

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Background

page 1/21

major Baltic inflow = voluminous inflow of highly saline water into the Baltic Sea

importance

- hydrographic structure and salinity balance
- deep water oxygenation (ecosystems!)

characteristics

- sporadic increase of bottom salinity
- significant rise of Baltic water level
- typical occurrence between Sep—Mar

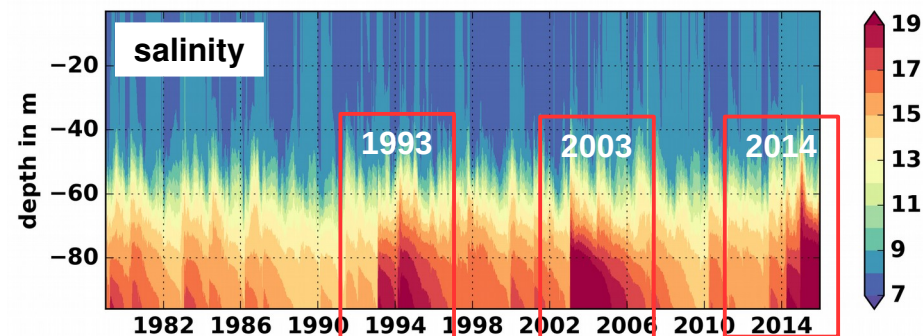
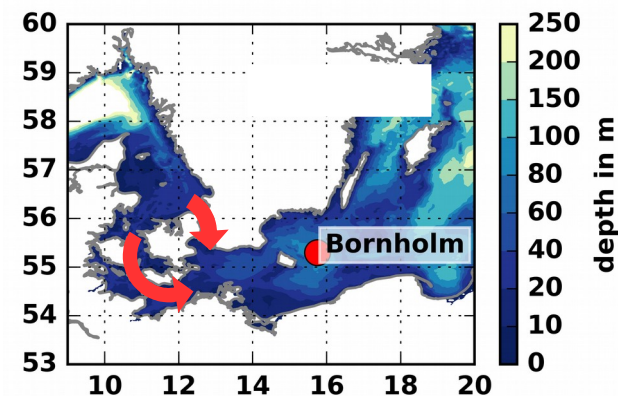


Figure: simulated Bornholm Basin salinity for the period 1979-2015 and map of Baltic Sea bathymetry

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

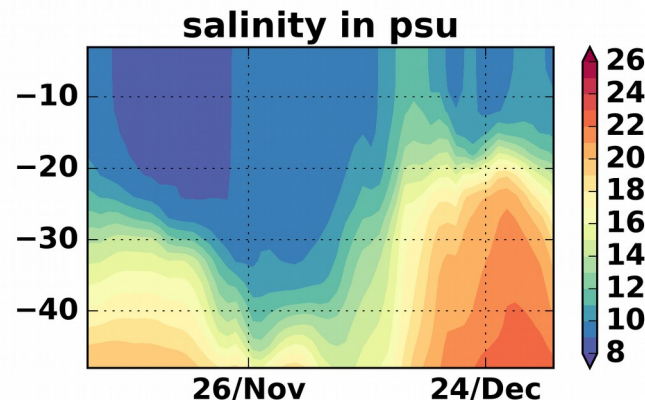
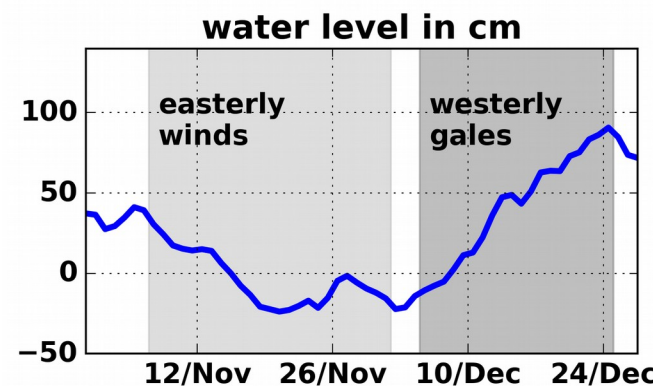
Mechanism

page 2/21

current “mechanistic understanding” is rather descriptive:

- sequence of easterly winds lowers the Baltic Sea water level
- westerly gales push large amount of highly saline water over entrance sills

e.g. Mohrholz et al. 2015, Matthäus et al. 2008, ...



Figures: Landsort sea level and Arkona Basin salinity associated with Dec/2014 inflow

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Research Questions

page 3/21

“problem”: sequences of easterly and westerly circulation do not only force highly saline inflows but large barotropic inflows in general (e.g. Schinke 1996, Lehmann and Post 2015)

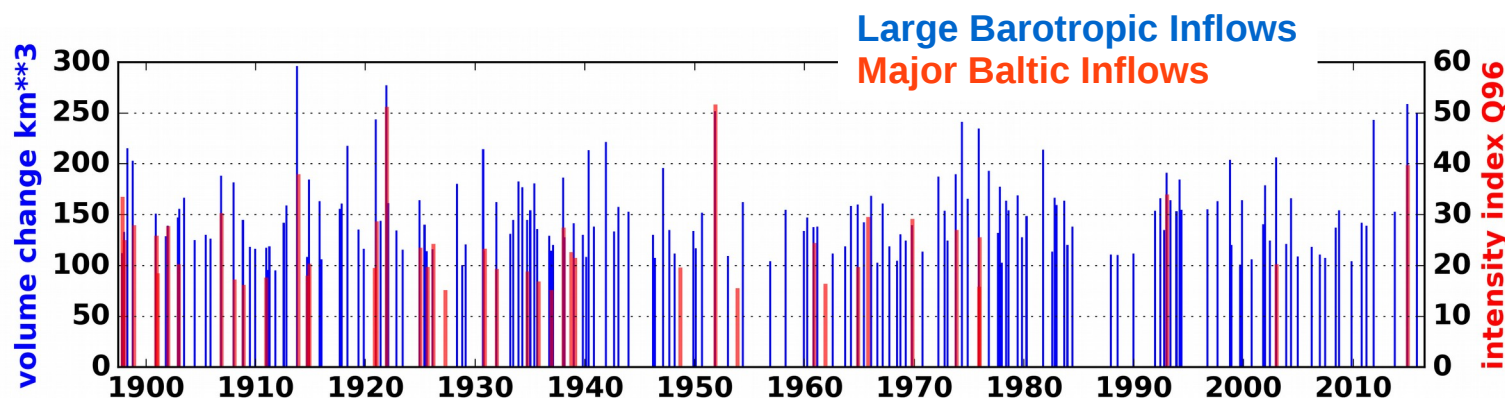


Figure: Barotropic inflows identified from Landsort sea level variations and major inflows with $Q96 > 15$ after Matthäus et al. 2008 and Mohrholz et al. 2015

Questions: What atmospheric and oceanic factors cause the culmination of a barotropic inflow into a major Baltic inflow? Is the current mechanistic understanding complete?

