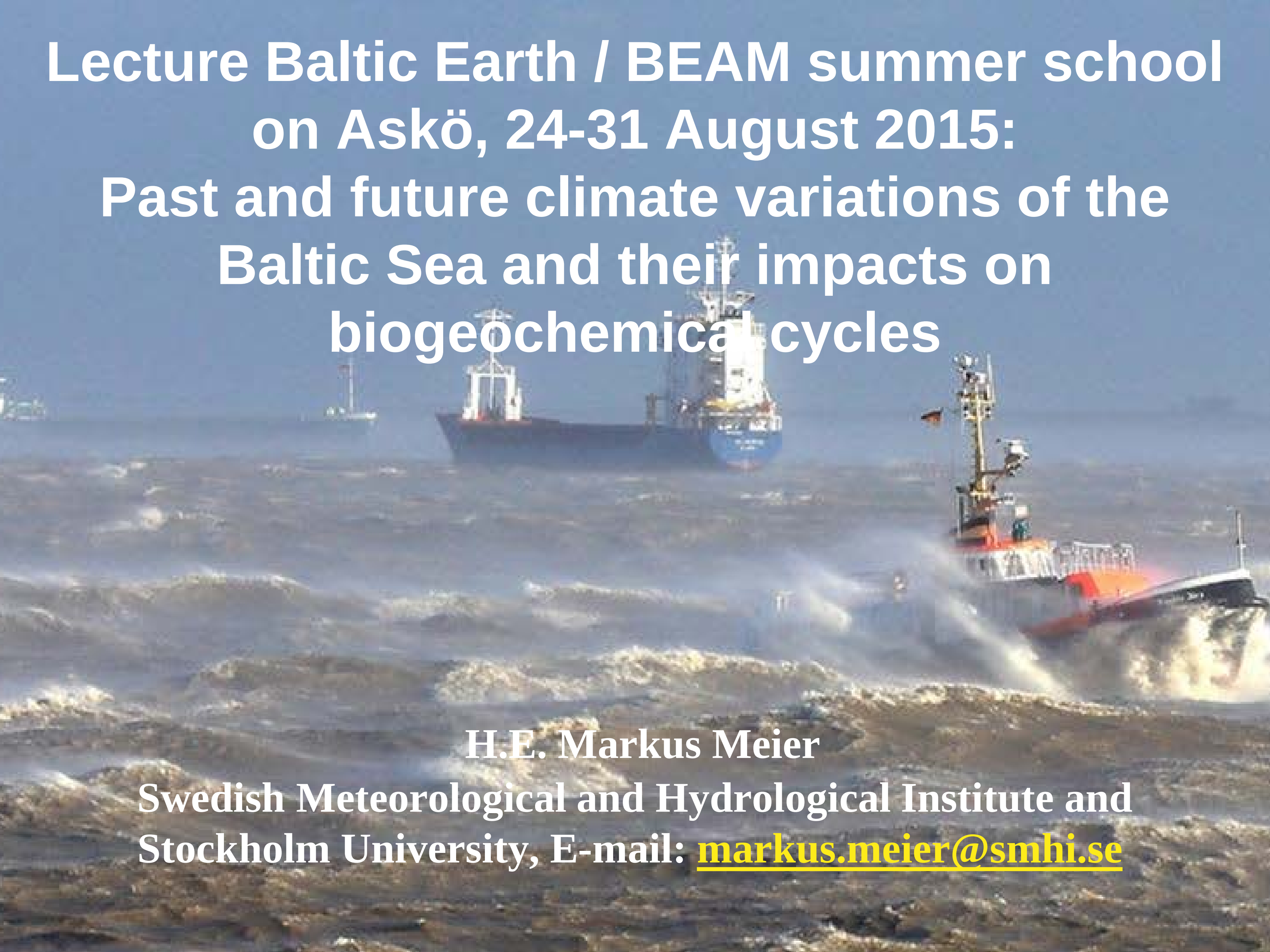
Lecture Baltic Earth / BEAM summer school on Askö, 24-31 August 2015: Past and future climate variations of the Baltic Sea and their impacts on biogeochemical cycles



H.E. Markus Meier
Swedish Meteorological and Hydrological Institute and Stockholm University, E-mail: markus.meier@smhi.se

Take home message:

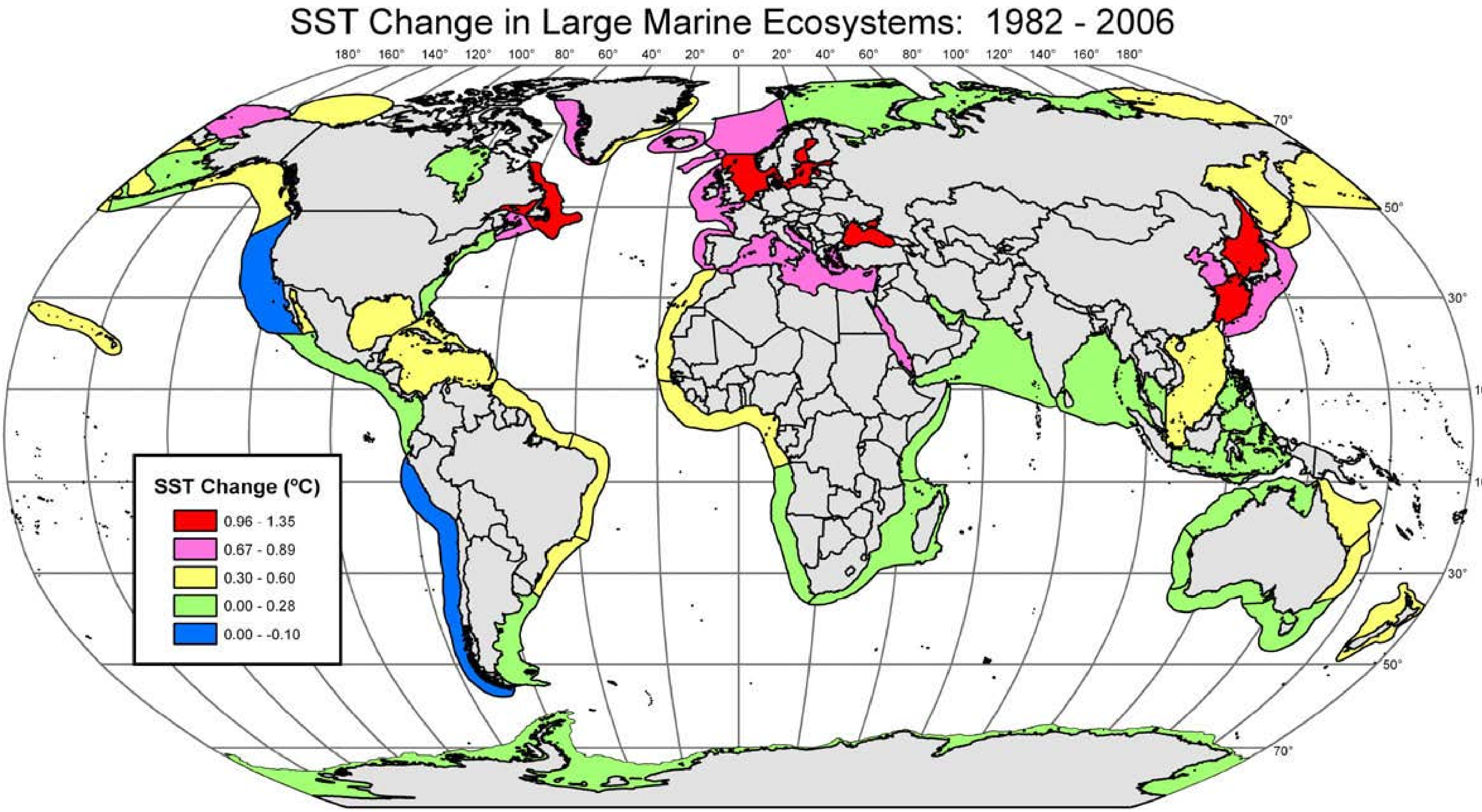
We are still extremely uncertain how climate change will affect the Baltic ecosystem.

Ragnar Elmgren, DEEP,
Stockholm University

What is needed for the production of climate change projections for the Baltic Sea?

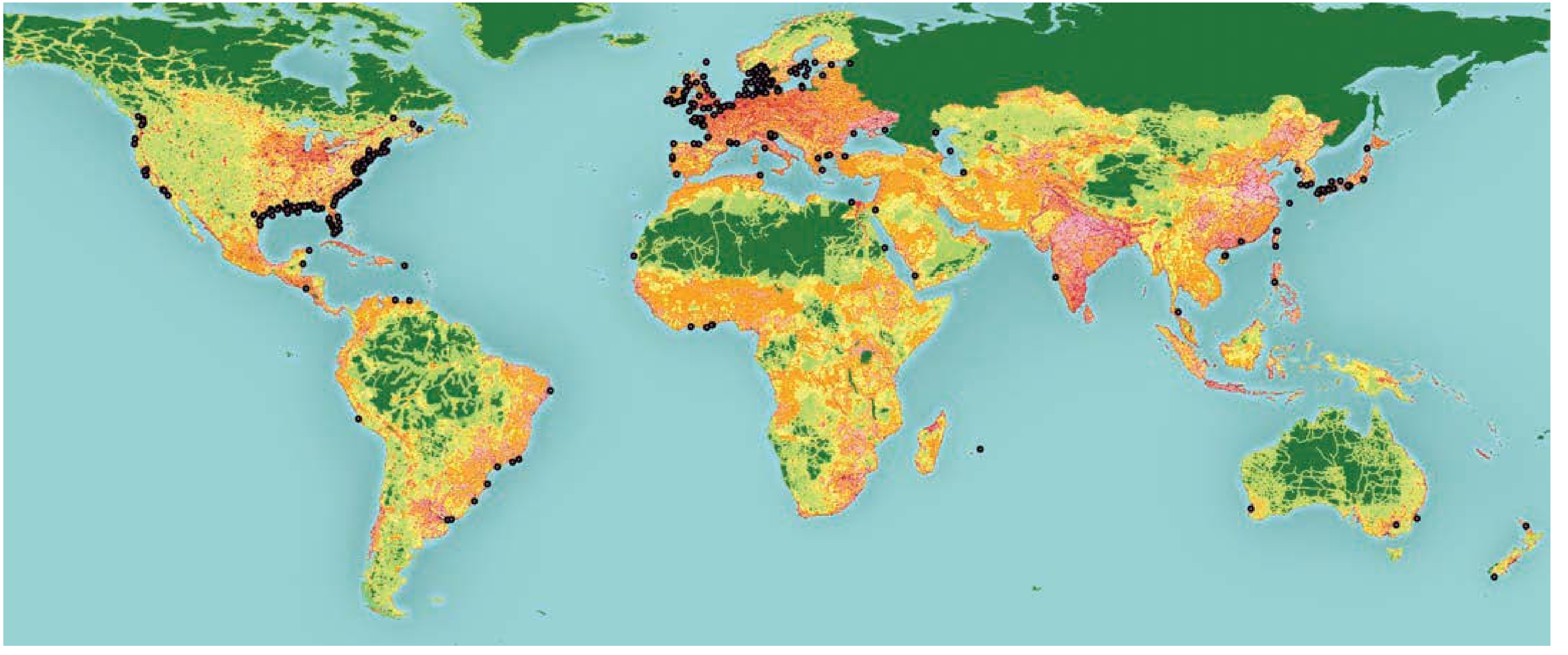
Overview:

1. How does the Baltic work?
2. Decadal climate variability and its causes during the 20th century
3. Regional climate models and dynamical downscaling
4. Uncertainties in projections
5. Projections of Baltic Sea climate at the end of the 21st century:
   - Sea surface temperature
   - Sea ice
   - Salinity
   - Oxygen
   - Cyanobacteria



Net SST change (C) in Large Marine Ecosystems, 1982–2006

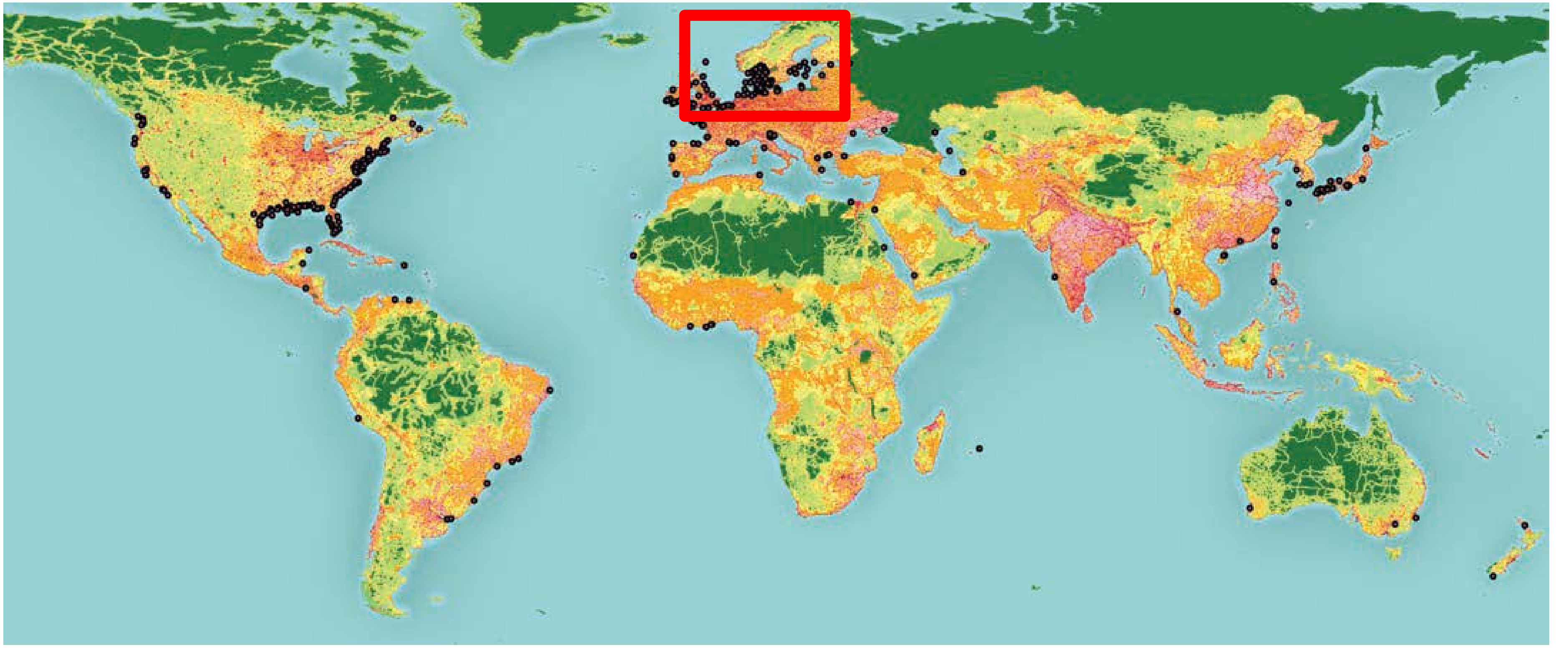
(Source: Belkin 2009)



