Presented at: International advanced PhD course on
Impact of climate change on the marine environment with special focus on the role of changing extremes
Askö Laboratory, Trosa, Sweden, 24 - 30 August 2015

PHYSICS AND CHEMISTRY OF THE BALTIC SEA

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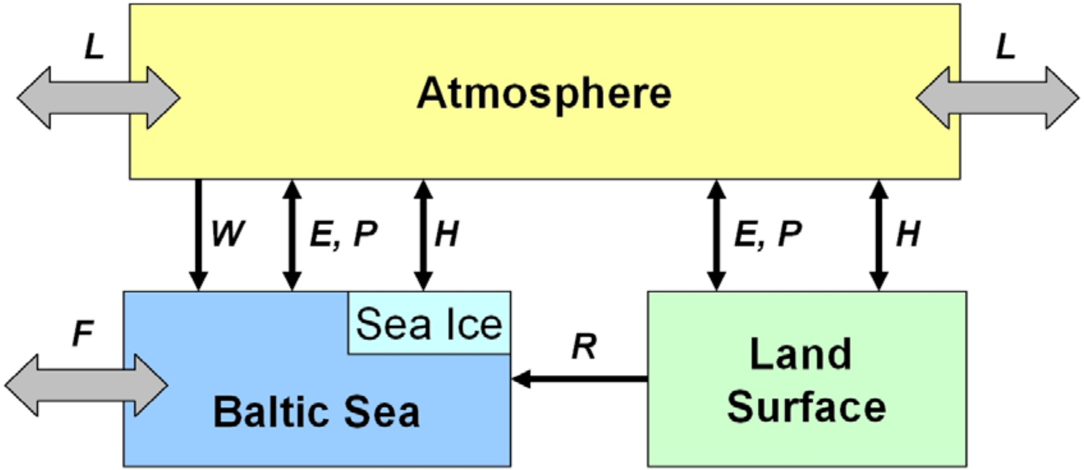
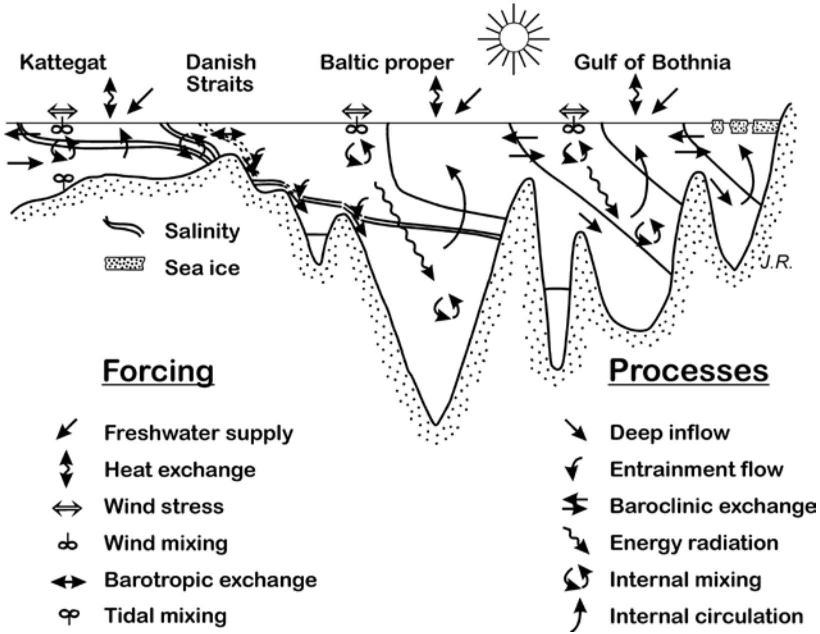
1. Introduction: What controls the physical and chemical properties of the coastal seas?

- Boundary conditions (water, energy and mass balances)
- Internal physical processes
- Chemical components and reactions
- Biological processes
- Human impact in many different ways

Boundary conditions (water and heat balances)



Forcing and internal physical processes



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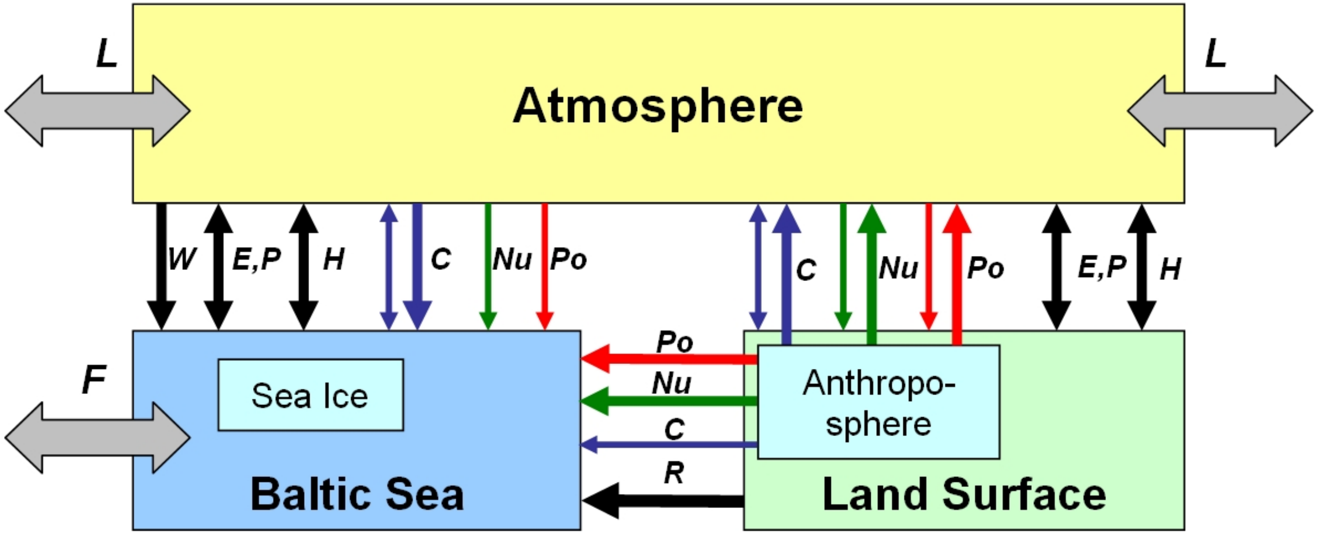
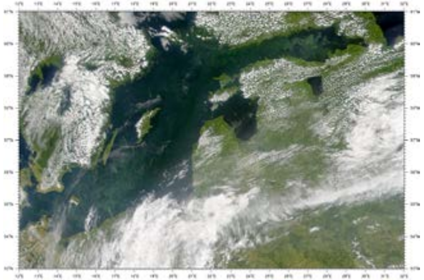
Baltic Earth

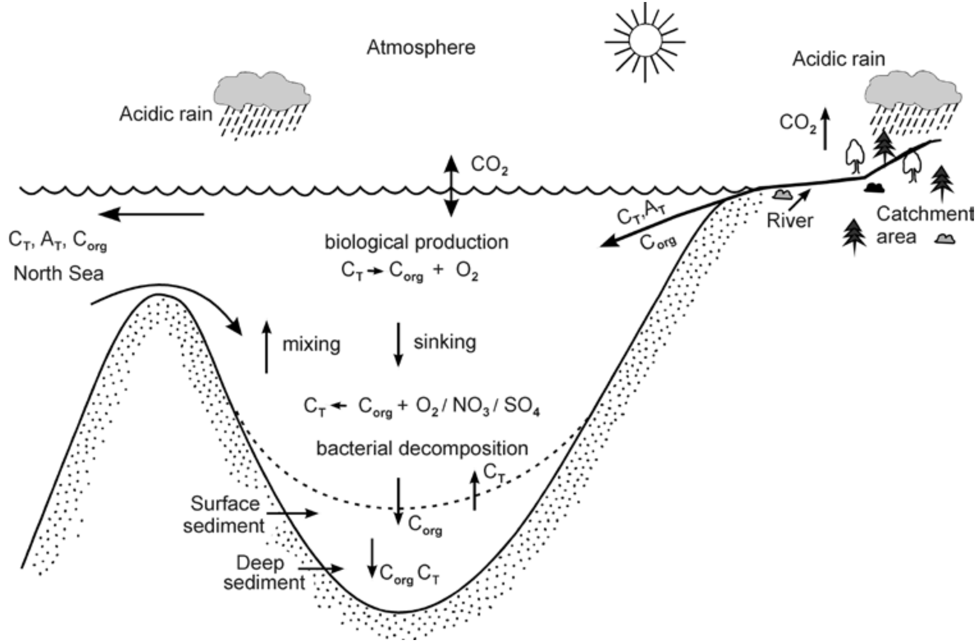
$$a\,CO_2 + b\,HNO_3 + c\,H_3PO_4 + (a+b)\,H_2O$$
$$\Leftrightarrow (CH_2O)_a(NH_3)_b(H_3PO_4)_c + (a+2b)\,O_2$$

Material balances, chemical components and reactions



Biological processes





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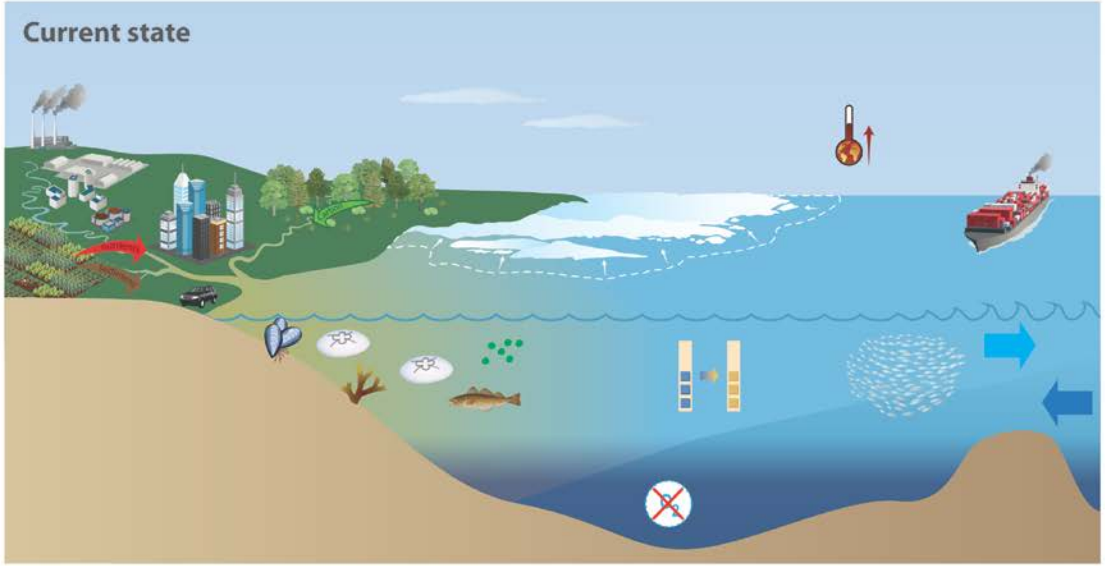
Baltic Earth

Human impacts



The Baltic Sea will become more acidic and more nutrients will leak into the system unless strong steps are taken to reduce CO_2 and nutrient loads.