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de



Navigation

page 4/21

[Introduction](#) 3 pages

- major Baltic inflows
- motivation and research question

[Results](#) 10 pages

- key ingredients to major Baltic inflows
- sensitivity experiment with Dec/2014 inflow
- salinity dynamics along Great Belt route

[Data and Methods](#) 3 pages

- time series from an OGCM
- correlation and regression analysis on key ingredients to major Baltic inflows
- sensitivity experiment with major inflow of Dec/2014 as proof of concept
- salinity dynamics along Great Belt route to understand factors for the prerequisite

[Summary](#) 2 pages

- improved mechanistic understanding
- greater context of this work

[Further Thoughts](#) 1 page

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Data ▪ Time Series from an OGCM

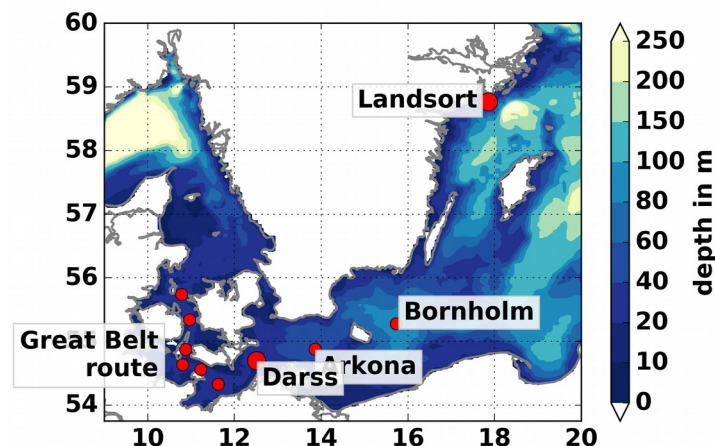
page 5/21

Baltic Sea Ice Ocean Model setup for the hindcast period 01/1979—01/2016

- atmospheric forcing taken from ERA-Interim reanalysis data (Dee et al. 2011)
- monthly runoff for period 1979—2010 corrected using annual accumulated runoff for extension into 2015 (e.g. Lehmann et al. 2014)
- water mass characteristics of North Sea are relaxed to climatology and sea level variations are calculated from Baltic Sea Index (e.g. Lehmann et al. 2014)
- 2.5 km horizontal resolution, 3 m vertical resolution, 240 sec time stepping

Time series used:

- **Landsort sea level** as measure for Baltic Sea water level variations
- **hydrographic profiles** along Great Belt route from southern Kattegat over Darss Sill into Arkona and Bornholm basin



Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Methods 1 - Ingredients to Major Baltic Inflows

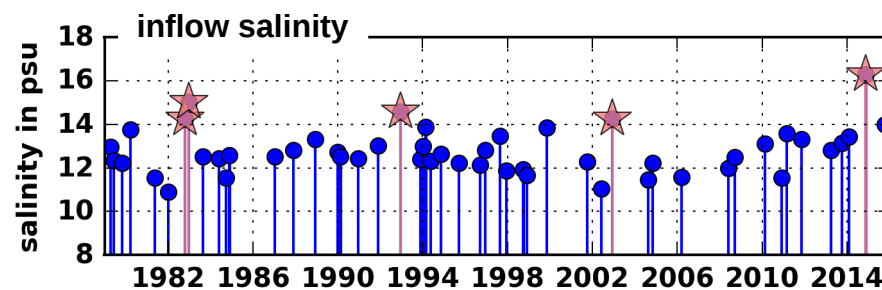
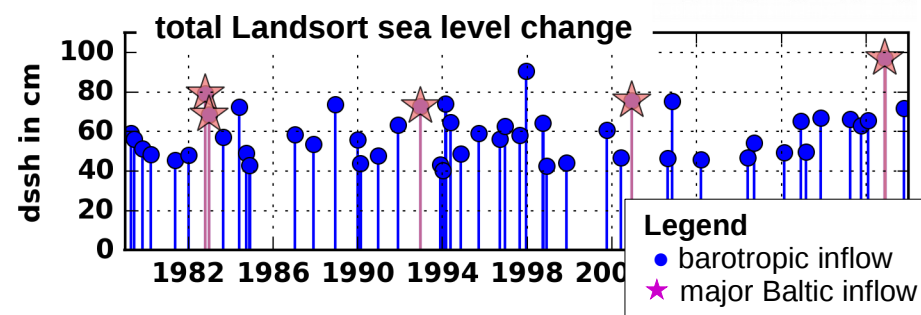
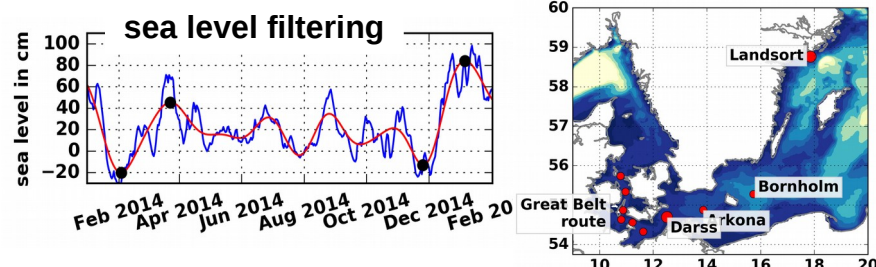
page 6/21

barotropic inflows are identified from low-pass filtered Landsort sea level using a Butterworth filter with 1.45 month cutoff period

large barotropic inflows: inflows greater than 100 km^3 (about 40cm) which marks lower limit for major Baltic inflows at $100\text{--}300 \text{ km}^3$

salinity of large barotropic inflows: average salinity at Darss Sill between minimum and maximum water level (= inflow phase)

major Baltic inflows are the most saline inflows!



Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

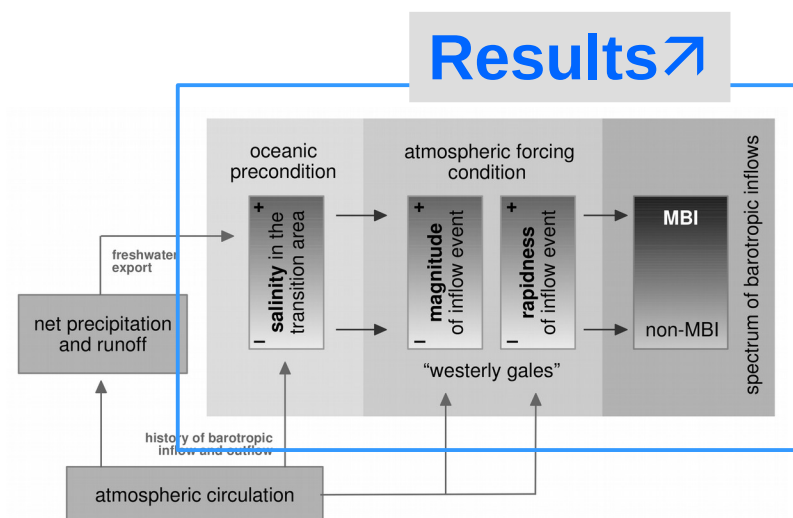
Methods 1 - Ingredients to Major Baltic Inflows

page 7/21

Idea: understand ingredients by explaining occurrence of major inflows within large barotropic inflow spectrum → predict salinity of barotropic inflow from atmospheric and oceanic conditions using correlation and multiple linear regression analysis

potentially important factors:

- magnitude/rapidness of inflow event determined by strength/duration of wind
- penetration of Kattegat waters along Great Belt route (= salinity in transition area)
- absolute Baltic water level as prerequisite for potential amount of inflowing water
- freshwater input during the event



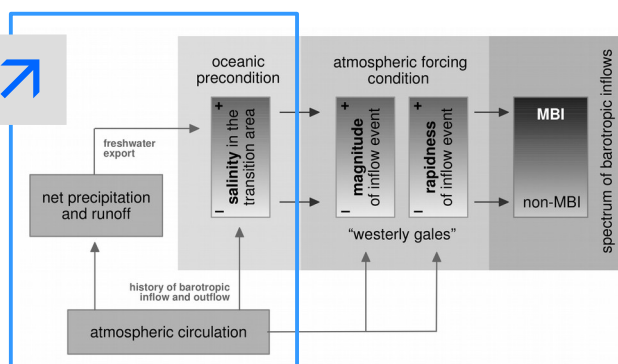
Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Methods 2 and 3 - Salinity and Sensitivity Experiment

page 8/21

Results 



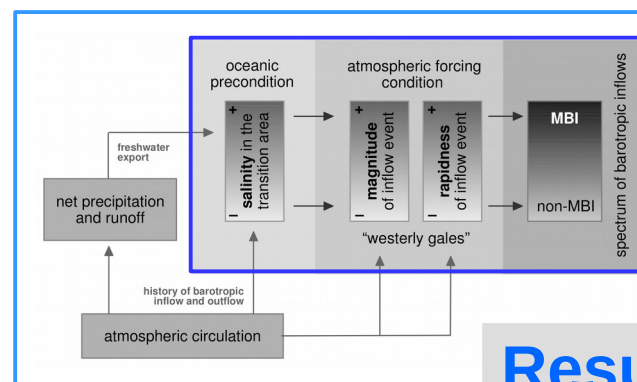
Idea: Proof of concept! Can the efficiency of the strong major inflow of Dec/2014 be reduced?

simulate major Baltic inflow from less favorable saline conditions and investigate effect on Bornholm Basin

Idea: better understand impact of atmospheric circulation and freshwater on salinity structure in transition area

- understand daily variations
- interannual variations in seasonal cycle
- sensitivity experiment for freshwater

 back to Navigation



Results 

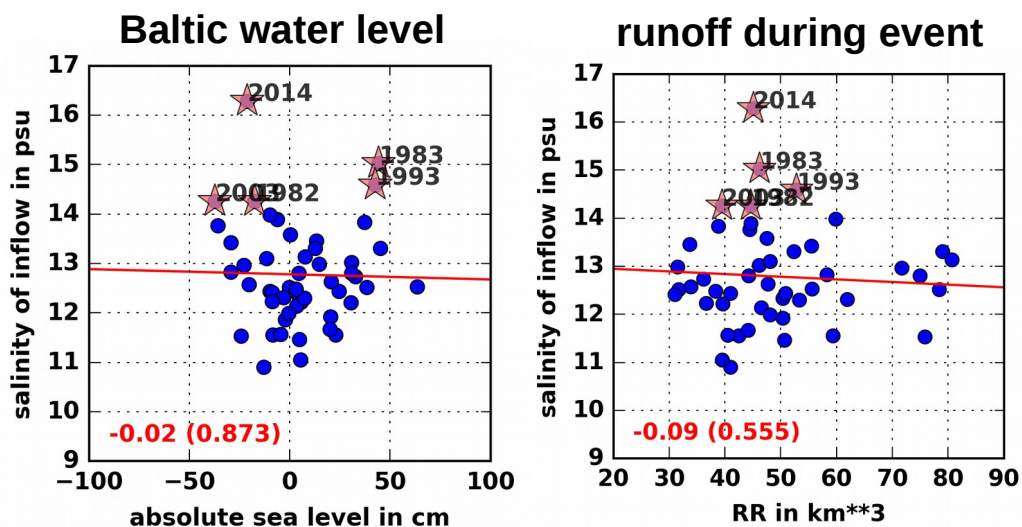
Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 1 - Key Ingredients to Major Baltic Inflows

page 9/21

Are absolute Baltic Sea water level and freshwater input during the inflow event related to occurrence of major inflows?



Legend

- barotropic inflow
- ★ major Baltic inflow

method: correlation of inflow salinity with absolute Landsort sea level at onset of event and total volume input by runoff during the inflow phase

absolute Baltic water level and freshwater input during event are not related to salinity of inflow and with that to occurrence of major inflows

interestingly, below average water levels have been stated as important prerequisite for the occurrence of major inflows and absence of inflows was related to periods with high freshwater input and high water level e.g. Schinke and Matthäus 1998