Eutrophication-associated dead coastal zones

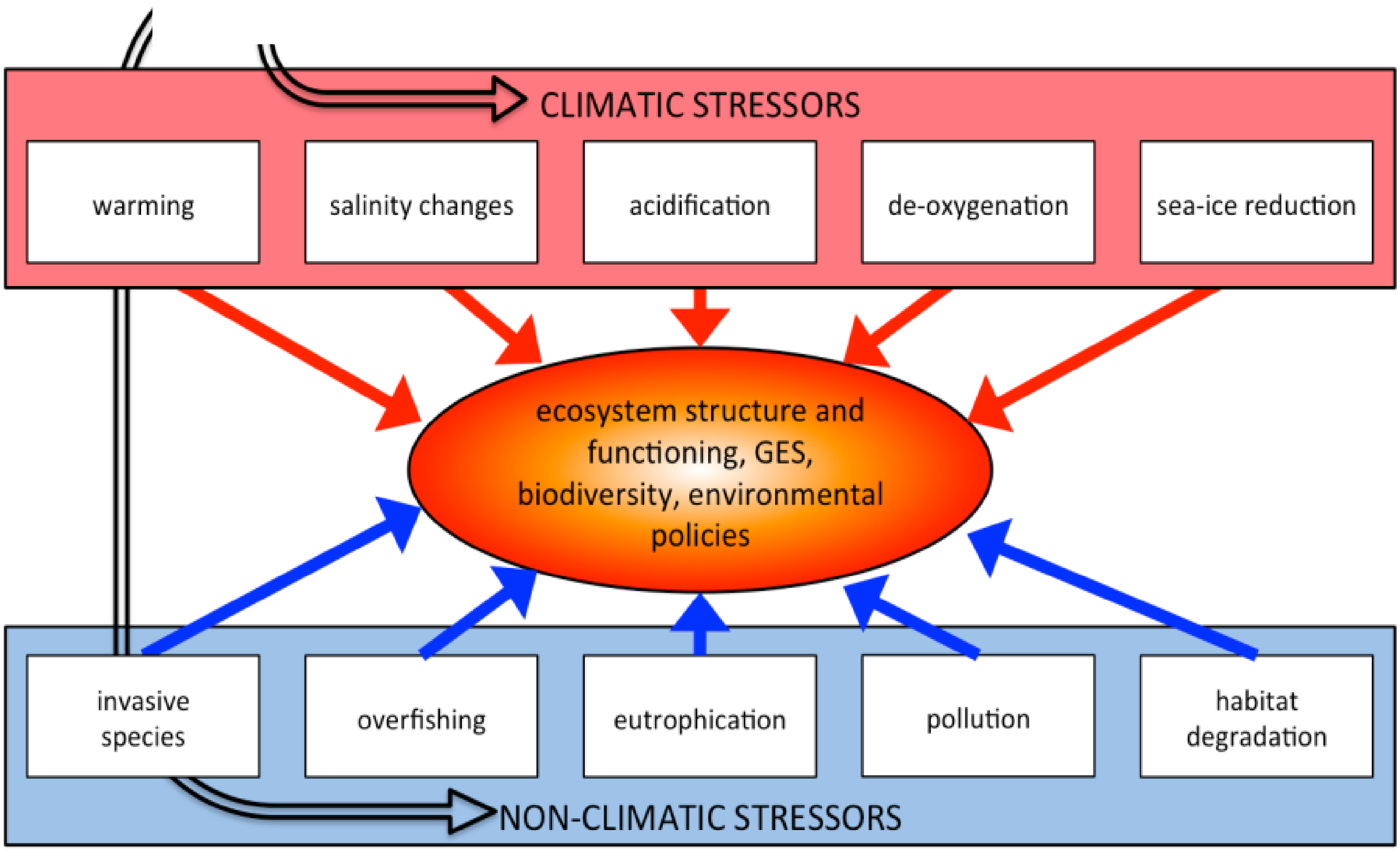
(Source: Diaz and Rosenberg, 2008)

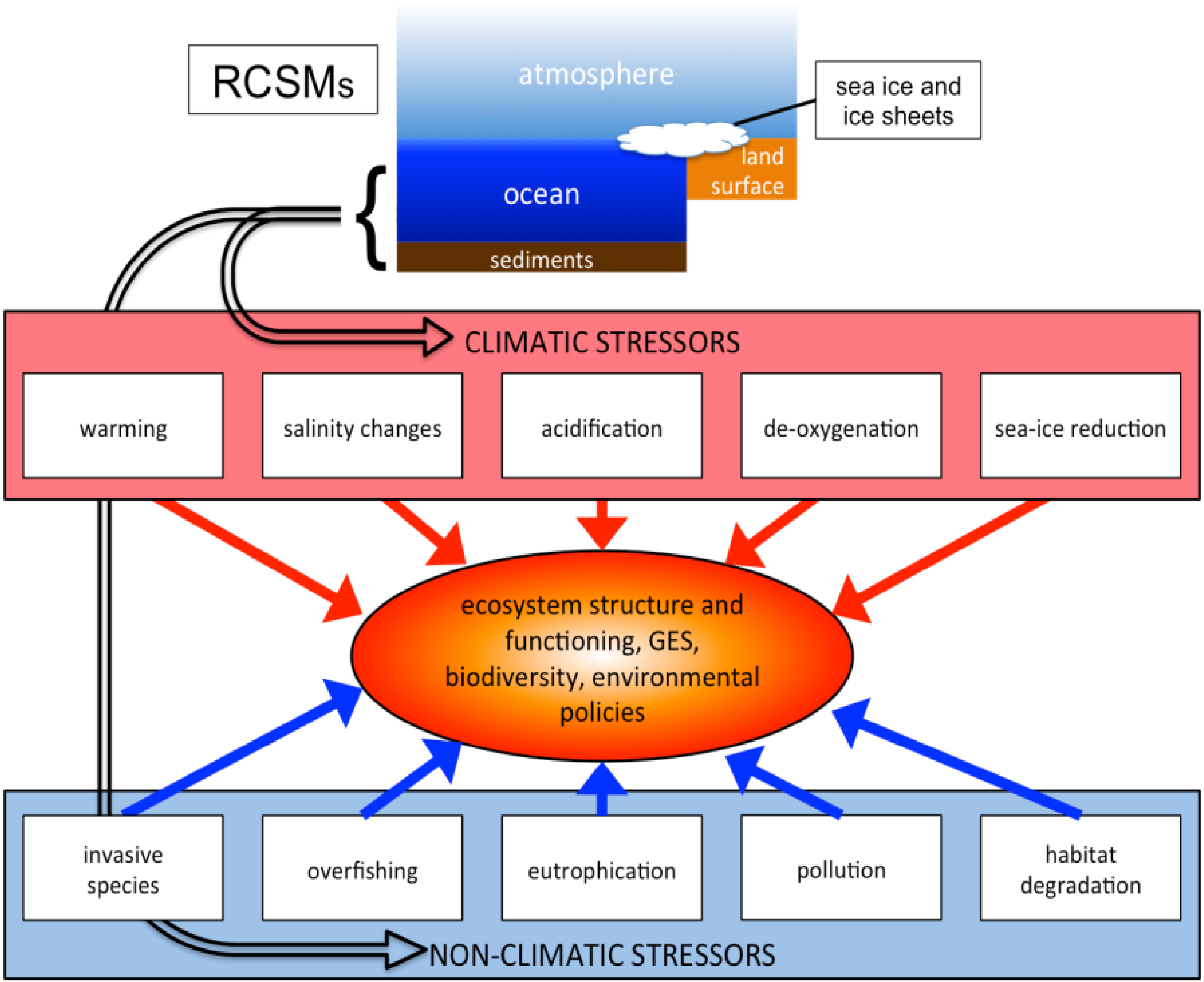
SMHI



Eutrophication-associated dead coastal zones

(Source: Diaz and Rosenberg, 2008)

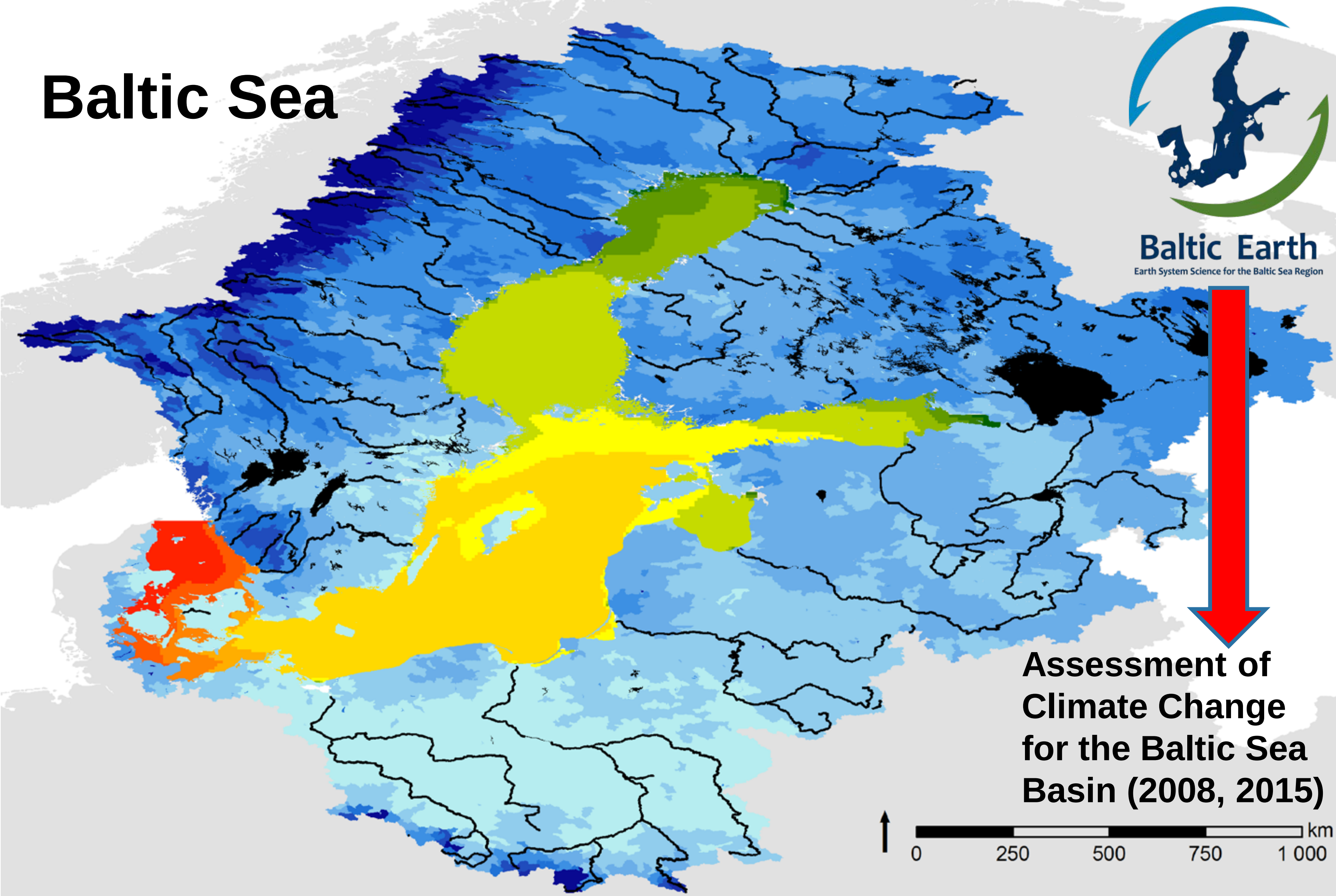

CLIMATIC STRESSORS
warming
salinity changes
acidification
de-oxygenation
sea-ice reduction
ecosystem structure and functioning, GES, biodiversity, environmental policies
invasive species
overfishing
eutrophication
pollution
habitat degradation
NON-CLIMATIC STRESSORS



RCSMs
atmosphere
sea ice and ice sheets
land surface
ocean
sediments
CLIMATIC STRESSORS
warming
salinity changes
acidification
de-oxygenation
sea-ice reduction
ecosystem structure and functioning, GES, biodiversity, environmental policies
invasive species
overfishing
eutrophication
pollution
habitat degradation
NON-CLIMATIC STRESSORS