- *Increasing air and water temperatures*
- *Decreasing sea ice*
- *Slight increase in marine acidification*
- *Declining water quality*
- *Annual cyanobacteria blooms*
- *Increasing forest growth & carbon transport*
- *Fair coastal biodiversity & health*
- *Anoxia*

BACC II, 2015

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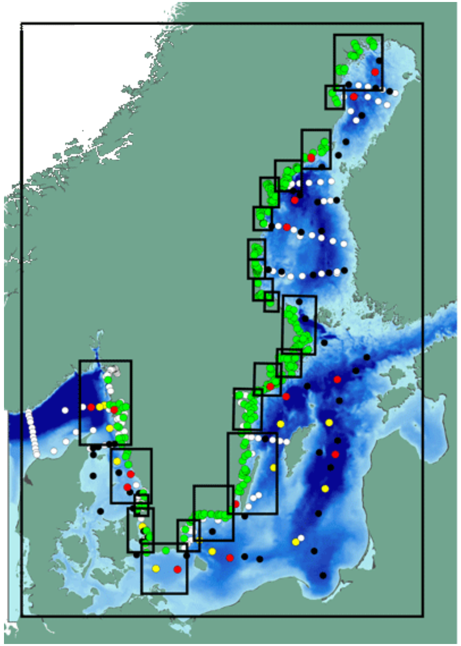
Baltic Earth

2. Marine observations often available but not easy to evaluate

##
Data uttagna från Svenska Nationella Marina Data Arkivet
Station: BY15 GOTLANDSDJ
##

Data layout efter kolumn:
01: Fartygskod
02: Hemisfär
03: Latitud (D) (°)
04: Latitud (M) (')
05: Longitud (D) (°)
06: Longitud (M) (')
07: År
08: Månad
09: Dag
10: Decimalår
11: Serie
12: Djup
13: Temperatur (° C)
14: Salinitet (psu)
15: pH
16: Syre (ml/l)
17: Svavelväte (µmol/l)
18: Fosfat (µmol/l)
19: Totalfosfor (µmol/l)
20: Nitrit (µmol/l)
21: Nitrat (µmol/l)
22: Ammonium (µmol/l)
23: Totalkväve (µmol/l)
24: Alkalinitet
25: Kisel (µmol/l)
26: PON (µmol/l)
27: POC (µmol/l)
28: Klorofyll a (µg/l)



SMHI-Shark data portals

http://www.smhi.se/oceanografi/oce_info_data/SODC/download_sv.htm

The ICES oceanographic database holds a history of oceanographic data from 1877 to present.

All data are quality controlled according to the DIG guidelines and visually inspected by experienced staff to further improve the quality of the data.

Core parameters held in the ICES oceanographic database are available for download:
Temperature
Salinity
Oxygen
Phosphate, Total Phosphorus
Silicate
Nitrate, Nitrite, Ammonium, Total Nitrogen
Hydrogen Sulphide
pH, Alkalinity
Chlorophyll a
Secchi depths
Member countries are encouraged to submit their hydrographical data to ICES Data Centre.

ICES data portals

http://ices.dk/marine-data/data-portals/Pages/ocean.aspx

Other useful data hosts:

Climate explorer:
http://climexp.knmi.nl/start.cgi?id=someone@somewhere
The Global Runoff Data Center:
http://www.bafg.de/GRDC/EN/Home/homepage_node.html
The Permanent Service for Mean Sea Level:
http://www.psmsl.org/
NOAA Satellite and Information Service:
http://www.nesdis.noaa.gov/
Baltic Nest Institute
http://www.balticnest.org/balticnest/
IOW: Baltic Atlas of Long-Term Inventory and Climatology (BALTIC)
http://www2008.io-warnemuende.de/BALTIC/
…….

Manual for Marine Monitoring in the COMBINE Programme of HELCOM

3. Monitoring data

B.1.1 NEED FOR QUALITY ASSURANCE OF ANALYTICAL PROCEDU MARINE MONITORING

It has been seen that, although there has been considerable improvement in analytical procedures over the past two decades, it has been obvious that a large number of European laboratories which still had difficulties in providing reliable data in routine work…, and which have shown that there are large inter laboratory differences. …….

Quality assurance of great demand and challenges

4. Model data

Models introduce an even greater problem compared to observations, as they are often undergoing development and are unavailable to the broader scientific community. The need to make model codes, model forcing data, and output data available to other groups is therefore fundamental.

Reproducibility of model and model data are of great demand and challenges

Improving model practice

14.7 Recommendations for standards and guidelines

1. Report all equations, parameterisations and parameter values used in publications
2. Model code must be archived, ideally under version control. If possible, it should be made publicly available.
3. Carbonate chemistry must be correctly calculated (the most recent OCMIP protocol is recommended: http://www.ipsl.jussieu.fr/OCMIP/)
4. Models must be evaluated against observations and their uncertainty documented and accounted for when drawing conclusions.
5. Ongoing data compilation and synthesis efforts are needed for model evaluation; they must be pursued and amplified. For example, data sets of seasonal changes and secular trends in carbonate chemistry, distribution and rate of calcification and biological responses to seawater chemistry are very useful. A good example is the EPOCA/EUR-OCEANS data compilation project (http://www.epoca-project.eu/index.php/What-do-we-do/Science/Data.html).
6. New targeted laboratory mesocosms and field perturbation experiments should be conducted to test and improve the functional form and parameters for parameterising biological processes.

Oschlies et al., 2010

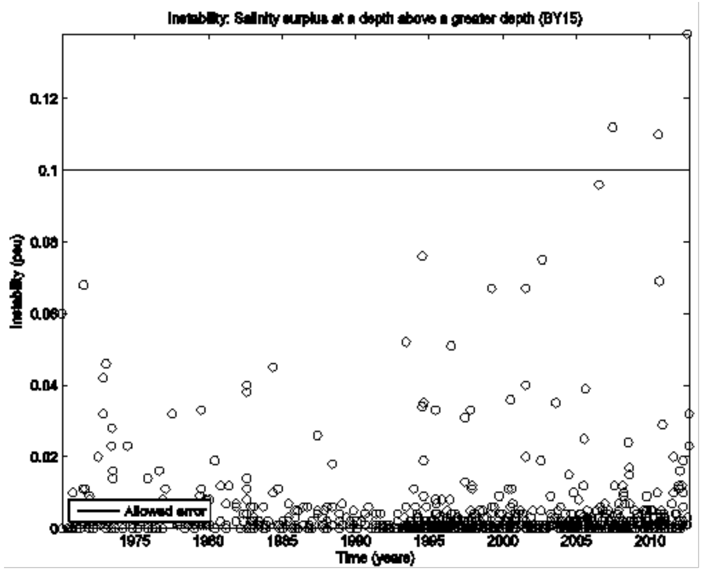
5. Data and their quality?

Some aspects for evaluating marine monitoring data

- Data availability and distribution (space and time, research vessel, country)?
- Check for data reporting errors and formatting consistency (units, missing data)? Pay special attention to:
  - missing values erroneously formatted as zeros;
  - zeros returned by spreadsheet functions when one of the arguments is missing; and missing values formatted as impossible values such as 99, 999, or –999?
- Look for outliers:
  - realistic minimum and maximum values;
  - single observations far from the great majority of all other data; and
  - clusters of surprisingly large or small observations.
- Check that density is stable over depth.
- Calculation of means, anomalies and time series.
- Assess overall temporal changes using uni- and/or multivariate Mann-Kendall tests (Software for performing multivariate Mann-Kendall tests in Excel or “R” can be downloaded from www.miljostatistik.se.)

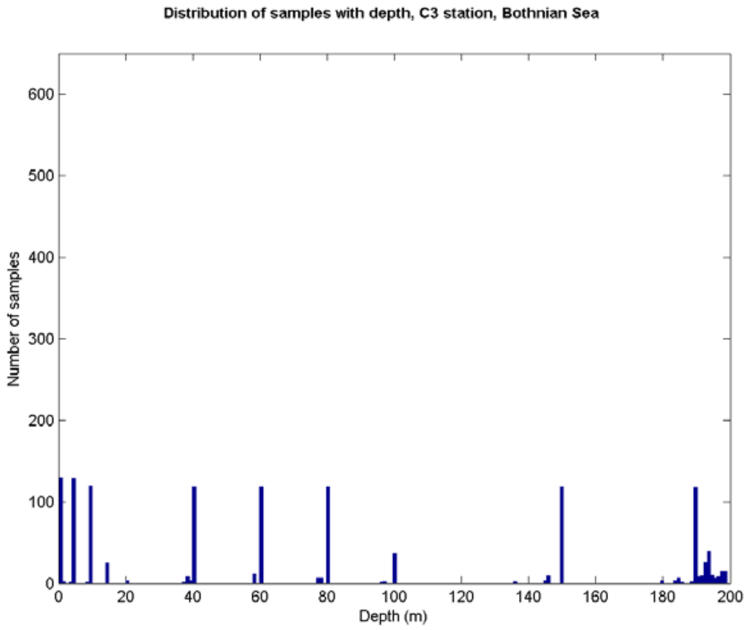
Instability indicate measuring errors

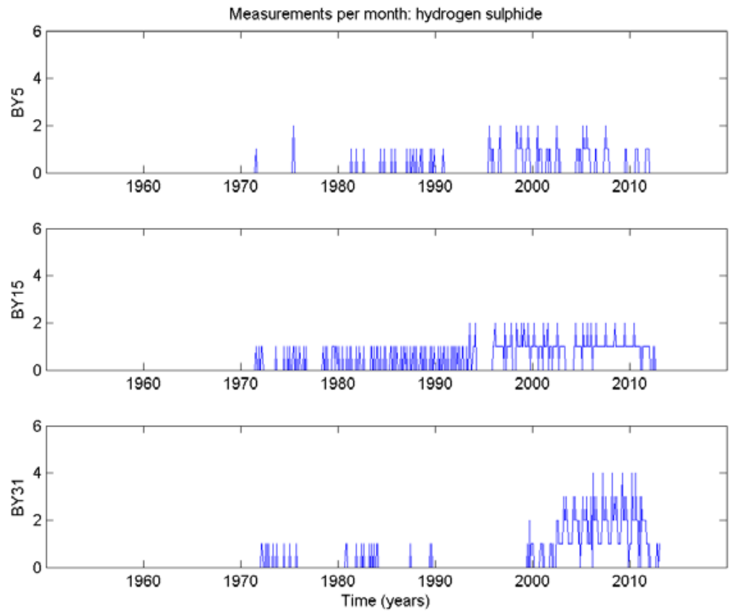
Instability in terms of salinity of the observed data from the Gotland Basin, displayed as salinity surplus at a depth above a greater depth; a difference of up to 0.1 psu was set as the allowed error.



Elam, Grimvall and Omstedt (2014)

Most marine observations are irregular distributed





Elam, Grimvall and Omstedt (2014)

Observations and models have information with quite different resolution.

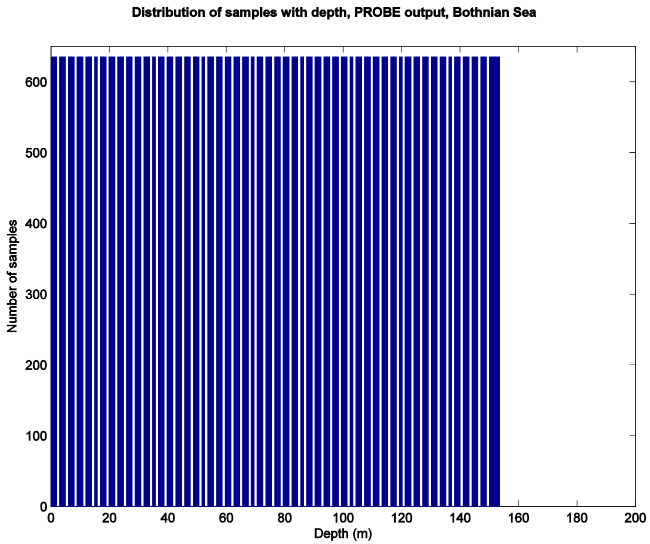


Fig. 3b Histogram of amount of model output (*y*-axis) per depth (*x*-axis) from the Bothnian Sea.

