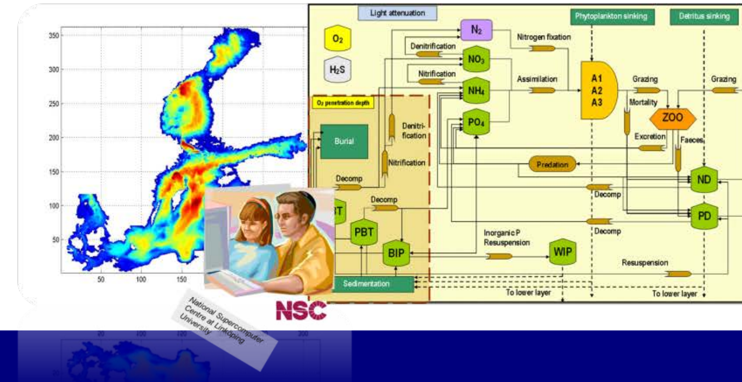




Biogeochemical cycles
in the Baltic Sea

Askö Summer course
2015

Presentation: Kari Eilola
Research and development, Department of Oceanography
SMHI

The global physical and biological pumps

http://www.igbp.net/

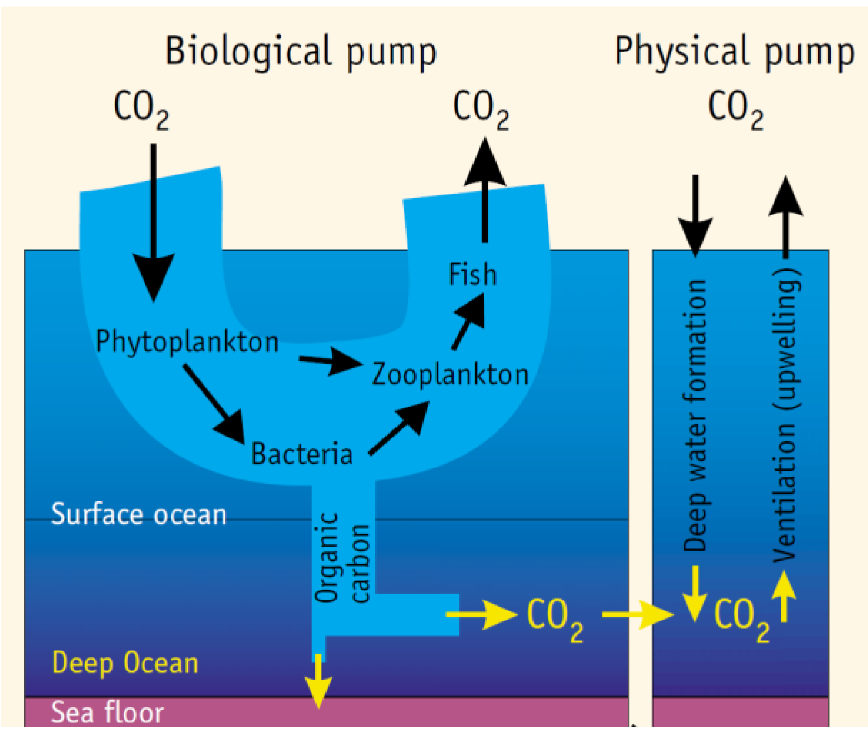
IGBP Science No. 2 GLOBAL CHANGE

The International Geosphere-Biosphere Programme:
A Study of Global Change of the International Council for Science (ICSU)
Stockholm, Sweden

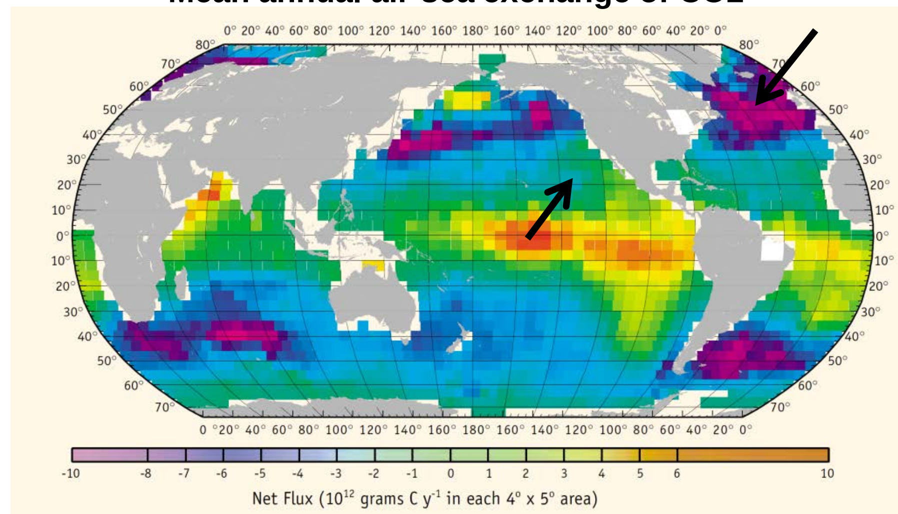
Ocean Biogeochemistry and Global Change:

JGOFS Research Highlights 1988-2000

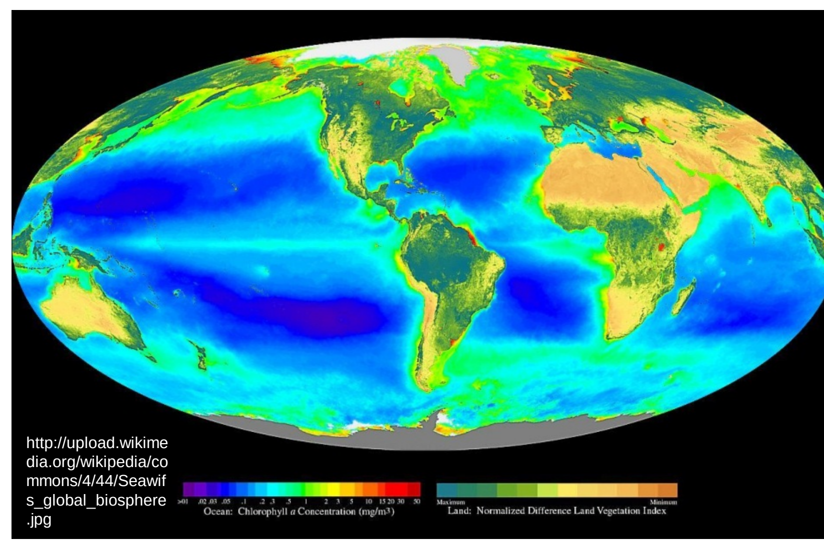
Edited by Beatriz M. Baliño, Michael J.R. Fasham and Margaret C. Bowles



Mean annual air-sea exchange of CO2

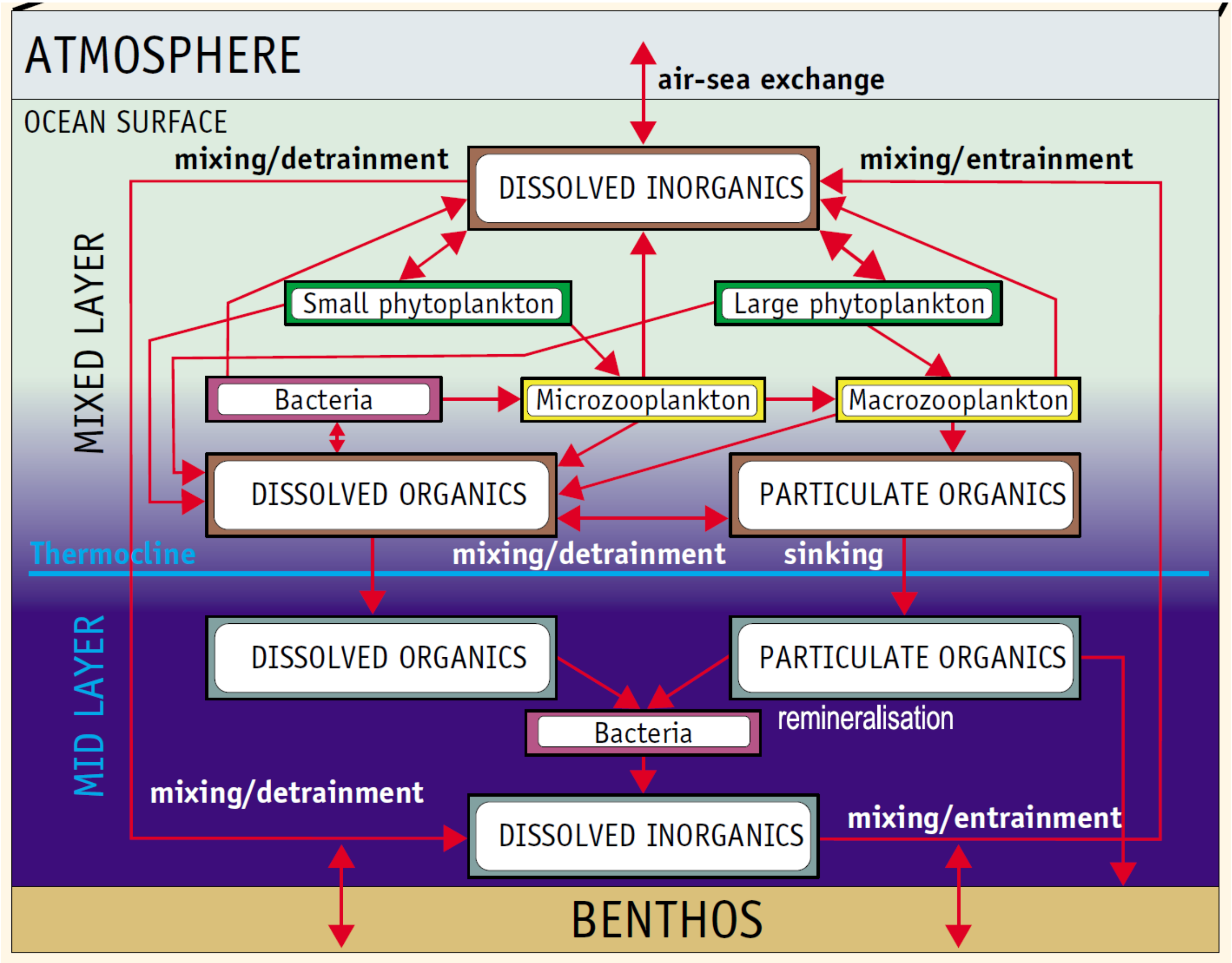


Satellite estimate of autotroph biomass



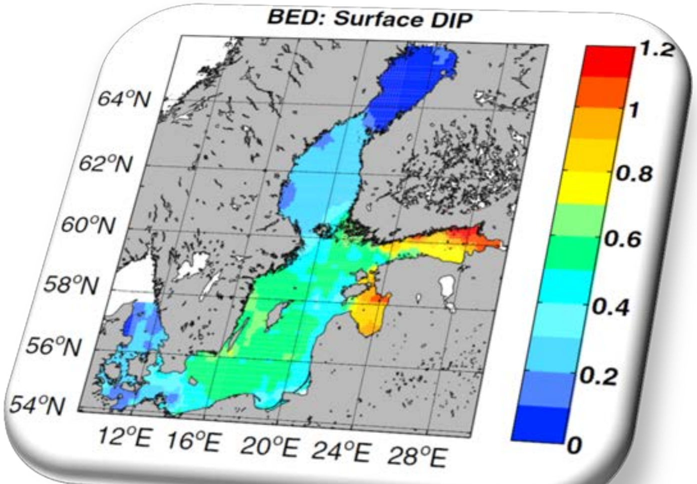
http://en.wikipedia.org/wiki/Primary_production

Regulation of the biological pump

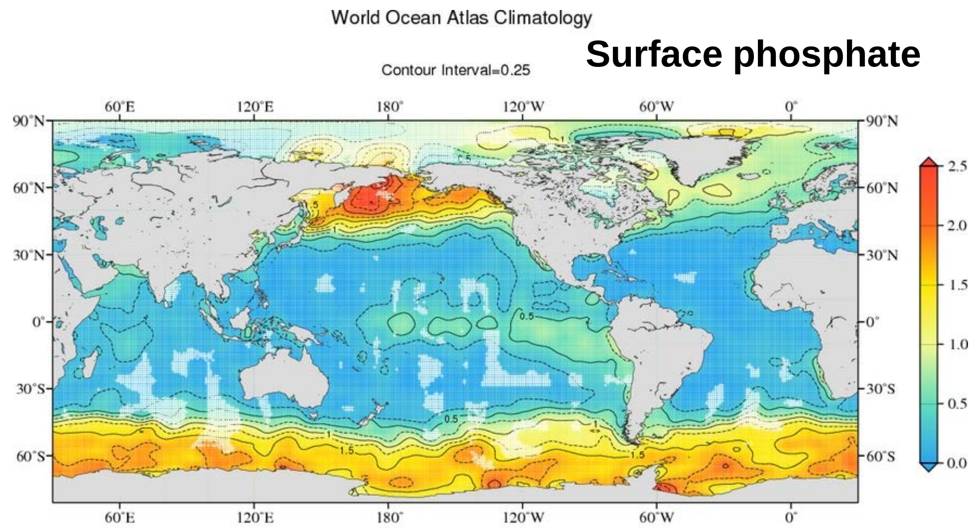


Regulation of the biological pump

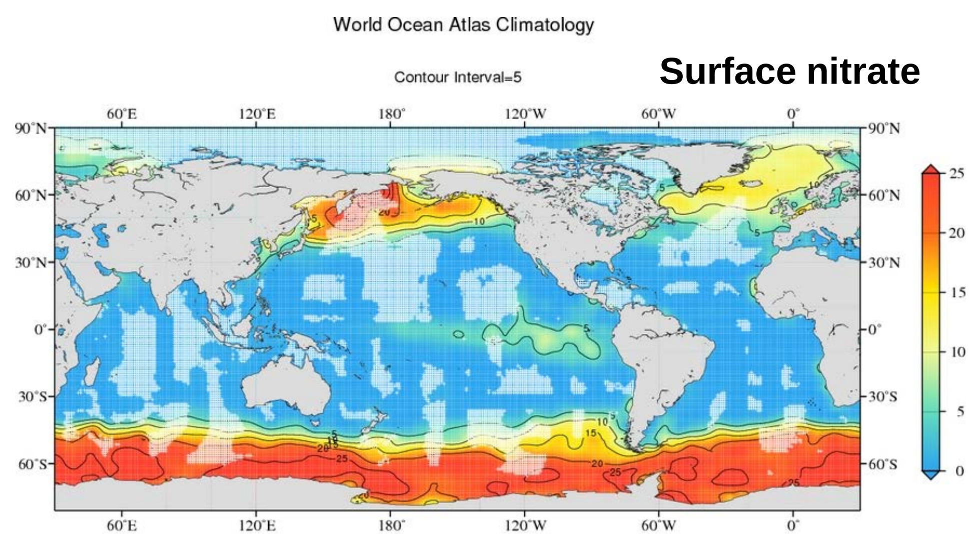
NOAA NATIONAL OCEANOGRAPHIC DATA CENTER (NODC)
UNITED STATES DEPARTMENT OF COMMERCE



Source: Eilola et al. 2011



Winter (Jan.-Mar.) phosphate [umol/l] at the surface (one-degree grid)



Winter (Jan.-Mar.) nitrate [umol/l] at the surface (one-degree grid)

- **Inorganic carbon is in excess**
- **Generally nutrient limitation of phytoplankton growth is due to nitrogen, phosphorus and silicon**

Regulation of the biological pump

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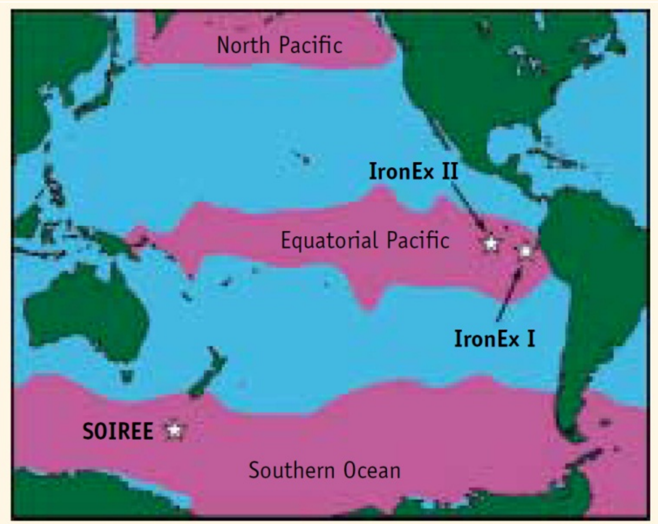
NOAA NATIONAL OCEANOGRAPHIC DATA CENTER (NODC) UNITED STATES DEPARTMENT OF COMMERCE

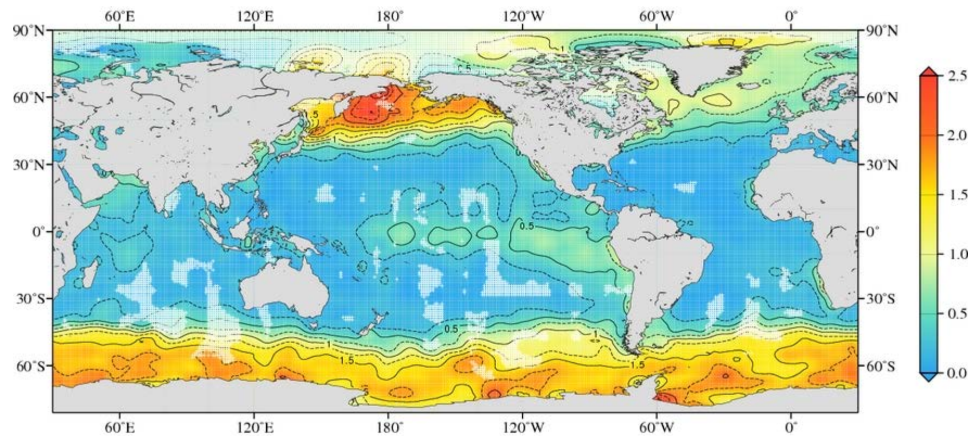
High Nutrient-Low Chlorophyll (HNLC) Areas



World Ocean Atlas Climatology

Surface phosphate

Contour Interval=0.25

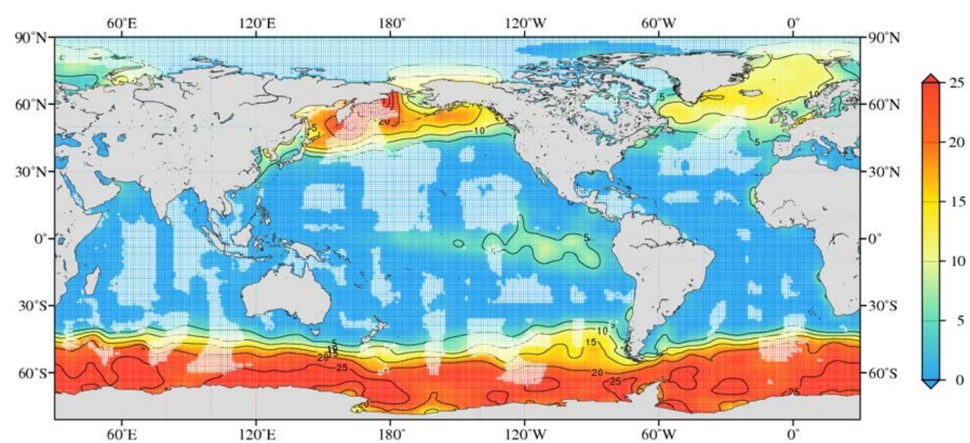


Winter (Jan.-Mar.) phosphate [umol/l] at the surface (one-degree grid)

World Ocean Atlas Climatology

Surface nitrate

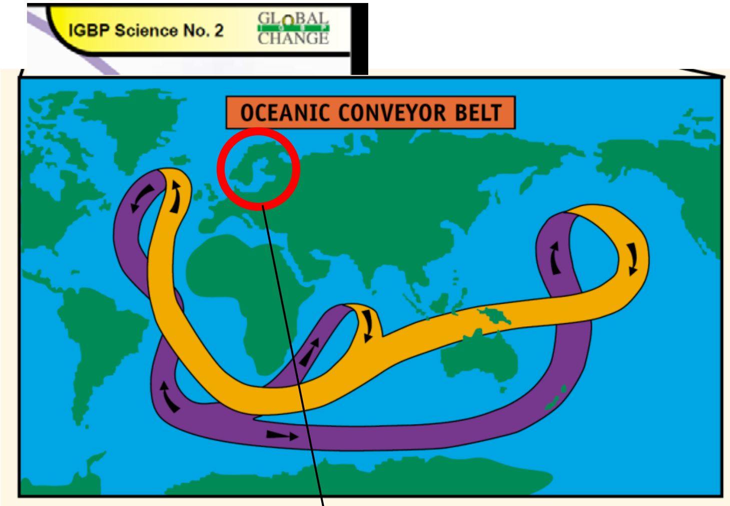
Contour Interval=5



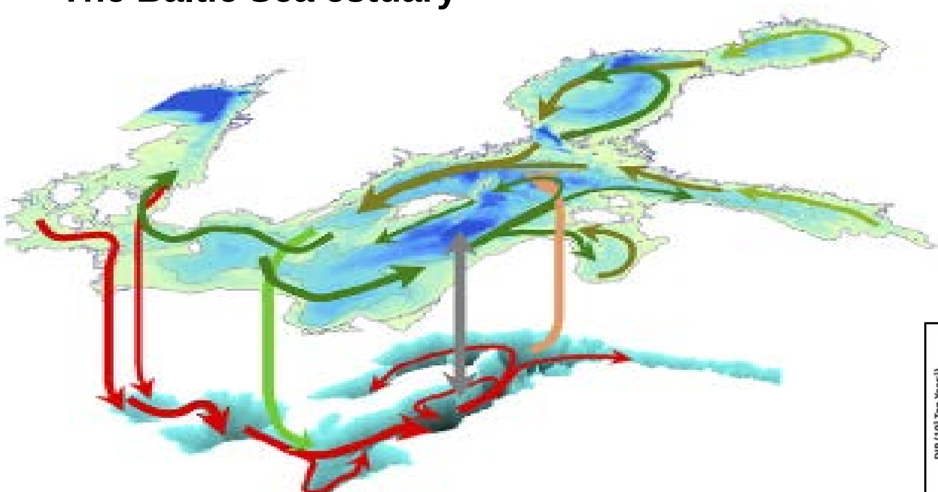
Winter (Jan.-Mar.) nitrate [umol/l] at the surface (one-degree grid)

- **In HNLC-areas (purple) nutrient availability exceed demands.**
- **Hypothesis: Iron is limiting**

The Baltic Sea example

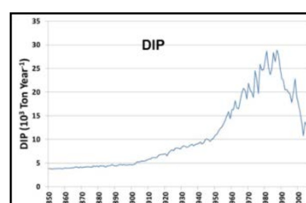


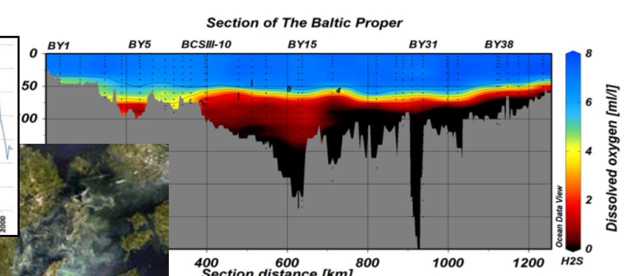
The Baltic Sea estuary

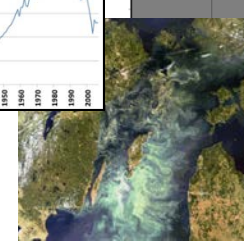


Schematic view of the large-scale water circulation
BACC author team 2008

- **Semi-enclosed marginal sea**
  - Restricted water exchange
  - Weak tides
- **Large freshwater supply**
  - Low salinity
  - Low biodiversity
- **Strong salinity stratification**
  - Shallow mixed surface layer
  - Sea ice during winter
  - Frequently anoxic in deep waters
- **Large nutrient supply**
  - Partly eutrophic
  - Wide spread anoxia
  - Large blooms of cyanobacteria



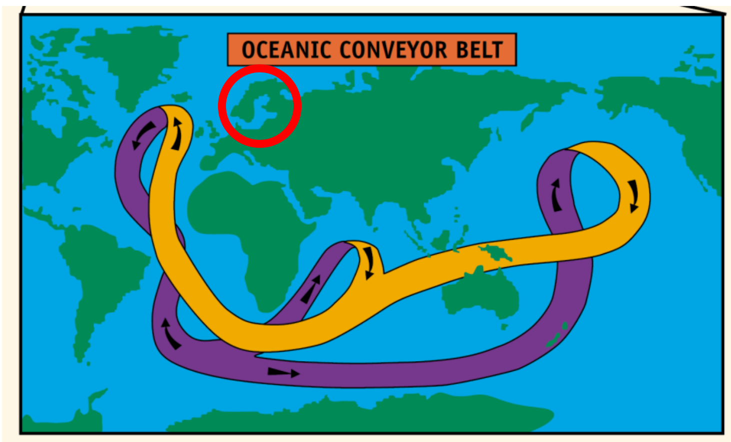




BACC Author Team, 2008. BALTEX assessment of climate change for the Baltic Sea basin. Regional Climate Studies. ISBN: 978-3-540-72785-9. Springer-Verlag.