1. How does the Baltic work?

Baltic Sea

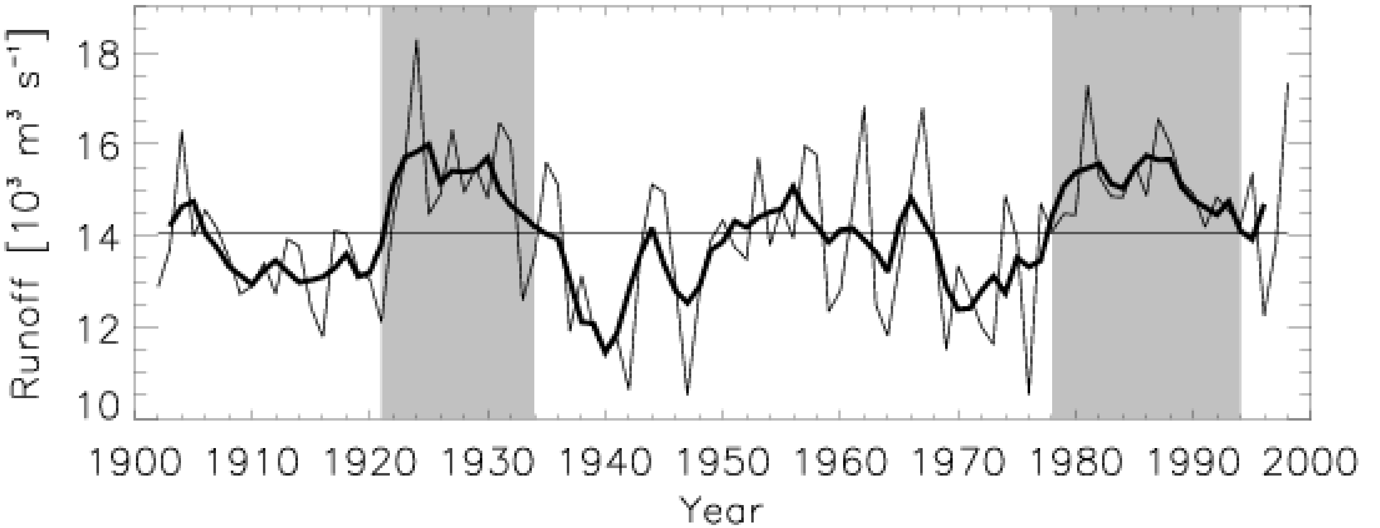


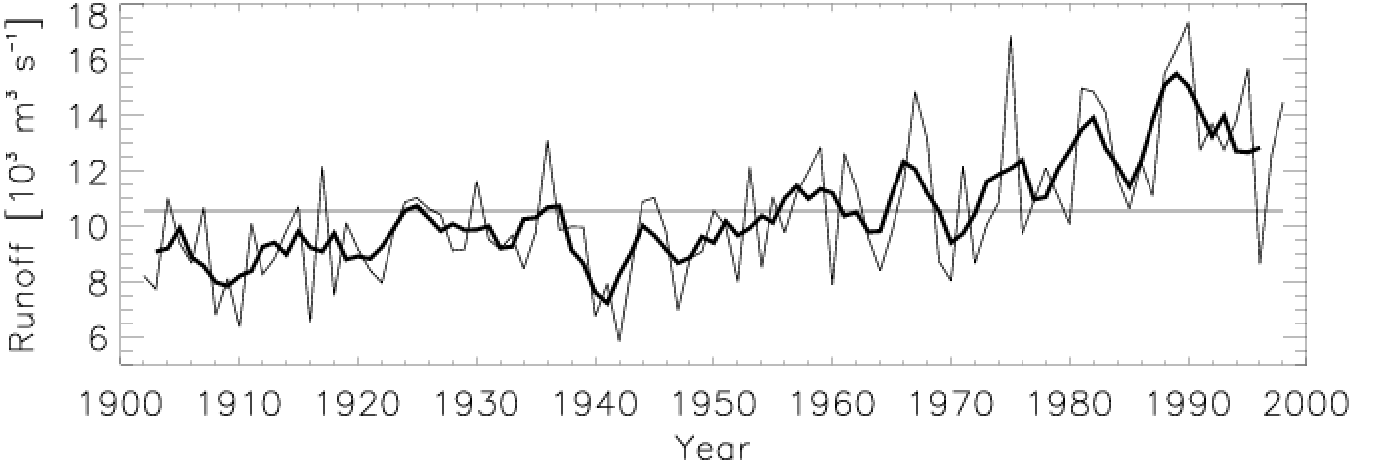
Baltic Earth
Earth System Science for the Baltic Sea Region

Assessment of Climate Change for the Baltic Sea Basin (2008, 2015)

(Source:
Meier et al., 2014; Eos)

Annual and winter (JFM) mean runoff

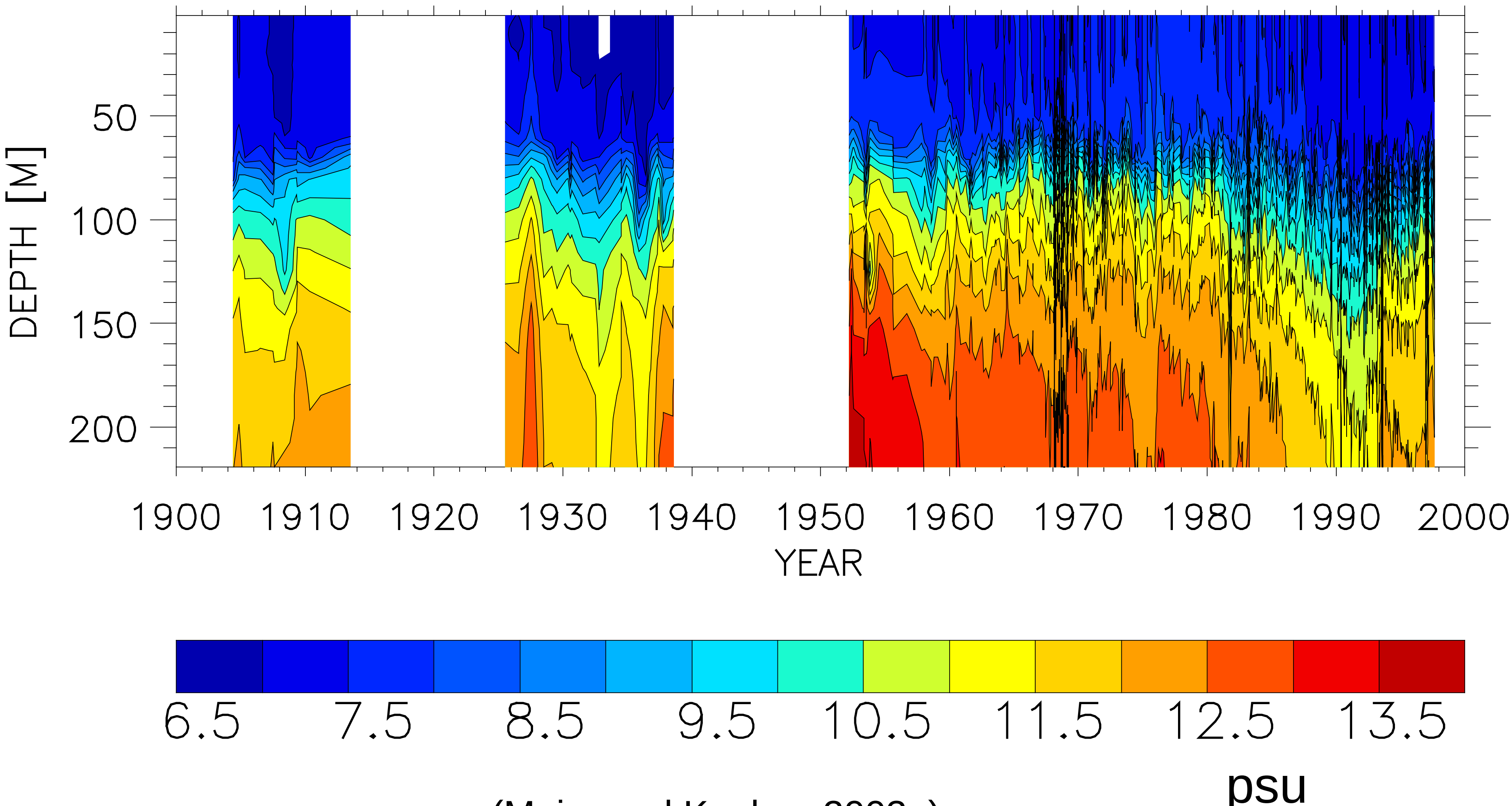




(Meier and Kauker, 2003a)

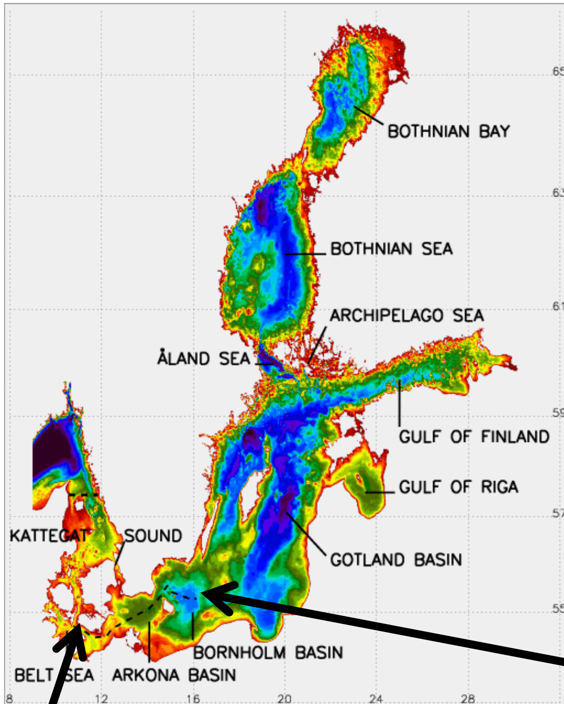
(thick line: 4-year running mean runoff)

Salinity as function of time and depth at Gotland Deep

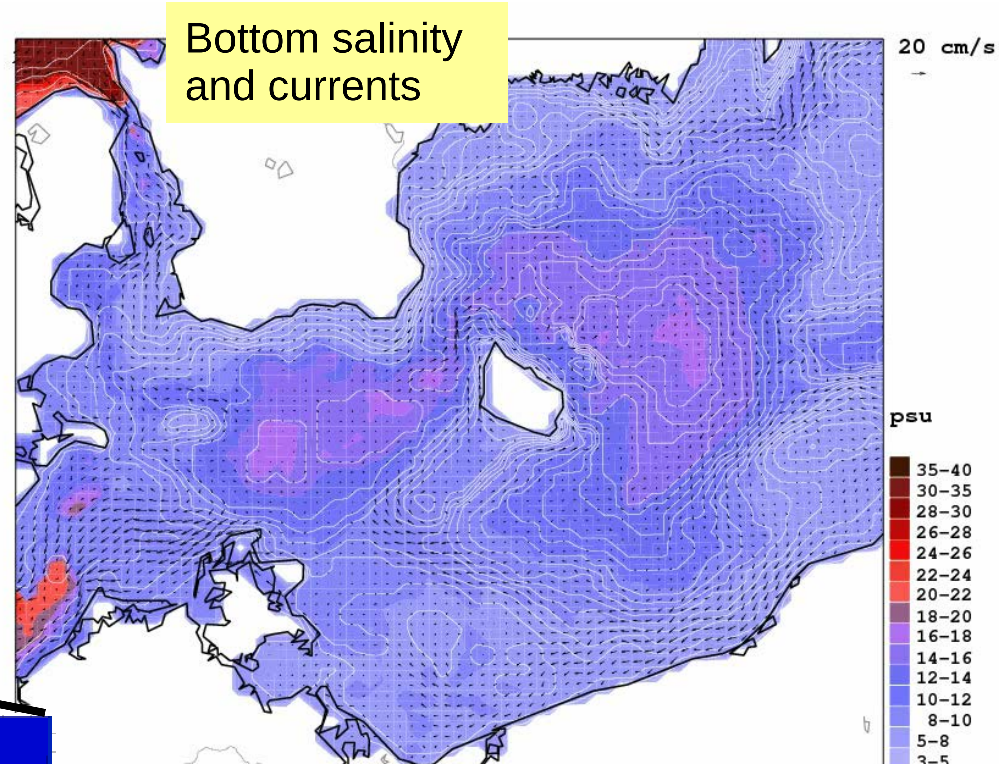


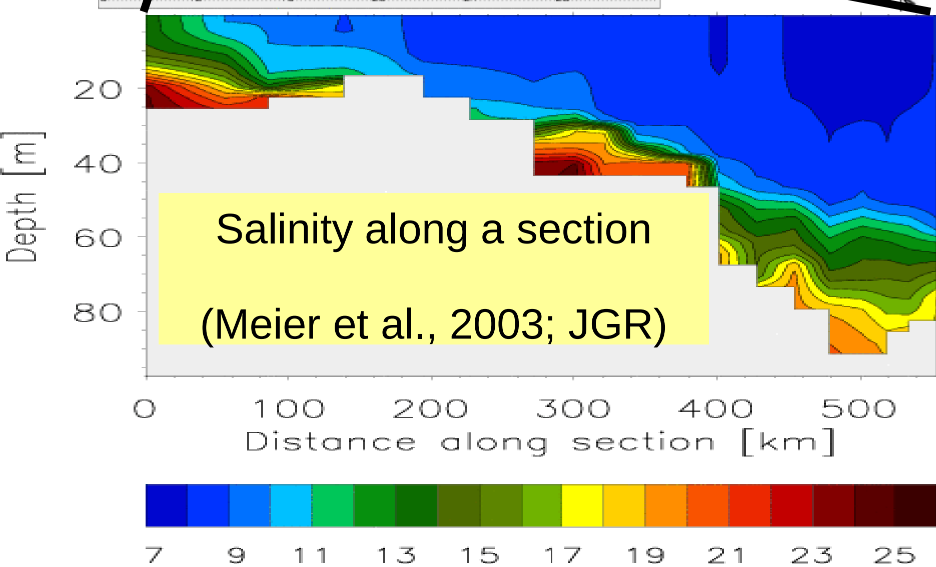
(Meier and Kauker, 2003a)