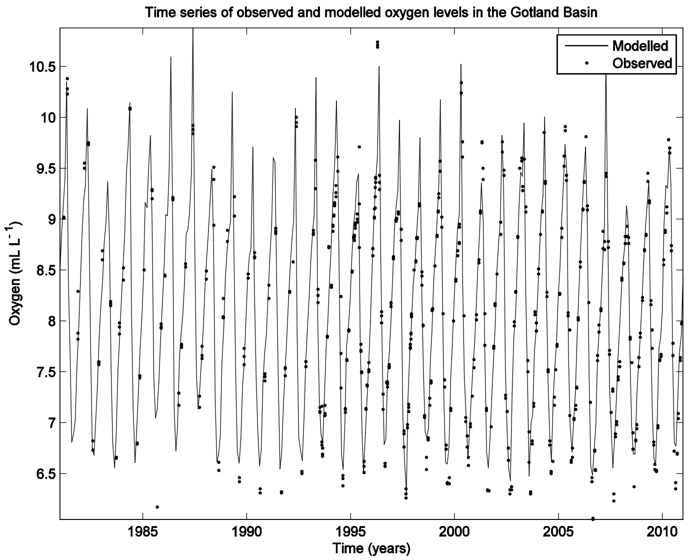
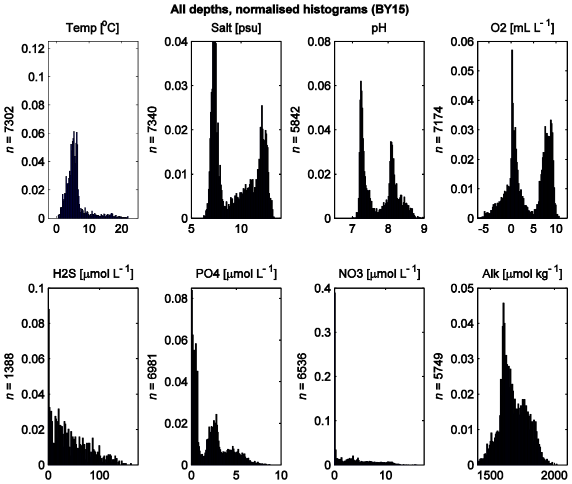


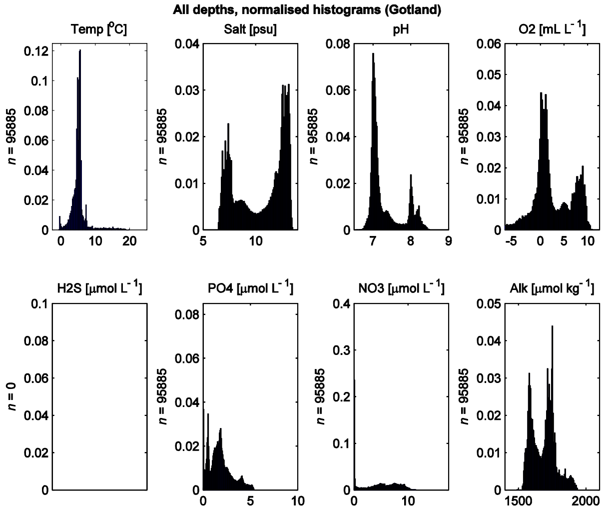
Fig. 4 Time series of observed and modelled oxygen levels in the Gotland Basin.

Elam, Grimvall and Omstedt (2014)

Data distribution observations and models differs greatly (note scales)



Histogram of number of observations (*y*-axis) per value (*x*-axis) from the Gotland Basin for all eight parameters used.



Histogram of model output (*y*-axis) per value (*x*-axis) from the Gotland Basin, for all eight parameters used.

Elam, Grimvall and Omstedt (2014)

Trends may differ from observed and model data

Mann-Kendall trend test results for trends in the 1980–2010 period: a) comparing the results of the observed data and the data from model run 1

Green = Good correlation defined as statistical significant trends of equal sign.
Yellow = Non-significant correlation defined as at least one non-significant trend.
Red = Poor correlation defined as significant trends of opposite signs.
- = Insufficient data.
* = Not significant trend.

a) Table of trends in the surface layer, observed and model run 1 data

		Temp	Sal	O2	pH	At	PO4	NO3
AE/KA	Obs	↗	↘*	↘	↘	↗	↘	↘
	Run 1	↗	↗	↘	↘	↗	↘	↘
BY5/BH	Obs	↗	↘	↘	↘*	↗	↗	↘
	Run 1	↗	↘	↘	↘	↗	↘	↗
BY15/GO	Obs	↗	↘	↘	↗*	↗	↗*	↘
	Run 1	↗	↘	↘	↘	↗	↘	↘
BY31/NW	Obs	↗	↘	↘*	↘	↗	↘	↘
	Run 1	↗	↘	↘	↘	↗	↘	↘
C3/BS	Obs	↘*	↗*	-	↗	↘*	↗*	↘*
	Run 1	↗	↘	↘	↘	↘	↘	↘
F9/BB	Obs	↘*	↘	↘	↘	↗	↗	↗*
	Run 1	↗	↘	↘	↘	↘	↘	↘

Elam, Grimvall and Omstedt (2014)

Object measure on model data performance

Correlation r, and
Cost function C

$$r = \frac{\sum_{i=1}^{n}(P_i - \overline{P})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2 \sum_{i=1}^{n}(O_i - \overline{O})^2}}$$

$$C = \frac{\sum_{i=1}^{n}\left|\frac{P_i - O_i}{SD(O_i)}\right|}{n}$$

Dissolved CO_2 system and redox reactions 81

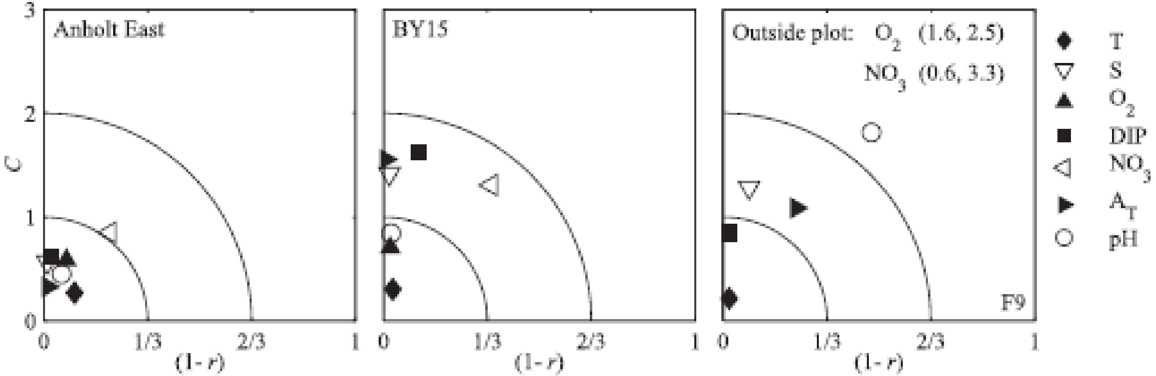


Fig. 2. The dimensionless quality metrics *r* (the correlation coefficient) and *C* (the volume-weighted mean of the cost function), at Sta. Anholt East, BY15, and F9 for the 1995–2004 period. The inner field (C = 0–1, 1 − r = 0–1/3) indicates good agreement and strong correlation between model and observations. The middle field (C = 1–2, 1 − r = 1/3–2/3) indicates reasonable agreement and moderate correlation between model and observations. The outer field indicates poor agreement and weak or negative correlation between model and observations.

Edman and Omstedt (2013)

6. Data interpretation

Often we are looking for something and forget important aspects.
Surprises are often present in science!

1.3. Trends, Jumps and Oscillations – the Problem of Detecting Anthropogenic Climate Change 15

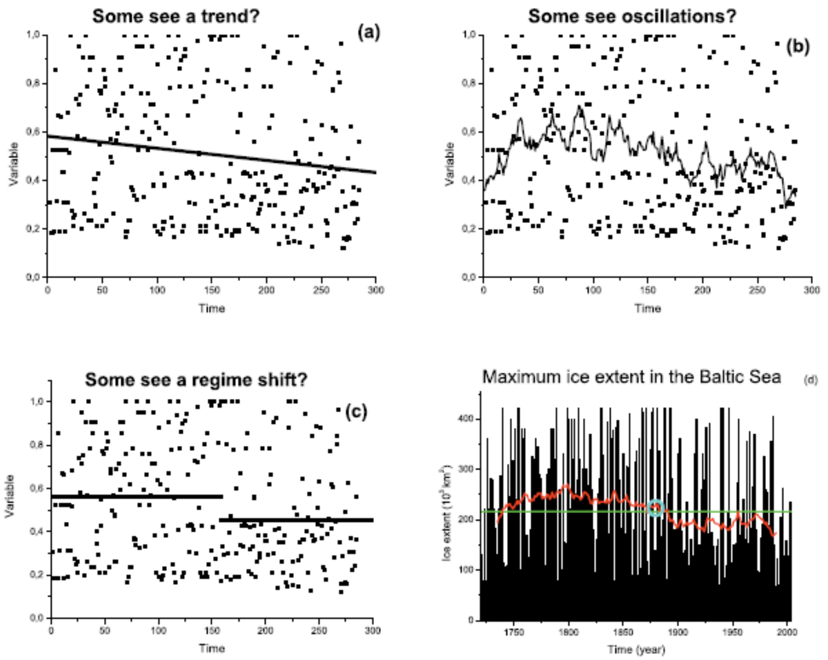
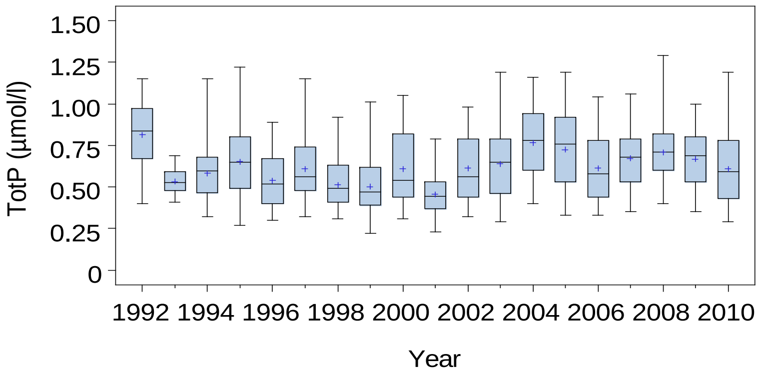


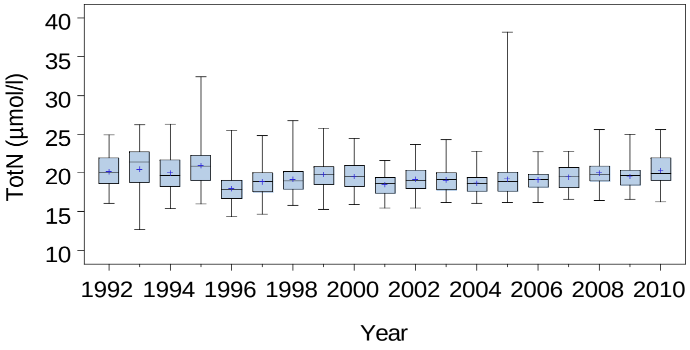
Fig. 1.13. Climate change can be detected by trends, oscillations and jumps or regime shifts. In this figure the same data sets is used and normalised (Figs. **a**–**c**). The original data set is illustrated in Fig. (**d**), for details see Omstedt and Chen (2001)

BACC Author Team (2008)

Box and whisker plots are uniform in their use of the box: the bottom and top of the box are always the first and third quartiles, and the band inside the box is always the second quartile (the median). The ends of the whiskers can represent several possible alternative values, among them the minimum and maximum of all of the data.