⏪ back to Navigation

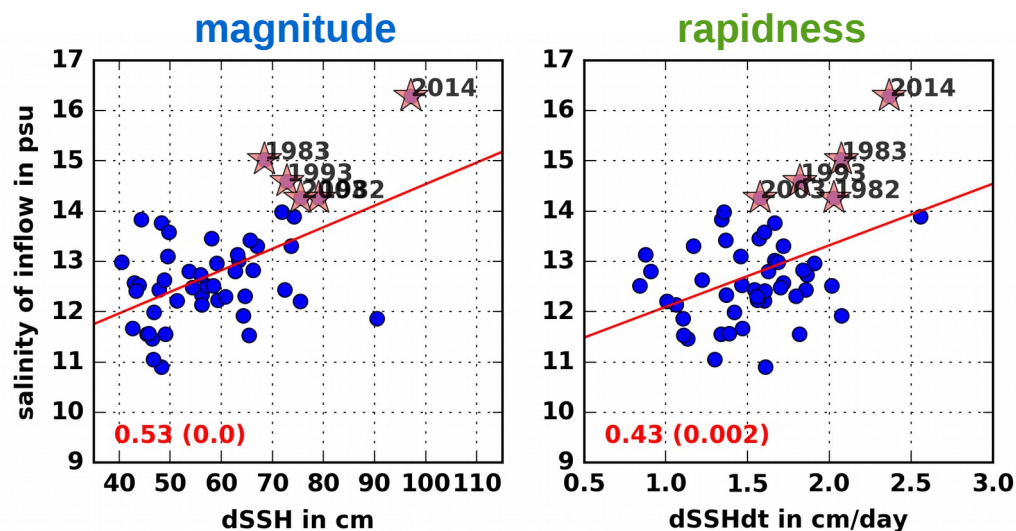
Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 1 - Key Ingredients to Major Baltic Inflows

page 10/21

Are atmospheric conditions such as strength and duration of the westerly wind during the inflow phase related to the occurrence of a major inflow?



method: correlation of inflow salinity with magnitude and rapidness of inflow event as measure for strength/duration of westerly wind

magnitude and rapidness of event are good predictors for salinity of inflow event

→ strength and duration of westerly wind are important

Legend

- barotropic inflow
- ★ major Baltic inflow

⏪ back to Navigation

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

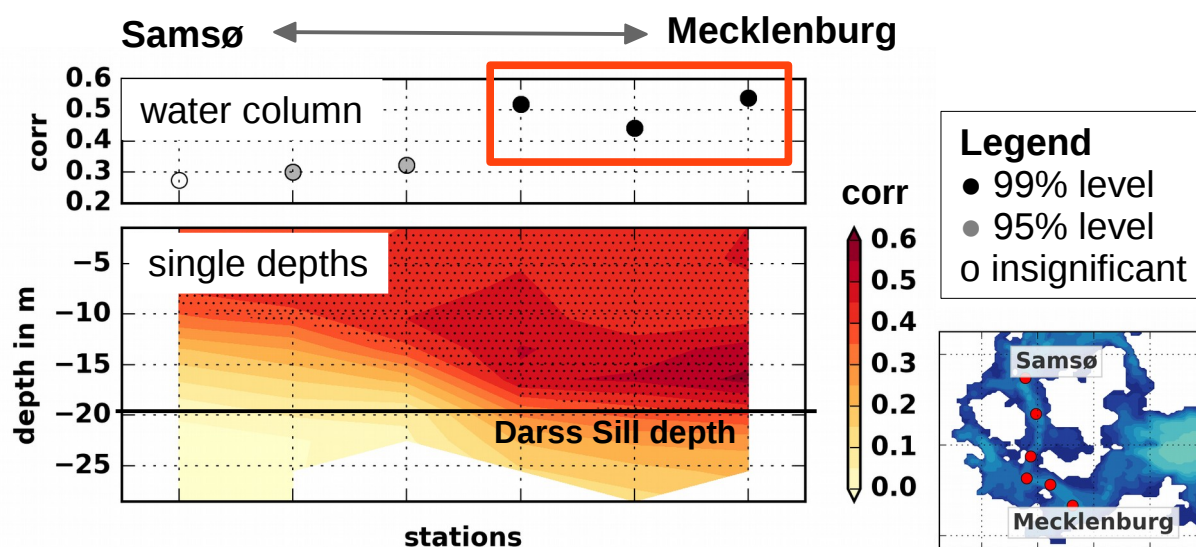
by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 1 - Key Ingredients to Major Baltic Inflows

page 11/21

Is salinity along the Great Belt route related to the occurrence of major inflows?

method: correlate inflow salinity with salinity of water column and at different depths in the Belt Sea directly at onset of the inflow event



inflow salinity strongly related to salinity of the water column south of Langeland Belt

highest correlation found for Mecklenburg Bight at 18 m depth

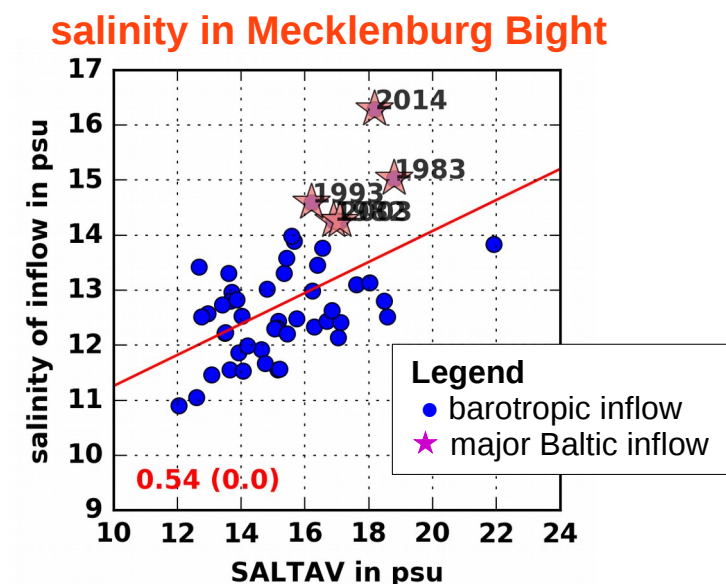
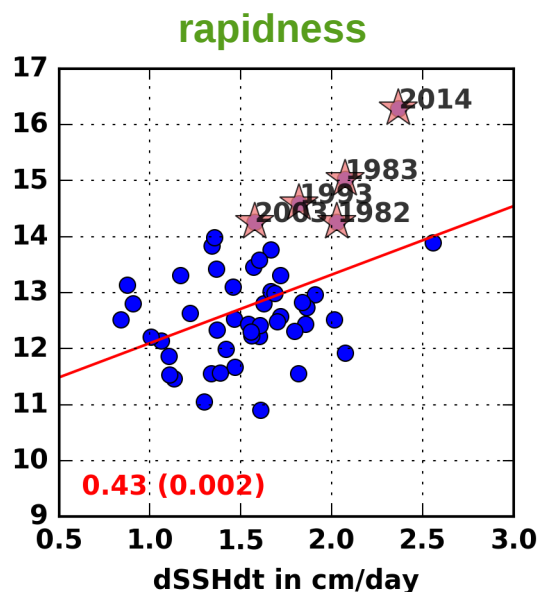
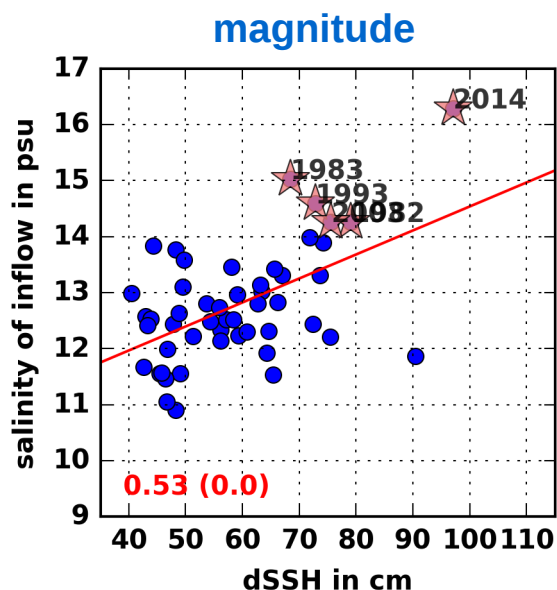
→ thickness and penetration of saline bottom layer towards sill is an important prerequisite?