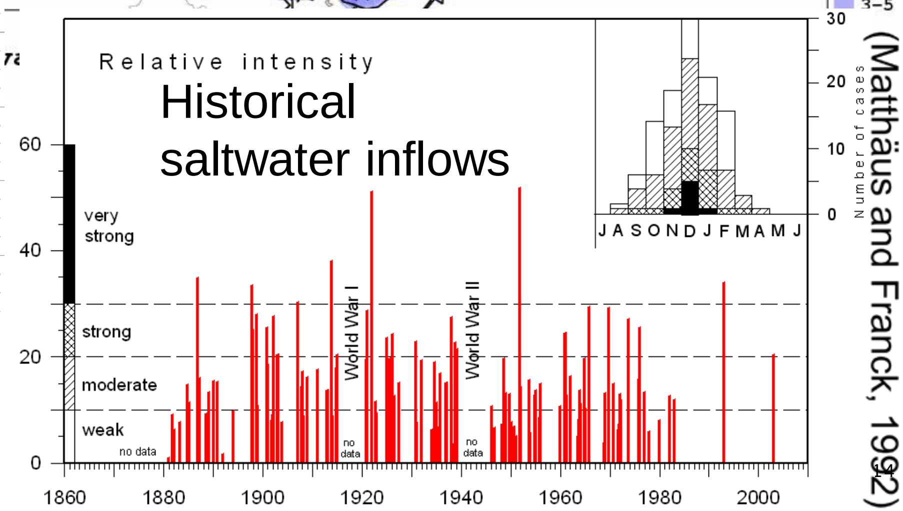
Water exchange between Baltic and North Sea



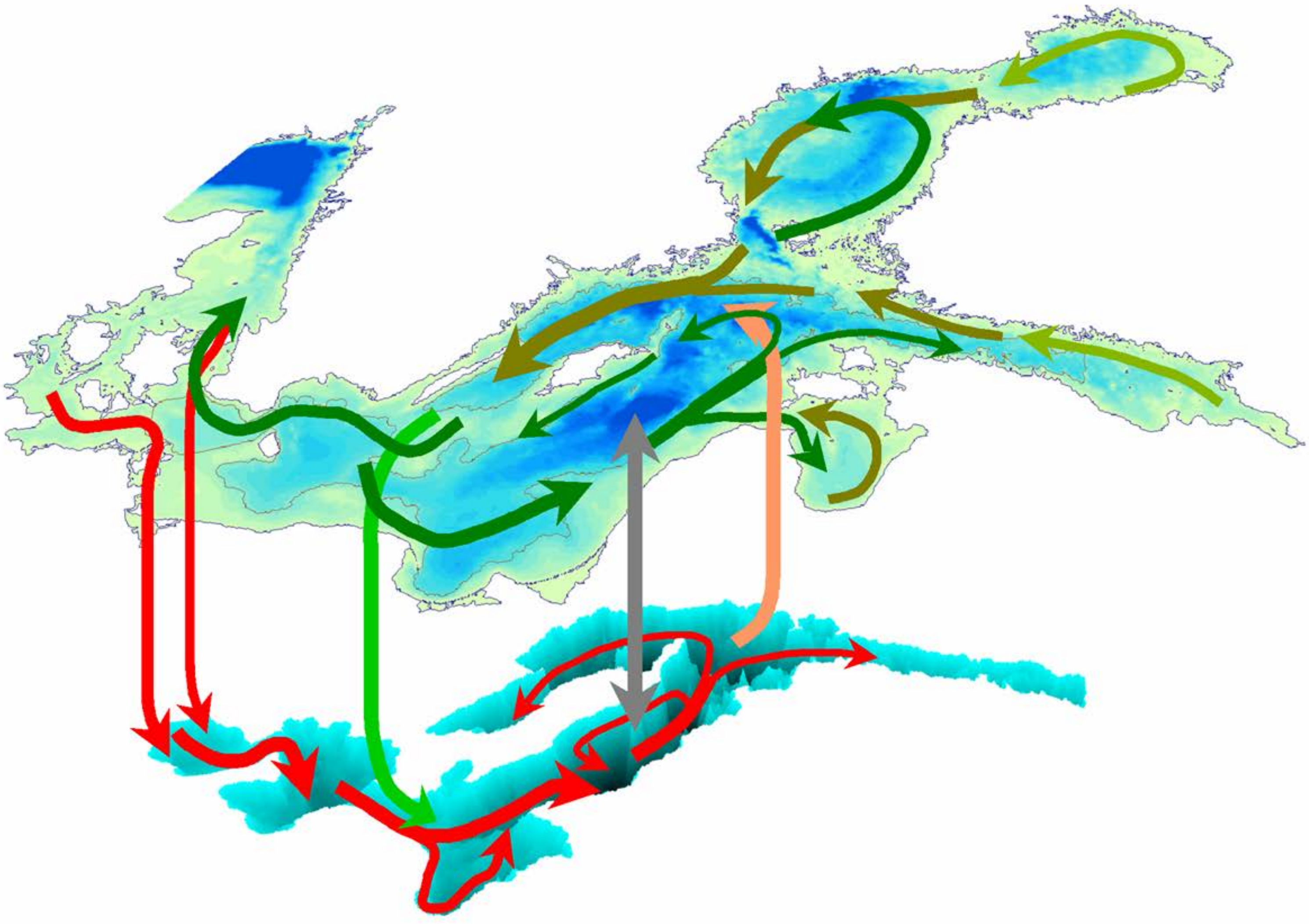
Saltwater inflow January 1993



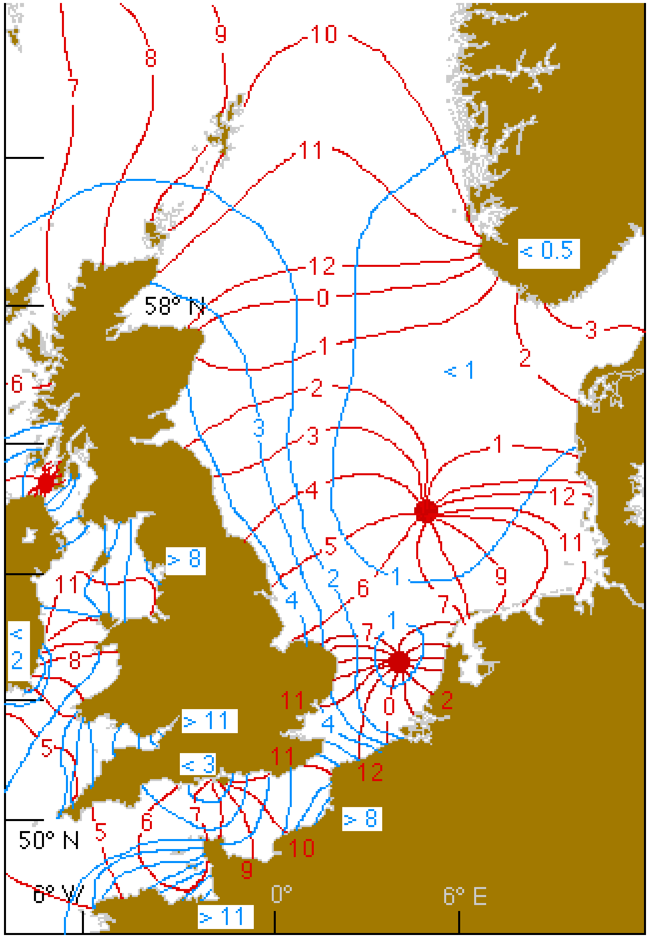




Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2008)

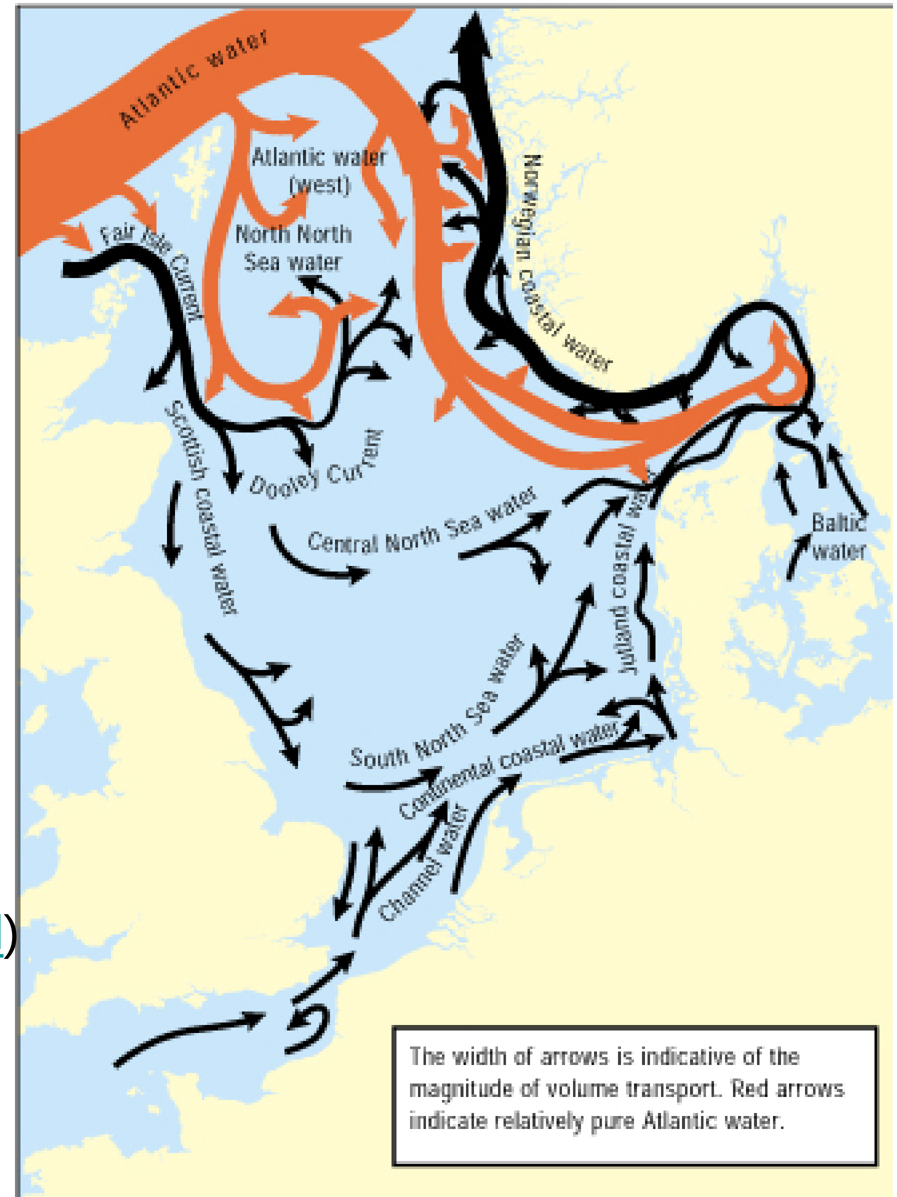


North Sea



Co-phase (in hours) and co-range lines (in metres) for the semidiurnal tides M_2+S_2

(Source: http://www.geog.ucsb.edu/~dylan/ocean.html)

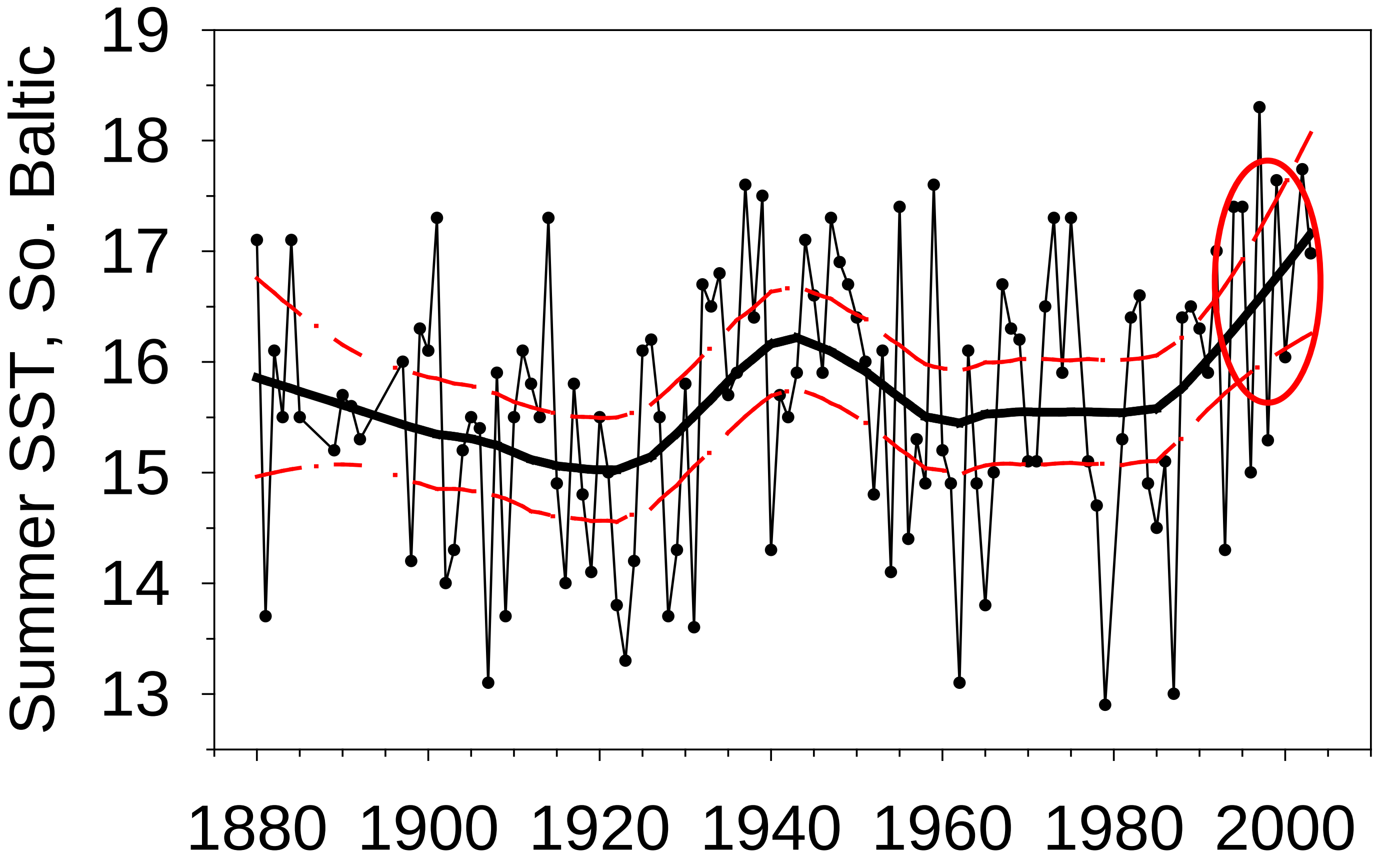


Schematic diagram of general circulation in the North Sea. After Turrell et al. (1992). (Source: OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic)