7. Some useful plots

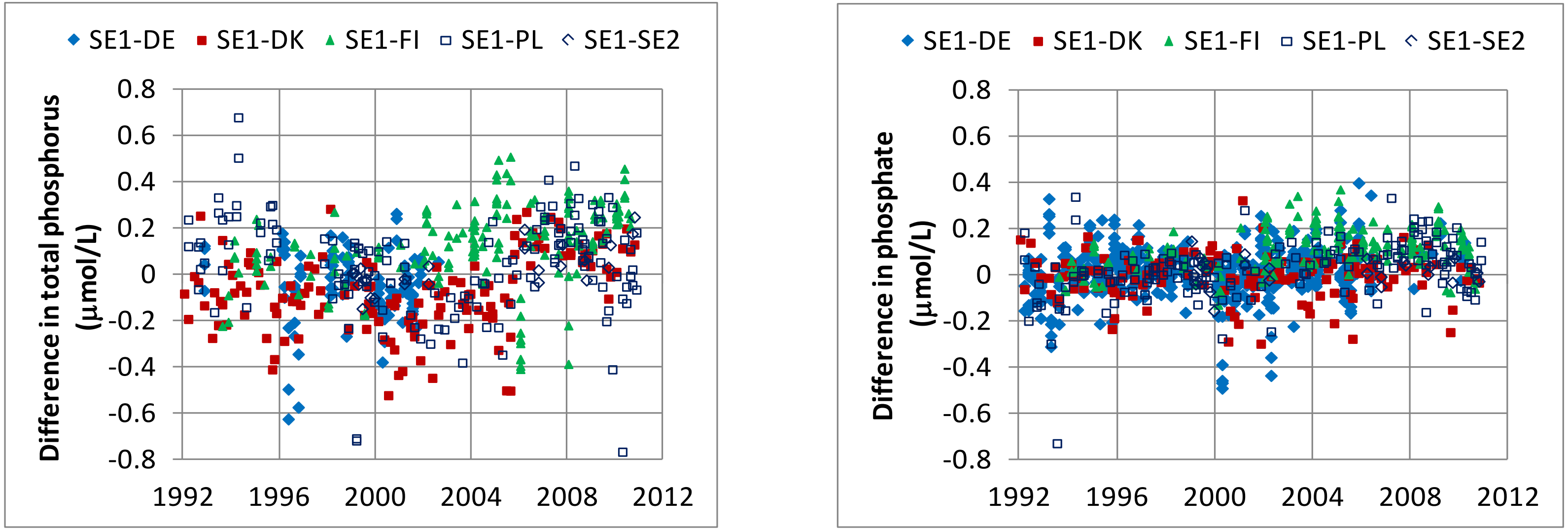




Box plots of measured concentrations of total phosphorus and nitrogen at the sampling site BY15 in the Gotland Deep in the Baltic Proper. The graphs summarize concentrations measured at depths less than 40m. Data source: SMHI (SHARK).

Grimvall and Omstedt (2012)

Anomaly plots make things more easy to notice

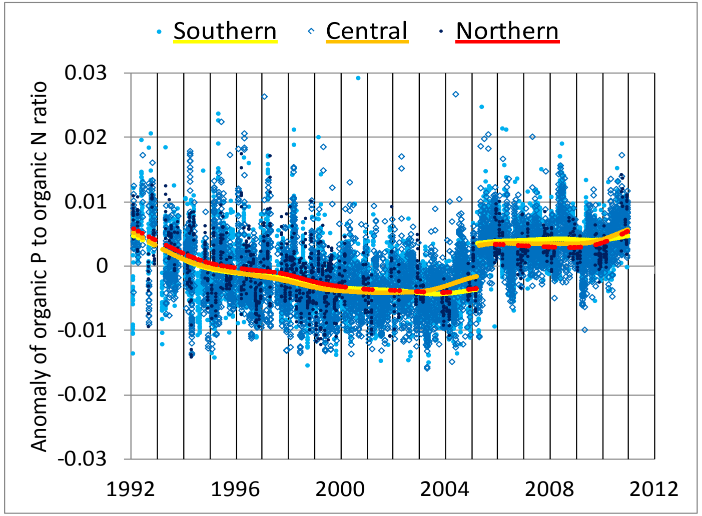


Differences in phosphorus concentrations measured at the same site during the same month but reported by different nations. Data source: HELCOM (ICES).

Grimvall and Omstedt (2012)

An example of change point. Measuring errors or?

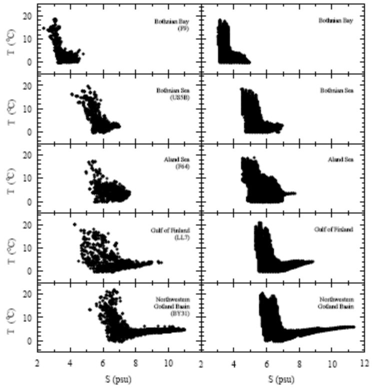
Ratios of organic phosphorus to organic nitrogen in water samples from the Baltic Proper. Data source: SMHI (SHARK), samples collected by the Swedish ship Argos.



Grimvall and Omstedt (2012)

Water mass analysis based on the T-S structure

Water mass studies has been the start for understanding ocean circulation and provides An easy way to examine the circulation and quality in model simulations



Omstedt and Axell (2003)

Vertical profiles are the important aspect of many processes

Vertical profiles give insight in physical processes such as e.g. turbulent mixing and circulation.

82 *Edman and Omstedt*

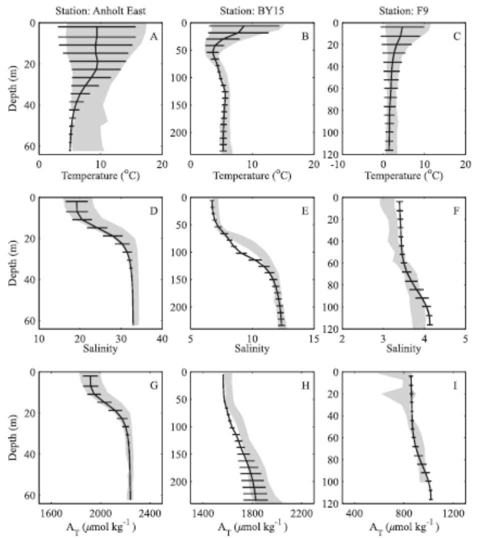


Fig. 3. (A–C) The mean depth profiles (1995–2004) of temperature (°C), (D–F) salinity, and (G–I) total alkalinity (A_T [μmol kg^{-1}]). Model results are indicated by black lines, with ± 1 standard deviation (black lines), and observed data with ± 1 standard deviation of the mean are indicated by a gray area. The figure shows results from the three validation stations, Anholt East, BY15, and F9.

Edman and Omstedt (2013)

Contour plots give a good overview of data

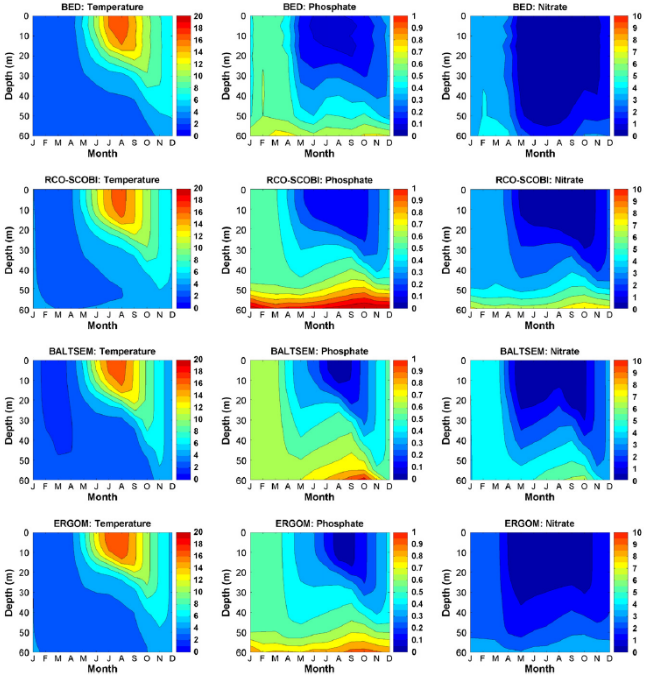


Fig. 4. The annual cycle of monthly average (1970–2005) temperature (°C), phosphate (μmol P l^{-1}), and nitrate (μmol N l^{-1}) at BY15 for BED data (row 1) and the RCO–SCOBI, BALTSEM and ERGOM models in rows 2, 3 and 4, respectively.

Eilola, K., B.G. Gustafson, I. Kuznetsov, H.E.M. Meier, T. Neumann, O. P. Savchuk, (2011)

8. Integration of physical and chemical properties in space give important budget information

Baltic Sea mean (horizontal and vertical averaged) salinity based on all available observations

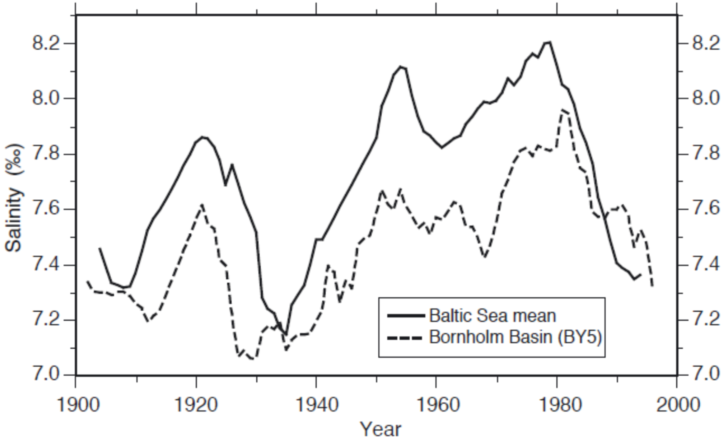


Fig. 15 (corrected). Surface salinity in the Bornholm Basin (BY5) and mean salinity of the Baltic Sea, calculated from freshwater content. Both series 5 yr running means. For details see Winsor et al. (2001)

Winsor et al., 2001, 2003

Baltic Sea mean (horizontal and vertical averaged) temperature based on all available observations

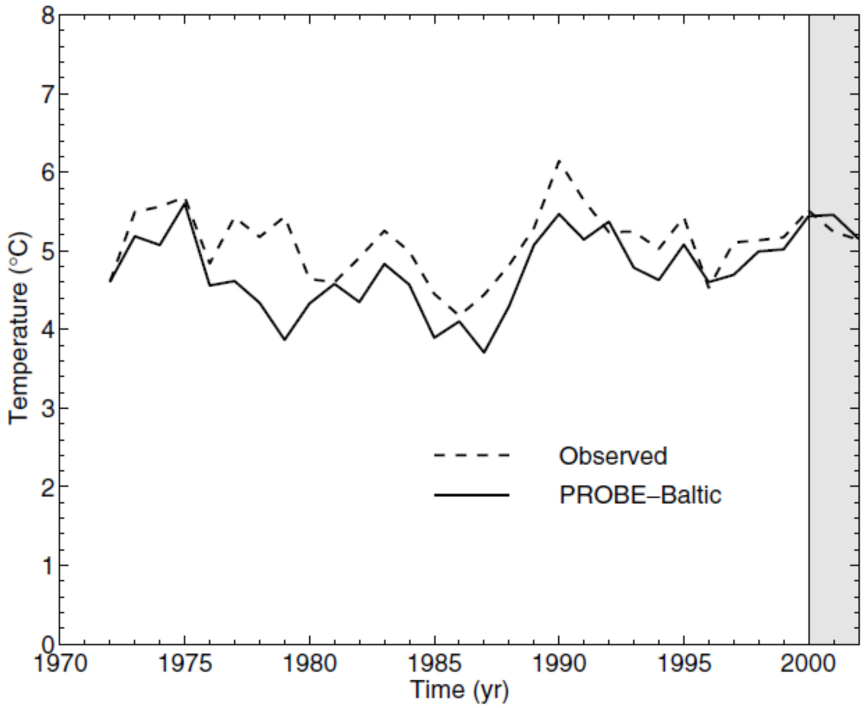
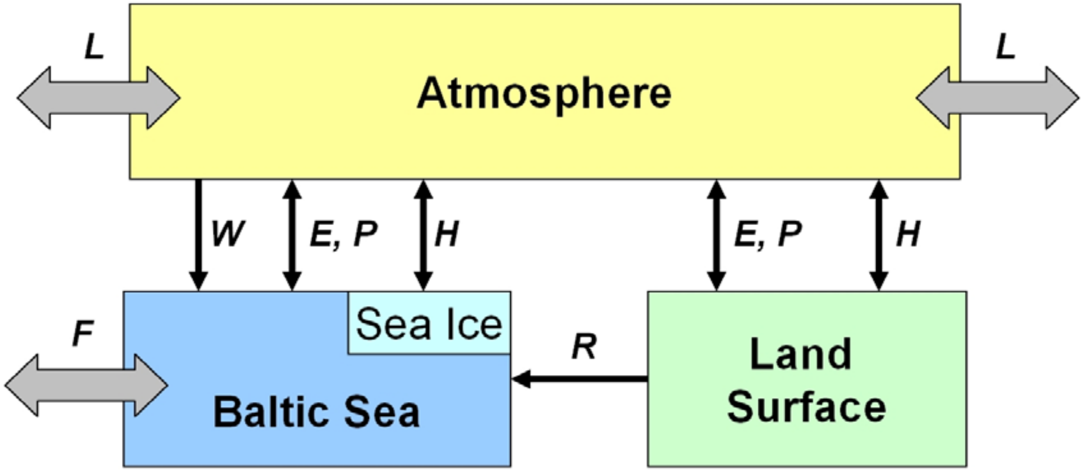


Fig 5. Observed (dashed line) and modelled (solid line) annual variation of Baltic Sea mean water temperature. The BALTEX/*BRIDGE* period is marked.