Hansson, M., L. Andersson, and P. Axe, 2012. Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011. SMHI Report Oceanography No. 42.

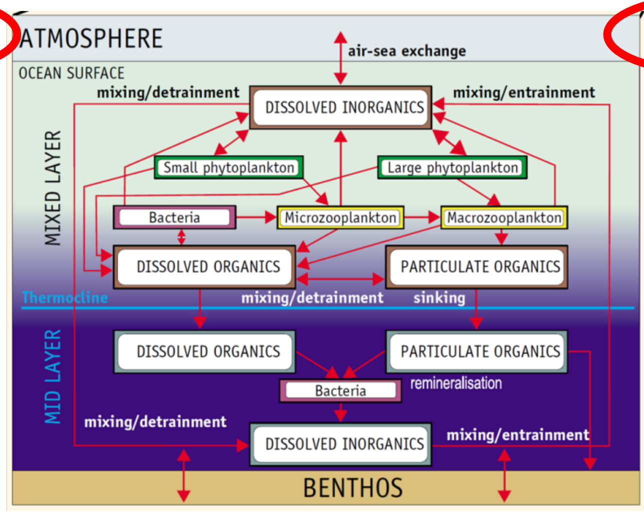
The Baltic Sea example



Regulation of the biological pump in shallow and deep areas

Deep ocean

Baltic Sea



~100 m | ~ 10 m

~ 1000 m | ~ 100 m

- **Semi-enclosed marginal sea**
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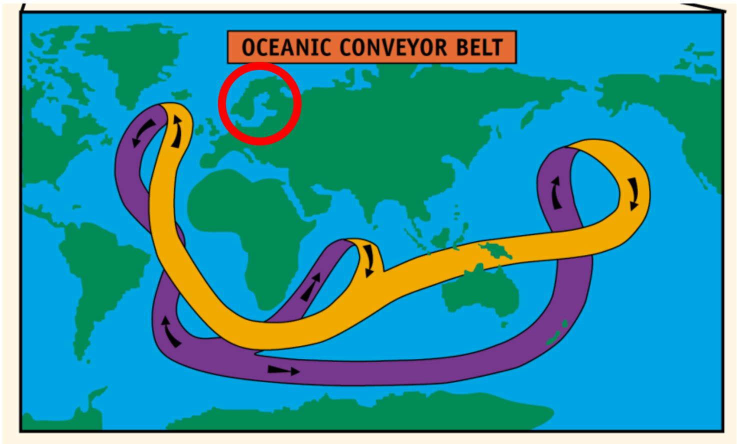
  - Wide spread anoxia
  - Large blooms of cyanobacteria
- **Shallow water depth**
  - Sinking organic particles reach bottoms
  - Resuspension and sediment fluxes important

The Baltic Sea example



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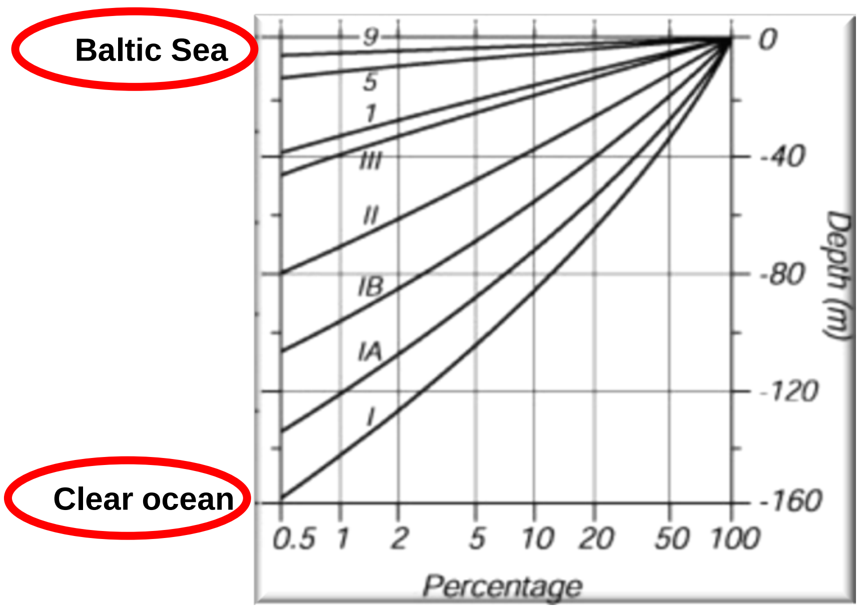
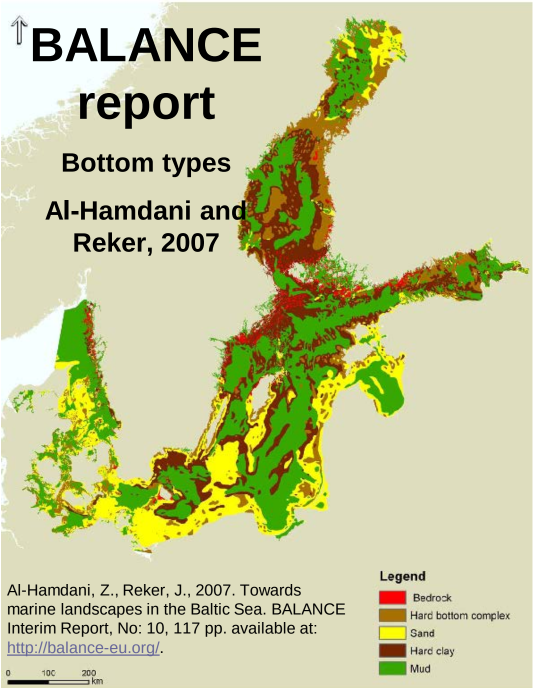
  - Sea ice during winter
  - Frequently anoxic in deep waters
- **Large nutrient supply**
  - Eutrophication
  - Large blooms of cyanobacteria
- **Shallow water depth**
  - Sinking organic particles reach bottoms
  - Resuspension and sediment fluxes important
- **Reduced light transmission**
  - Large impact from colored matter (CDOM)
  - Shallow euphotic zone

Euphotic zone in clear and turbid waters

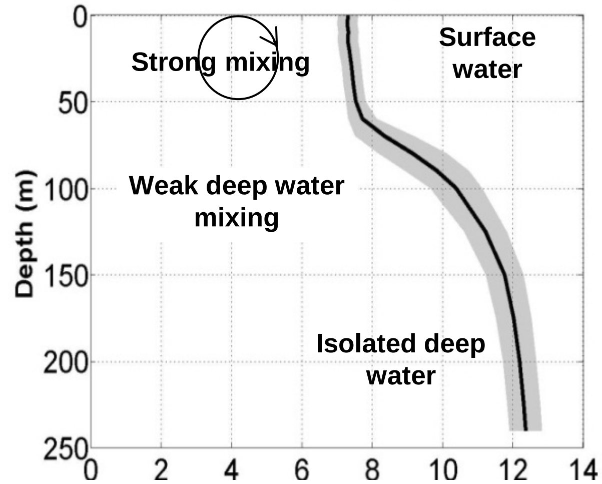


Light transmittance 495 nm (Jerlov, N. G., 1976. *Marine optics*. Elsevier.)

Climate impact on biogeochemical cycling?

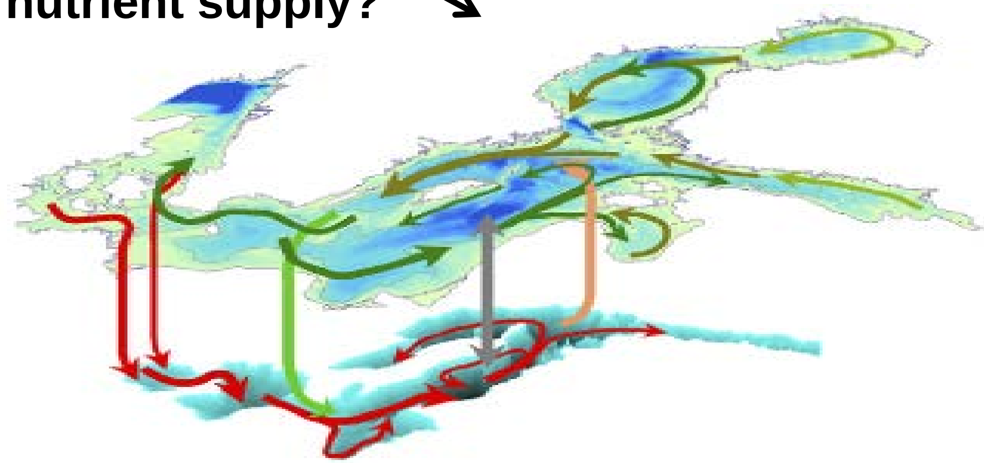


- **Changed salinity and stratification?**



- **Changed sea ice cover?**

- **Changed winds?**
- **Changed freshwater and nutrient supply?** ↘
- **Changed deep water formation?** →
- **Changed water temperature?**



Biogeochemical cycling of nutrients and oxygen

Photosynthesis

- Primary production of phytoplankton.
- Transformation of carbon dioxide and inorganic nutrients to living organic matter.
- Production of Oxygen.
- Phosphorus, Nitrogen are essential nutrients.
- Nitrogen fixation may add new bioavailable nitrogen from dissolved atmospheric N_2.

Litoral ecosystem figure from:

Merentutkimuslaitos
Havsforskningsinstitutet
Finnish Institute of Marine Research

Biogeochemical cycling of nutrients and oxygen

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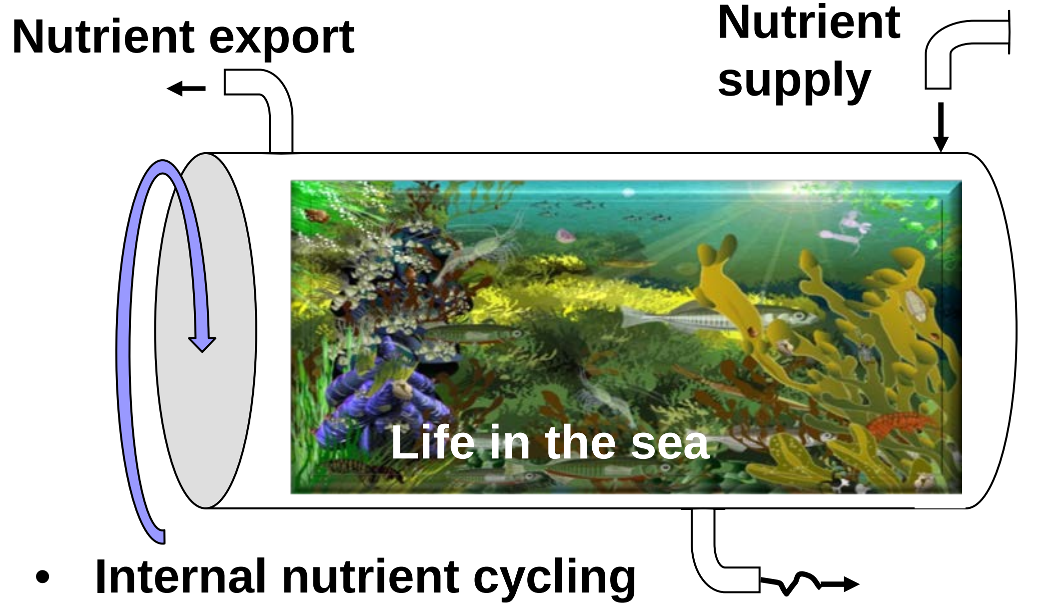


- Internal nutrient cycling and biogeochemical processing.
- Internal nutrient removal

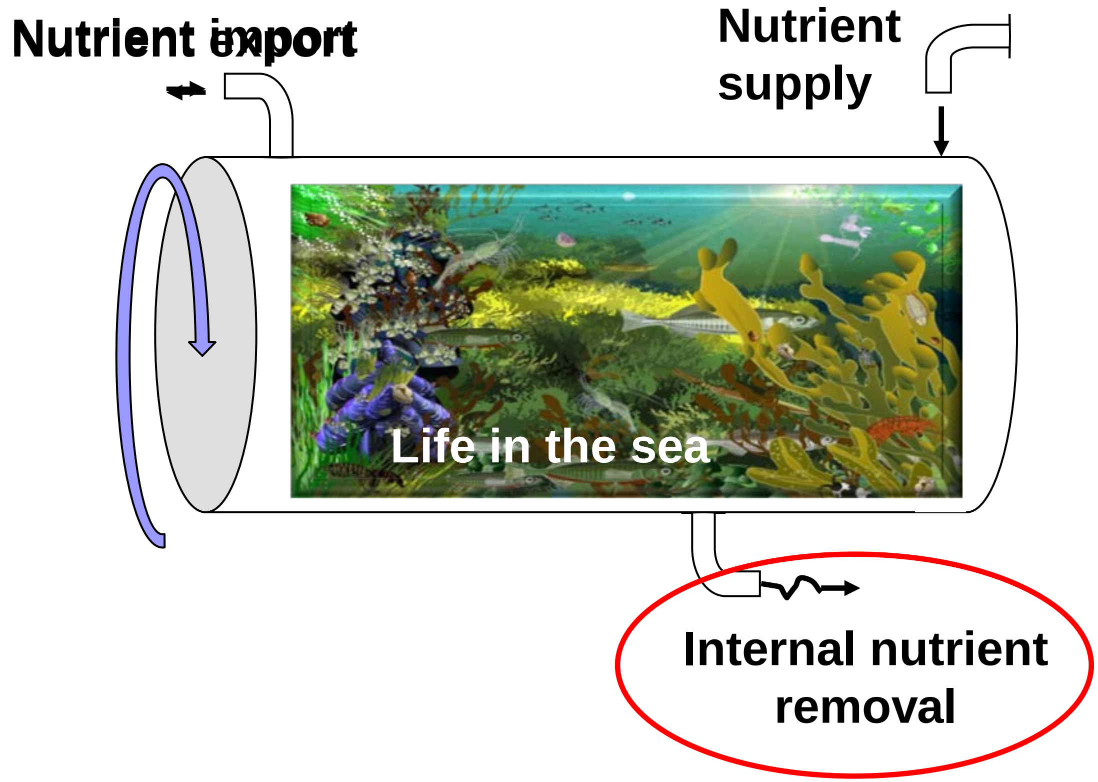
Litoral ecosystem figure from:

Merentutkimuslaitos
Havsforskningsinstitutet
Finnish Institute of Marine Research

Biogeochemical cycling of nutrients and oxygen

Thought experiment

1. The import of nutrients from the North Sea will become important.
2. The long-term net nutrient import is balanced to the internal nutrient removal in the Baltic Sea.



Litoral ecosystem figure from:

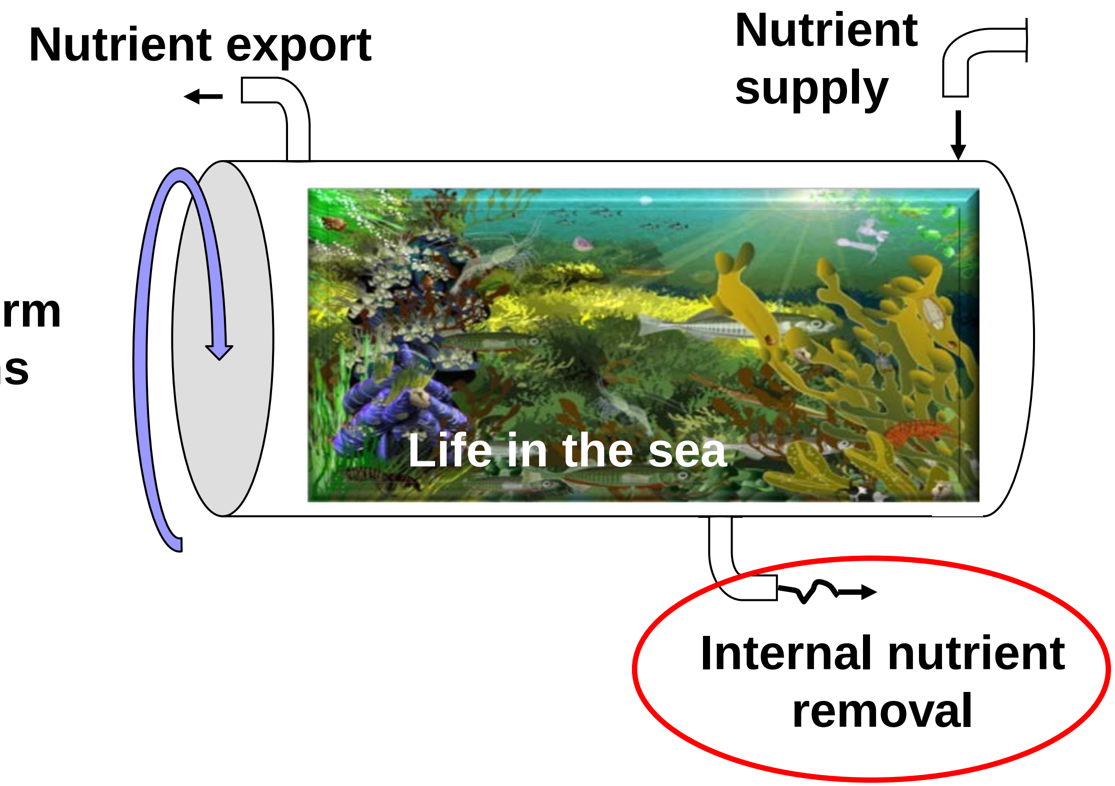
Merentutkimuslaitos
Havsforskningsinstitutet
Finnish Institute of Marine Research

Biogeochemical cycling of nutrients and oxygen

Thought experiment 2

- What happens in a closed sea/ocean?
- What determines the long-term mean nutrient concentrations in the water?
- What happens if there is no internal removal?

The long-term nutrient supply is balanced to the internal nutrient removal.



Litoral ecosystem figure from:

Merentutkimuslaitos
Havsforskningsinstitutet
Finnish Institute of Marine Research

Biogeochemical cycling of nutrients

Nutrient Budgets (biologically available nutrients)

Ecosupport model ensemble
Meier et al. (2012)

- **N and P budgets 1978-2007**
  The 30-year control period of Ecosupport climate scenarios

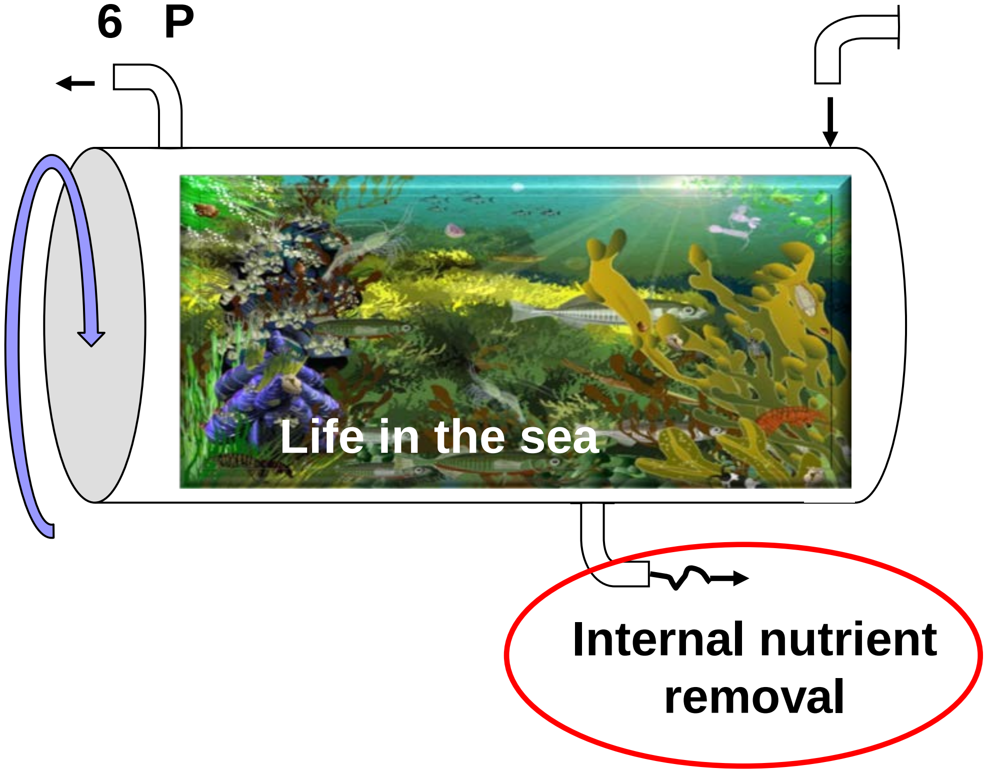
Units: 10^3 Ton yr^{-1}

Nutrient supply

835 N
39 P

Nutrient export

23 N
6 P



Internal nutrient removal

- **N= 97% of supply remains in the Baltic Sea.**
- **P= 85% of supply remains in the Baltic Sea.**

Litoral ecosystem figure from:
Merentutkimuslaitos
Havsforskningsinstitutet
Finnish Institute of Marine Research

Meier, H.E.M., B. Muller-Karulis, H.C. Andersson, C. Dieterich, K. Eilola, B.G. Gustafsson, A. Höglund, R. Hordoir, et al. 2012. Impact of climate change on ecological quality indicators and biogeochemical fluxes in the Baltic Sea: A multi-model ensemble study. AMBIO 41: 558–573. doi:10.1007/s13280-012-0317-y.