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 1 - Key Ingredients to Major Baltic Inflows

page 12/21



Both atmospheric forcing and salinity prerequisite are of similar importance, how well do they predict the occurrence of a major inflow and should salinity be included for an improved mechanistic understanding?

[back to Navigation](#)

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de



Results 1 - Key Ingredients to Major Baltic Inflows

page 13/21

Should salinity be included for an improved mechanistic understanding?

method: multiple linear regression with true and predicted salinity according to $S = a \cdot \text{SALTAV} + b \cdot \text{dSSH} + c \cdot \text{dSSHdt} + d$



single predictor correlations

SALTAV	(*) significant	R = 0.54*
dSSH		R = 0.53*
dSSHdt		R = 0.43*

multiple predictor correlations

dSSH + dSSHdt	R = 0.62*
SALTAV + dSSH	R = 0.70*
SALTAV + dSSHdt	R = 0.72*
dSSH + dSSHdt + SALTAV	R = 0.80*

dSSH = magnitude of event
dSSHdt = rapidness of event
SALTAV = Belt Sea salinity

correlation between predictors

dSSH and dSSHdt	0.23
SALTAV and dSSH	0.15
SALTAV and dSSHdt	-0.10

salinity as prerequisite and atmosphere as principal forcing function are independent
salinity in transition area considerably improves atmosphere-only prediction

back to Navigation

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

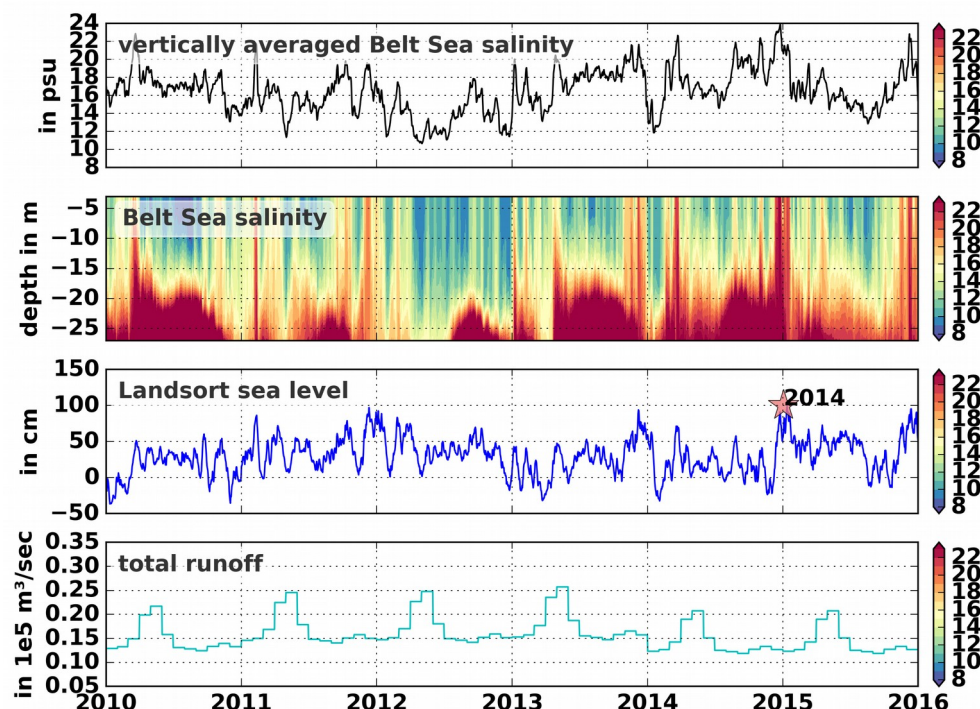


Results 2 - Salinity Dynamics along Great Belt Route

page 14/21

How large are variations in salinity? How do atmospheric forcing and freshwater input to the Baltic Sea determine these?

variations are large on different scales from weekly to interannual
vertically averaged salinity seems related to thickness of bottom layer
barotropic forcing has severe impact upon salinity structure is able to set up and erode the bottom layer
role of freshwater not obvious



[back to Navigation](#)