Omstedt and Nohr (2004)

9. Budget calculations the start of science knowledge



Water balances and salinity

$$\frac{dV_0 S}{dt} = S_{in}Q_{in} - SQ_{out}$$

$$- S\left(\left(P - E\right)A_s + Q_r\right) + ...$$

Omstedt and Nohr (2004), steady state and present climate

$Q_{in} \approx 42x10^3$

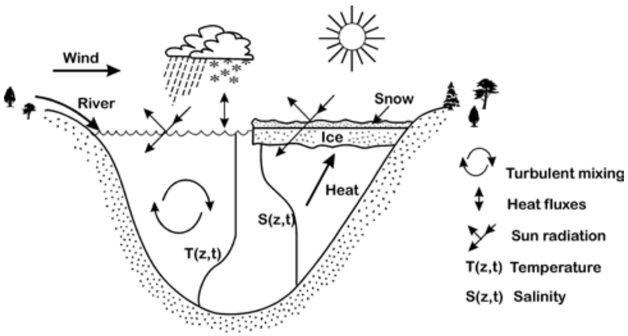
$Q_{out} \approx 59x10^3$

$Q_r \approx 15x10^3$

$A_s\left(P - E\right) \approx 2x10^3$

$$S = S_{in}\frac{Q_{in}}{Q_{out} + Q_r + A_s(P - E)}$$

$$\approx S_{in}0.55 \approx 14x0.55 = 7.7$$



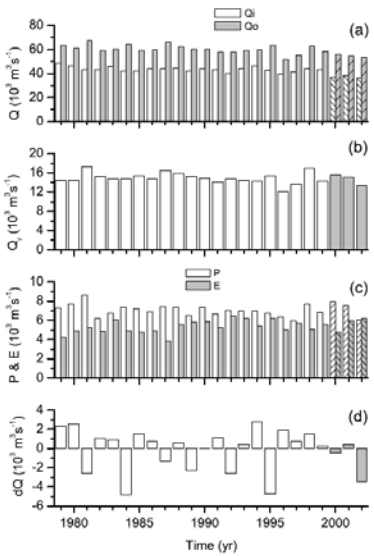
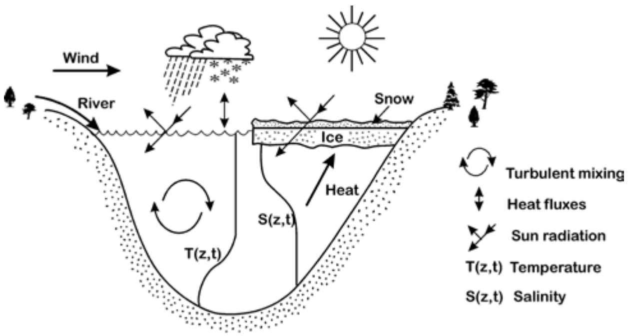


Fig 7. Baltic Sea (excluding the Kattegat and the Belt Sea) annual means of inflows and outflows (a), river runoff (b), precipitation and evaporation (c), and net volume change (d). The BALTEX/BRIDGE period is marked.

Omstedt and Nohr, (2004)

Heat balances and water temperature and ice

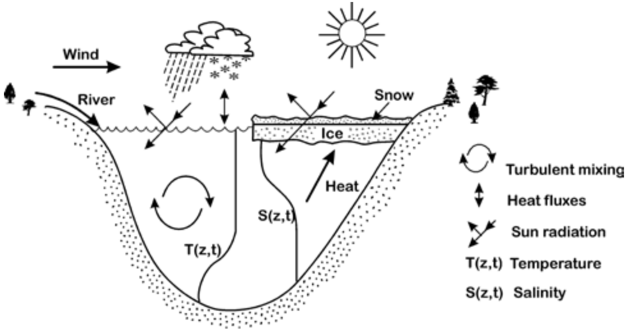


$$\frac{dH}{dt} = (F_i - F_o - F_{loss} + F_r)A_s \qquad H = \iint \rho c_p T dz dA$$

$$F_{loss} = (1 - A_i)(F_n + F_s^w) + A_i(F_w^i + F_s^i)$$

$$F_n = F_h + F_e + F_l + F_{prec}$$

Heat balances and water temperature and ice



Omstedt and Nohr(2004) assume steady state present climate

$$F_{loss} = F_{in} + F_r - F_{out}$$

$$F_{loss} A_{sur} = \rho_0 c_p T_{in} Q_{in} + \rho_0 c_p T_r Q_r - \rho_0 c_p T Q_{out}$$

$$\approx \rho_0 c_p \left[T_r Q_r - T \left(Q_{out} - Q_{in} \right) \right]$$

$$\approx \rho_0 c_p Q_r \left[T_r - T \right] \approx 0?$$

BALTIC SEA WATER AND HEAT BALANCES 409

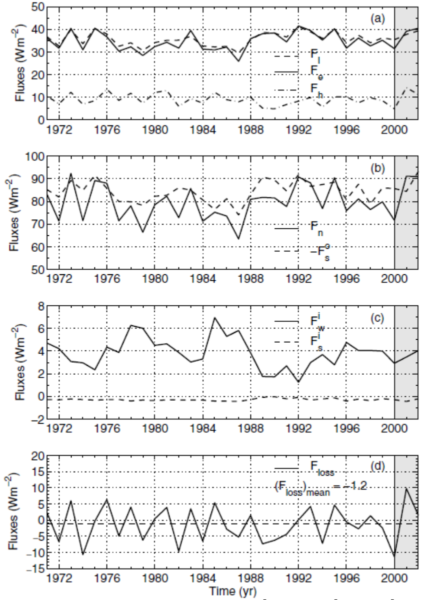


Fig 9. Annual means of sensible heat (F_h), latent heat (F_e), net long-wave radiation (F_l), net heat flux ($F_n = F_h + F_e + F_l$), sun radiation to the open water surface (F_s^o), sun radiation through ice (F_s^i), heat flow from water to ice (F_w^i), and net Baltic Sea heat loss $F_{loss} = (1 - A_i)(F_s^o + F_h + F_e + F_l) + A_i(F_s^i + F_w^i)$, where A_i is the ice concentration.

Omstedt and Nohr (2004)

Phosphorus balances in the Baltic Sea

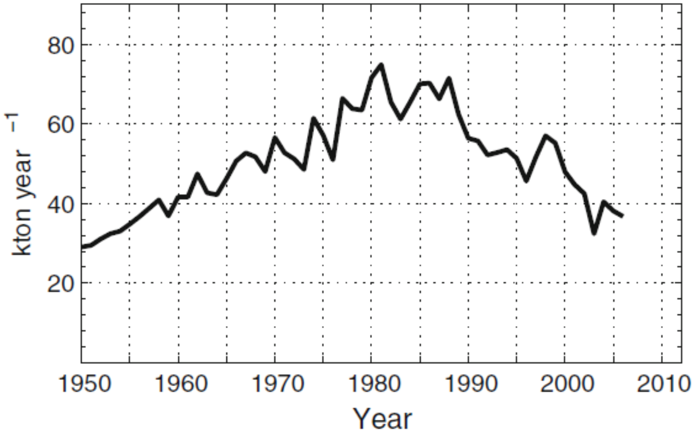


Fig. 1 The annual external supply of total phosphorus to the Baltic Sea excluding Kattegat and the Belt Sea (after Gustafsson et al. 2012)

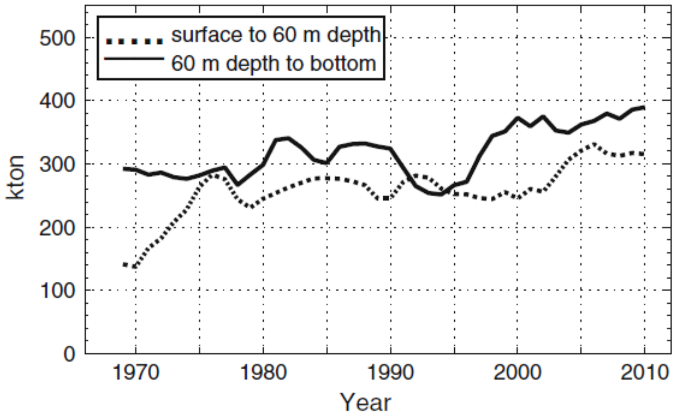
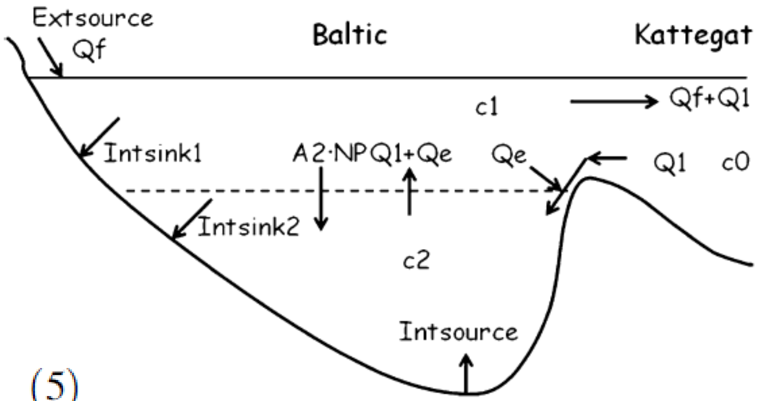


Fig. 2 Phosphorus contents (Tot-P, winter data) above and below 60 m depth, respectively (3 years moving averages) (original data can be found in Electronic Supplementary Material)

Stigebrandt et al., (2013)

Simple model

$$V\frac{d\bar{c}}{dt} = Extsource - Q_f c_1 - Q_1(c_1 - c_0) - Intsink + Intsource \qquad (5)$$



Two-layer model

Between 1980 to 2010 $V\frac{d\bar{c}}{dt} \approx 5000$ tons P/year

For 1980 and 2005: *Extsource* $\approx$ 60000 resp. 35000 tons P/year

$Q_f c_1$ at 1980 and 2010 about 7000 and 9000 tons P/year

$Q_1(c_1 - c_o) \approx 0$

For 1980 and 2005:*Intsink* - *Intsource* $\approx$ 48000 resp. 21000 tons P/year

Thus net internal source between 1980 to 2005 that is of same size as change in *Extsource*