Biogeochemical cycling of nutrients

Nutrient Budgets (biologically available nutrients)

Units: 10^3 Ton yr^{-1}

Impact from warmer climate

- **N and P budgets 1978-2007 and 2069-2097 (REF)**

	Nutrient export	Nutrient supply
1978-2007	23 N 6 P	835 N 39 P
2069-2097 (REF)	37 N 13 P	819 N 39 P

Internal nutrient removal

- **N= 97% (95%)**
- **P= 85% (67%)**

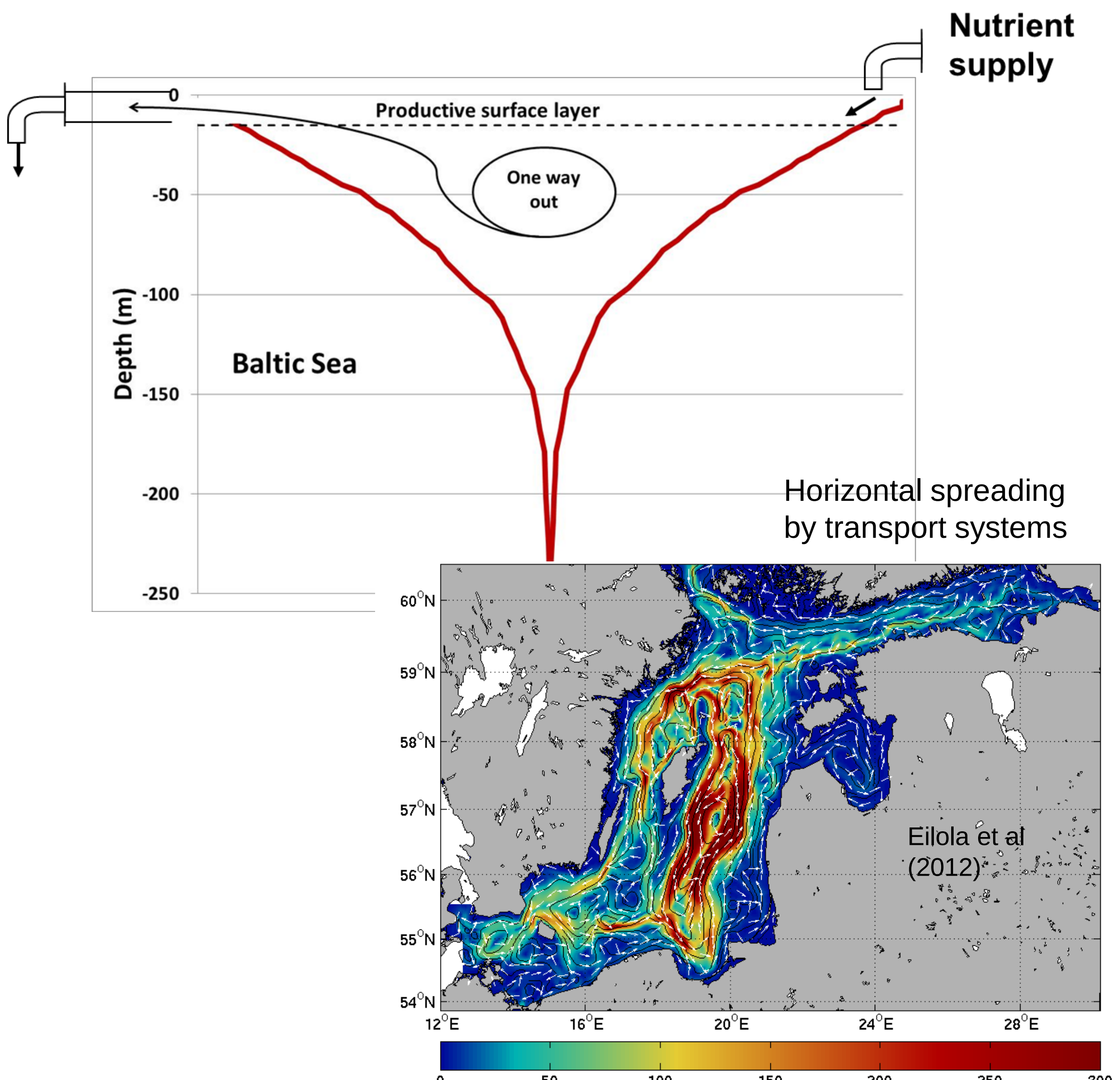
Changing P sink efficiency

- **21% weaker internal P sink efficiency in future climate scenario.**
- **Similar nutrient supply, but increased nutrient export due to the reduced sink efficiency**

REFerence (REF):
Current riverine nutrient concentrations and current atmospheric deposition

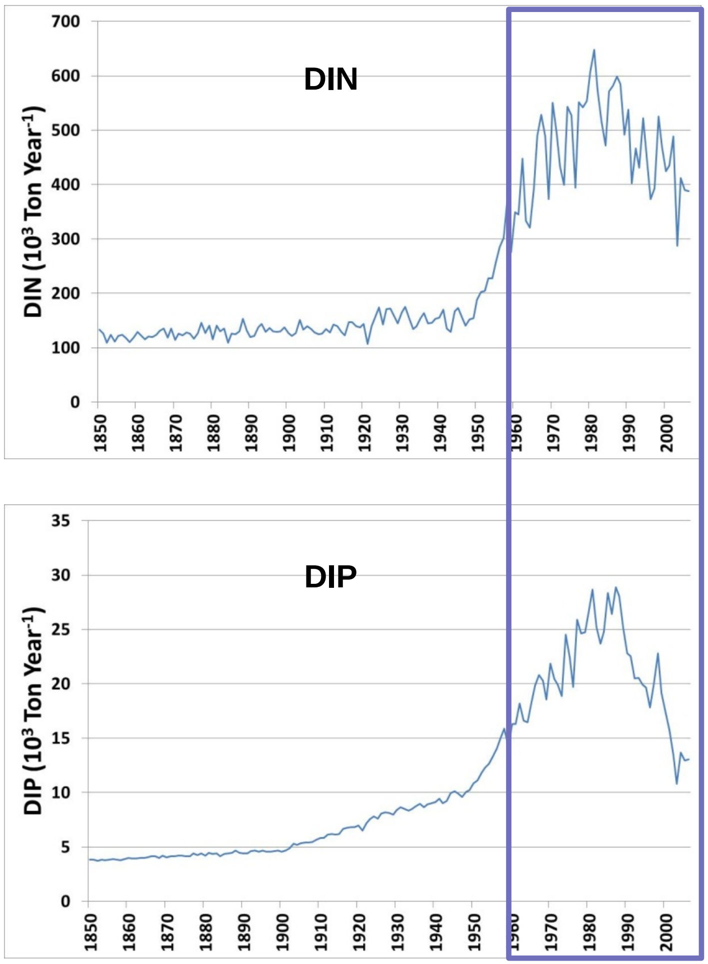
Biogeochemical cycling of nutrients

The internal nutrient removal is regulating the surface nutrient concentrations and the primary production.

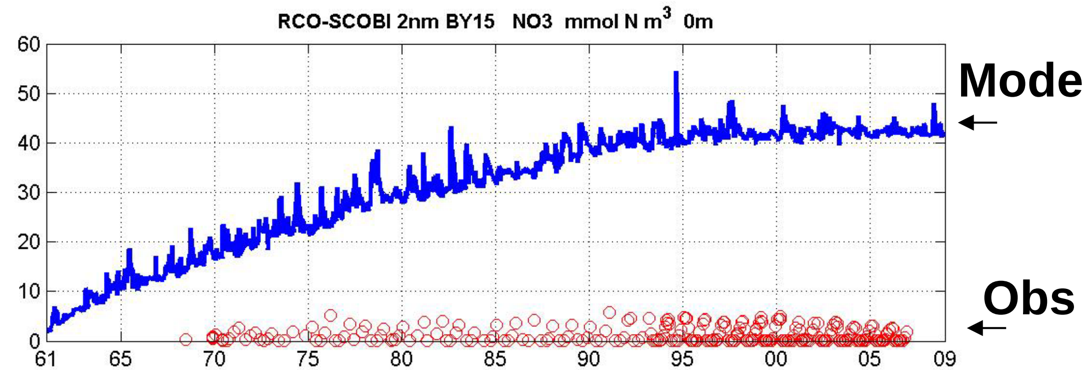


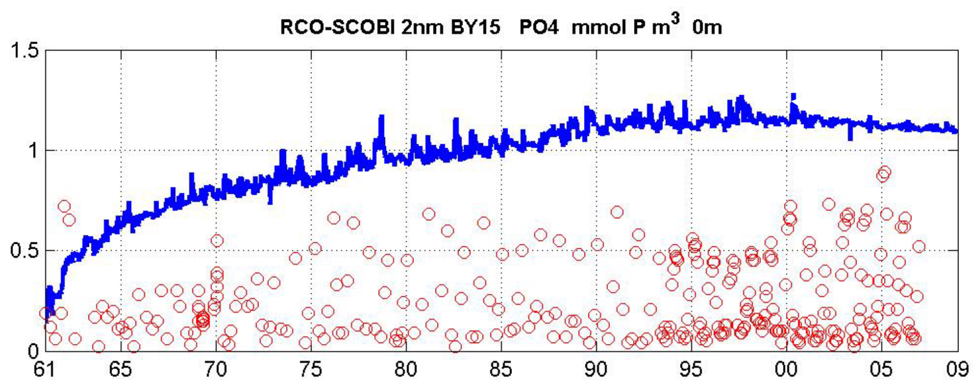
Biogeochemical cycling of nutrients

- **Nutrient supply 1850-2006**



- **No interna removal**
- **All supplied nutrients must be exported**





- ***RCO-SCOBI 2nm model (East Gotland Sea)***
- ***Surface observations SHARK***

Take home exercise:

Salinity and bioactive tracer -analytical experiments

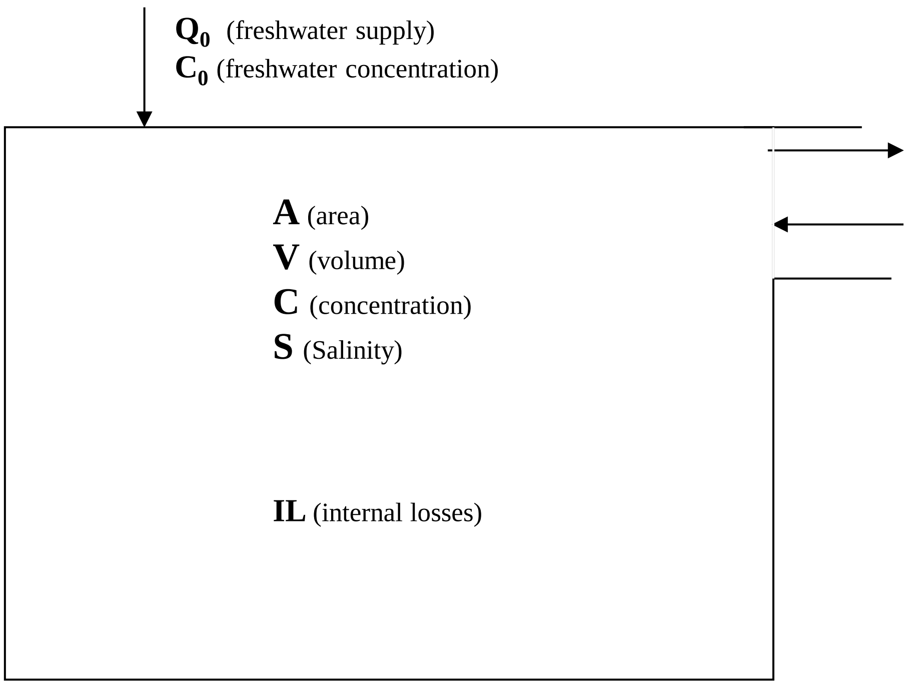
- **Investigate some basic characteristics for salinity and the bioactive tracer in an experimental sea.**

Tracer mass conservation:

$$V \cdot \frac{dC}{dt} = Q_0 \cdot C_0 + Q_2 \cdot C_2 - Q \cdot C - IL$$

- Supplied with a bioactive tracer with freshwater from land and with inflowing water from the adjacent sea.
- The bioactive tracer may be removed due internal losses.

- Well-mixed basin
- Fixed volume
- Flat bottom



- $\mathbf{Q_0}$ and $\mathbf{Q_2}$ are given

- Assume that a fraction Ω of the concentration C is removed with a constant rate due to internal losses ($IL = \Omega C$).
- Assume that the internal loss is proportional to the area A with an apparent removal rate v_s (i.e. $\Omega = v_s A$).

- Steady state, i.e. $V \cdot \frac{dC}{dt} = 0$

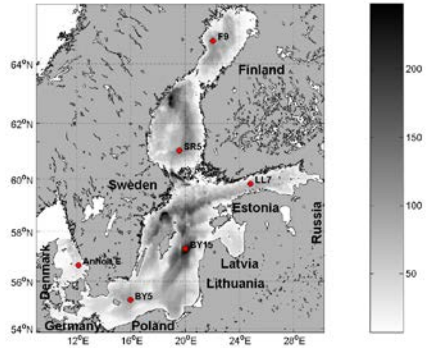
See also Wulff and Stigebrandt 1989
Time-dependent budget model for nutrients in the Baltic Sea.

Circulation model and climate forcing

Ocean model

RCO (Rossby Centre Ocean Model)

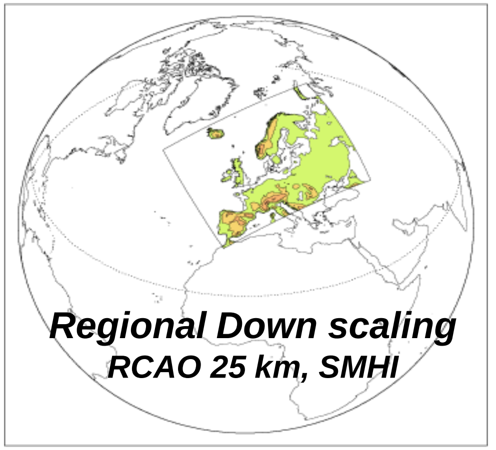
Resolution: 2nm horizontal and 3m vertical



Global Climate forcing

Global circulation models (GCM)
Model 1. ***HadCM3*** *(Hadley Centre, UK)*

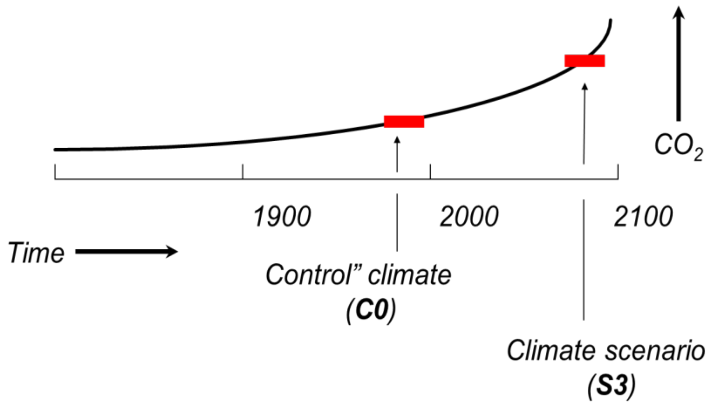
Model 2. ***ECHAM5****/MPI-OM (Max-Planck Institute, Germany)*



CO_2 emission scenario A1B

(IPCC SRES Medium-High)

- **C0 (Control period 1978-2007).**
- **S3 (Climate scenario 2069-2098).**

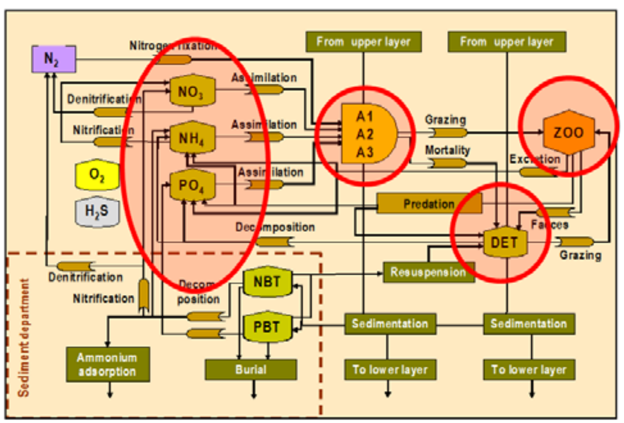


Nutrient cycling and forcing

Biogeochemical model

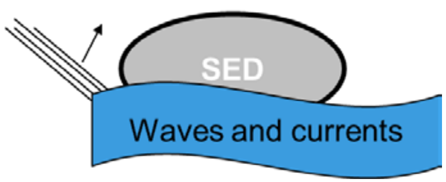
SCOBI
(Swedish Coastal and Ocean Biogeochemical Model)

- inorganic nutrients
- organic nutrients



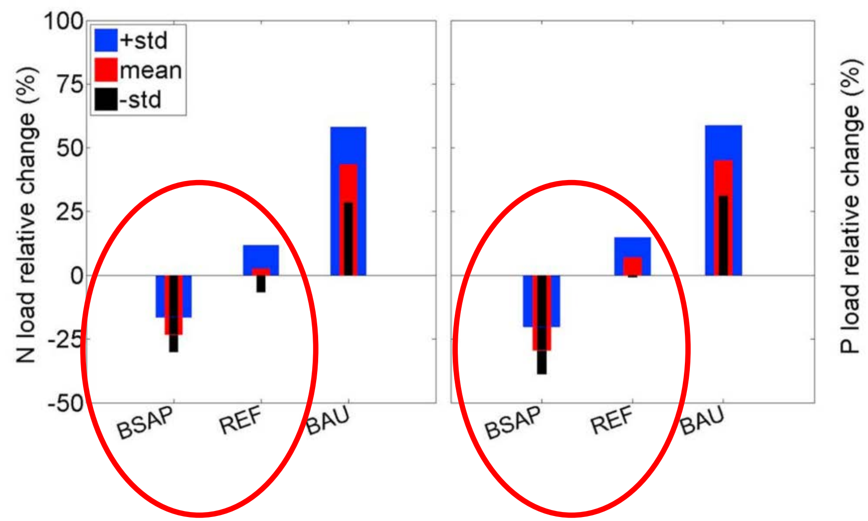
Resuspension

of sediments



Nutrient loads

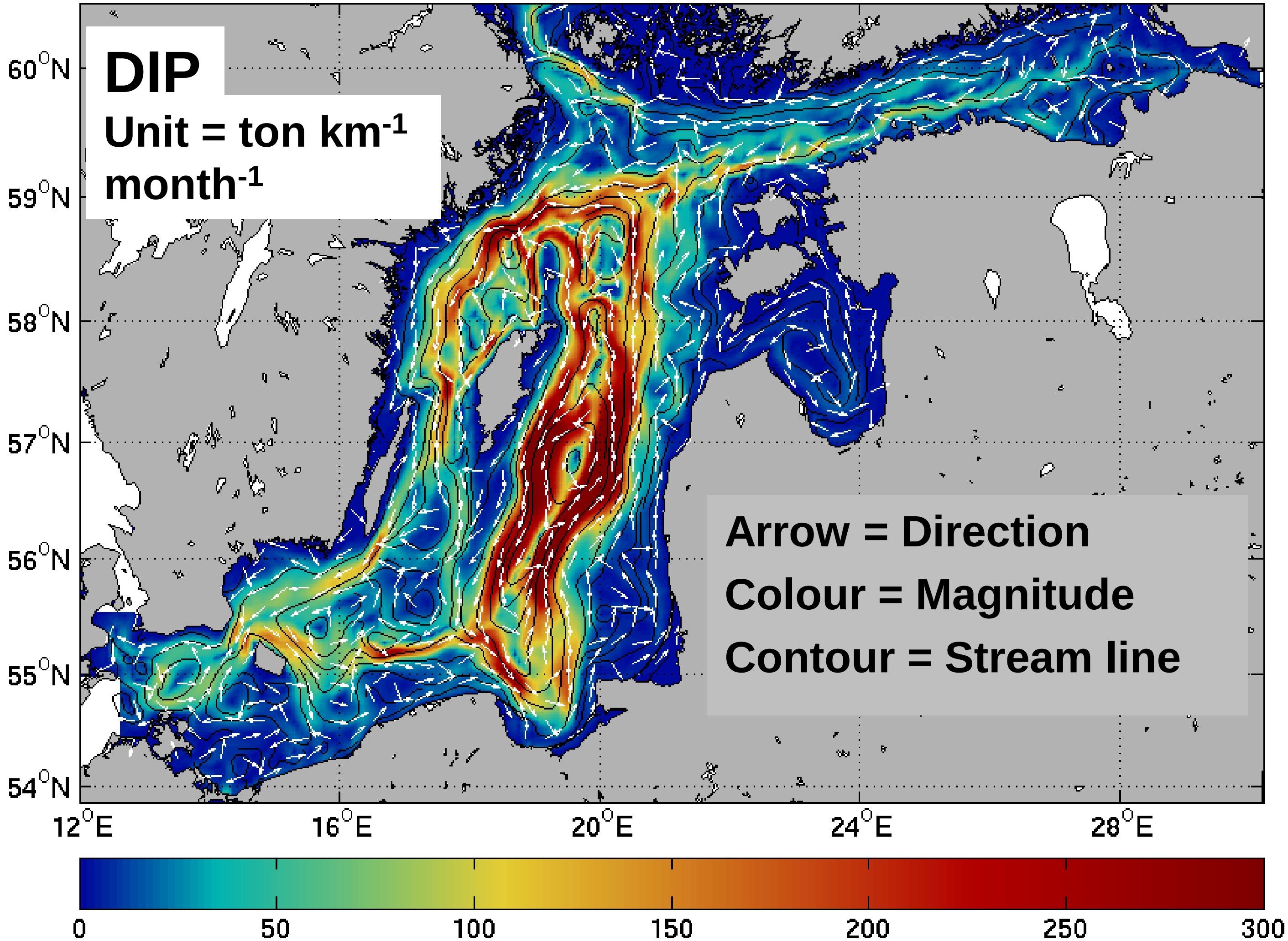
1. Reference scenario
2. Baltic Sea Action Plan
3. ~~Business as usual~~