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

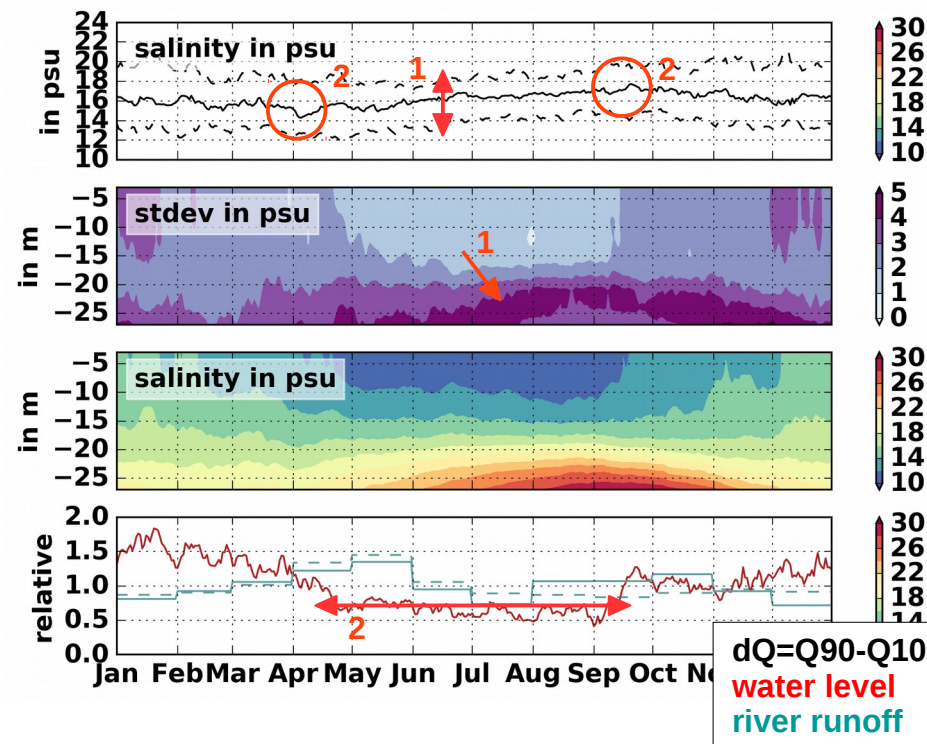
by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 2 - Salinity Dynamics along Great Belt Route

page 15/21

How large are variations in salinity? How do atmospheric forcing and freshwater input to the Baltic Sea determine these?

- (1) seasonal variations depend on characteristics of bottom layer where largest interannual variations are found
- (2) increase in average salinity from April to September linked to setup of saline bottom layer developing during calmer summer
role of freshwater not obvious



Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

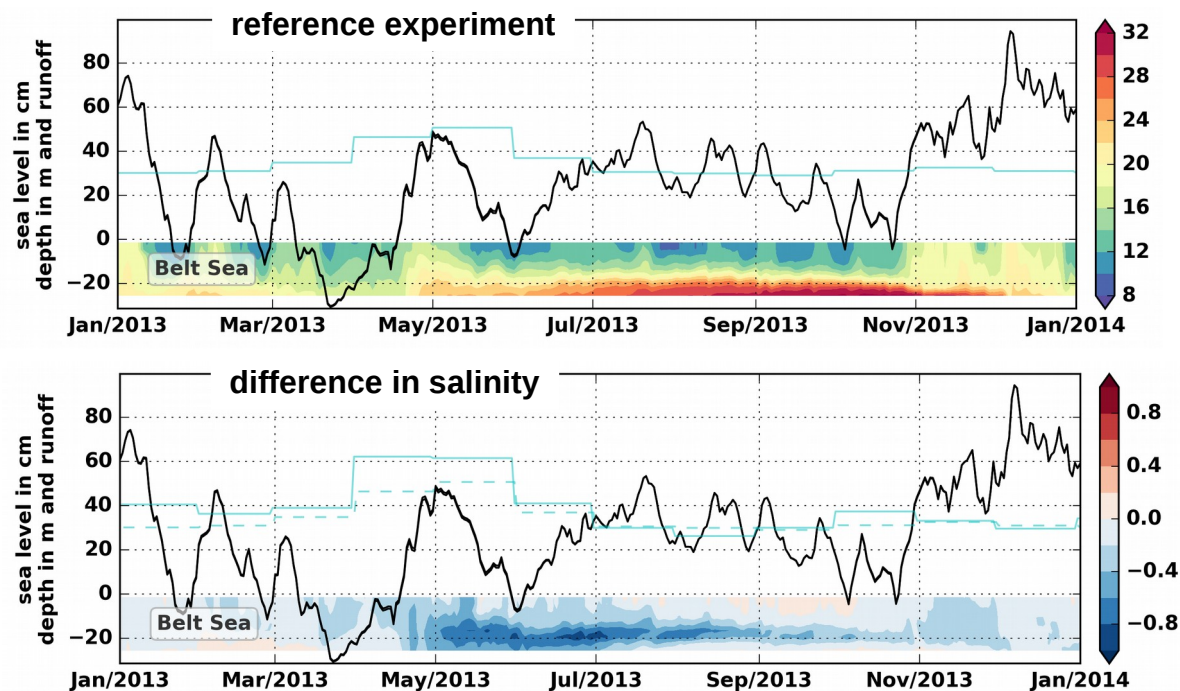
Results 2 - Salinity Dynamics along Great Belt Route

page 16/21

What is the impact of freshwater input?

method: sensitivity experiment
keeping atmospheric forcing and initial conditions identical but taking runoff from i.e. a different year

higher runoff corresponds to erosion of saline bottom layer and lower salinity in transition area



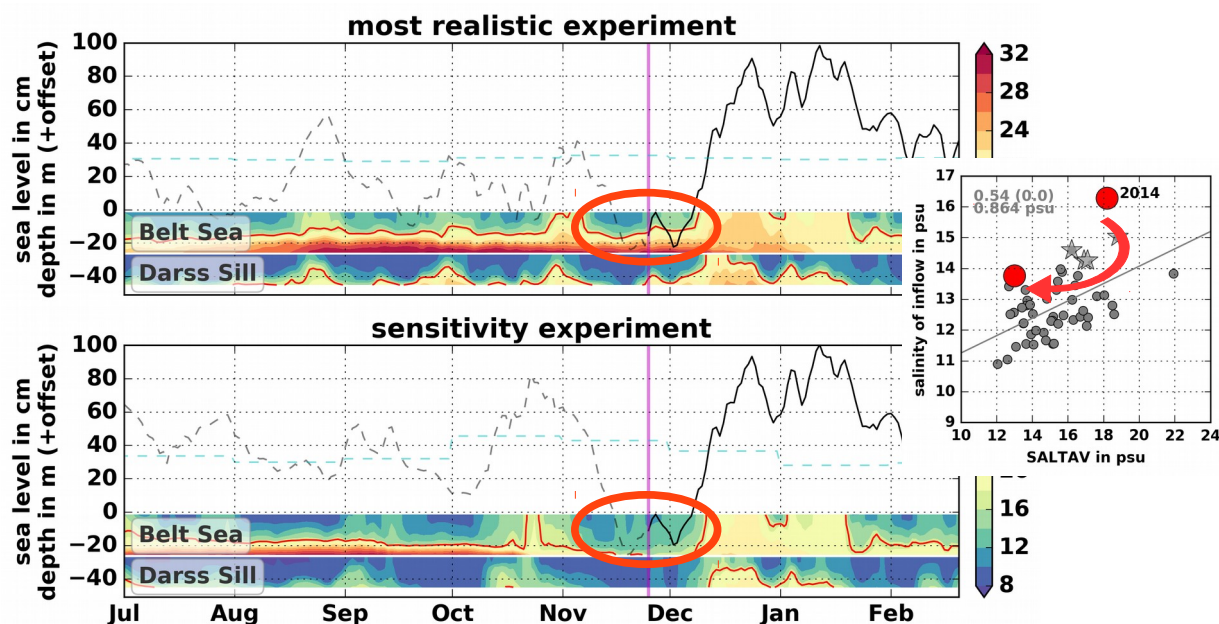
Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Results 3 - Sensitivity Experiment with Dec/2014 Inflow

page 17/21

Is the impact of the third strongest major inflow on record considerably decreased from unfavorable saline conditions in the Belt Sea?