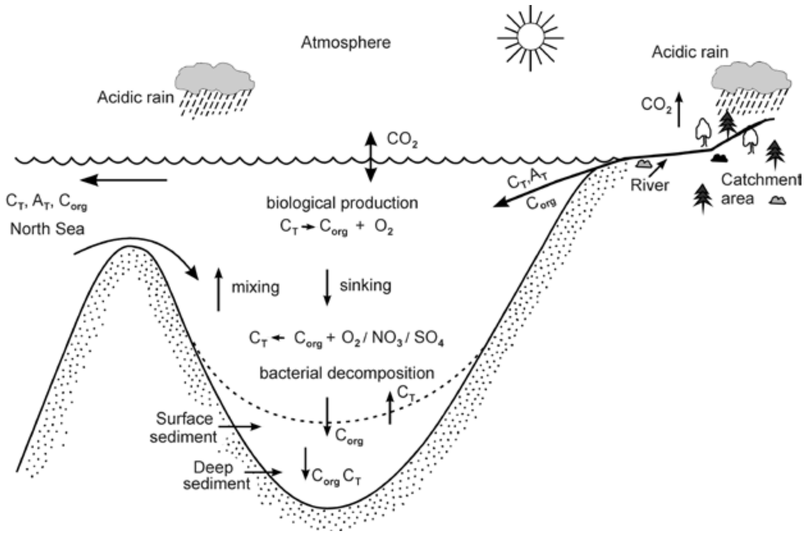
Stigebrandt et al., (2013)

Carbon balances

State variables for dissolved inorganic carbon

$$C_T = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

$$A_T \approx [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] - [H^+]$$

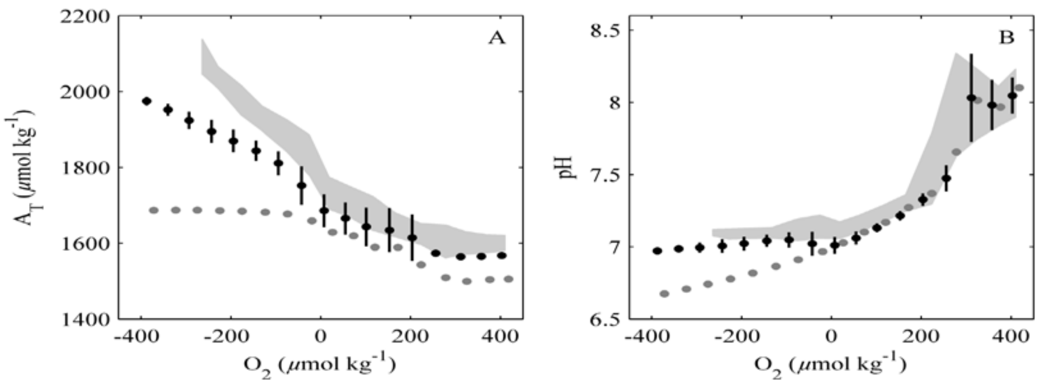


Carbon balances

C_T and A_T conservation and steady state:

$$A_{Tin}Q_{in} + A_{Tr}Q_r = A_T Q_{out}$$
$$C_{Tin}Q_{in} + C_{Tr}Q_r = C_T Q_{out}$$

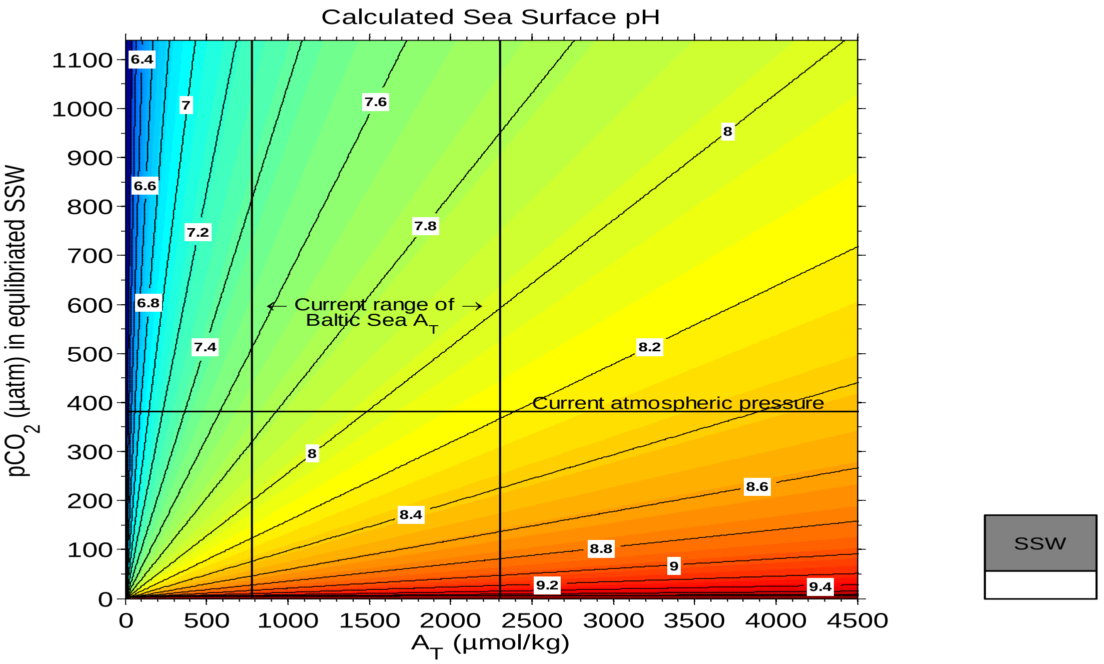
$$A_T = [A_{Tin}Q_{in} + A_{Tr}Q]/Q_{out} \approx [2000*42000 + 1200*15000]/59000$$
$$\approx 1730\ \mu\text{molkg}^{-1}$$
$$C_T = [C_{Tin}Q_{in} + C_{Tr}Q]/Q_{out} \approx [1800*42000 + 1350*15000]/59000$$
$$\approx 1625\ \mu\text{molkg}^{-1}$$



(A) Total alkalinity and (B) pH as functions of oxygen concentration for 0–250 m at station BY15, the Gotland Deep. The observational data (1995–2004) are indicated by ±1 standard deviation of the mean (light gray area). The black markers and lines represent a model run including internal generation of A_T, and the gray markers represent a model run excluding internal generation of A_T (Edman and Omstedt, 2013).

Ocean acidification

Rising atmospheric CO_2 and reducing inflow of A_T from river *may cause marine acidification*



Omstedt, Edman, Anderson, Laudon (2010)

10. Natural and anthropogenic changes

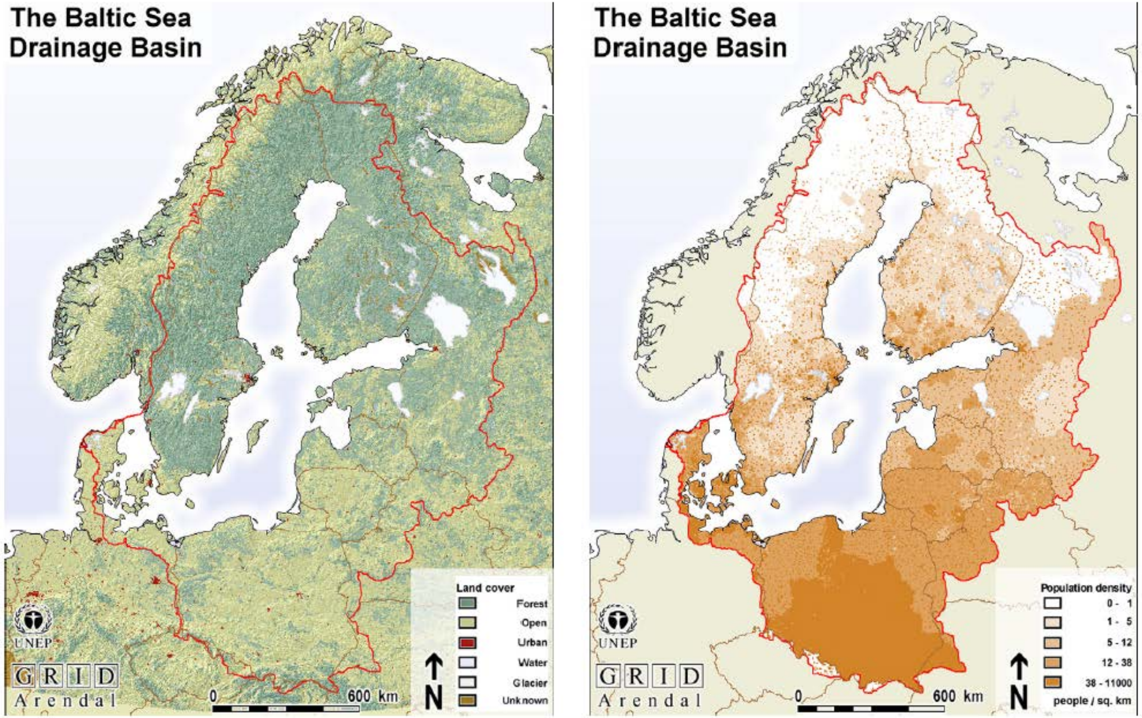
Some definitions:

- Climate is statistical properties for a number of parameters and a defined period.
- Climate variability is climate variation not related to anthropogenic influences.
- Climate change is climate variation that could be related both to natural and anthropogenic influences.
- Anthropogenic climate change is climate variation when human causes are attributable.
  Could be of different reasons.
- Detection of anthropogenic climate change require good data sets.
- Attribution of anthropogenic climate change require good models.

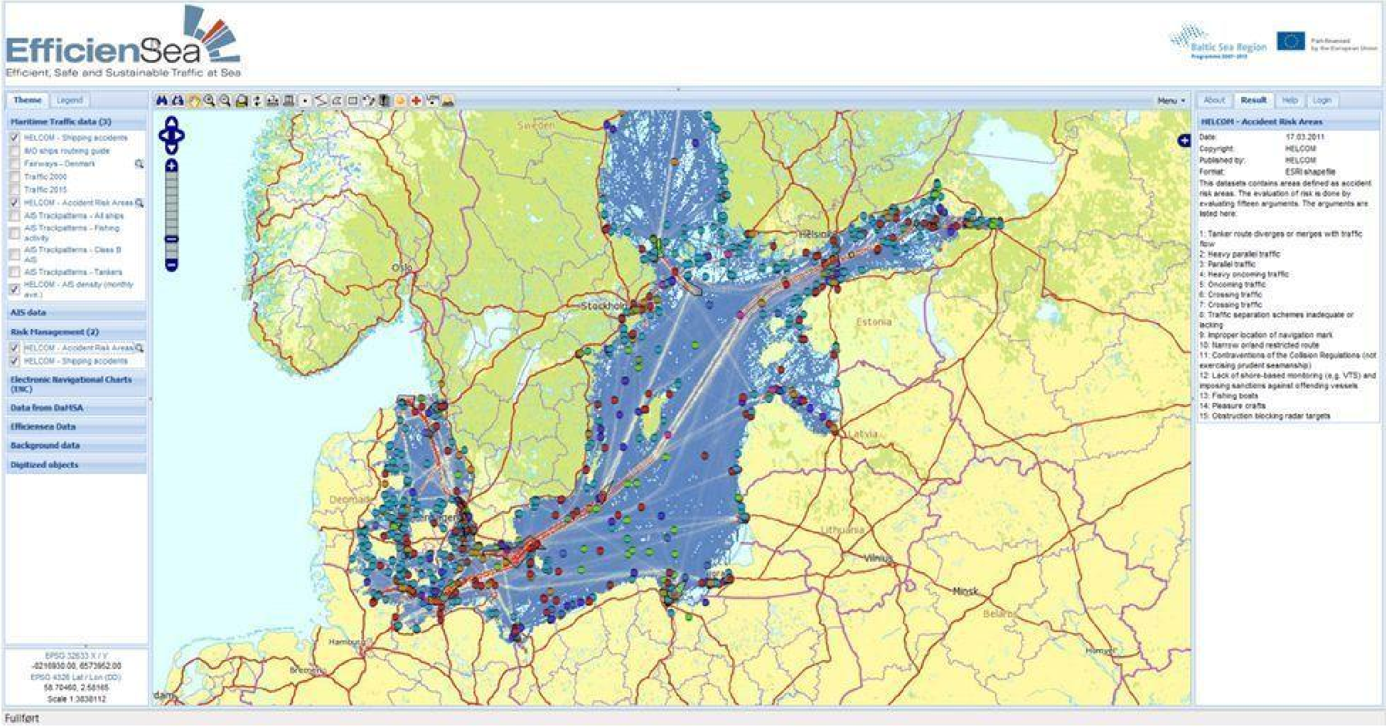
11. Human impacts: Land-surface and its changes

Why are often people missing in our figure?