2. Decadal climate variability

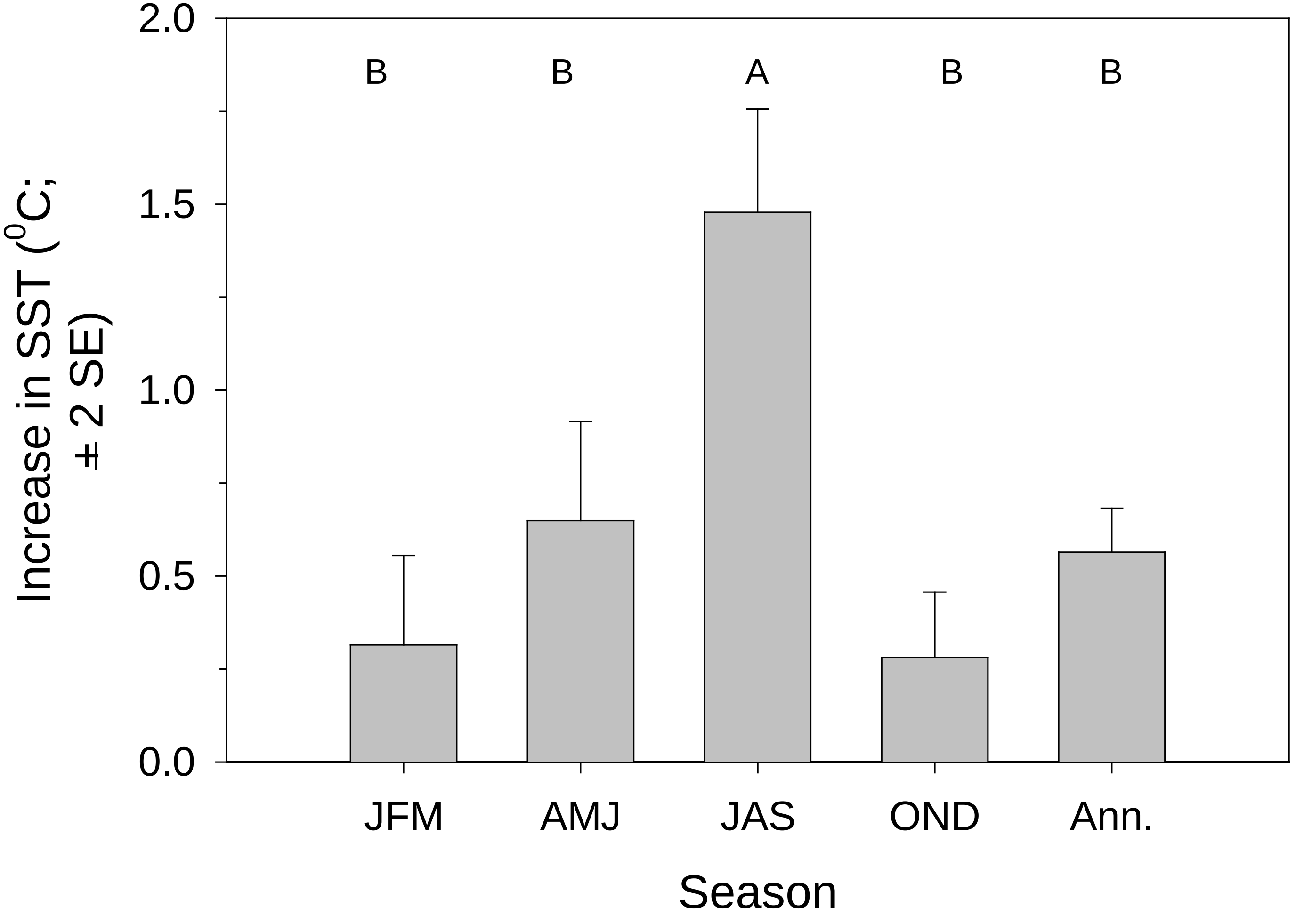
Positive trend of temperature during the 20th century at almost all stations and depths (Fonselius and Valderrama, 2003), no significant trend of salinity (Winsor et al., 2001; Meier and Kauker, 2003a)

Summer (JAS) SST
1880-2003



warm conditions during 1990s-2000s

(Source: MacKenzie & Schiedek 2007)

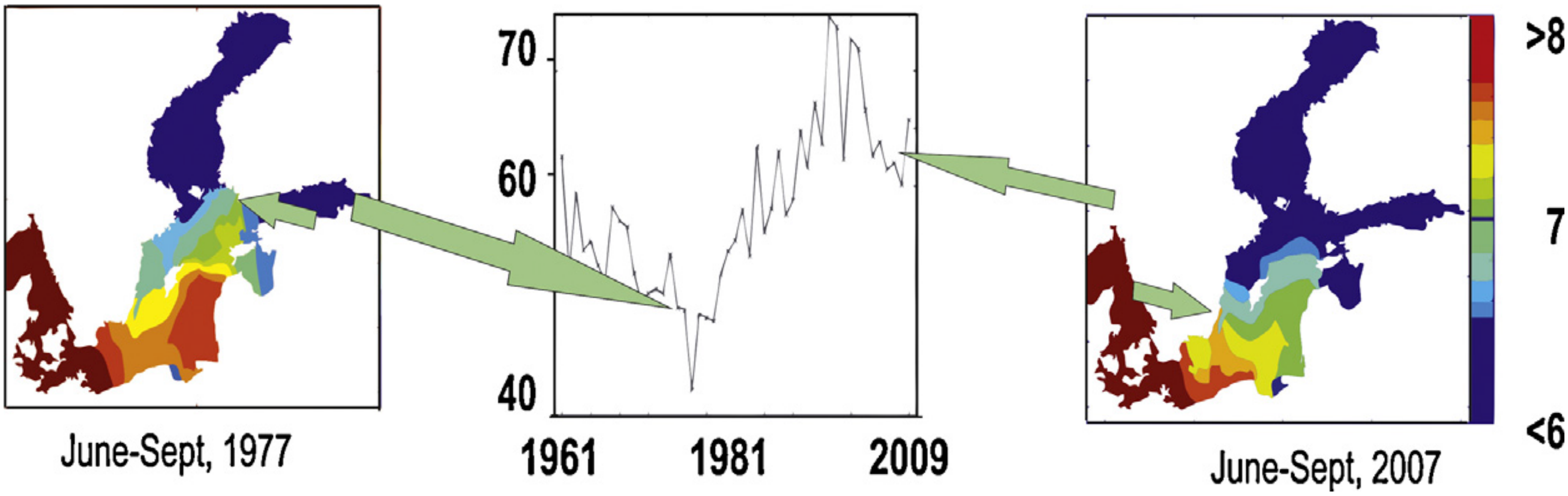


warming rates differ significantly among seasons

summers have warmed most (2-3x other seasons)

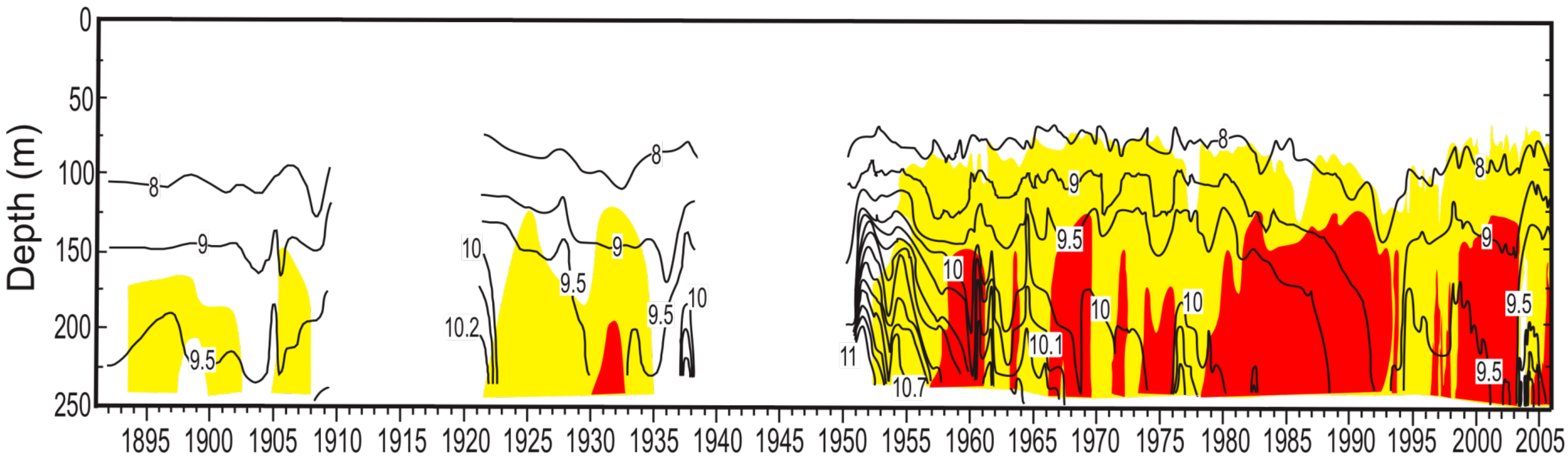
(Source: MacKenzie & Schiedek 2007)

Surface salinity



Percentage of area with sea surface salinity less than 7 in the Baltic Sea during the years 1961–2009 (middle panel) and the Baltic Sea surface water (0–25 m) salinities during the years 1977 (left panel) and 2007 (right panel) (Vuorinen et al., 2014)

Oxygen and density at Gotland Deep 1890-2006



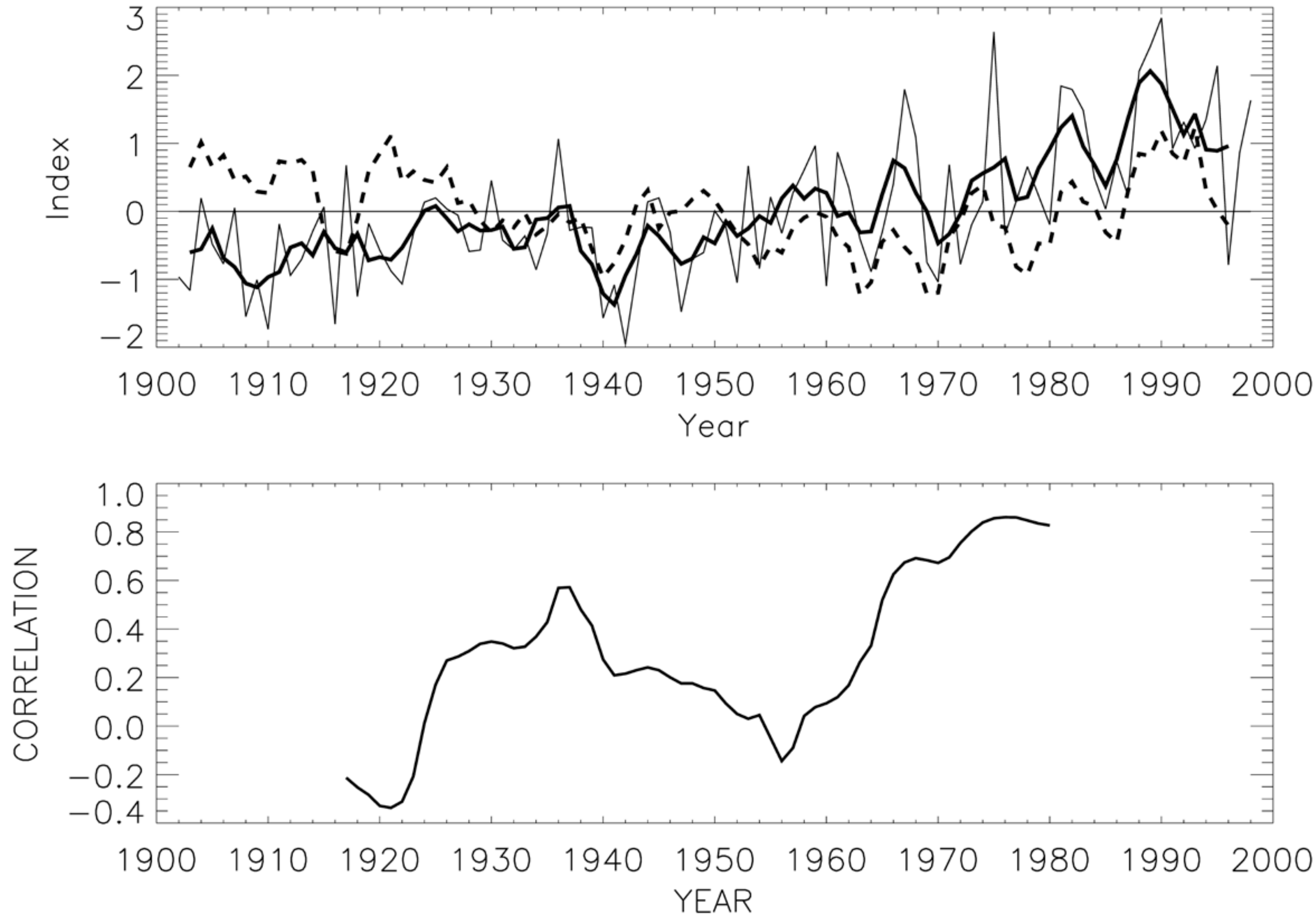
Isopycnals (– 1000 kg/m³) **(Source: Conley et al. 2009)**

Hypoxia (O2 concentration < 2 ml/l) yellow

Anoxia (O2 = 0) red

The oxygen variability during 1958-2006 is well explained assuming constant oxygen removal rates in the sub-basins (Gustafsson and Omstedt, 2009).