Nutrient transports

Annual average <u>vertically integrated</u> DIP transport

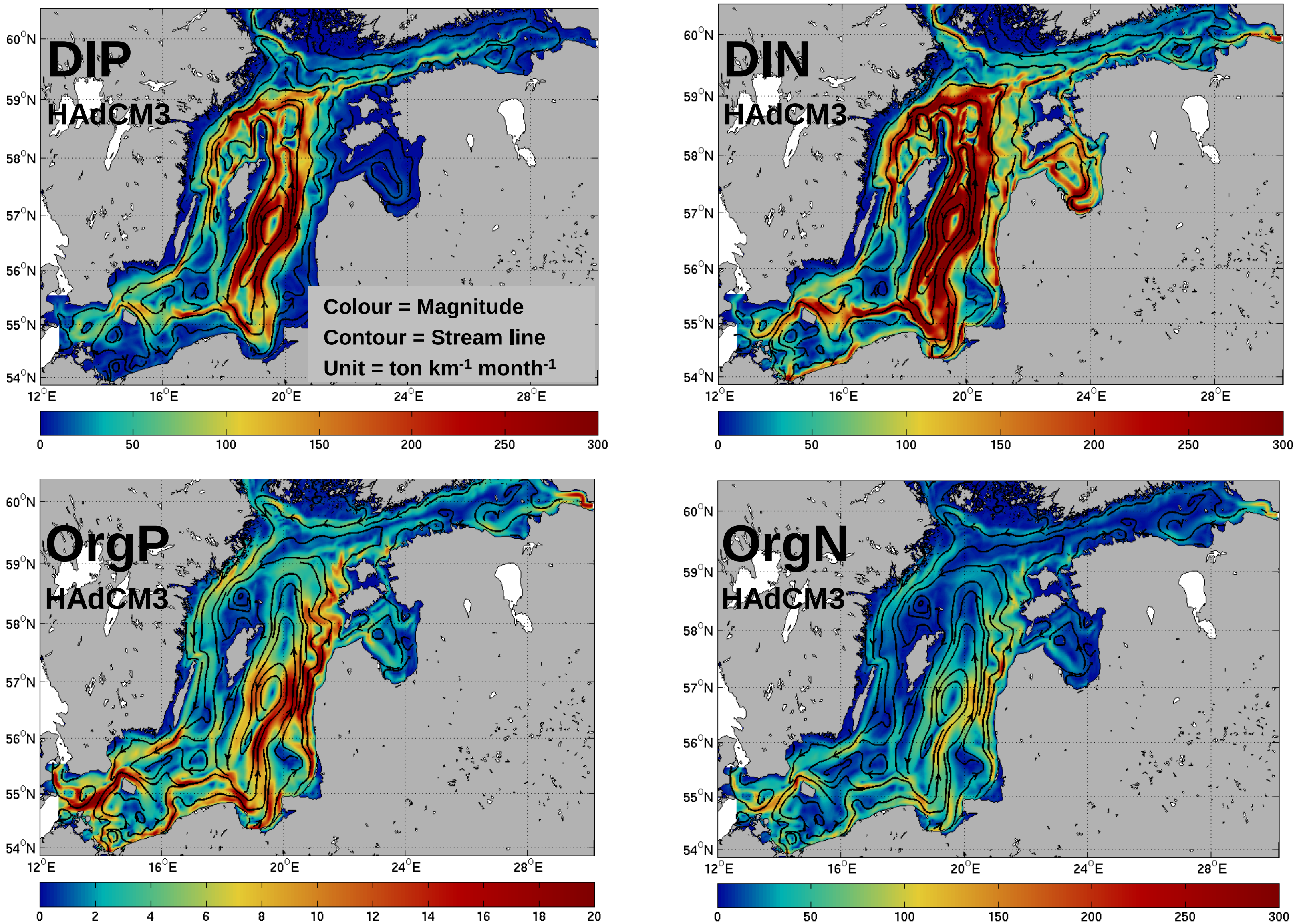
Control period (30 years): HadCM3 A1B



- **Nutrient transports follow mainly the large-scale internal water circulation**
- **Only small circulation changes in the future projections**

Nutrient transports

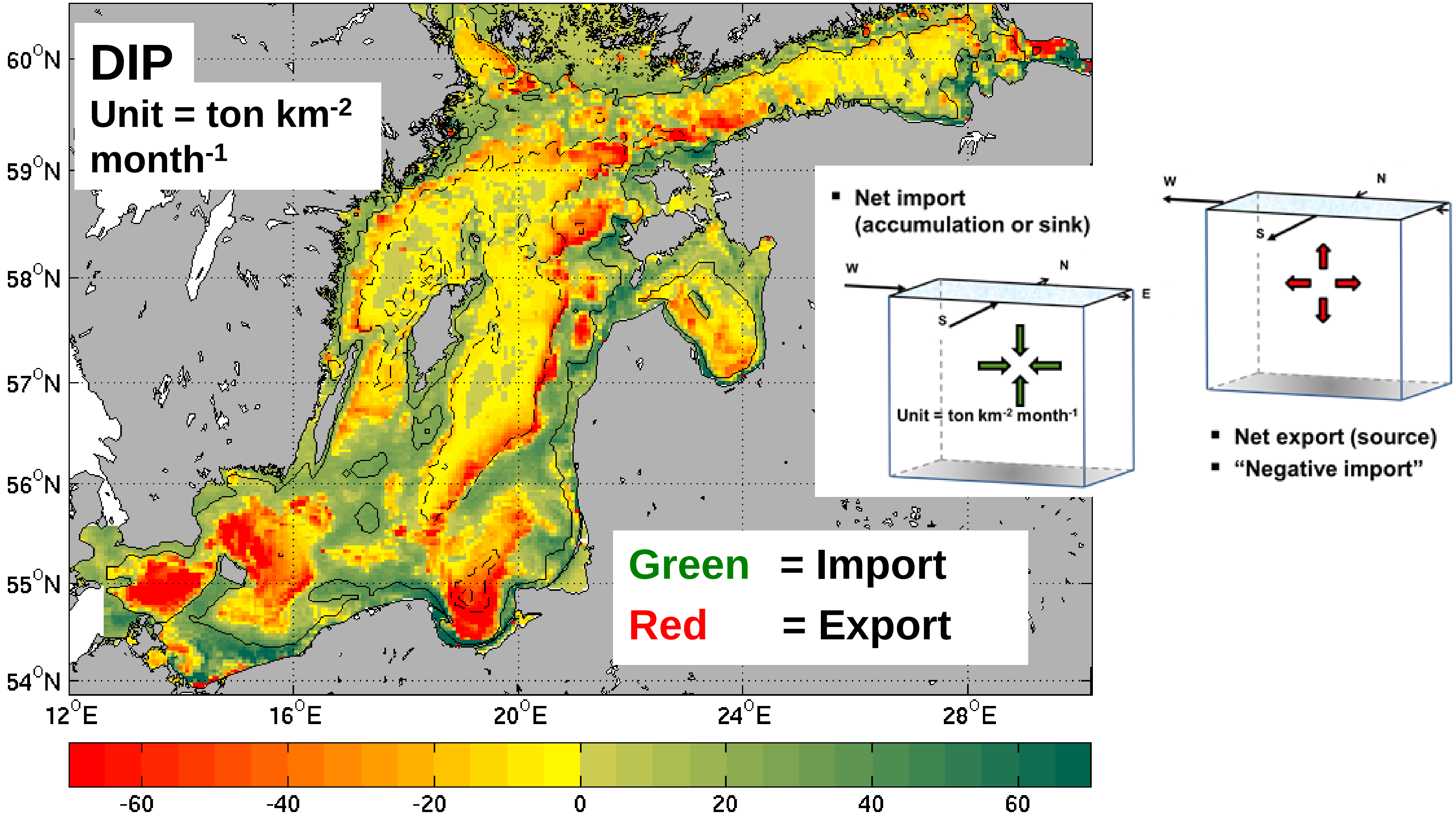
Annual P and N transport - Control period



Nutrient transports

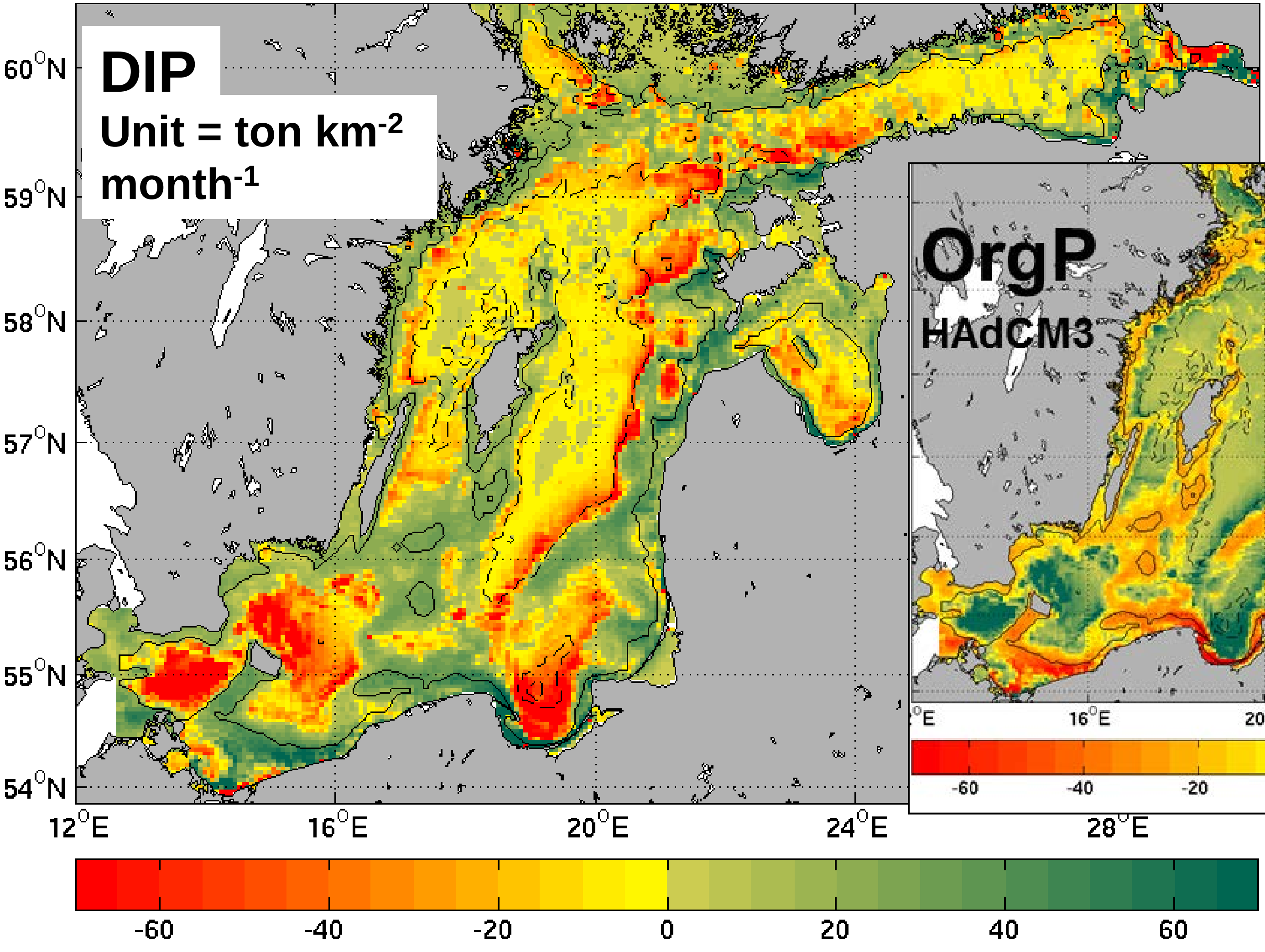
Annual average DIP import (source and sink distributions)

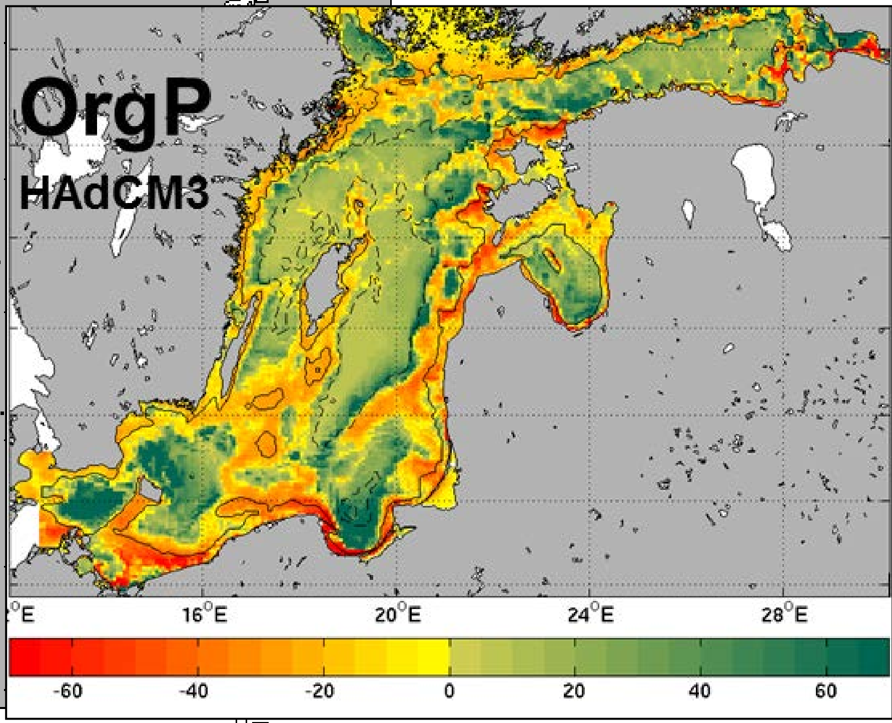
Control period (30 years): HadCM3 A1B



Nutrient transports

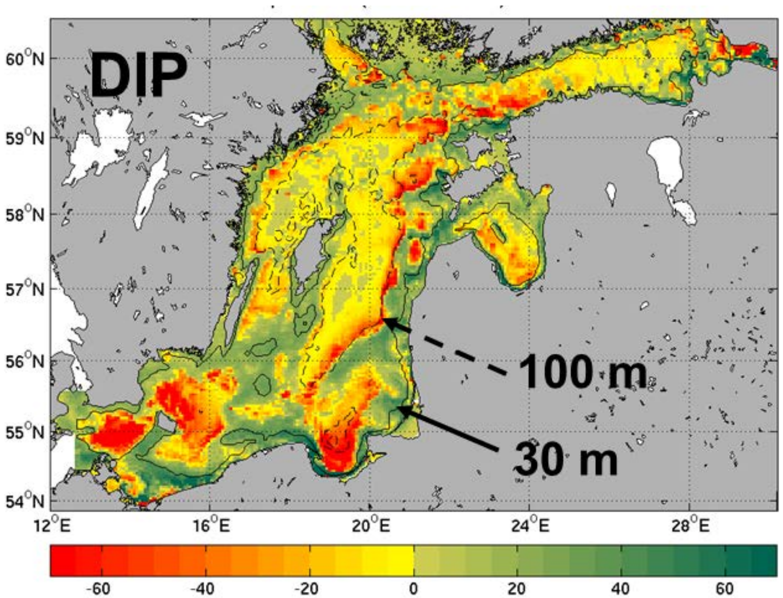
Internal nutrient cycling

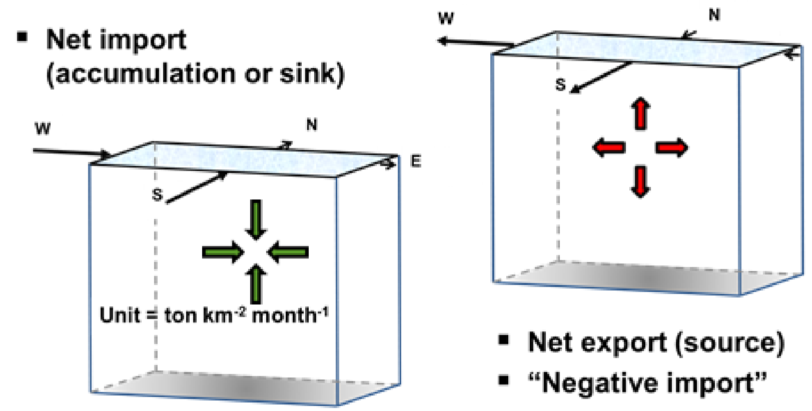


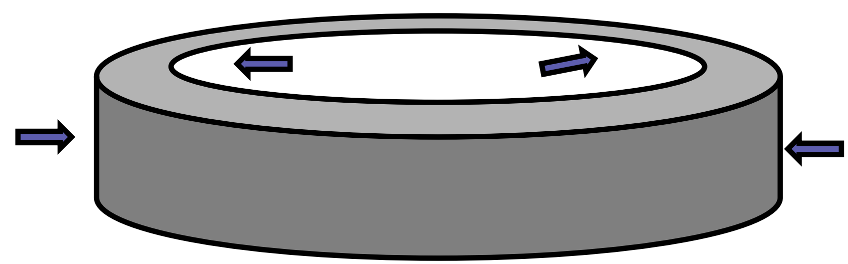


Nutrient transports

Horizontally integrated import of DIP







Summarize the import to all cells having the <u>same bottom depth</u>

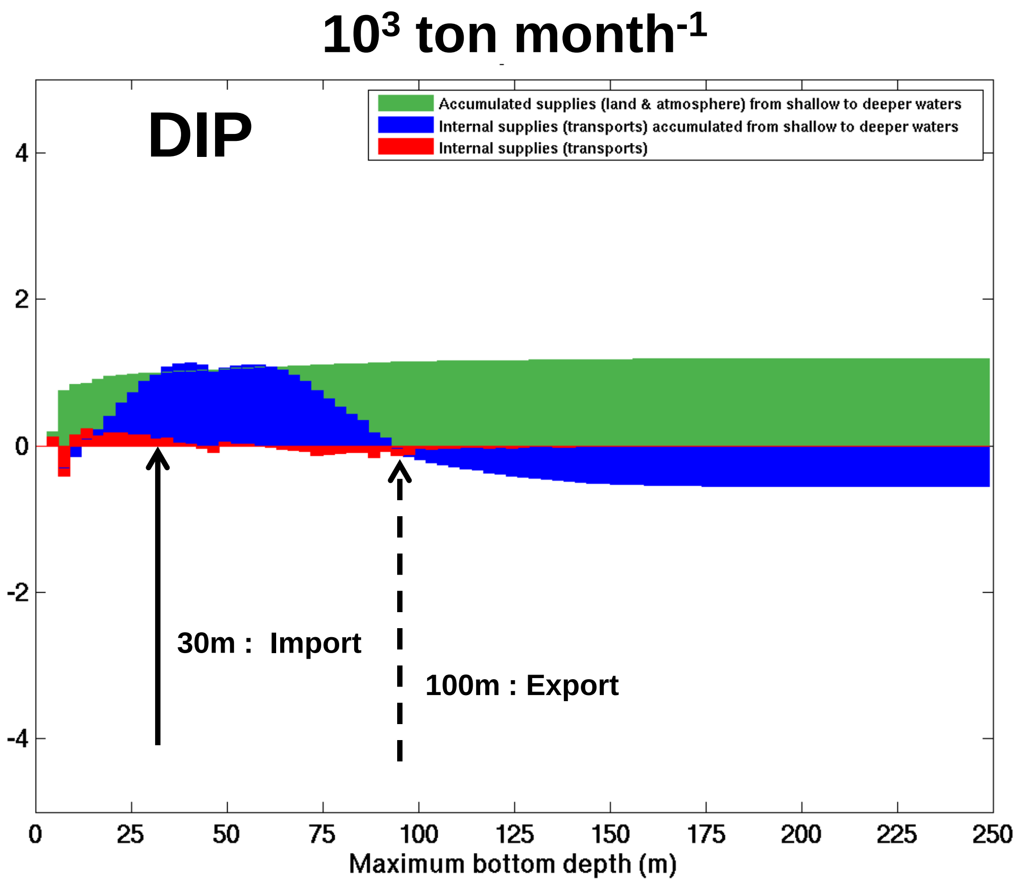
Nutrient transports

Baltic Proper integrated import of DIP

Red bars summarize the import to all cells having the <u>same bottom depth</u>

Blue bars accumulate the imports (starting from shallow waters)

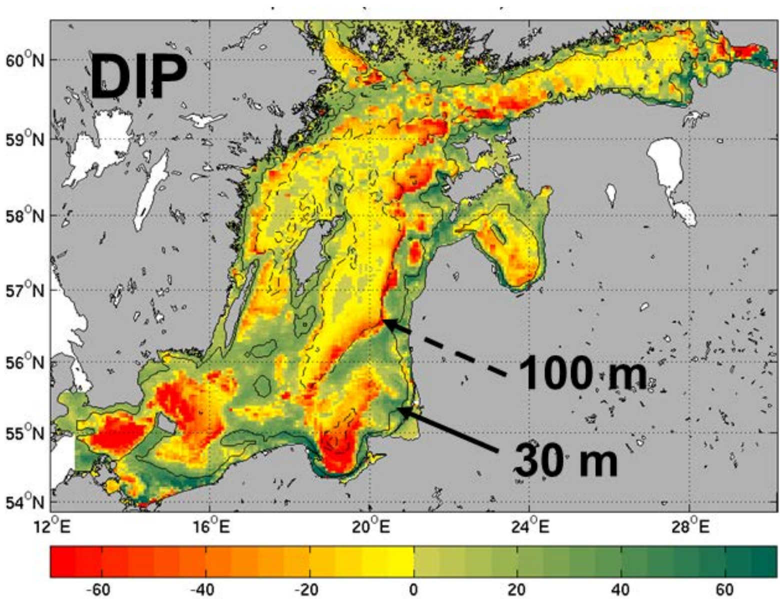
Green bars accumulate the loads from rivers, point sources and the atmosphere (starting from shallow waters)

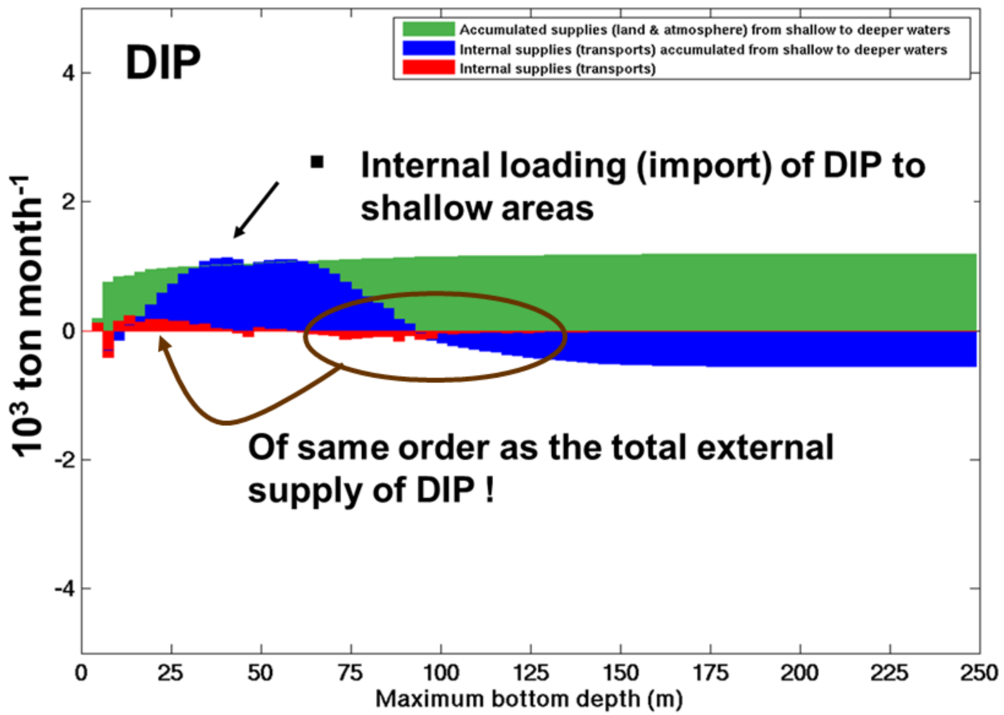


Nutrient transports

Baltic Proper integrated import of DIP

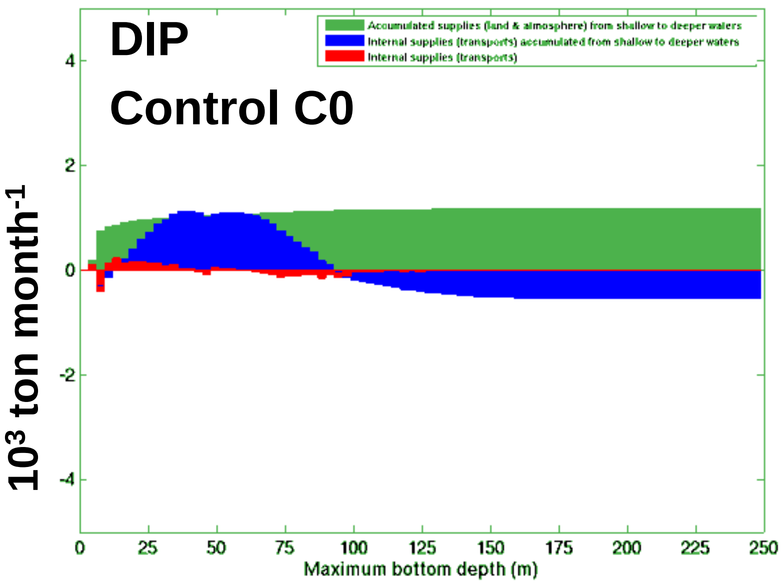
- DIP is transported from deeper areas to the productive shallow areas.