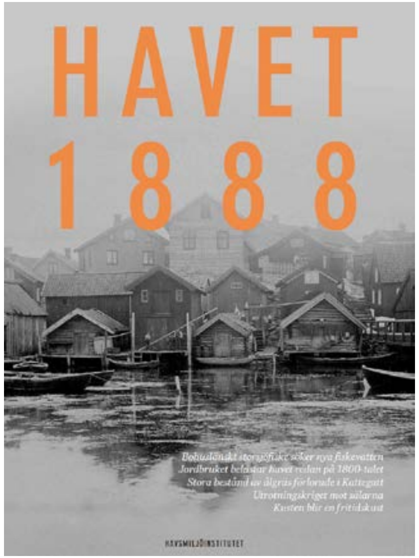
S. Jutterström et al. / Marine Pollution Bulletin 86 (2014) 468–480



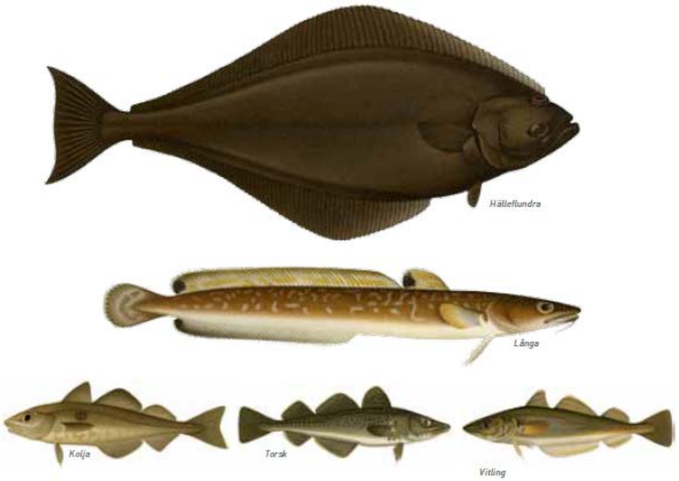
Human impacts: Shipping



Human impacts: Urbanization and modern tourism



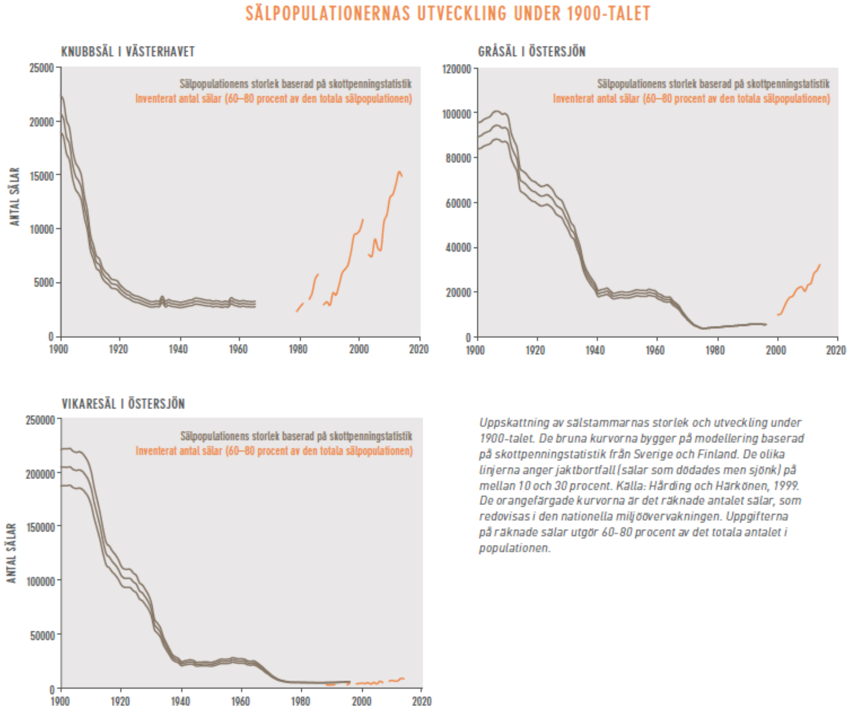
Human impacts: Fishery



Tillgänglig statistik visar att skillnaderna i hur fångsten av olika arter har varierat mellan mitten av 1800- och mitten av 1900-talet är stora. Medan fångsten av långa var relativt oförändrad i storsjöfisket under hela perioden sjönk fångsten av hälleflundra kraftigt. Illustrationer: Bröderna von Wright.

Havet 1888

Human impacts
Fishery



Havet 1888

Human impacts

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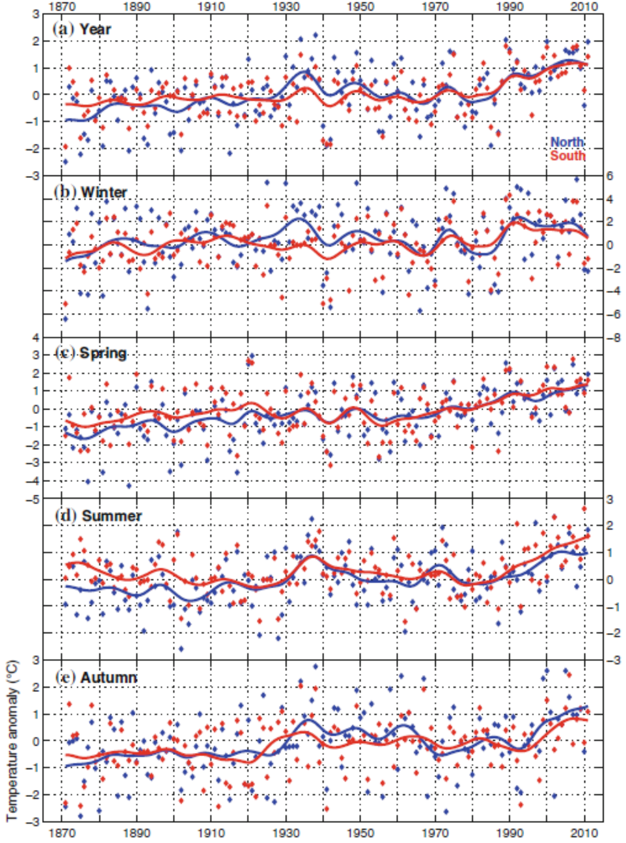
Fig. 4.11 Annual and seasonal mean surface air temperature anomalies (relative to 1960–1991) for the Baltic Sea basin 1871–2011, calculated from 5° by 5° latitude, longitude box average taken from the CRUTEM3v dataset (Brohan et al. 2006) based on land stations (from *top* to *bottom*: **a** annual, **b** winter (*DJF*), **c** spring (*MAM*), **d** summer (*JJA*), **e** autumn (*SON*). *Blue* comprises the Baltic Sea basin north of 60°N and *red* south of 60°N. The dots represent individual years and the smoothed curves (Gaussian filter, σ = 3) highlight variability on timescales longer than 10 years



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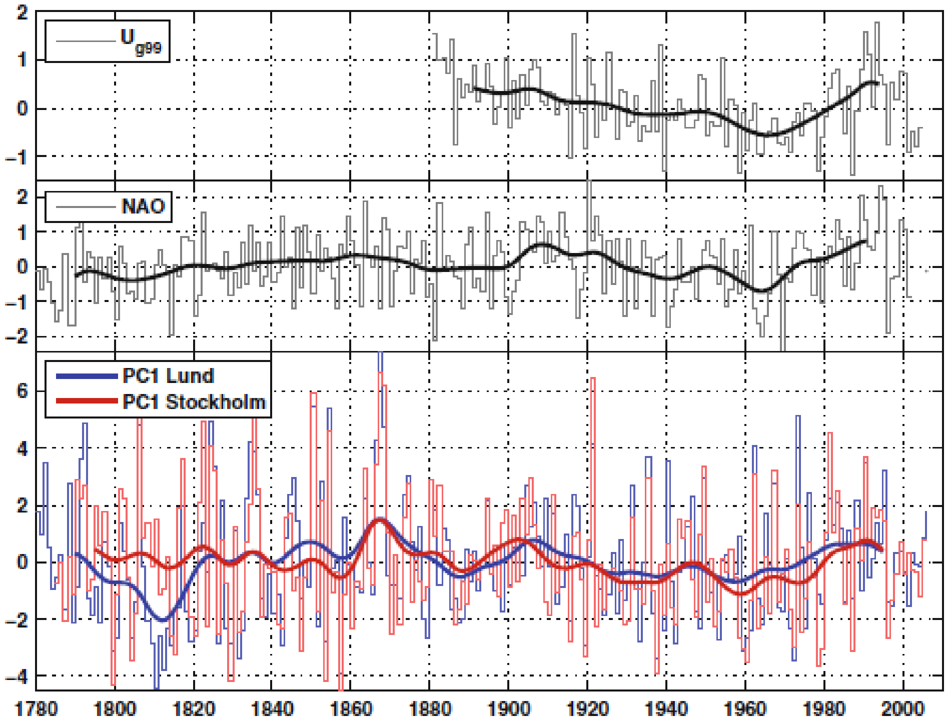
Human impacts

Fig. 4.2 Time evolution of the 99th percentiles of the geostrophic wind index (Alexandersson et al. 1998, 2000, *top*), a reconstructed NAO index (Luterbacher et al. 2002, *centre*) and the first principal components of the Lund and Stockholm storminess indices (PC1) over the Baltic Sea region. *Thick curves* are filtered with a Gaussian filter (σ = 4) to focus on inter-decadal variations (Bärring and Fortuniak 2009)



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Baltic Earth

Human impacts: Nutrient and CO_2

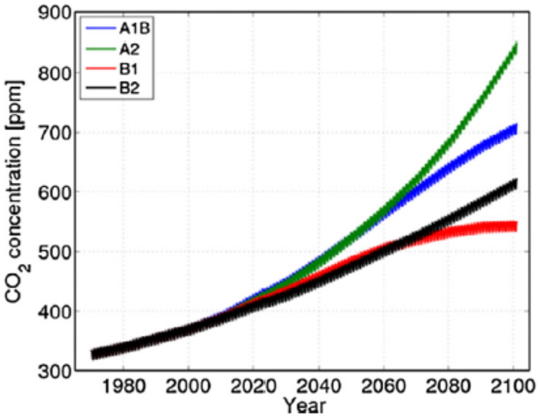

Fig. 6. Atmospheric CO_2 concentrations projected by four of the IPCC-SRES narratives: A1B, A2, B1, B2 (Nakićenović et al., 2000; figure courtesy of Anders Omstedt).

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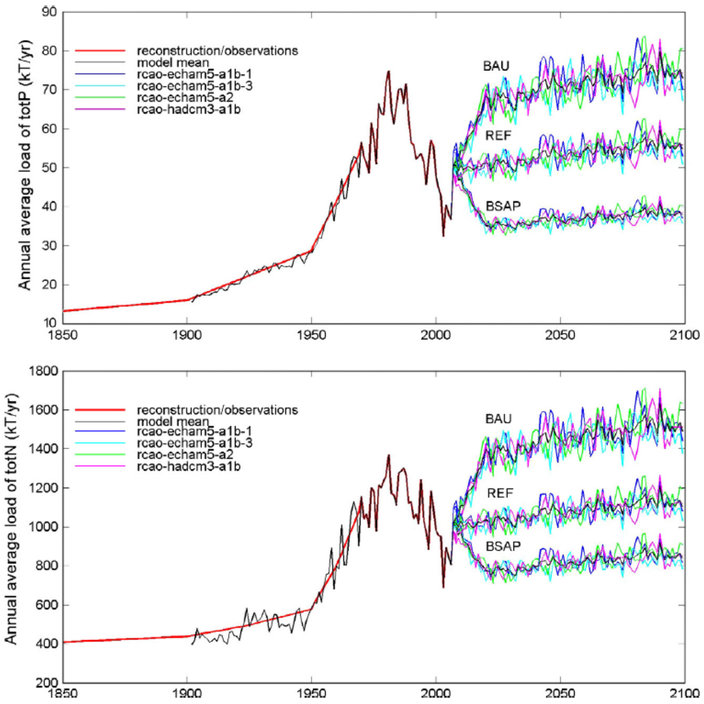


ıt loads to the Baltic Sea, total phosphorus (top) and total nitrogen (bottom) right. Results from Gustafsson et al. (2011, 2012).