different “history” of atmospheric forcing and freshwater input leads to differences in saline prerequisites

method: take initial conditions from arbitrary year with similar Baltic Sea water level but less favorable saline conditions and simulate the inflow (important to note that such conditions actually exist!)

unfavorable saline conditions in Belt Sea strongly reduce salinity of inflowing water ...

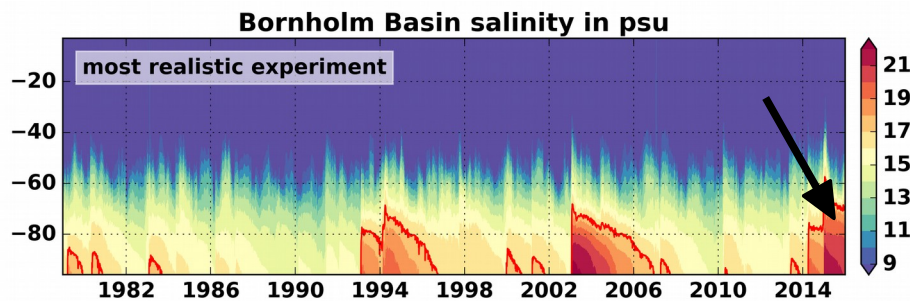
Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

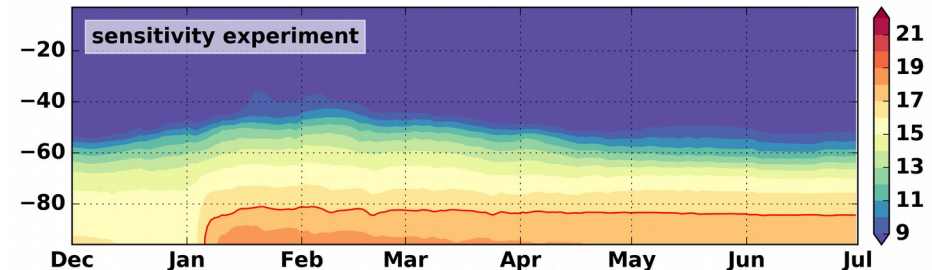
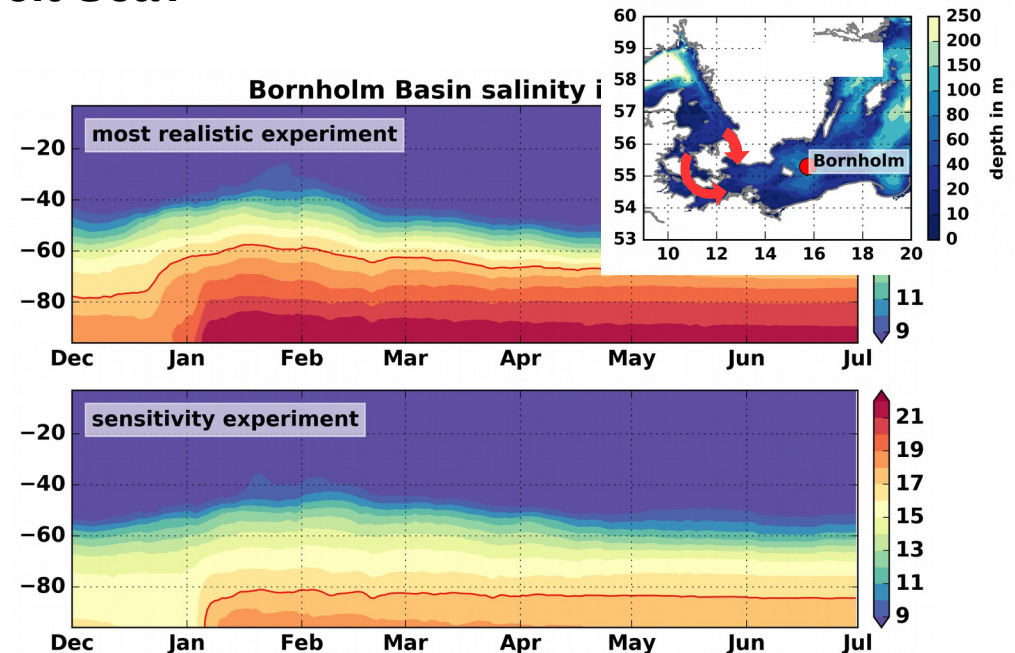
Results 3 - Sensitivity Experiment with Dec/2014 Inflow

page 18/21

Is the impact of the third strongest major inflow on record considerably decreased from unfavorable saline conditions in the Belt Sea?