What is the role of NAO?

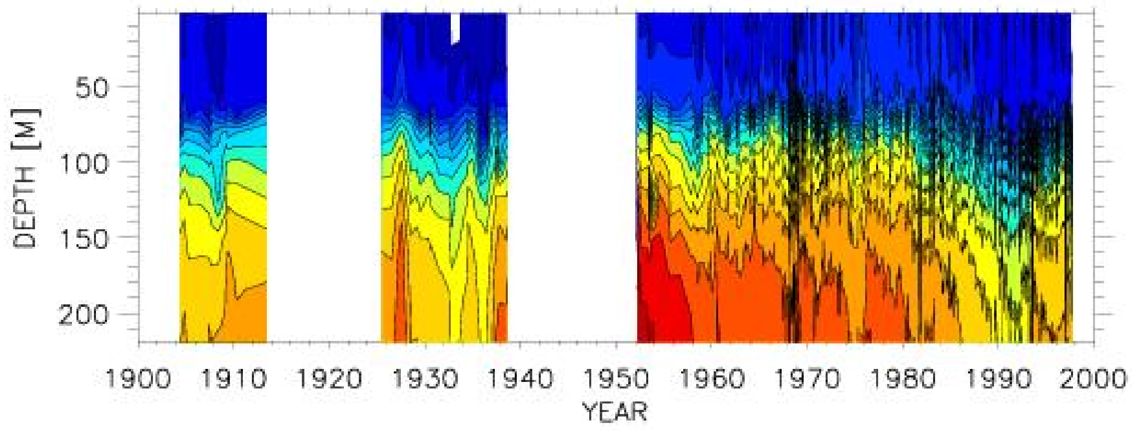


(a) With one standard deviation normalized annual mean winter (January through March) **river runoff** (thin line) to the Baltic Sea without Kattegat, 4-year running mean winter river runoff (solid), and 4-year running mean winter (December through March) NAO index (dashed). (b) 31-year moving **correlation between** the 4-year running mean winter (January through March) **river runoff** to the Baltic Sea without Kattegat **and** the 4-year running mean winter (December through March) **NAO index**. (Meier and Kauker, 2002)

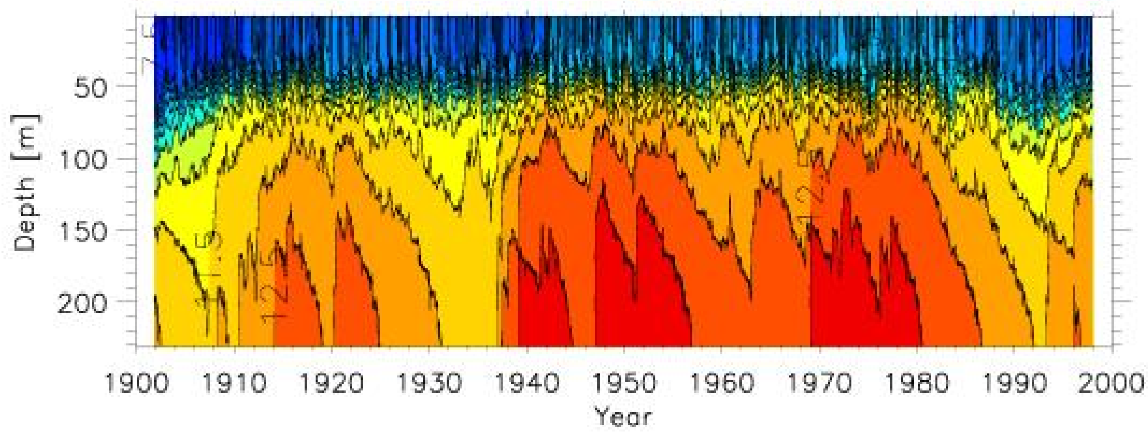
Causes of decadal variability during the 20th century

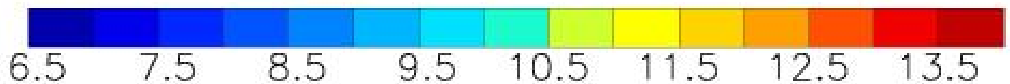
Salinity Gotland Deep

Data



Model



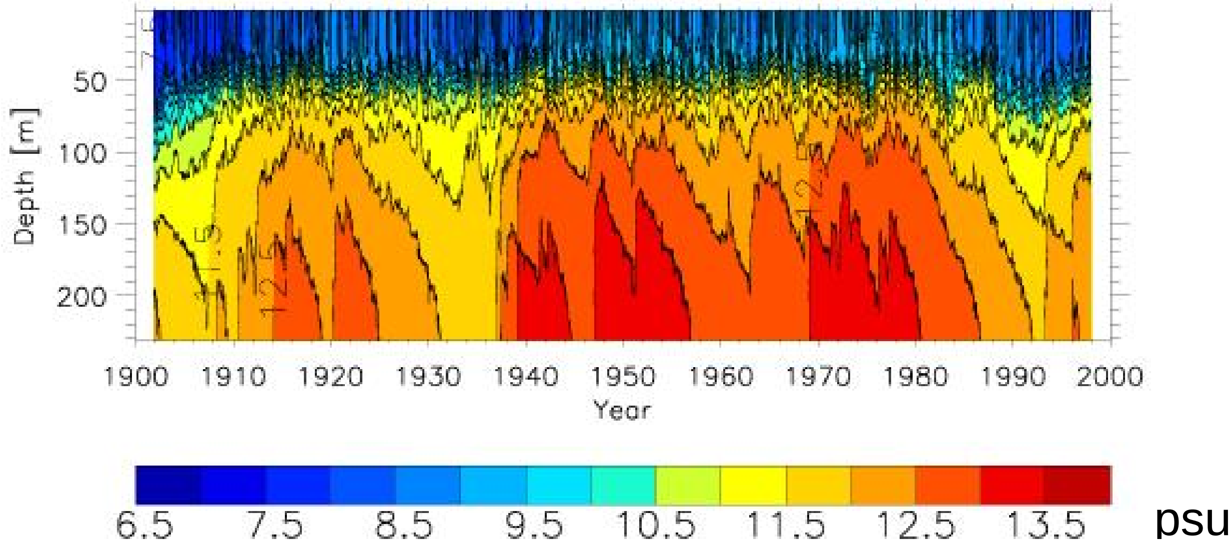


psu

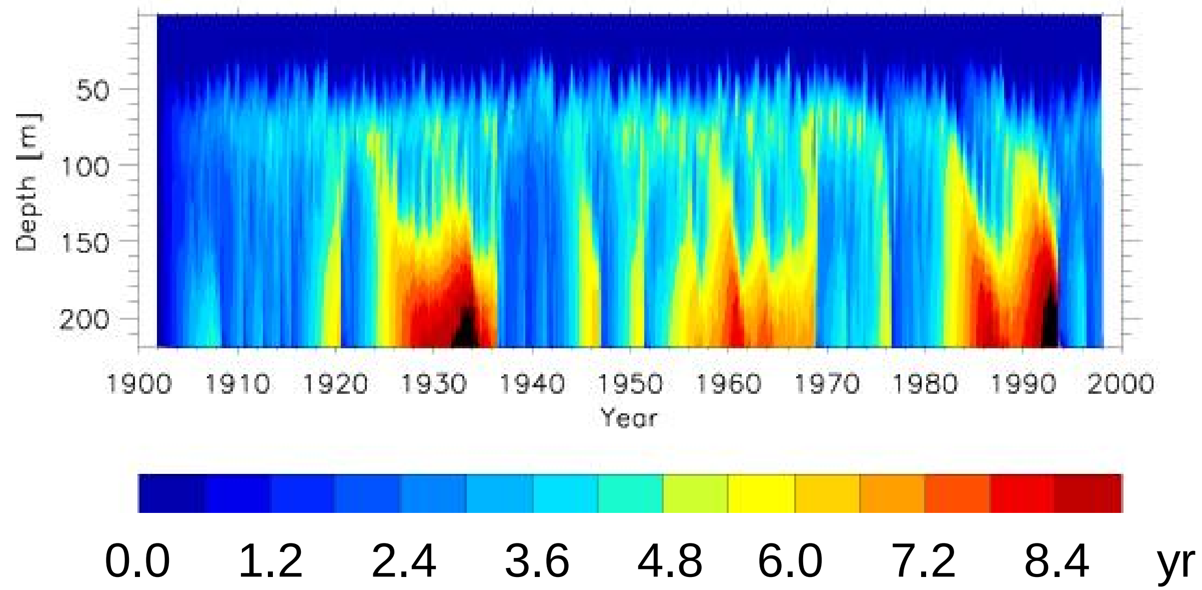
(Meier, 2005)

Stagnation periods

Salinity



Age

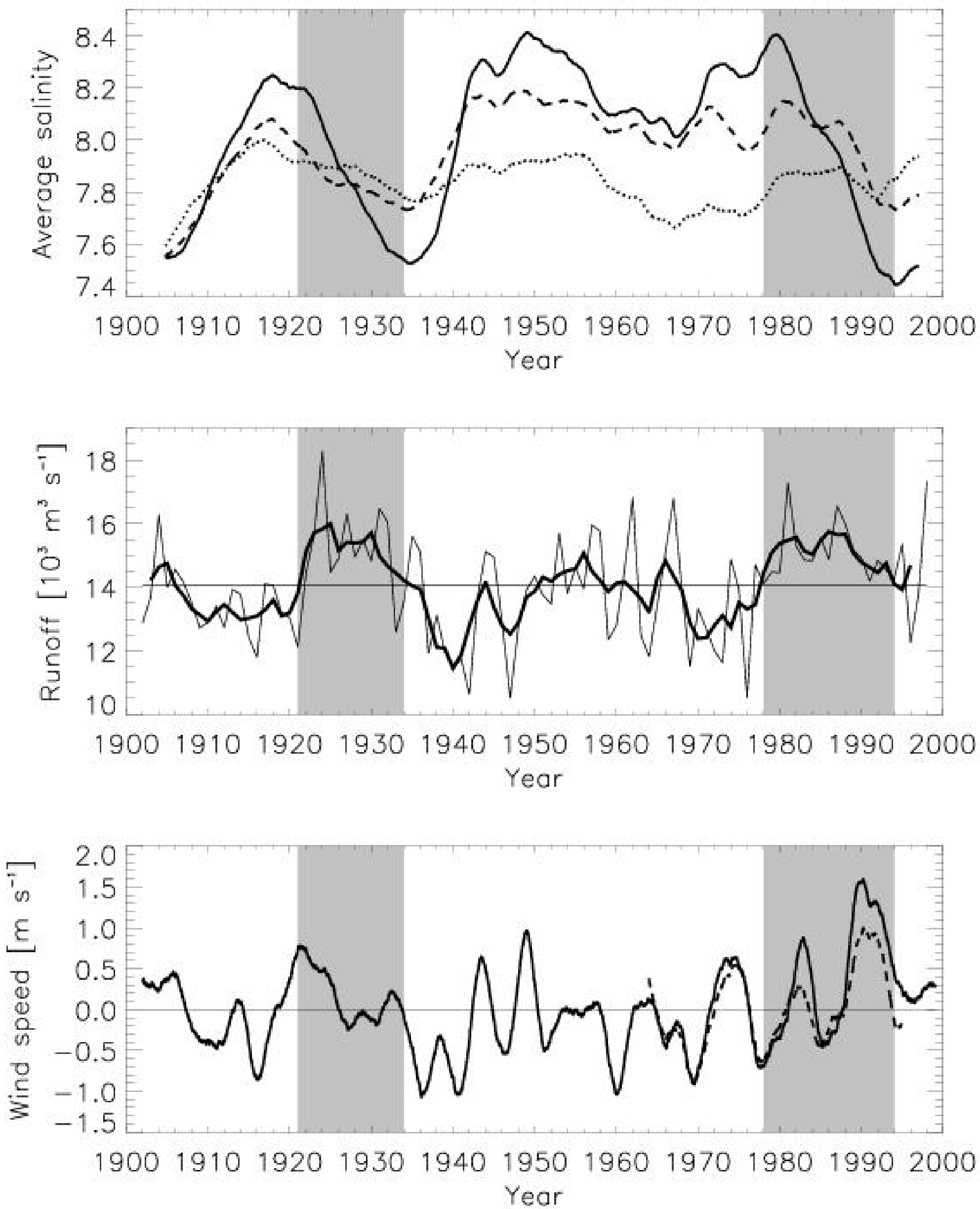


(Meier, 2005)