Human impacts; SO_x, NO_x and NH_x

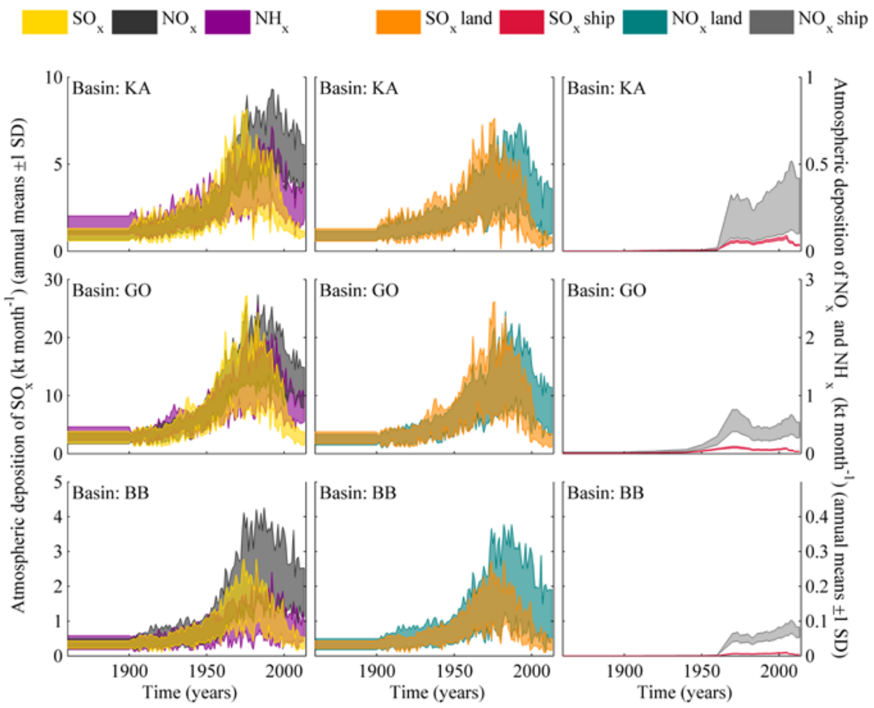


Fig. 3. Left: Reconstructed annual atmospheric depositions of SO_x, NO_x, and NH_x (±1 SD) for the three model sub-basins, i.e., the Kattegat (KA), Eastern Gotland Basin (GO), and Bothnian Bay (BB). Centre: Reconstructed annual atmospheric depositions of SO_x and NO_x from land (±1 SD) for the three model sub-basins. Right: Reconstructed annual atmospheric depositions of SO_x and NO_x from sea (±1 SD) for the three model sub-basins (Omstedt et al, 2015).

Human impacts: Multiple stressors

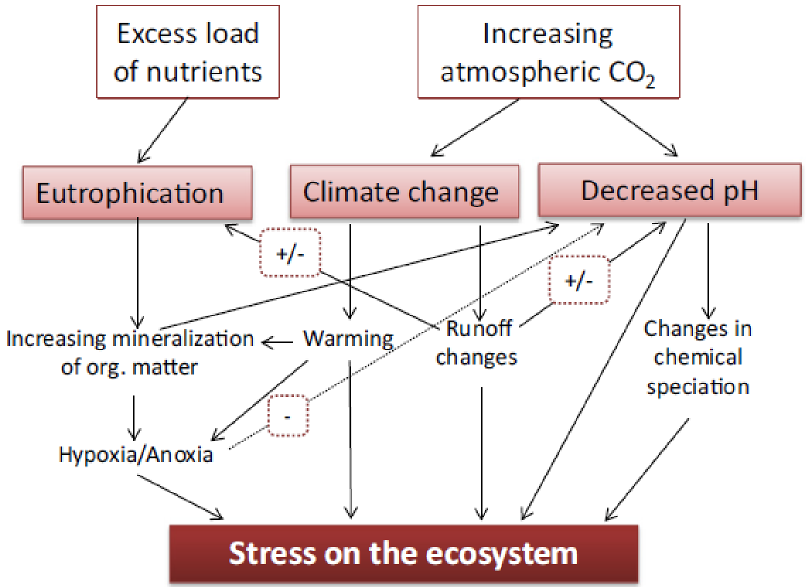
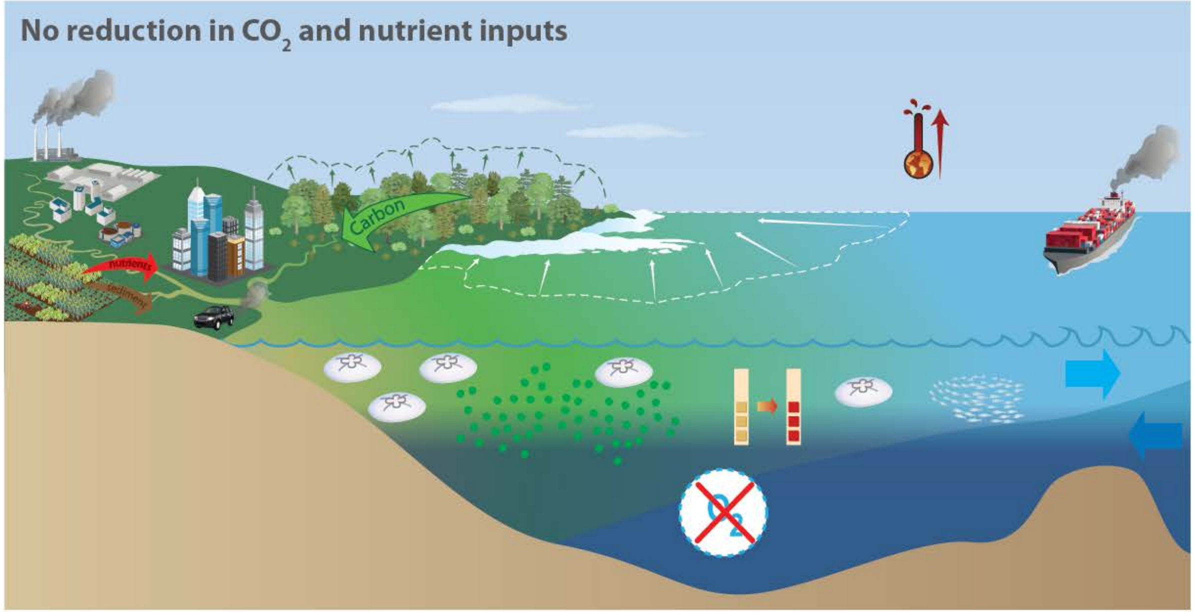


Fig. 9. Flowchart of the impact and interconnectivity of the effects from increased nutrient loads and atmospheric CO_2.

Jutterström et al 2014

Human impacts (BACC II, 2015)



With no reduction in CO_2 emissions and nutrient inputs, water temperatures will increase, sea ice will decrease, and cyanobacteria blooms worsen.

Increased CO_2 emissions lead to increased marine acidification. More nutrient inputs leads to increased algal blooms, while warmer waters decreases the uptake of O_2 in the water. Increased acidification and increased anoxic waters will threaten the marine ecosystem.

- *Increased air and water temperatures*
- *Decreased sea ice*
- *Acidification worsens*
- *Reduced water quality*
- *Increased cyanobacteria blooms*
- *Increased forest growth & carbon transport*
- *Poor coastal biodiversity & health*
- *Increased anoxia*

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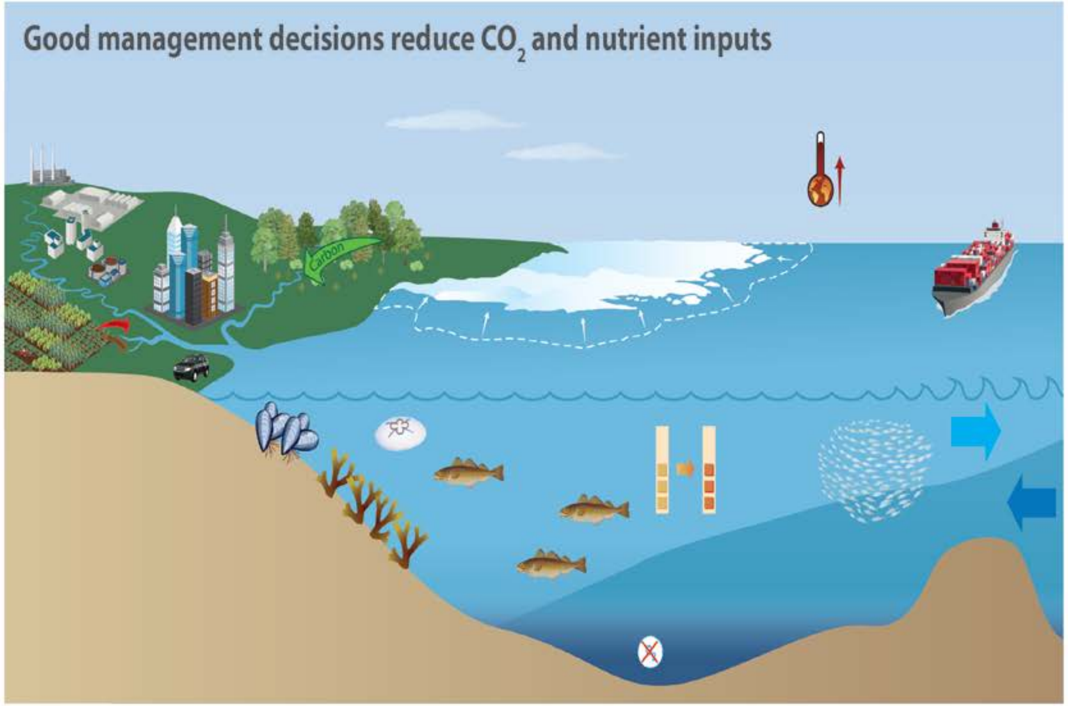
Human impacts: What we do can make a difference



Good management decisions such as:

- switching to alternative renewable energy for industry, vehicles, and shipping;
- improved land management and farming practices;
- improved lifestyle choices including food consumption, travelling, and living.

While marine acidification and climate change will continue, it will be slowed down.

Slight increase in air and water temperature

Slight decrease in sea ice

Slight increase in marine acidification

Improved water quality

Good coastal biodiversity & health

Decreased anoxia

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12. Exercises

a) Can knowledge about the Baltic Sea be gained without observations?

b) Where can you get Baltic Sea observations and list some limitations within present available observation data sets?

c) Where can you get Baltic Sea models, model data sets and list some limitations within present available model data sets?

d) List some considerations needed when comparing observations and model data?

e) What kind of information can you get from a time serie of surface data, a vertical profile, X-Y plots, integrated (vertical as well as horizontally) parameters, budgets and models?

f) When presenting trends, oscillations or regime shifts in your data what will the message be for people outside science?

12. Exercises cont.

g) Give examples on natural and anthropogenic changes in coastal seas.

h) How can one detect anthropogenic changes?

i) What is needed to be able to explaining the reason for anthropogenic changes?

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Askö Laboratory, Trosa, Sweden, 24 - 30 August 2015

Thanks for your interest!