... and the impact of the inflow on the salinity structure in the Bornholm Basin



Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

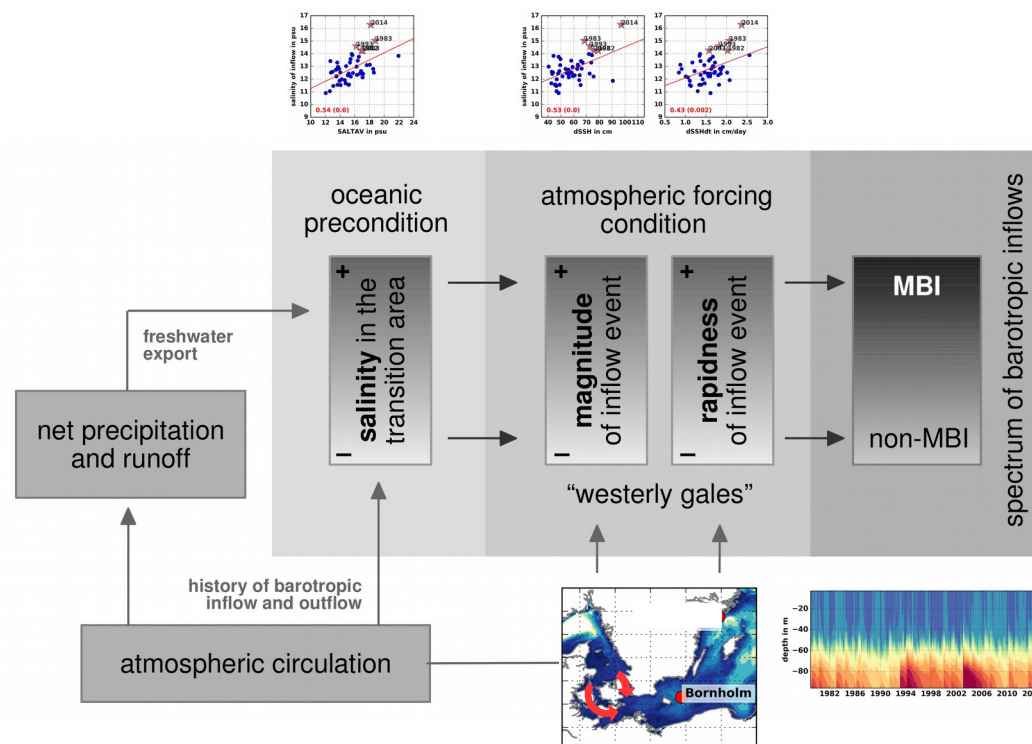
Summary ▪ Improved mechanistic understanding

page 19/21

What factors cause the culmination of a barotropic inflow event into a major Baltic inflow?

the higher the salinity in the Belt Sea and the stronger the atmospheric forcing the more likely the occurrence of a major Baltic inflow

salinity is decreased by higher freshwater input and stronger atmospheric circulation so that calm and dry summers increase the chance for occurrence of major inflows



[back to Navigation](#)

See also: Lehmann et al. (2017). Pathways of deep cyclones associated with large volume changes and major Baltic inflows.

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de



Highlights of this Work

page 20/21

consideration of major Baltic inflows in “coherent framework” of barotropic water exchange leads to improved mechanistic understanding of major Baltic inflows and to more holistic understanding of central Baltic deep water ventilation

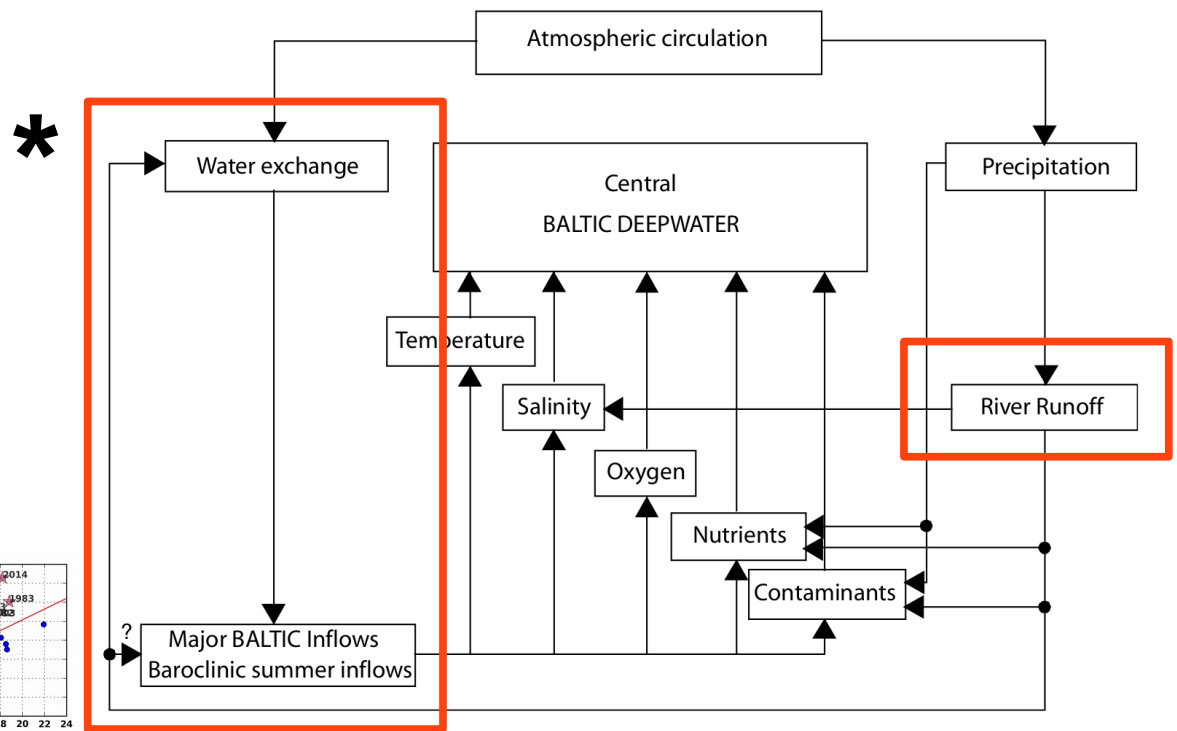
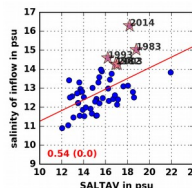
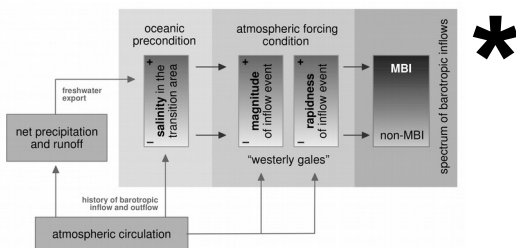


FIGURE 10.10 Schematic diagram of the influence of variability in atmospheric circulation on the central Baltic deepwater (from Matthäus and Nausch, 2003, modified).

from Matthäus et al. 2008, The inflow of highly saline water into the Baltic Sea, in: State and Evolution of the Baltic Sea 1952—2005

Towards an improved mechanistic understanding of major saltwater inflows into the Baltic Sea

by Katharina Höflich, Andreas Lehmann and Kai Myrberg khoeflich@geomar.de

Further Thoughts

page 21/21

What is the benefit from an improved mechanistic understanding?

- might help to better understand the occurrence of “stagnation periods” as single or combined consequence from lack in atmospheric forcing and favorable saline conditions in the Belt Sea (in present day literature there are different opinions about whether freshwater or atmospheric forcing are responsible! both are in principal also related)
- assessments on occurrence of major Baltic inflows in climate change projection studies because the mechanism has to be understood if both study design and conclusions are to be reasonable and of maximum scientific value