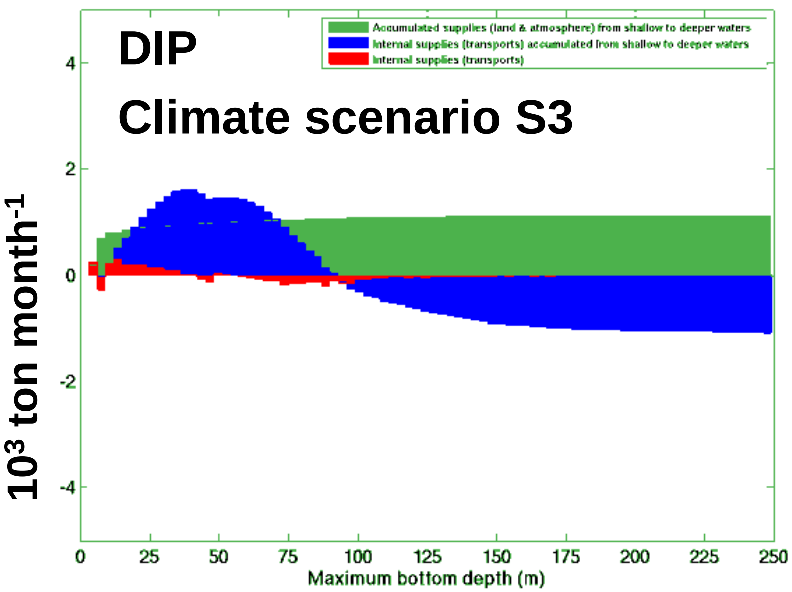




Nutrient transports

Climate impact HadCM3 A1B





- **The internal P-cycling intensifies in warmer future climate.**
- **Increased internal loading to shallow areas**
- **The internal removal of P is much lower in warmer future climate.**
- **A major fraction of the total DIP supply is exported to adjacent seas**

Nutrient transports

Baltic Proper integrated import of DIP

- **DIP is transported from deeper layers to the productive shallow areas.**
- **The internal P-cycling intensifies in warmer future climate.**
- **Increased internal loading to shallow areas.**

- **Interactions between coastal regions and the open sea in the Baltic Sea: A model study in present and future climate. (*Use a coupled physical-biogeochemical model*)**

  Eilola, K., E. Almroth-Rosell, C. Dieterich , F. Fransner, A. Höglund, H. E. M. Meier; AMBIO 2012

- Question: Where is DIP uplifted from the deep water to the surface layers and what is the role of inflows?

- **Impact of saltwater inflows on phosphorus cycling and eutrophication in the Baltic Sea. A 3D model study. (*Use passive tracers*)**

  Eilola, K., E. Almroth-Rosell, H. E. M. Meier; Tellus A 2014

Uplift of tracers from below halocline

Horizontal distribution

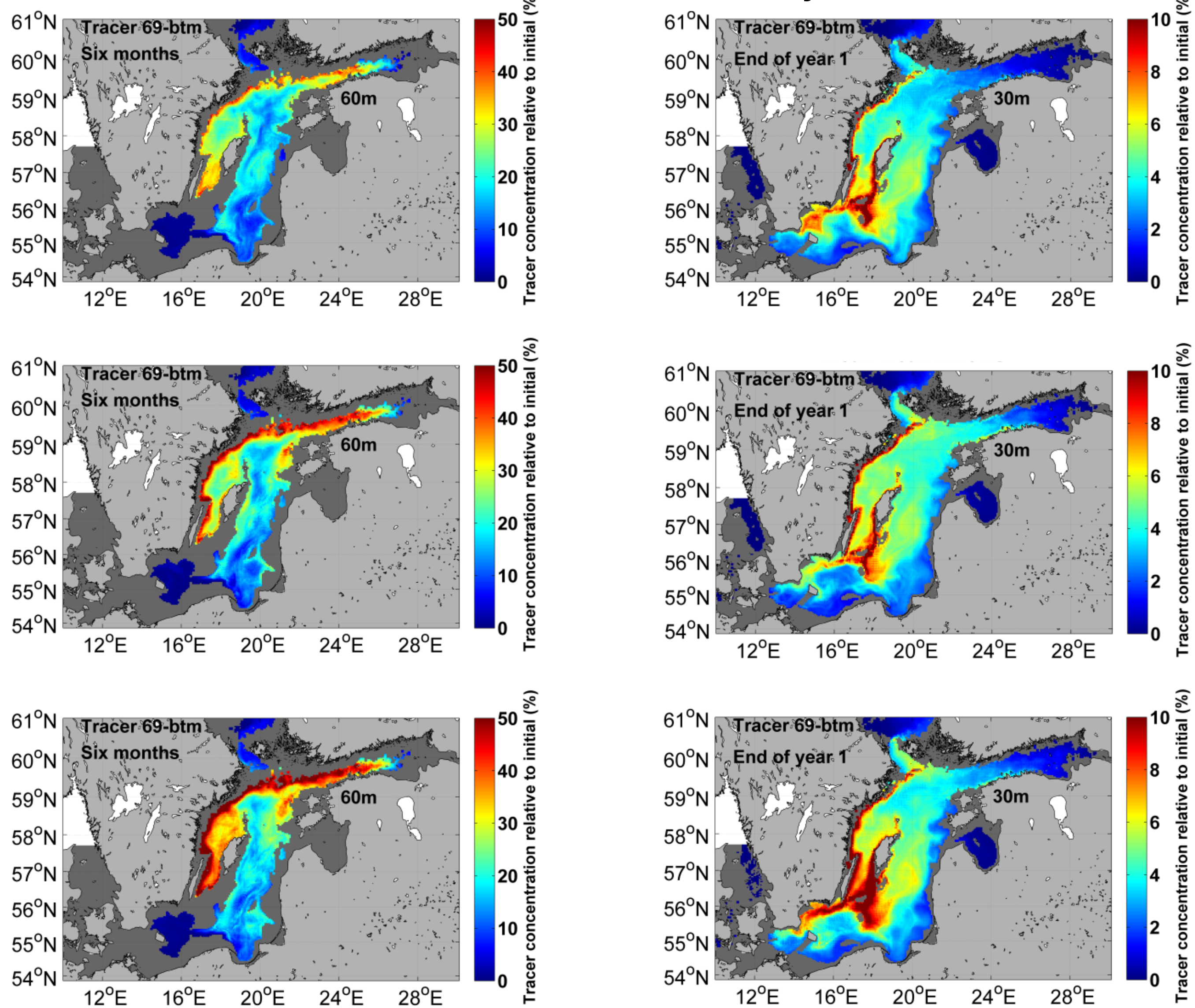
at 60m depth — **Six months after initiation**

at 30m depth — **One year after initiation**

No inflows

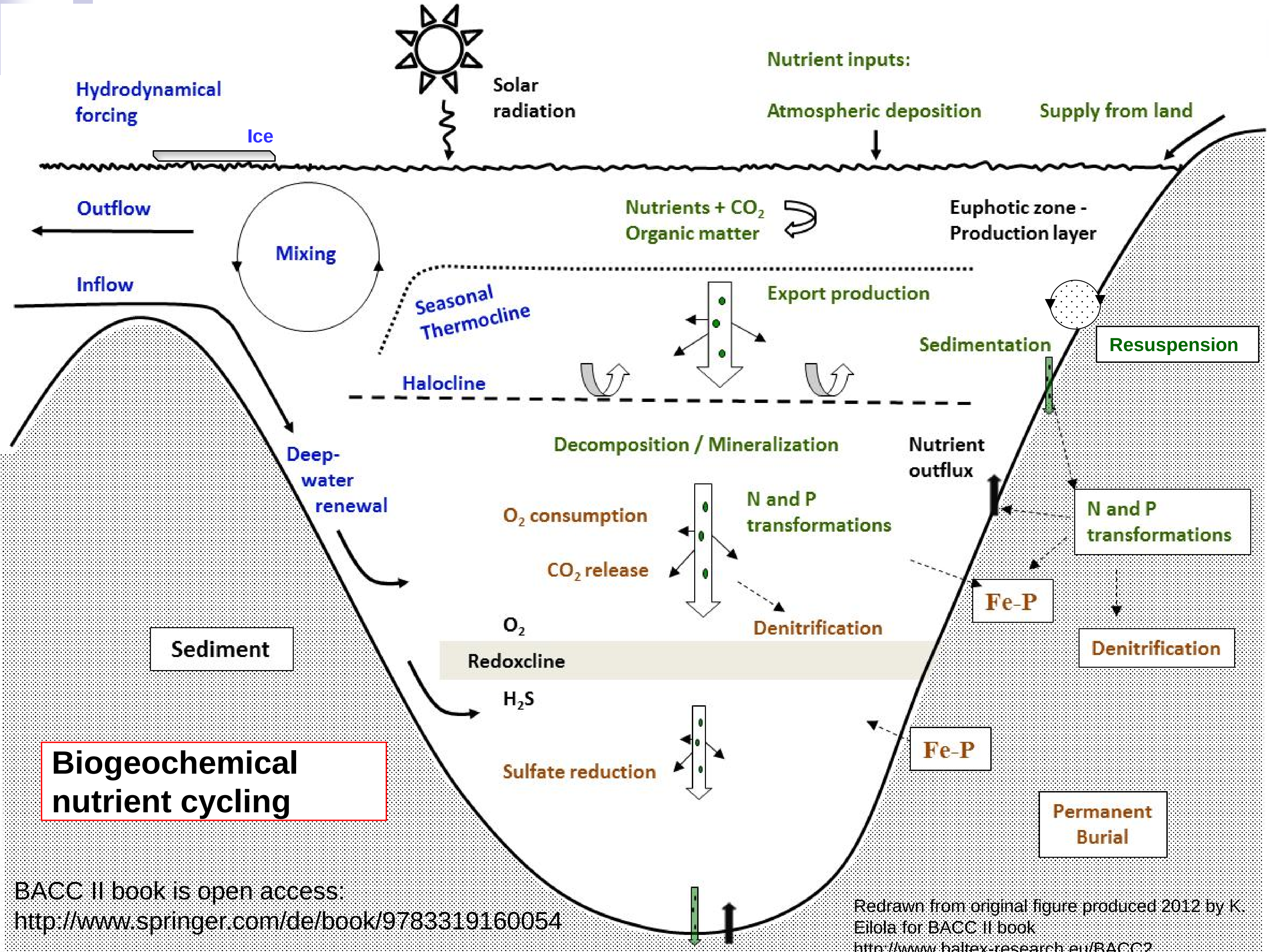
Weak inflows

Strong inflows



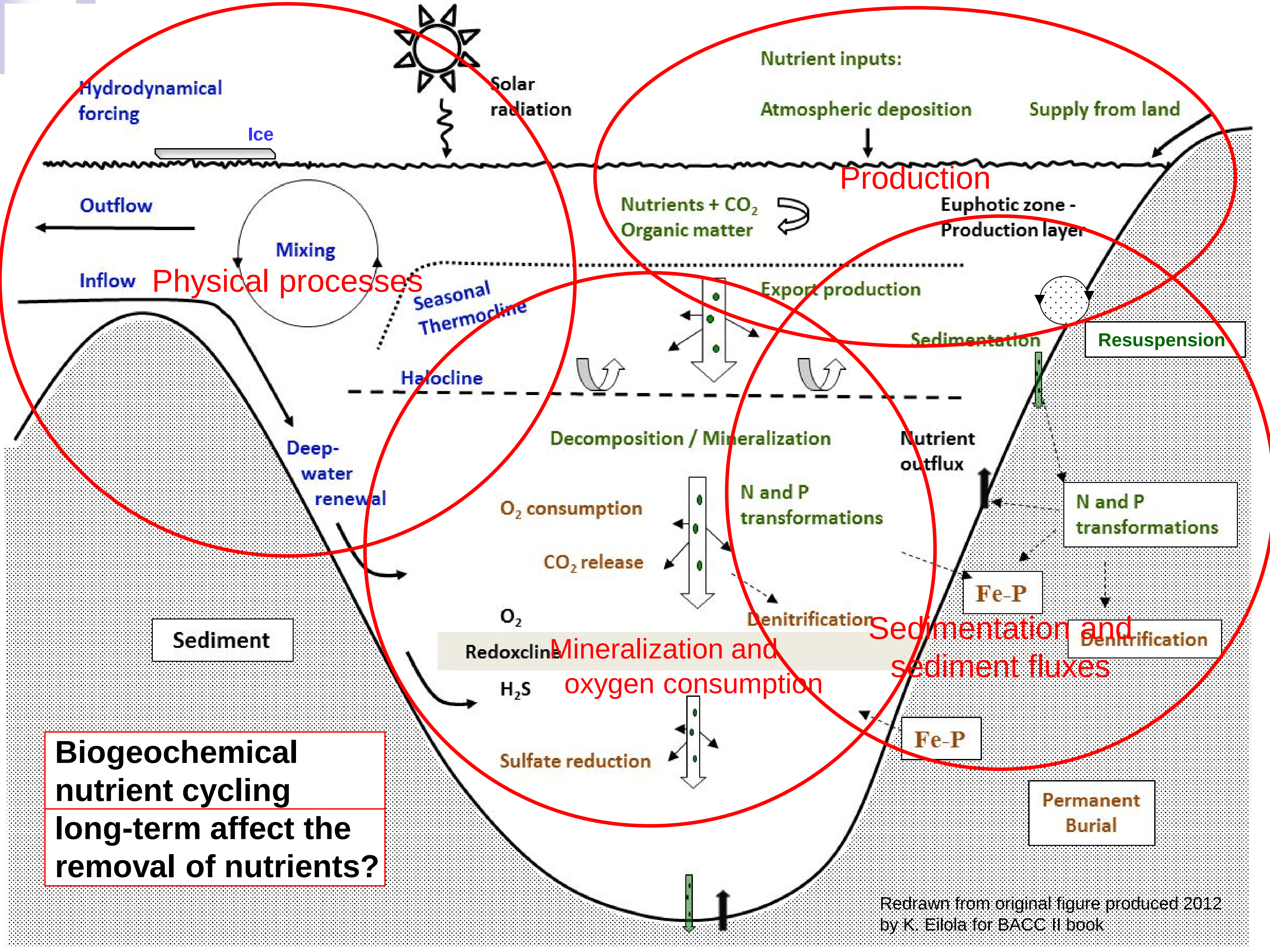
% of the initial concentration

Biogeochemical nutrient cycling



BACC II book is open access:
http://www.springer.com/de/book/9783319160054

Redrawn from original figure produced 2012 by K. Eilola for BACC II book
http://www.baltex-research.eu/BACC2

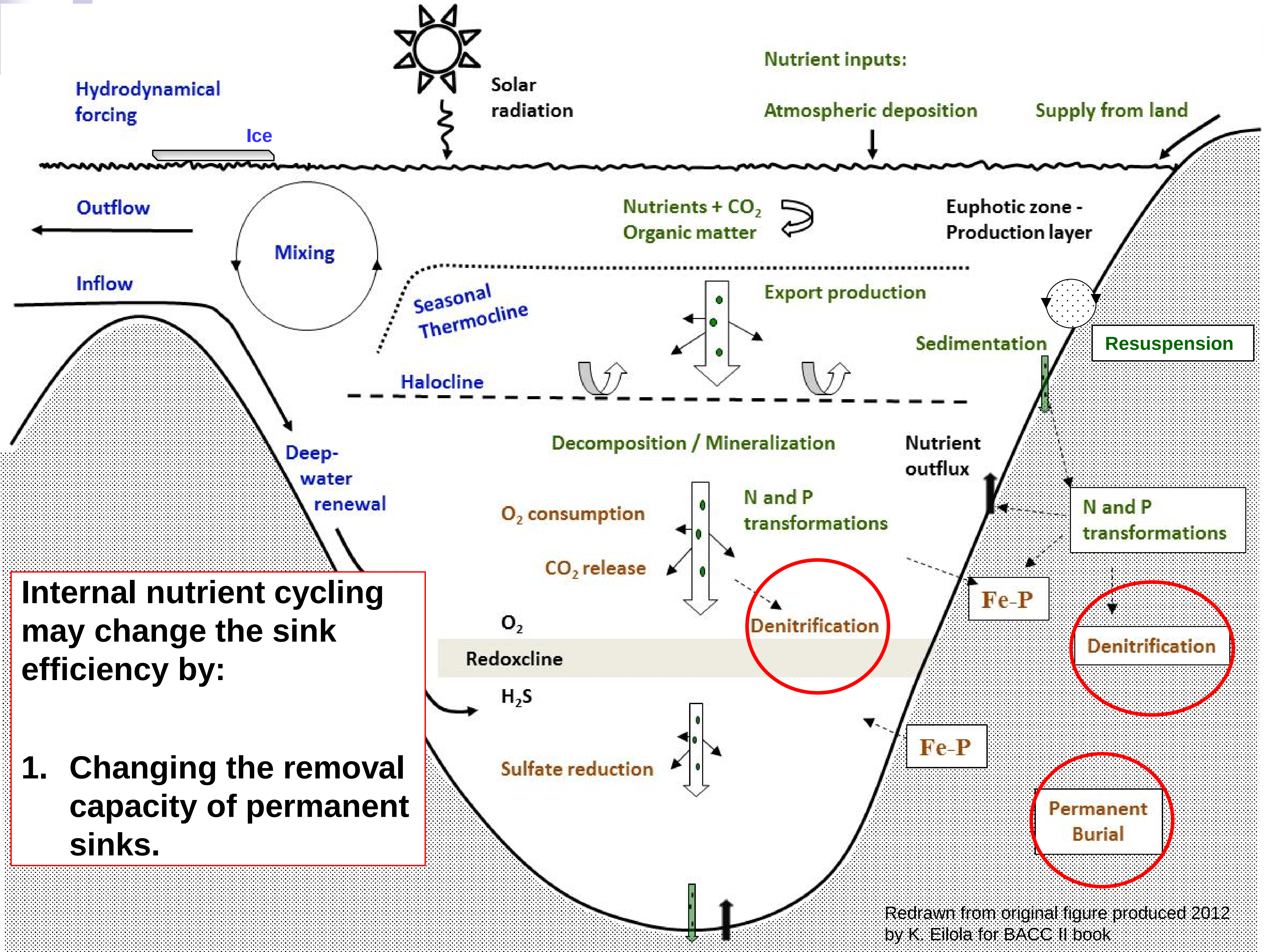


Biogeochemical nutrient cycling long-term affect the removal of nutrients?

Redrawn from original figure produced 2012 by K. Eilola for BACC II book

Internal nutrient cycling may change the sink efficiency by:

1. **Changing the removal capacity of permanent sinks.**



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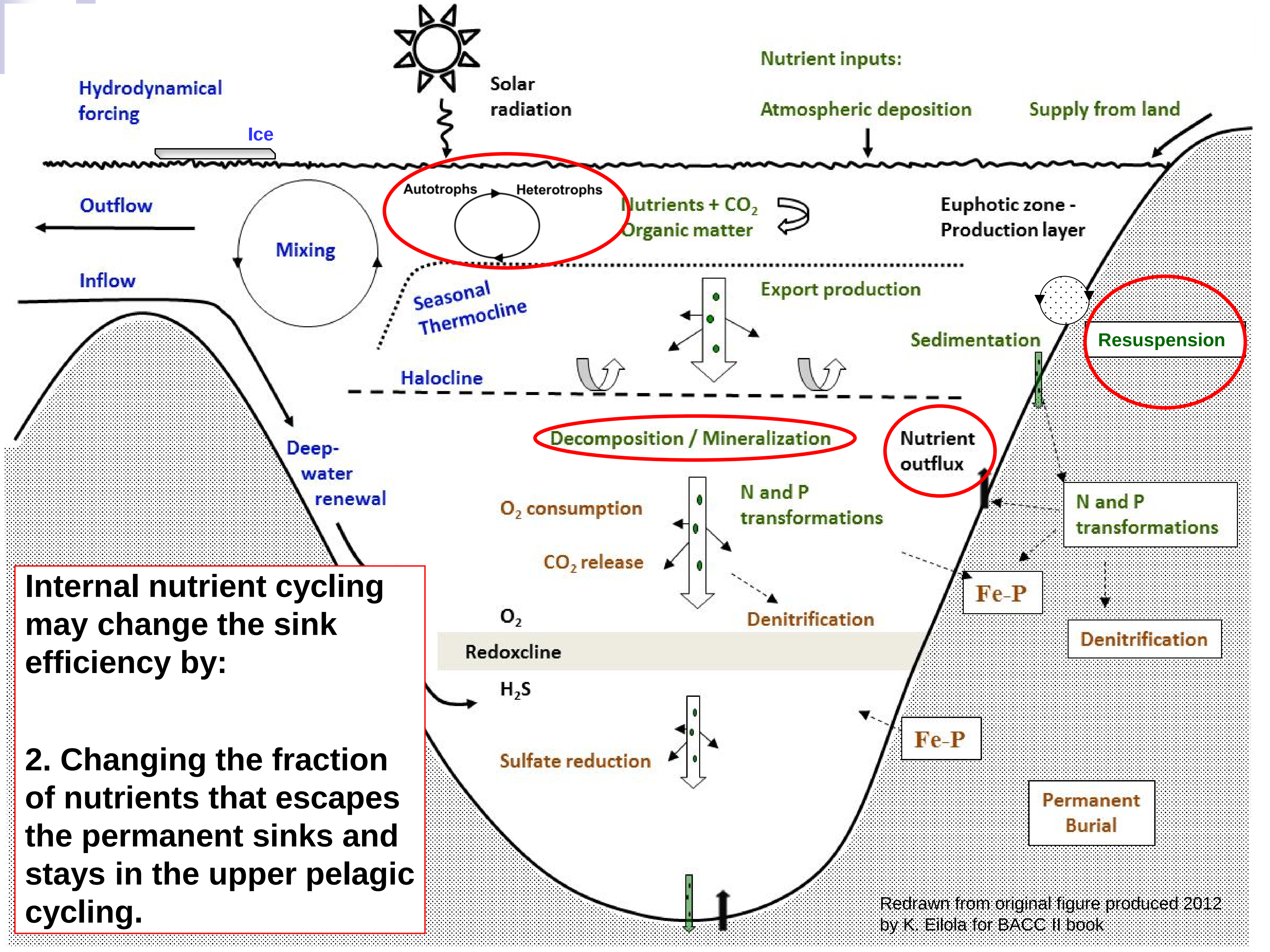
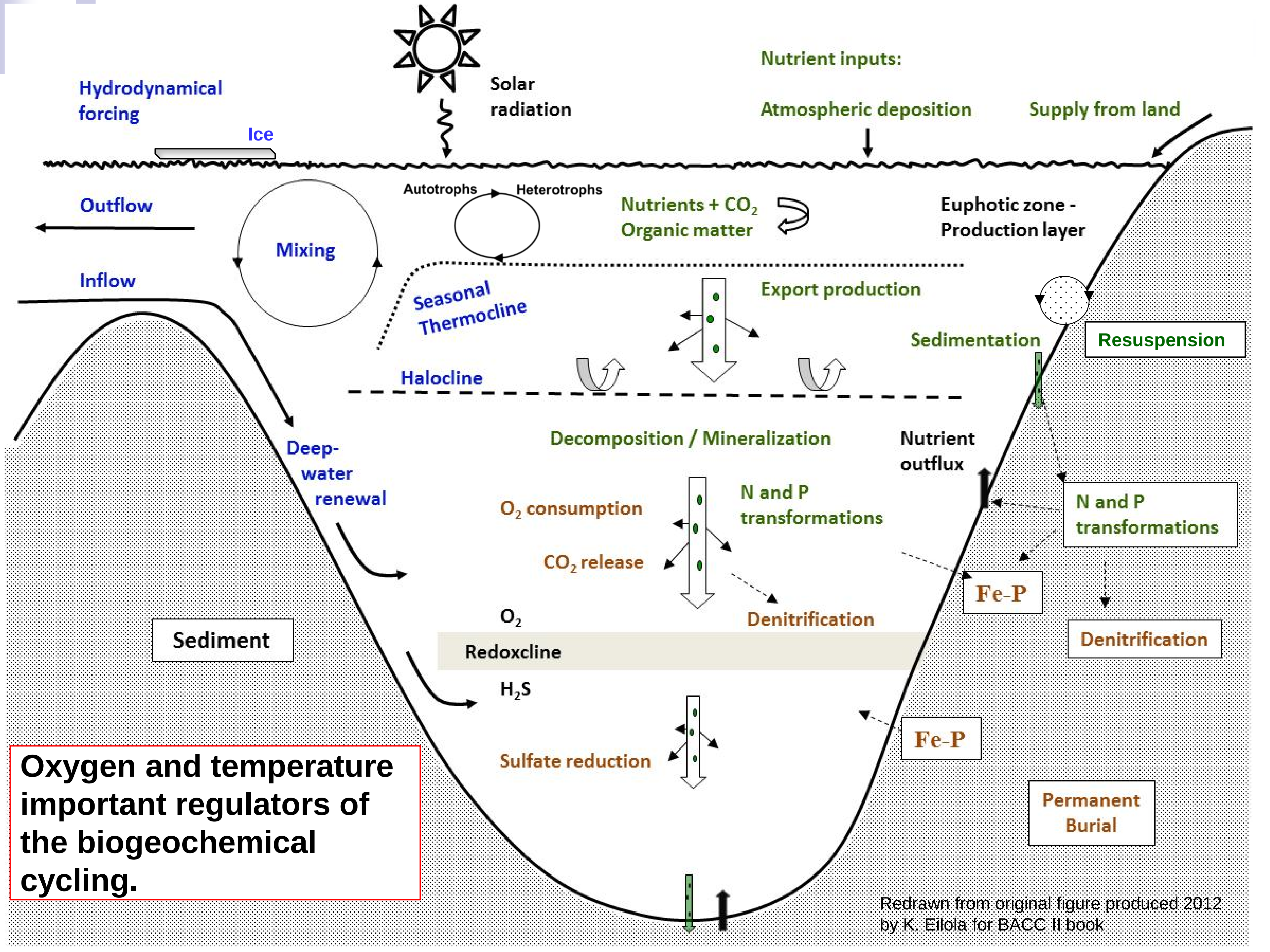