Salinity

Runoff

Wind



— 4-yr running mean

Stagnation periods are shaded

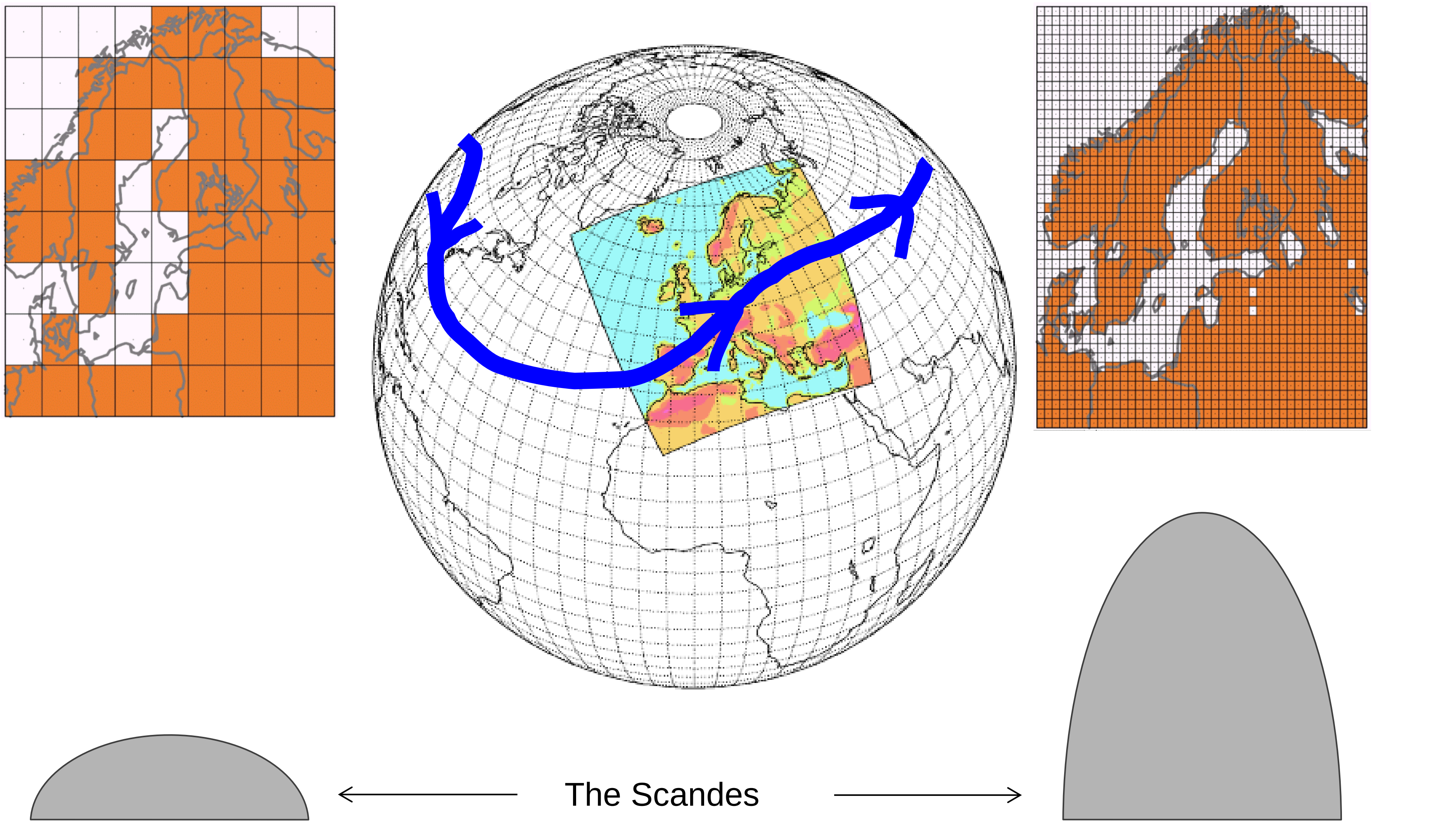
(Meier and Kauker, 2003a)

Summary of decadal variability

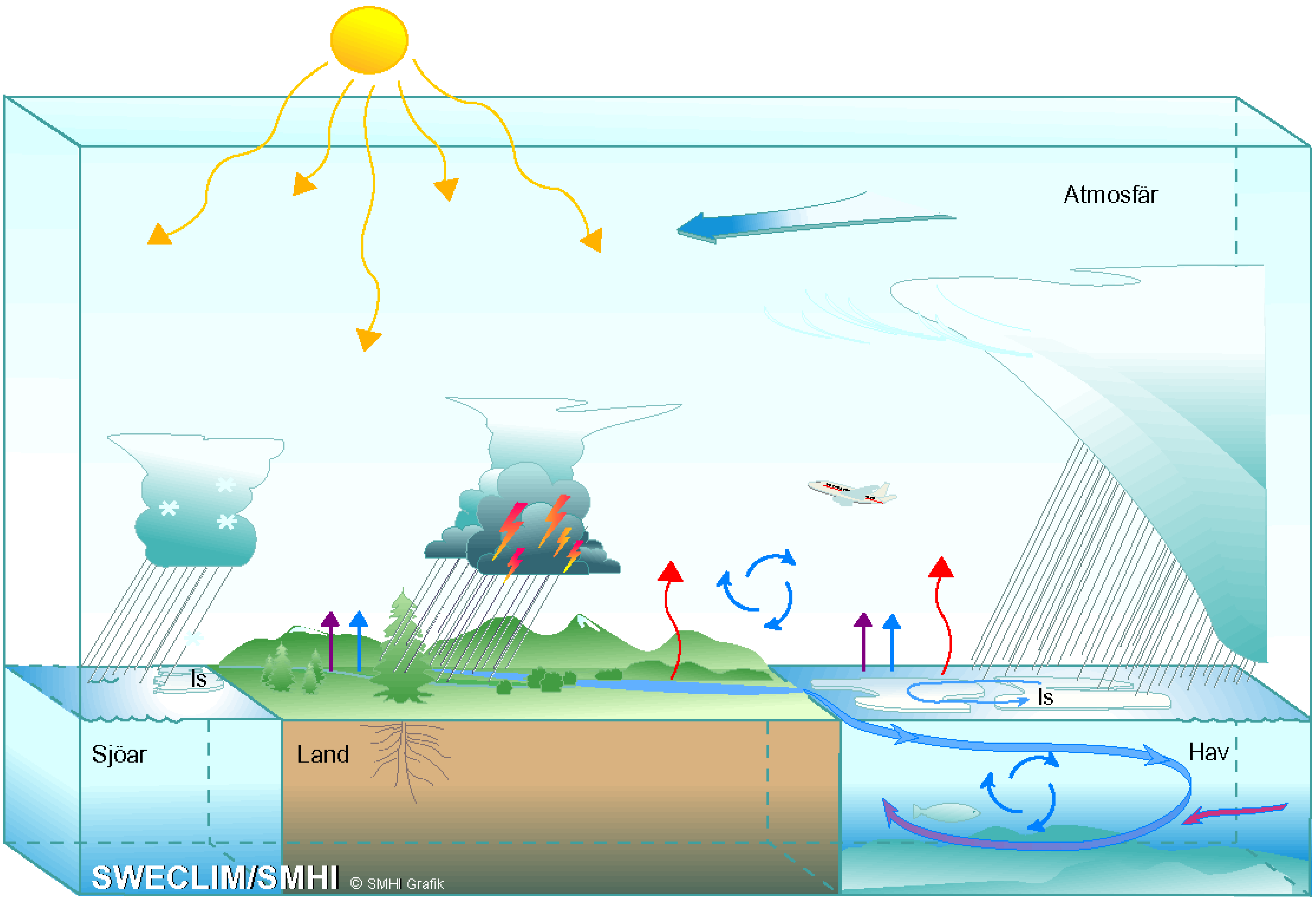
- half of the decadal variability of salinity is explained by accumulated freshwater inflow variations (Meier and Kauker, 2003a)
- another significant part is caused by the low-frequency variability of the wind (Meier and Kauker, 2003a)
- remainder might be caused by the high-frequency wind anomaly, i.e. specific atmospheric conditions causing major saltwater inflows (Lass and Matthäus, 1996)
- no impact of river regulation, sea ice (air temperature), sea level in Kattegat on decadal time scale

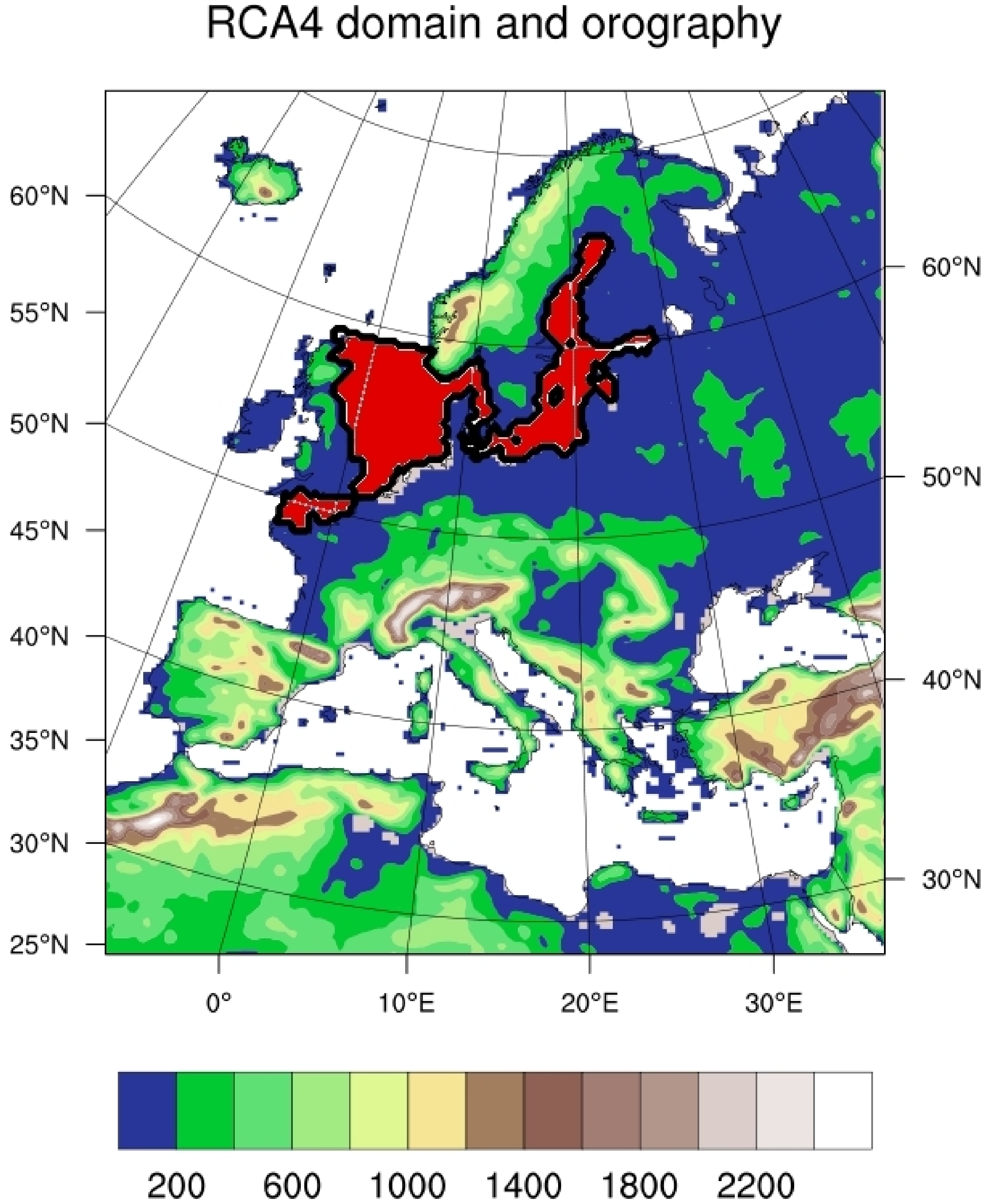
3. Regional climate models and dynamical downscaling

Using RCMs to refine the information from GCMs (spectral nudging)



Atmosphere-ice-ocean-land surface system





SMHI's regional climate model

(Source:
Dieterich et al., 2013;
Wang et al., 2015)

4. Uncertainties in projections

Projections versus predictions

1. What are the sources of uncertainty in climate change projections?

2. How should a scientist deal with the uncertainty?

Sources of uncertainty in climate change projection

1. **Emission scenarios**
   - Future behaviour of mankind

2. **Modeling uncertainty**
   - Climate response to changes in atmospheric composition (GCM)
   - Modelling of ocean circulation, biogeochemistry, etc. (RCSM)

3. **Natural climate variability**
   - Solar activity, volcanic eruptions
   - Internal (=unforced) variability generated by the non-linear dynamics of the climate system

5. Projections of Baltic Sea climate at the end of the 21st century

We have near-agreement that in the Baltic area

- CO_2 concentrations will increase
- Temperature will increase
- There will be less winter ice
- Absolute sea level will rise

