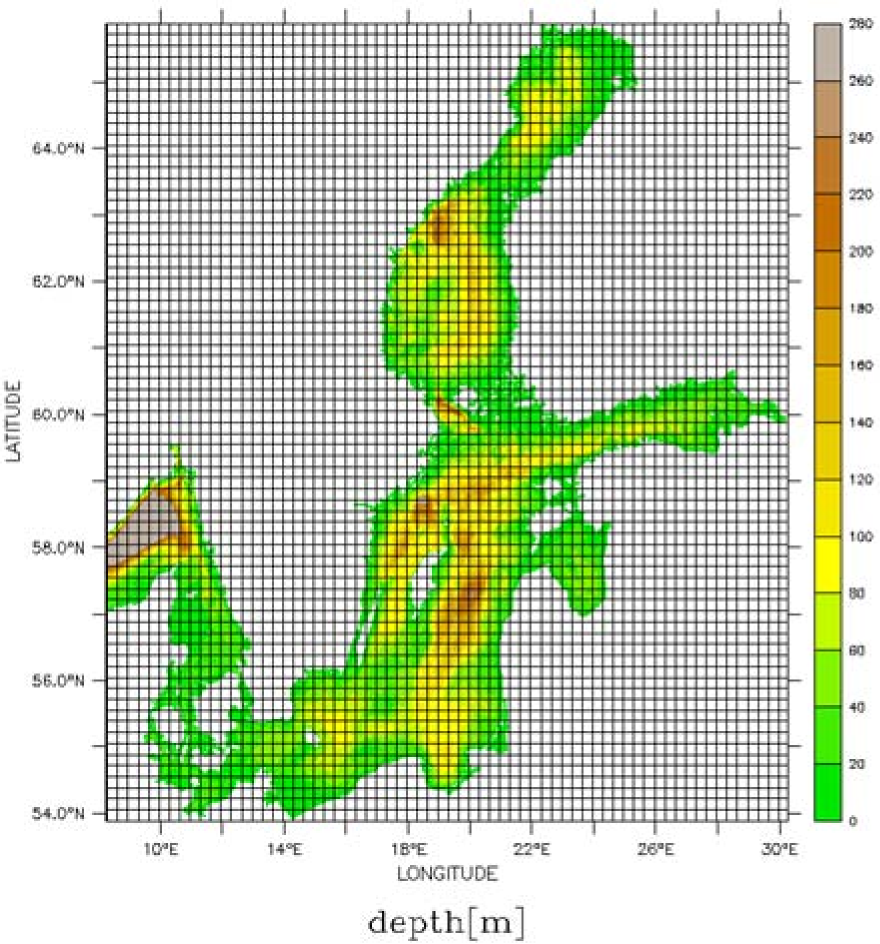


6.7.2001

MODIS NASA (Δ x=250m)

(courteously, H. Siegel, T. Ohde)





Resolution 3 n.m.
169 x 153 horizontal cells
77 levels
timestep: 12 min (MOM4) 4 min (MOM3)

Resolution 1 n.m.
660 x 720 horizontal cells
77 levels
timestep: ~ 4 min (MOM4)

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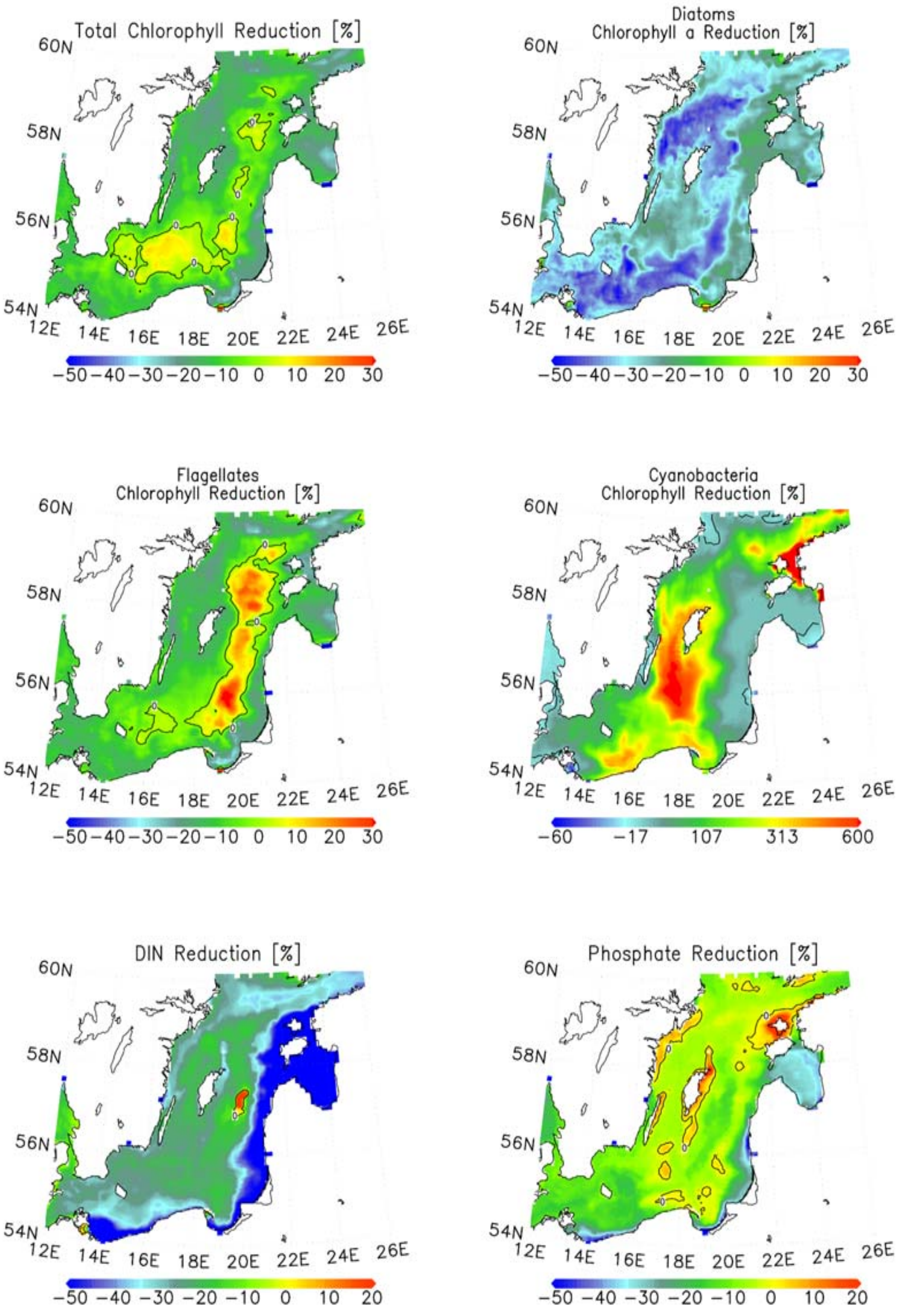

Load reduction experiment:
run 1982-1991

with halved river loads
of $N0_3$ and PO_4

← reference run
minus
run with reduced loads

averaged over the year 1991
and over upper 50m

T.Neumann, W.Fennel and C.Kremp
Global Biogeochemical Cycles,
*2002, **16,** 7-1 – 7-19*

HAB‘s are site-specific

models should involve currents and mixing processes
biogeochemical aspects of the site
nature of the HAB species, and
their ecological role

There is no quick solution,

Modeling HAB's requires:

partnership, networking and cooperation.

Perhaps it may take a generation time of researchers,

but there is no alternative

thanks