Redrawn from original figure produced 2012 by K. Eilola for BACC II book

Internal nutrient cycling may change the sink efficiency by:

2. Changing the fraction of nutrients that escapes the permanent sinks and stays in the upper pelagic cycling.

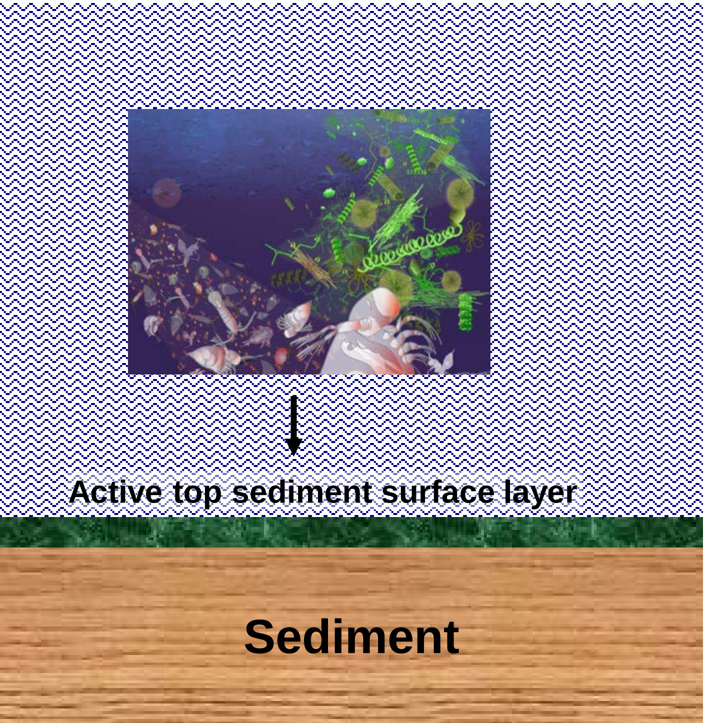


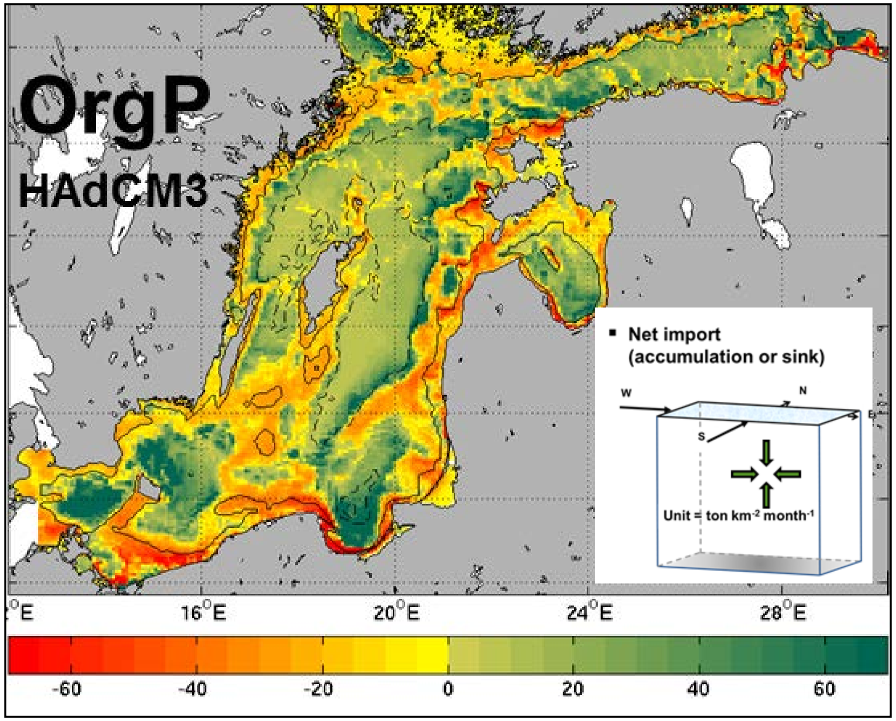
Oxygen and temperature important regulators of the biogeochemical cycling.

Sediment dynamics

Organic nutrients

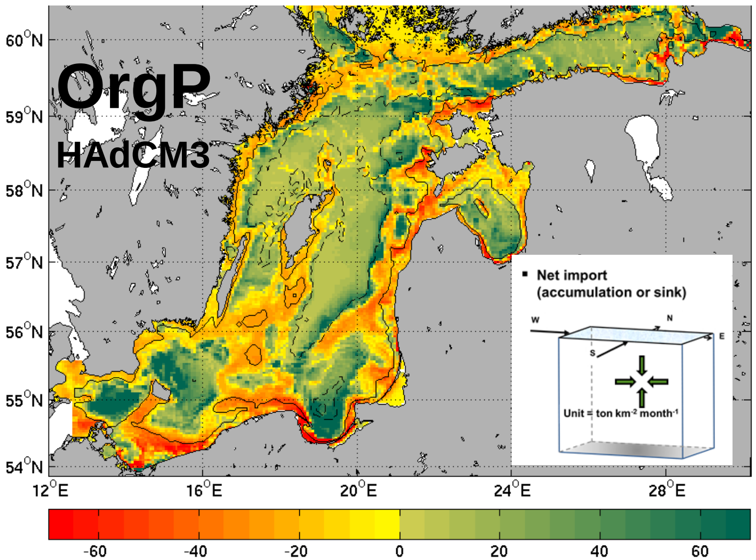
- **Accumulation of organic nutrients in sediments**

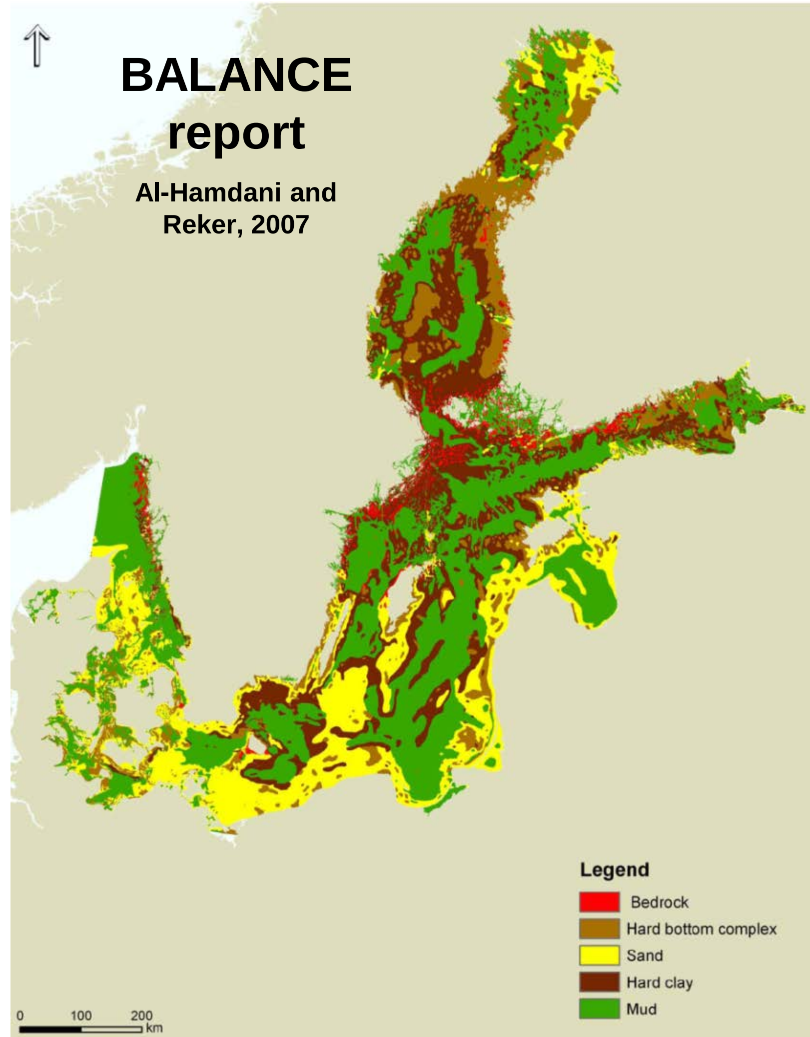




Bottom types

- **Accumulation**
- **Transport**
- **Erosion**

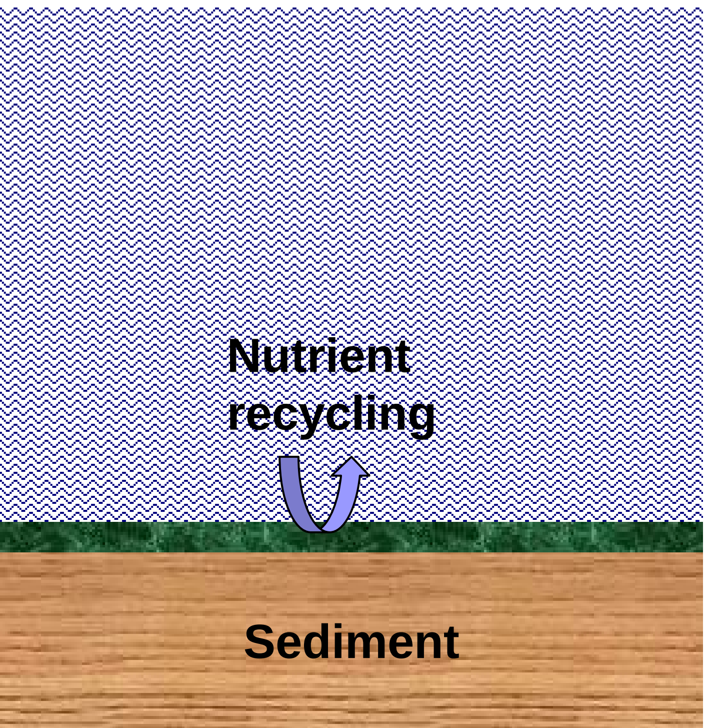


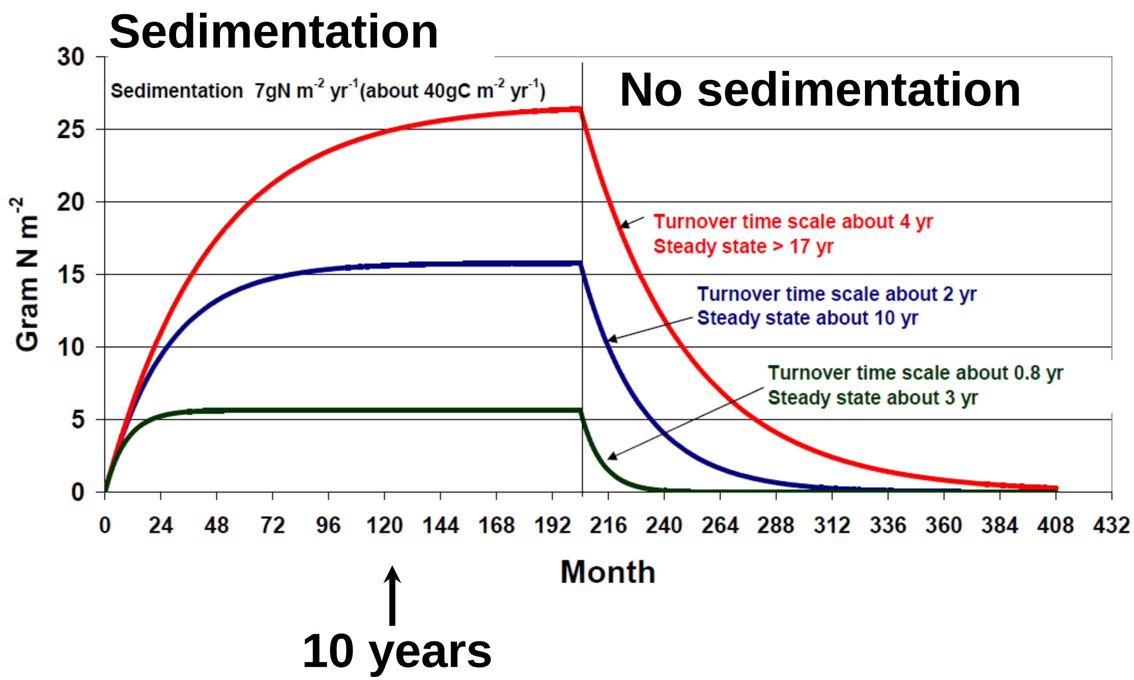


Sediment dynamics

Organic nutrients

- **Organic nutrient concentrations and time scales of changes in the sediment depend on the temperature dependent mineralization rate**

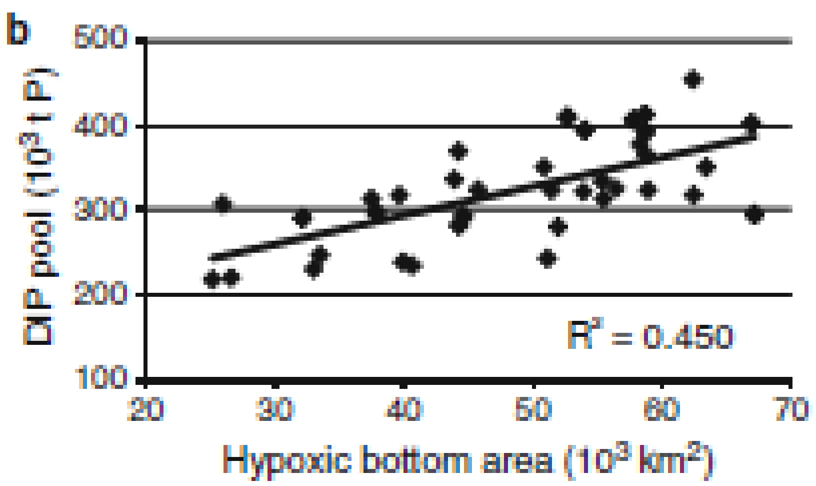


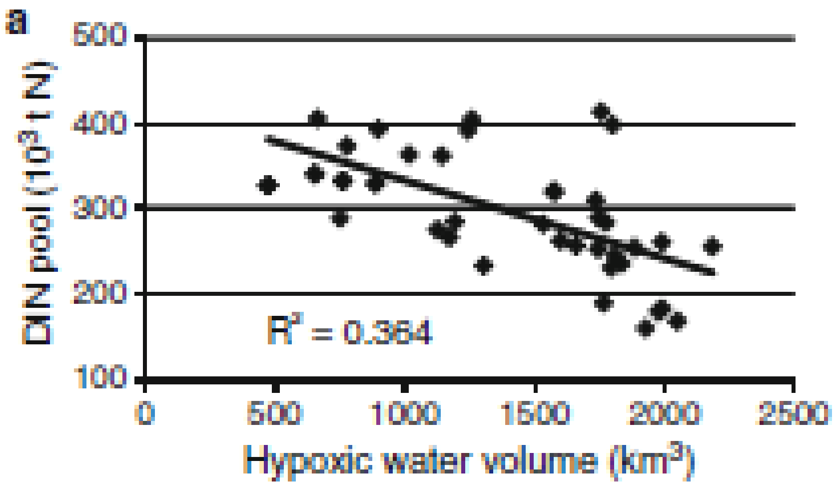


- **Excel sheet if time !**

Biogeochemical processes : Oxygen – Hypoxia dependence

Annual deep water (>60m) nutrient pools vs. hypoxic area (DIP) and hypoxic volume (DIN) (Savchuk, 2010).

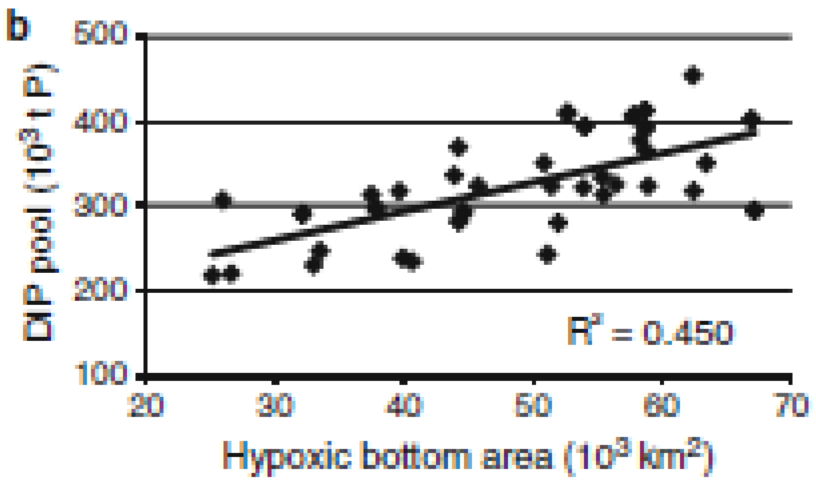




Savchuk, O. P., 2010: Large-scale dynamics of hypoxia in the Baltic Sea. In: Yakushev, E., (Ed.), Chemical structure of pelagic redox interfaces: observation and modelling. Hdb. Env. Chem., doi:10.1007/698_2010_53, Springer-Verlag, Berlin Heidelberg.

- **Phosphate has the ability to adsorb on hydrated metal oxides in the sediment, e.g. iron(III) oxy hydroxides (oxides) during oxic bottom water conditions.**

- **During anoxic periods the retention of mineralized phosphorus in the sediment is low and also previously adsorbed phosphorus is released and may diffuse to the water column.**

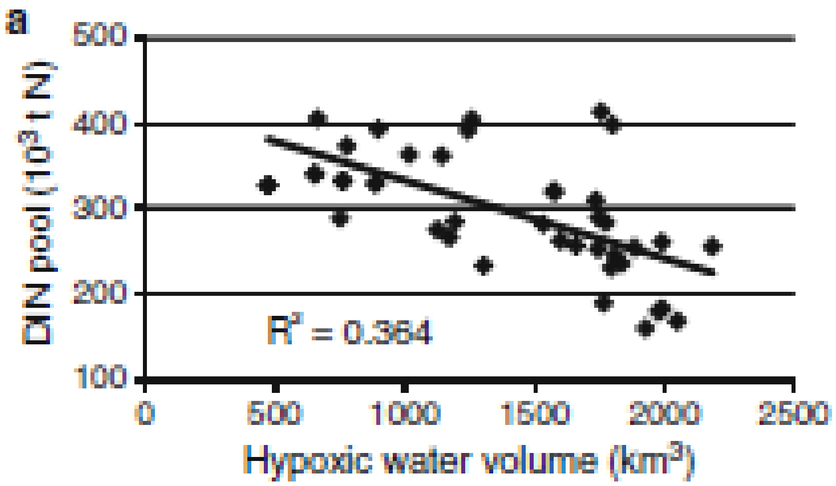


- Denitrification (anaerobic mineralization) transforms DIN to dissolved N_2 (less bioavailable form of nitrogen).

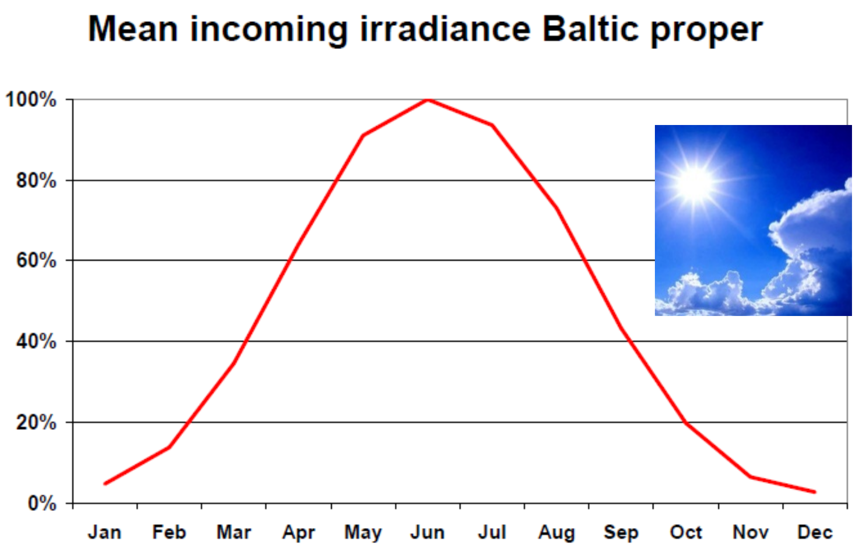
- Requires oxidized forms of nitrogen (i.e. oxygen is needed to produce nitrate).

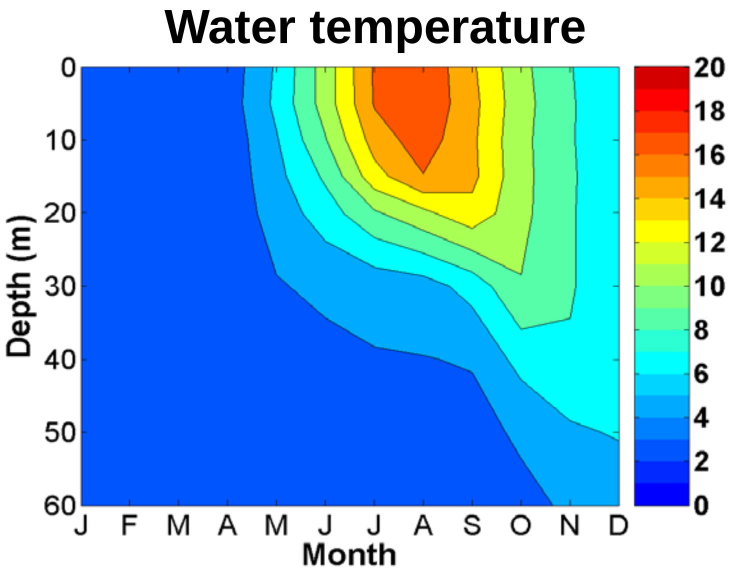
- Denitrification stops when nitrate is depleted.

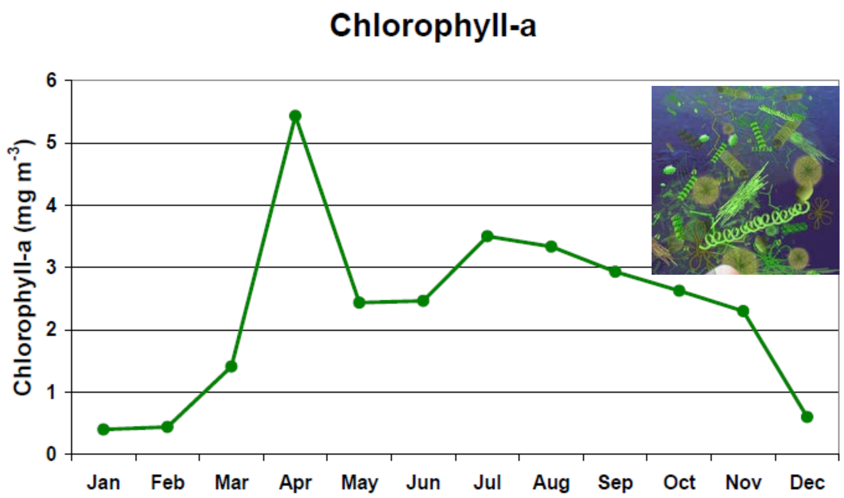
- Long-term wide spread anoxic areas may affect the efficiency of the nitrogen sink.



Seasonal cycles, phytoplankton production



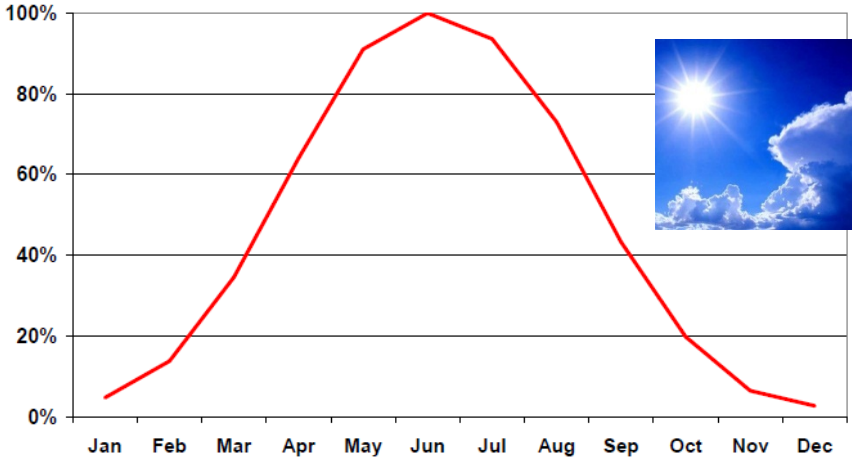




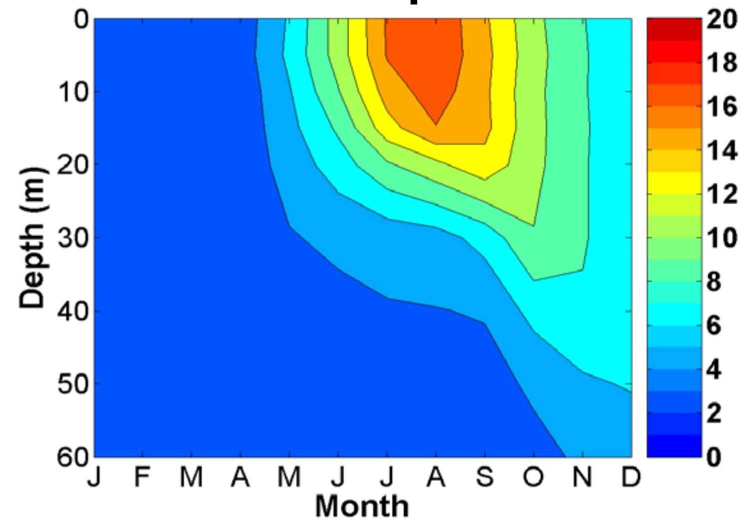
- **Increased temperatures may strengthen the thermal stratification and increase the length of the productive season.**
- **This may affect the plankton composition and the food web structure.**

Seasonal cycles, phytoplankton production and water transparency

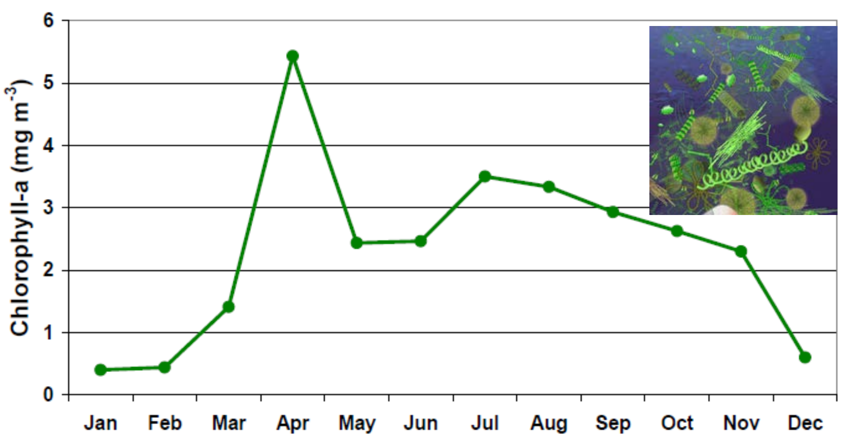
Mean incoming irradiance Baltic proper



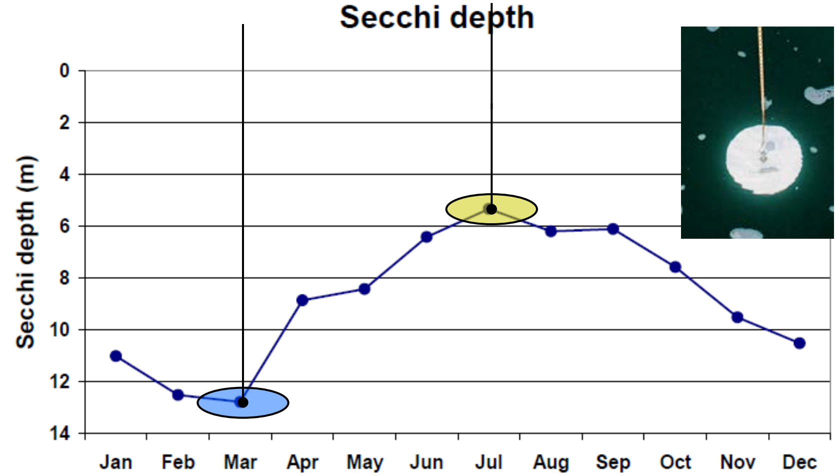
Water temperature



Chlorophyll-a



Secchi depth



- More organic matter → reduced transmission of light (energy)

Population dynamics

The dynamics of organic nutrients

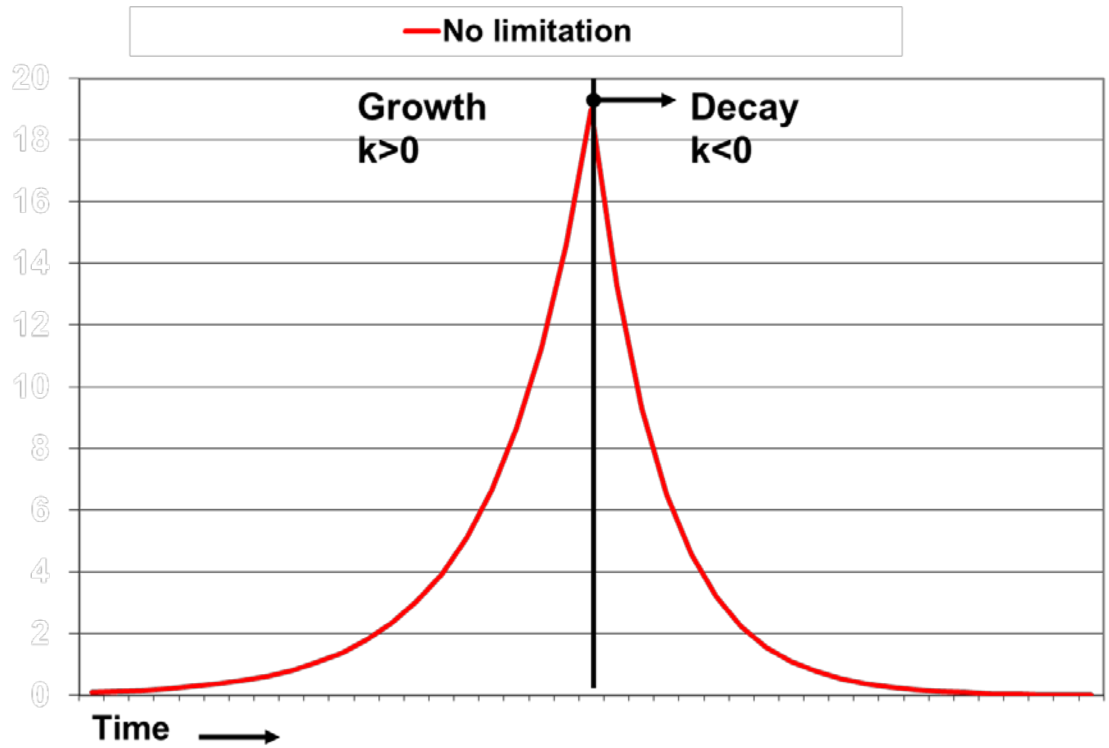
Exponential growth and exponential decay of population X

$$\frac{dX}{dt} = k \times X$$

k >0 $\rightarrow$ growth

k <0 $\rightarrow$ decay

k is assumed constant



Population dynamics

The dynamics of organic nutrients

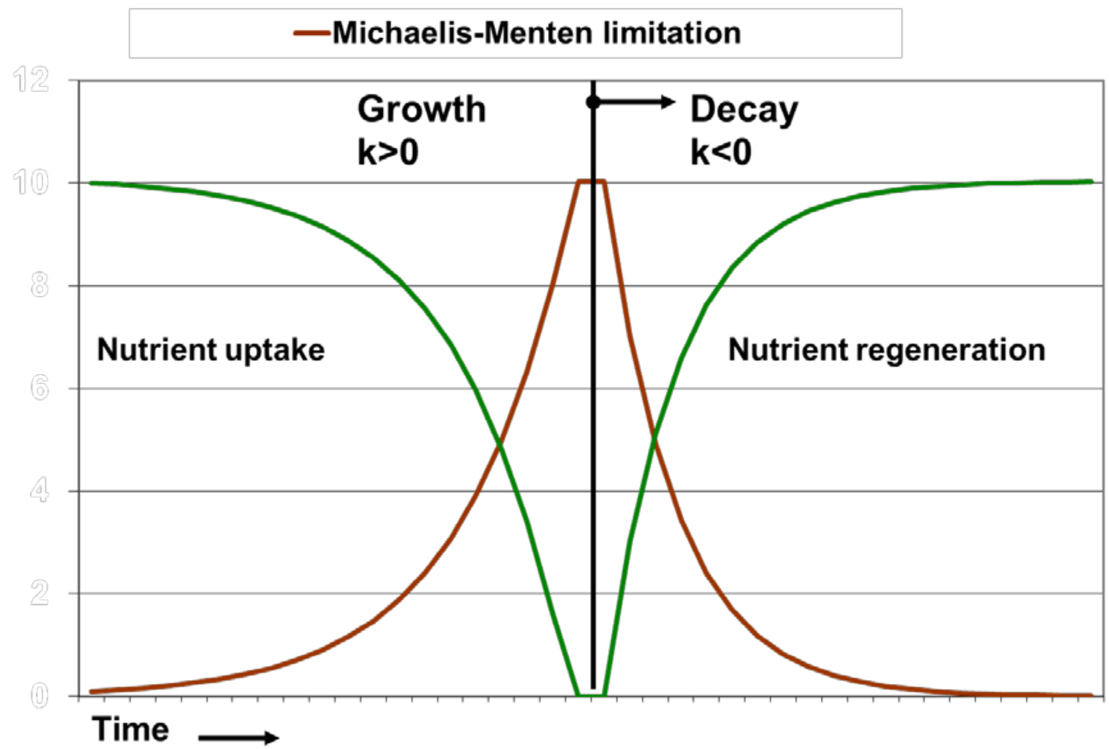
Nutrient limitation of growth, exponential decay of population X and nutrient regeneration

$$\frac{dX}{dt} = k \times X$$

k >0 $\rightarrow$ growth

k <0 $\rightarrow$ decay

k is assumed constant



Population dynamics

The dynamics of organic nutrients

Growth and regulation of growth rate

$$GROWTH_{PHY} = ANOX \cdot LTLIM \cdot NUTLIM_{PHY} \cdot GMAX_{PHY} \cdot PHY$$

Dependencies: Oxygen Light Nutrients Temperature Population size

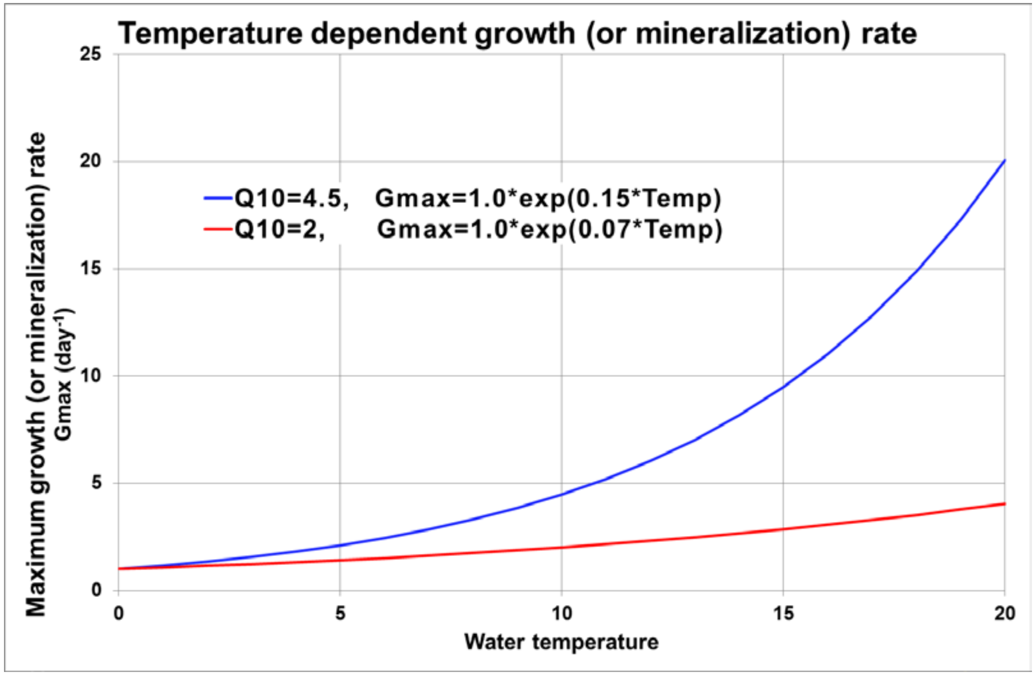
Population dynamics

The dynamics of organic nutrients

Temperature dependence, illustrating example;

$$GMAX = \alpha \cdot \exp(\beta \cdot T)$$

- **The temperature quotient "Q10" describes the ratio of activity for a 10 degree temperature change.**



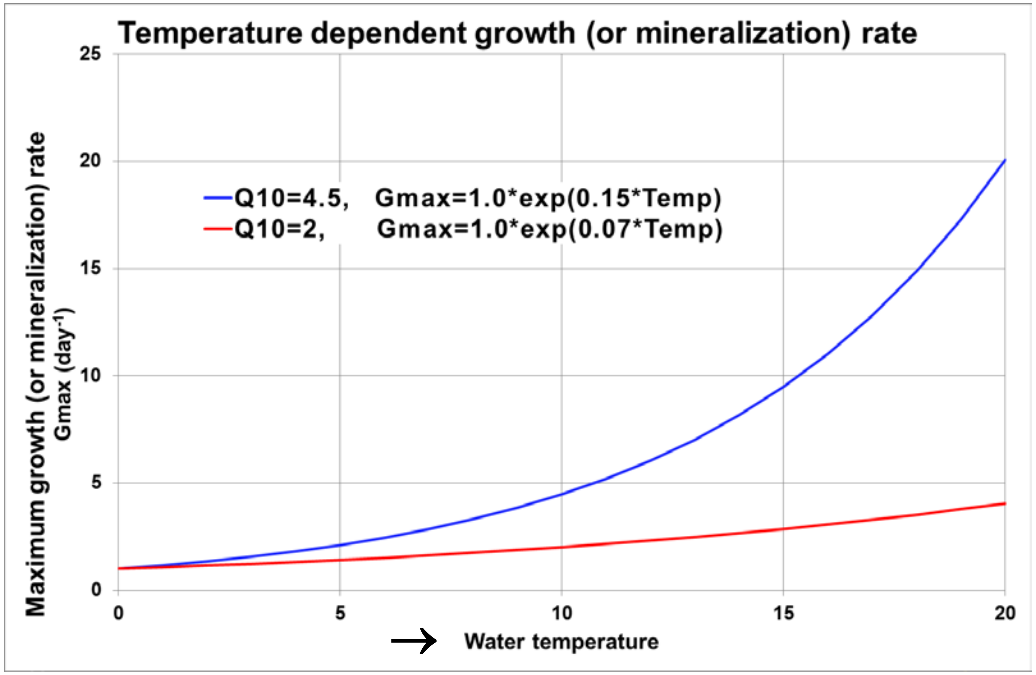
Population dynamics

The dynamics of organic nutrients

Temperature dependence, illustrating example;

$$GMAX = \alpha \cdot \exp(\beta \cdot T)$$

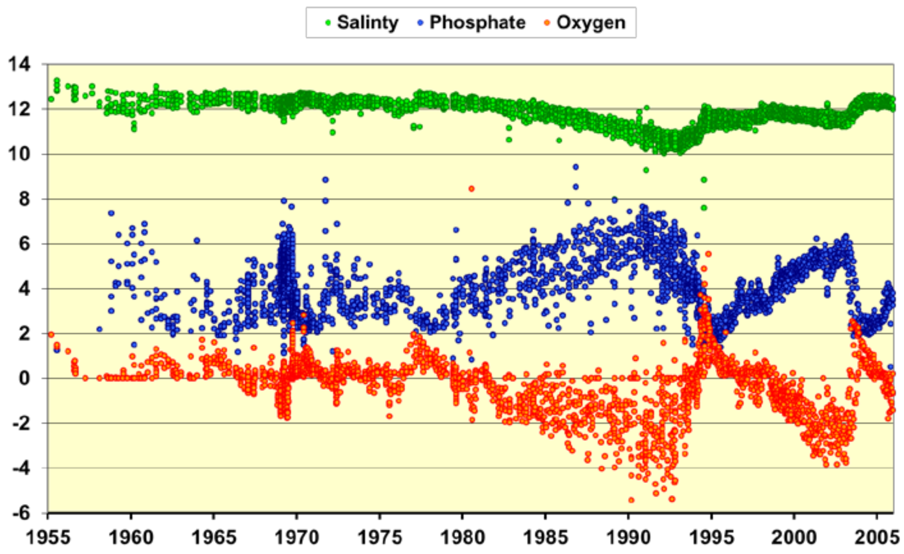
- **Q10=2 → doubling of the activity rate for a 10 degree temperature increase.**
- **Larger Q10 → higher sensitivity to changes in temperature.**

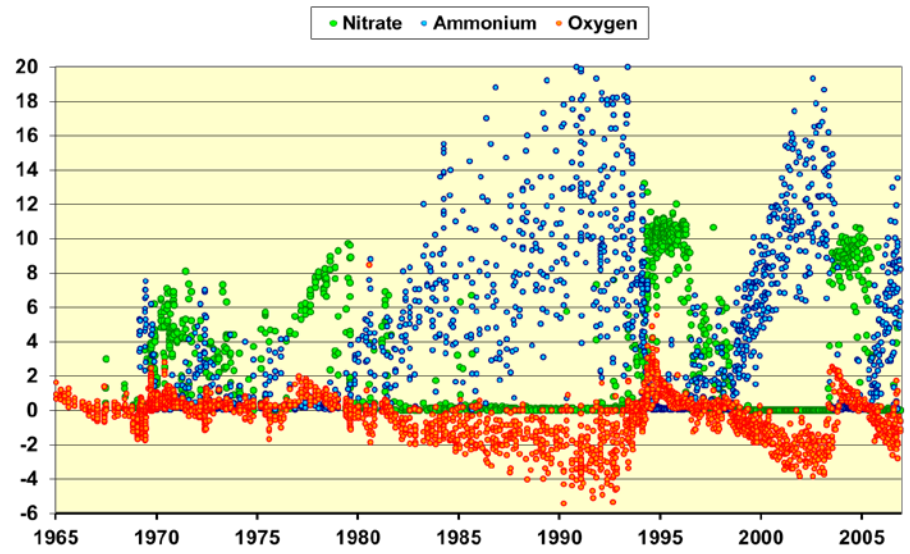


Warmer water → faster mineralization → faster oxygen consumption and nutrient recycling

Impact from deep water dynamics

Stagnation periods and inflows

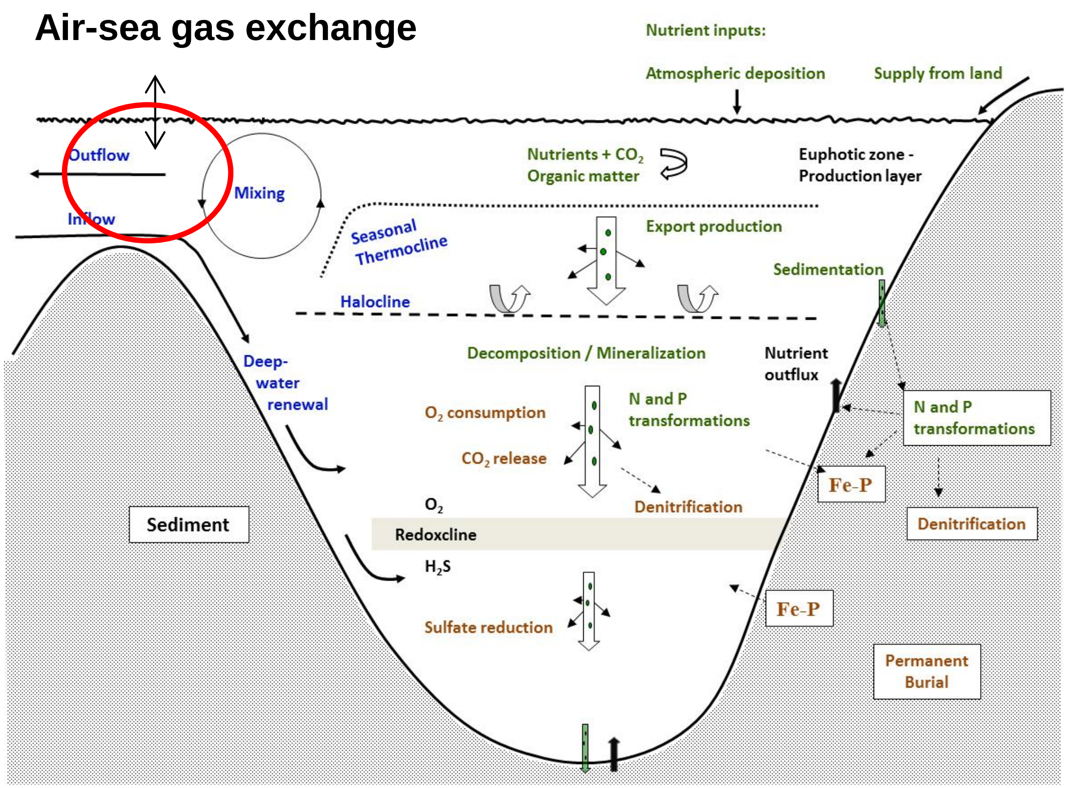


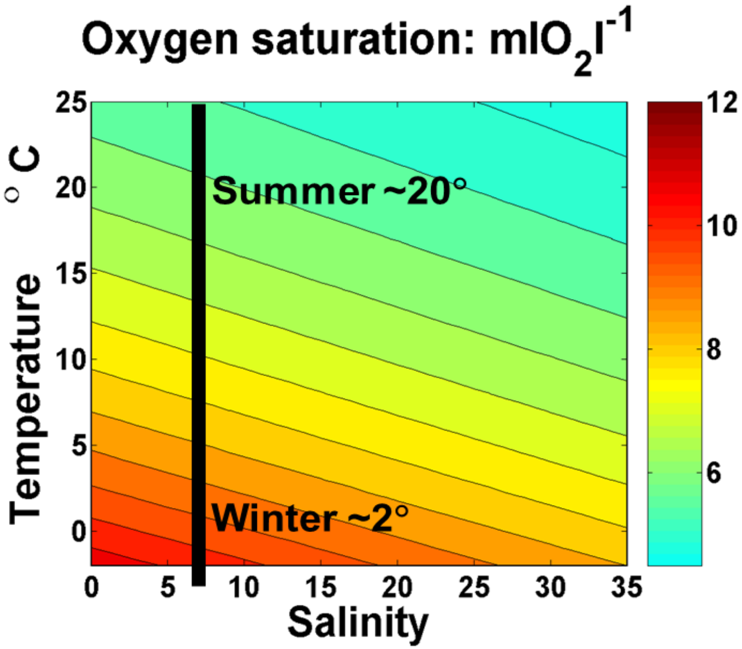


Central Baltic proper SHARK data 150-190 m depth

Units: **ml O_2 l^{-1}** **mmol P and N m^{-3}**

Changing temperature - impact on deep water oxygen concentrations



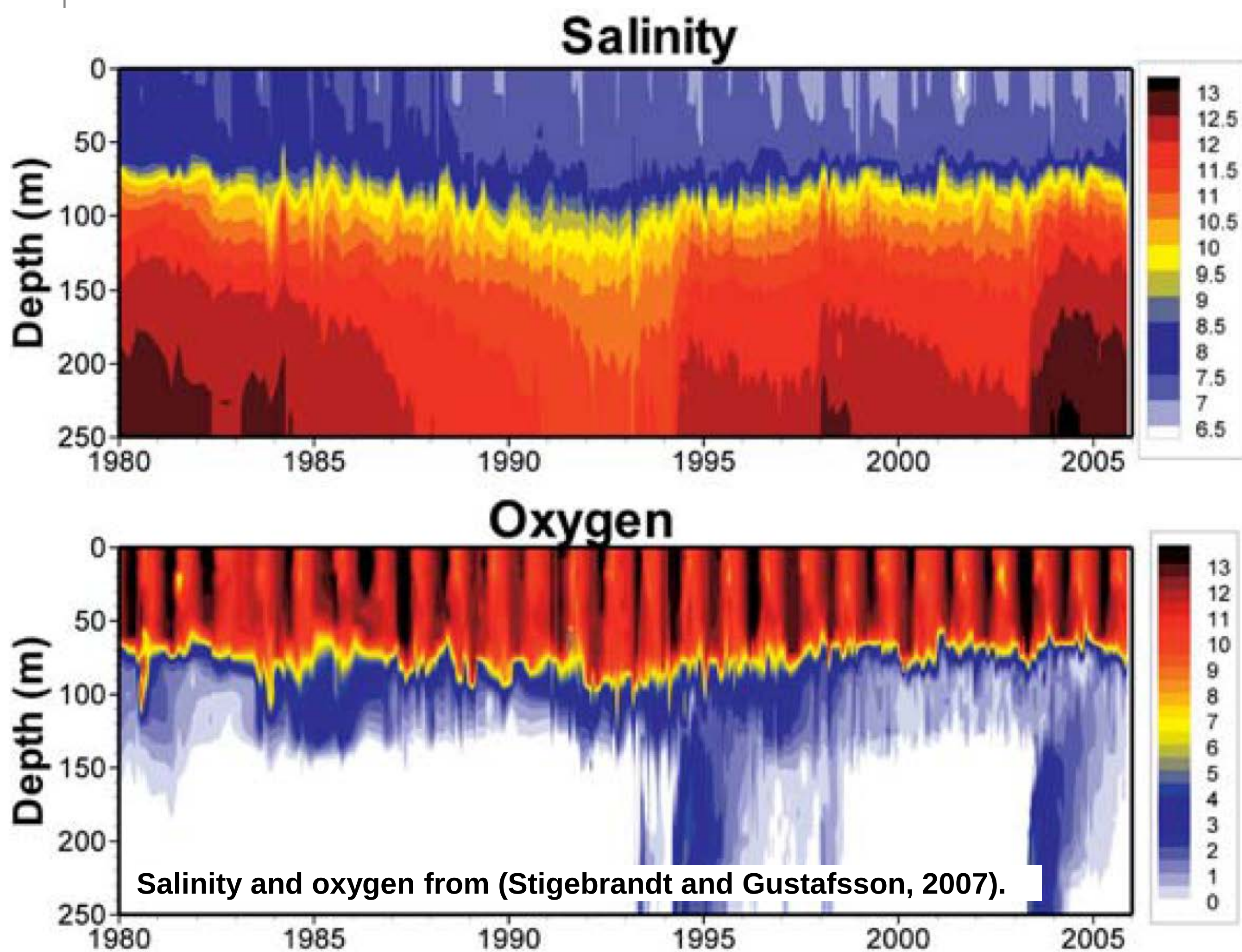


Temperature and salinity dependent oxygen saturation concentration

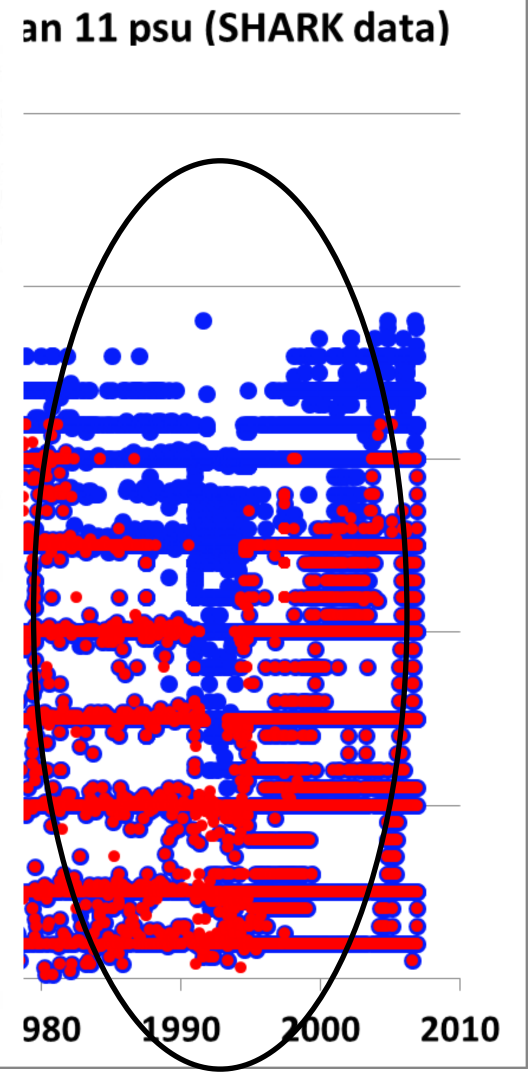
- T=2 °C and S=6; +4 °C → ≈ -1 ml O_2 l^{-1}
- Temperature impact is reduced with increasing salinity

Oxygen and stratification

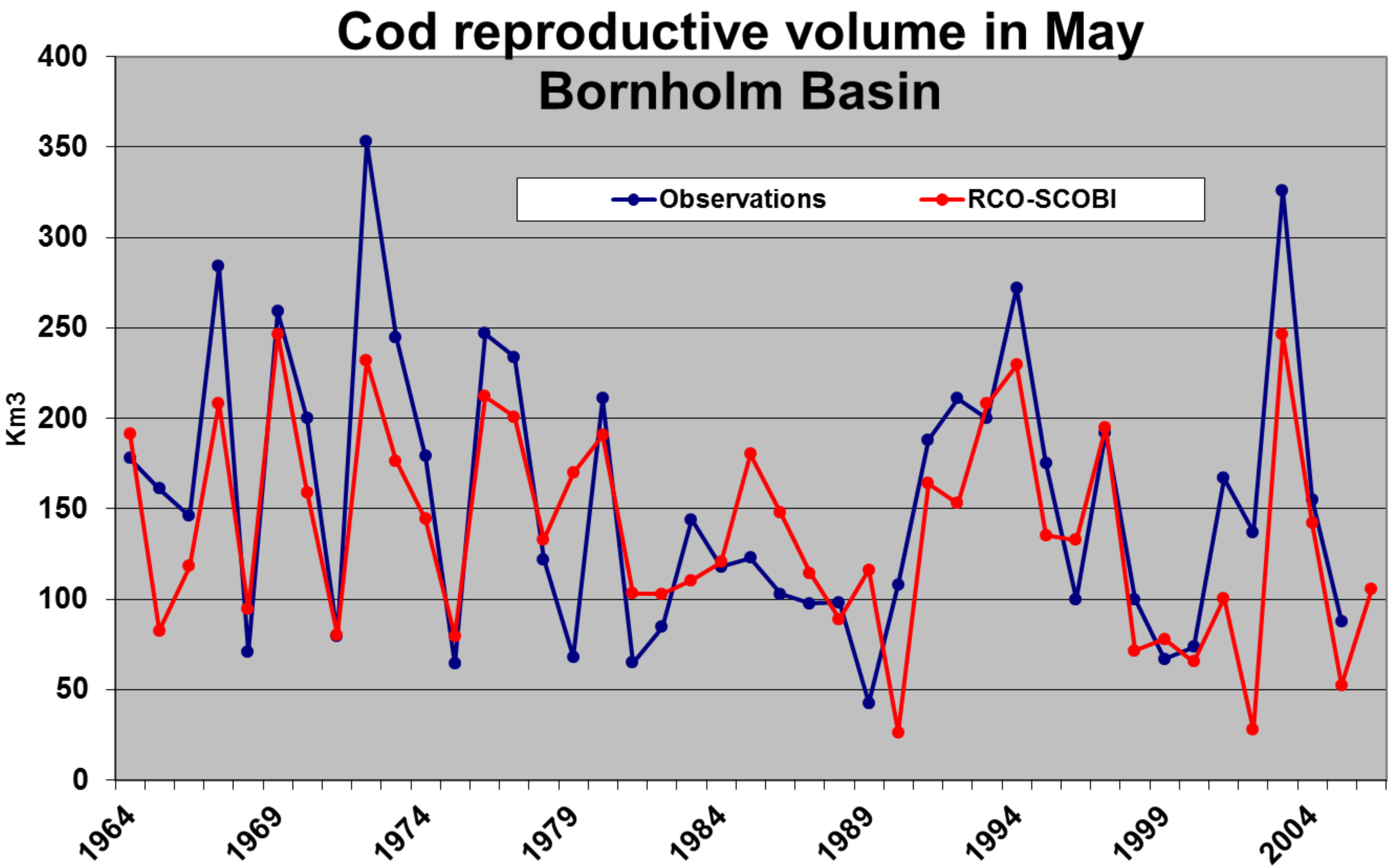
Central Baltic Proper 1900-2006



Salinity and oxygen from (Stigebrandt and Gustafsson, 2007).



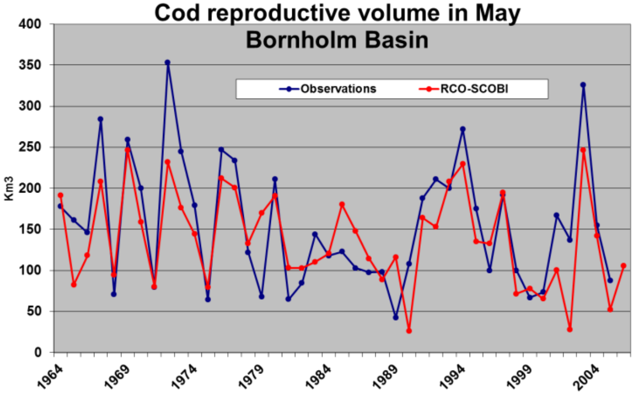
Stigebrandt, A., Gustafsson, B.G., 2007. Improvement of Baltic proper water quality using large-scale ecological engineering. Ambio 36, 280–286.


Cod reproductive volume in May
Bornholm Basin
Observations
RCO-SCOBI
Km3
0
50
100
150
200
250
300
350
400
1964
1969
1974
1979
1984
1989
1994
1999
2004

Baltic Sea cod reproductive volume (RV) 1961-2007.

Monthly mean values of RCO-SCOBI model results of 2nm x 2nm horizontal resolution.

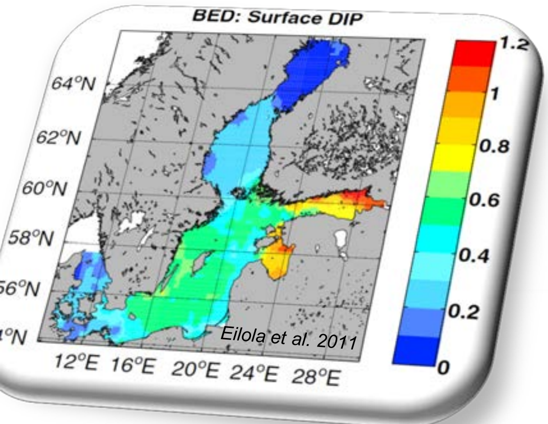
Cod RV is defined by the volume of water having salinity ≥ 11 psu and oxygen concentration ≥ 2 ml O_2 l^{-1}.



Compare e.g. with Mac Kenzie et al. 2000.

MacKenzie, B.R., Hinrichsen, H.-H., Plikshs, M., Wieland, K., and Zezera, A. 2000. Quantifying environmental heterogeneity: habitat size necessary for successful development of cod (*Gadus morhua* L.) eggs in the Baltic Sea. Mar. Ecol. Prog. Ser. **193**: 143–156.

Thank you

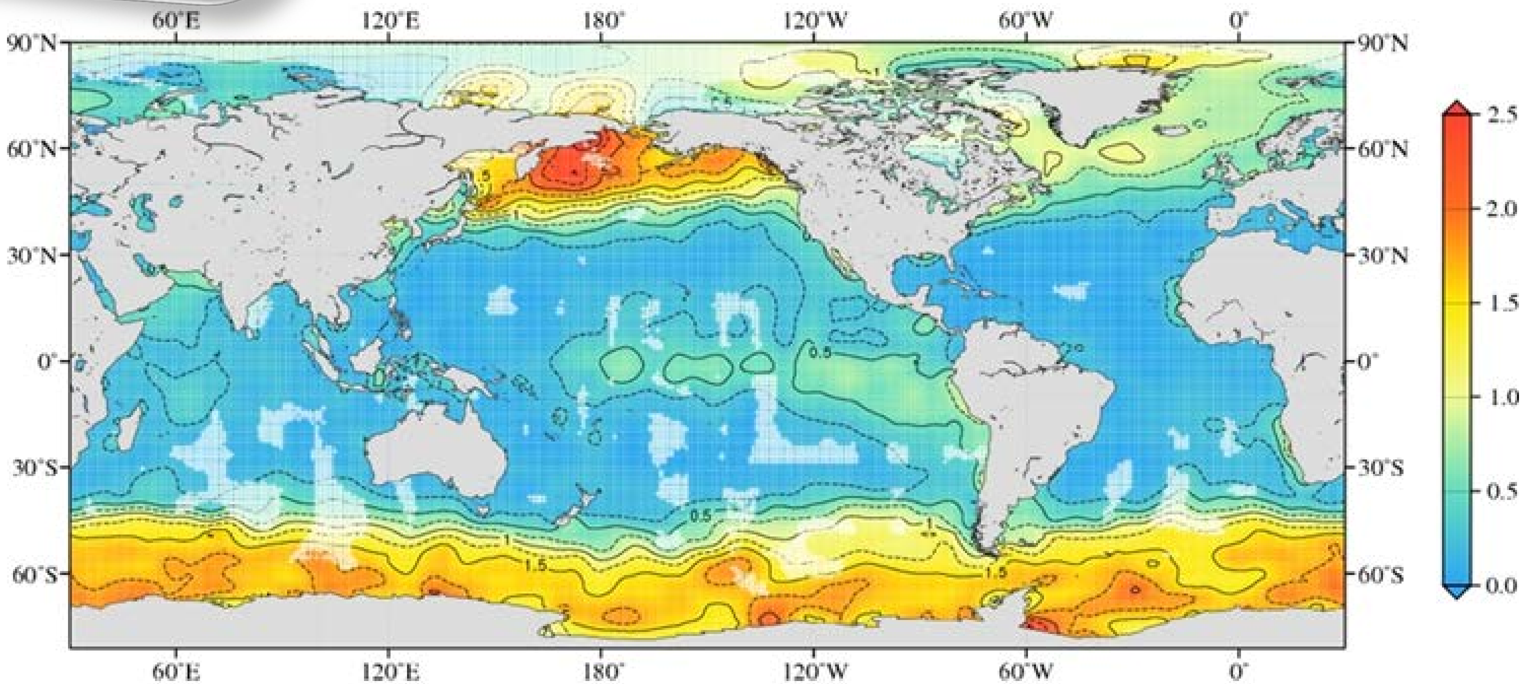


NOAA NATIONAL OCEANOGRAPHIC DATA CENTER (NODC)
UNITED STATES DEPARTMENT OF COMMERCE

World Ocean Atlas Climatology

Surface phosphate

Contour Interval=0.25



Winter (Jan.-Mar.) phosphate [umol/l] at the surface (one-degree grid)

Relevant books for the Baltic Sea

BACC II Author Team (2015). Second assessment of climate change for the Baltic Sea basin. Regional climate studies. Berlin, Springer.

Feistel, R., Nausch, G. and N., Wasmund (Eds), 2008. State and Evaluation of the Baltic Sea, 1952–2005. A detailed 50-year survey of Meteorology and Climate, Physics, Chemistry, biology, and Marine Environment. John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Fennel, W. and T., Neumann, 2004. Introduction to modelling the Marine Ecosystems. Elsevier Oceanography Series 72.

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Wulff, F., L. Rahm & P. Larsson (Eds), 2001. A Systems Analysis of the Baltic Sea. Ecological Studies, Vol. 148. Springer, Berlin.

Relevant own literature

Almroth-Rosell, E., K. Eilola, R. Hordoir, H. E. M. Meier, and P. Hall, 2011: Transport of fresh and resuspended particulate organic material in the Baltic Sea - a model study. J. Mar. Sys., 87, pp. 1-12.

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Eilola, K., 1997: The development of a spring thermocline at temperatures below the temperature of maximum density with application to the Baltic Sea. J. Geophysical Res. 102, C4, pp.8657-8662.

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Eilola, K., E. Almroth Rosell, C. Dieterich, F. Fransner, A. Höglund and H. E. M. Meier, 2012: Modeling nutrient transports and exchanges of nutrients between shallow regions and the open Baltic Sea in present and future climate. AMBIO, Vol. 41, Issue 6, 574-585, DOI: 10.1007/s13280-012-0319-9.

Eilola, K., S. Mårtensson, and H. E. M. Meier, 2013: Modeling the impact of reduced sea ice cover in future climate on the Baltic Sea biogeochemistry. Geophys. Res. Lett., Vol. 40, 1-6, doi:10.1029/2012GL054375.

Eilola, K., E. Almroth Rosell, and H. E. M. Meier, 2014: Impact of saltwater inflows on phosphorus cycling and eutrophication in the Baltic Sea. A 3D model study. Tellus A, 66, 23985, http://dx.doi.org/10.3402/tellusa.v66.23985.

Gustafsson, B.G., F. Schenk, T. Blenckner, K. Eilola, H.E.M. Meier, B. Müller-Karulis, T. Neumann, T. Ruoho-Airola, O. P. Savchuk, and E. Zorita, 2012: Reconstructing the development of Baltic Sea eutrophication 1850 – 2006. AMBIO, Vol. 41, Issue 6, 534-548, DOI: 10.1007/s13280-012-0318-x.

Liu, Y., H.E.M. Meier, and K. Eilola, 2014: Improving multi-annual high-resolution modelling of biogeochemical cycling in the Baltic Sea by using data assimilation. Tellus A 2014, 66, 24908, http://dx.doi.org/10.3402/tellusa.v66.24908.

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Observations and data:

Information about the physical, chemical and biological variables in the Baltic Sea is regularly gathered within national monitoring programs by Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden.

- Swedish Meteorological and Hydrological Institute (SMHI) (www.smhi.se)
- Baltic Marine Environment Protection Commission (HELCOM) (www.helcom.fi/)
- International Council for the Exploration of the Sea (ICES) (www.ices.dk)
- European Monitoring and Evaluation Programme (EMEP) (www.emep.int) that provides information about atmospheric emissions and depositions of nutrients.
- Baltic Nest Institute (BNI) (www.balticnest.org)

Annual P and N import - Control period