Ragnar Elmgren, DEEP,
Stockholm University

It also seems highly likely that

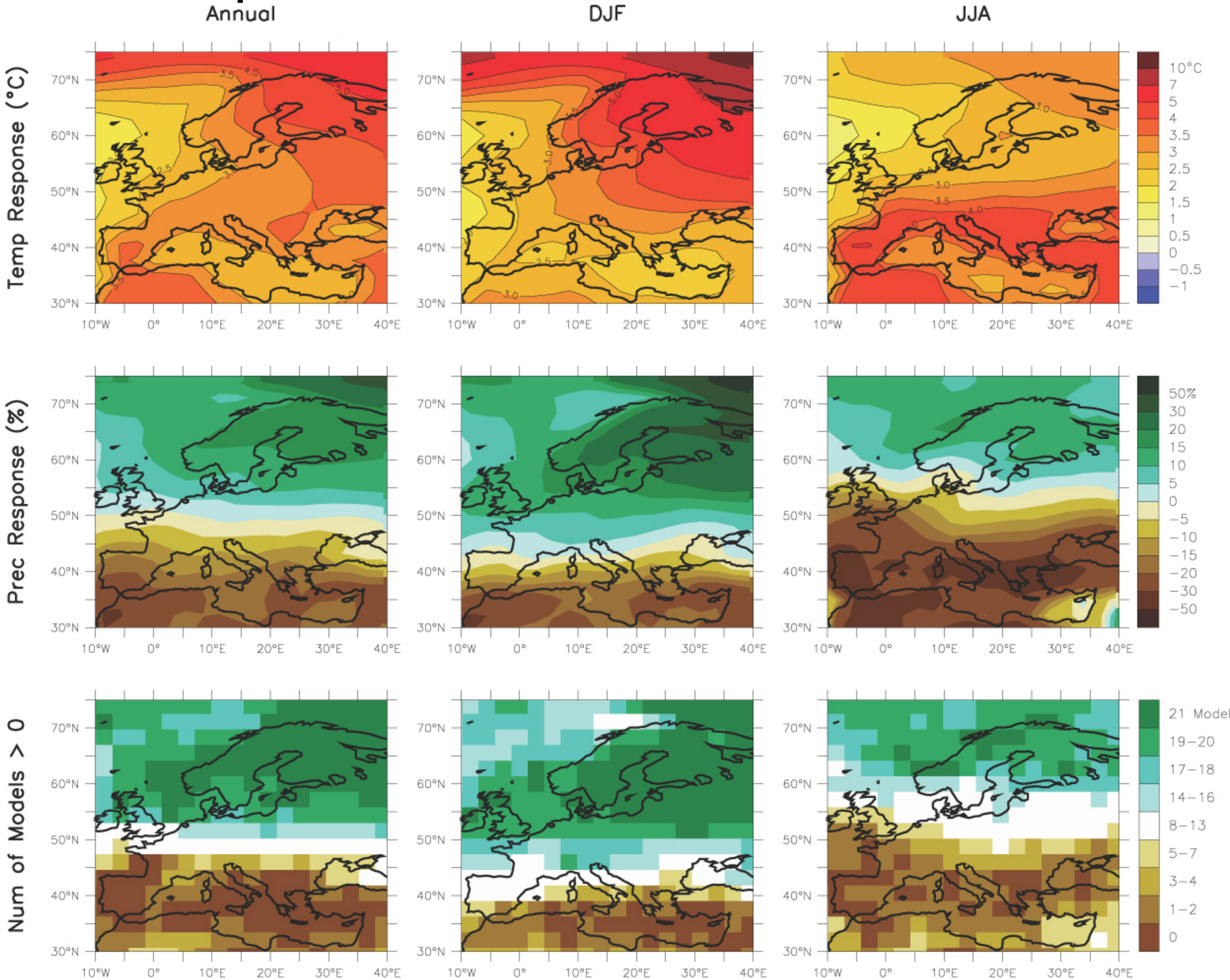
- Baltic water pH will decrease
- Precipitation & runoff will increase
- Coastal erosion will increase

We don’t know about

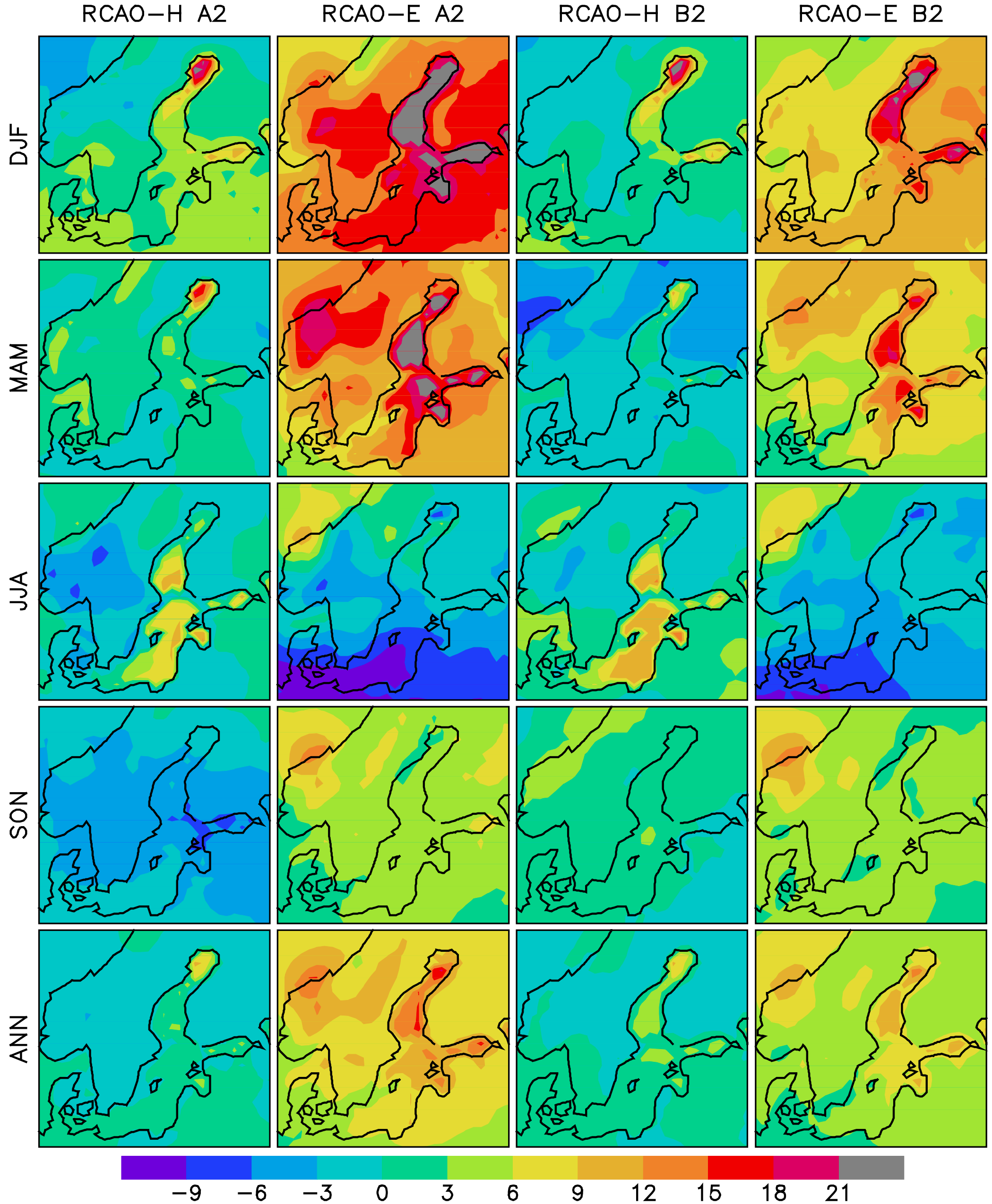
- Winds and storms
- Time and place of precipitation
- Major Baltic inflows
- Salinity effect of changes
- Clouds
- Immigration & invasion of species
- Many ecological interactions

Changes in the atmosphere and on the land surface

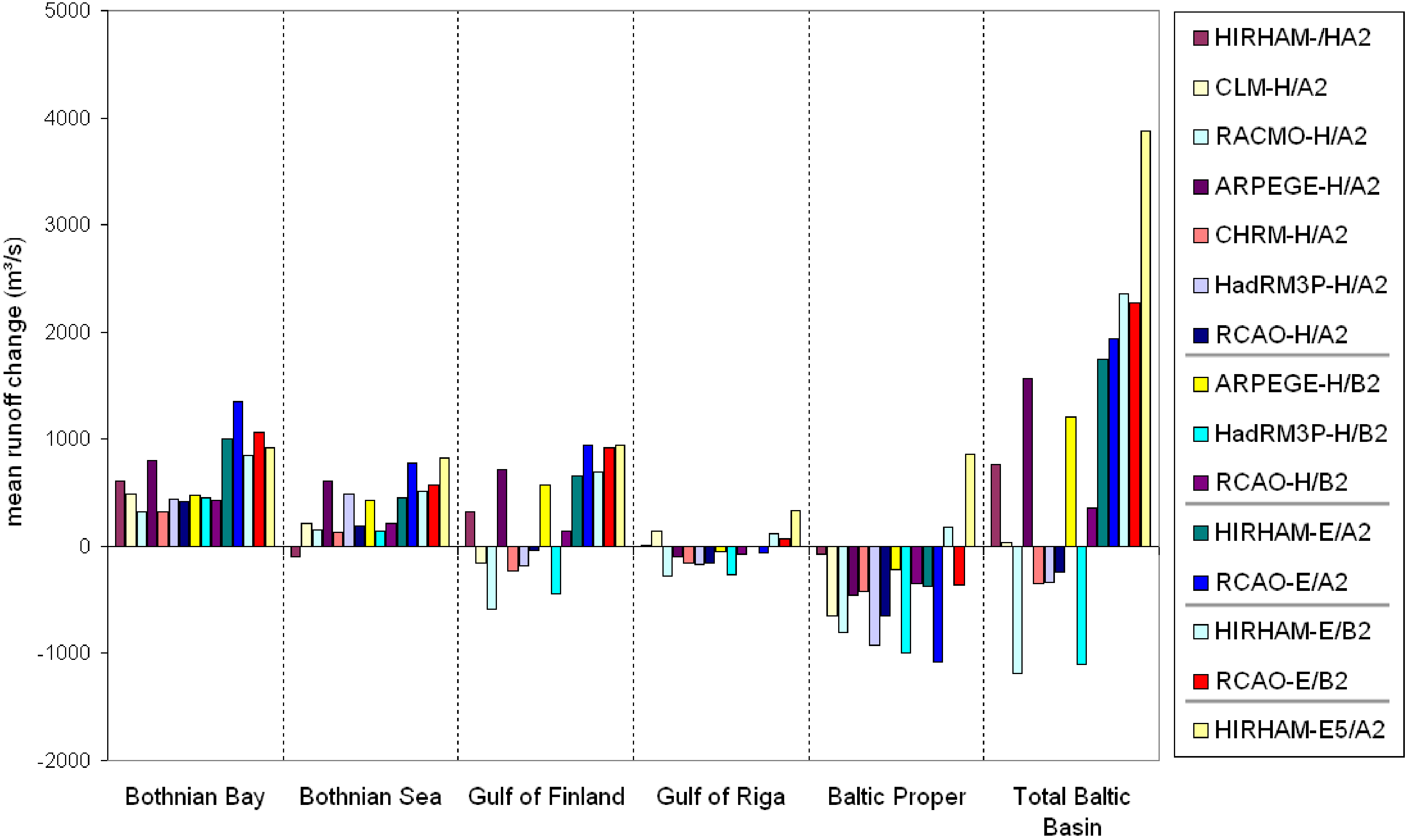
Temperature and precipitation changes over Europe in the A1B model ensemble



Wind speed changes [%]

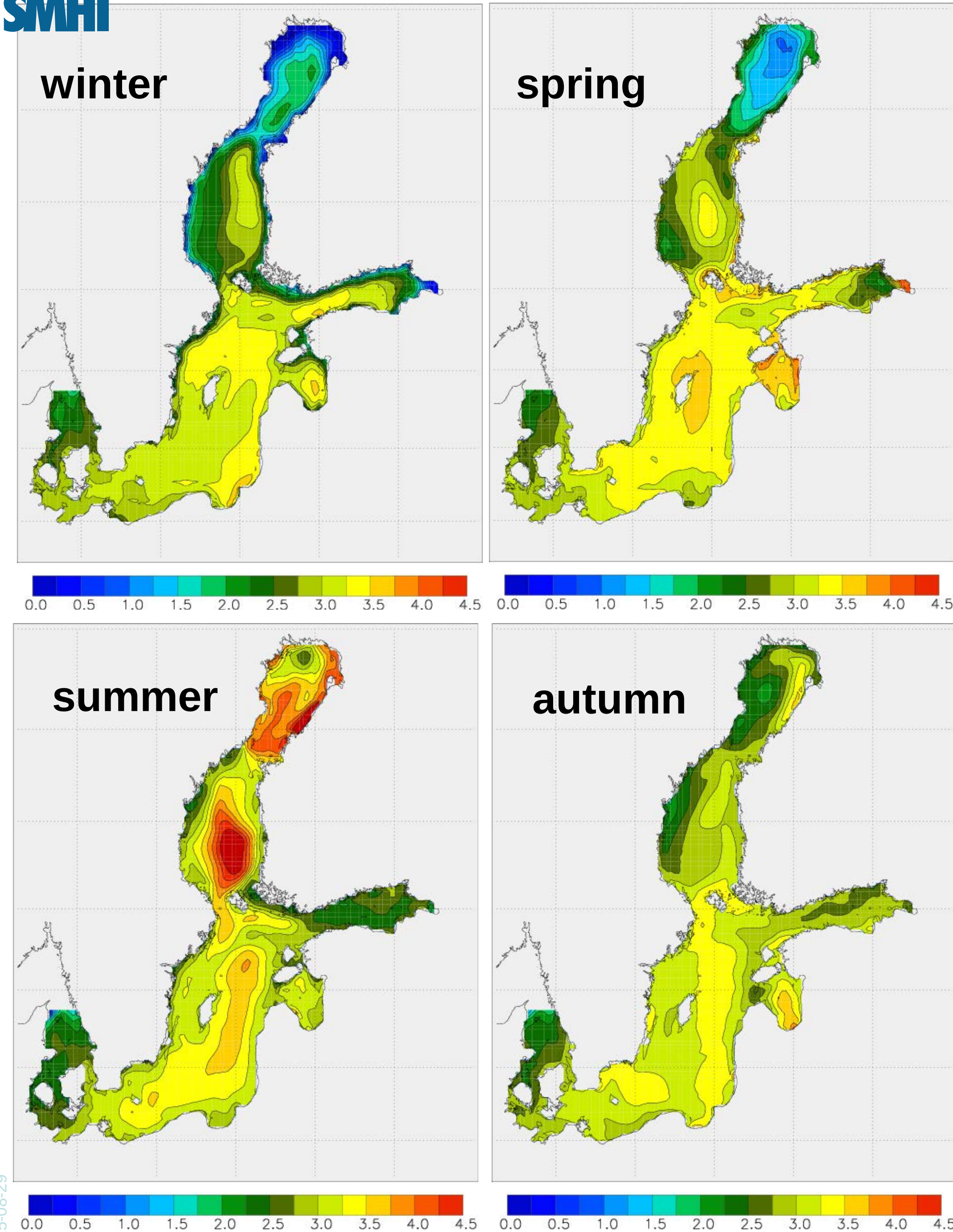


Mean Annual Change in Runoff



(Source: Phil Graham, SMHI)

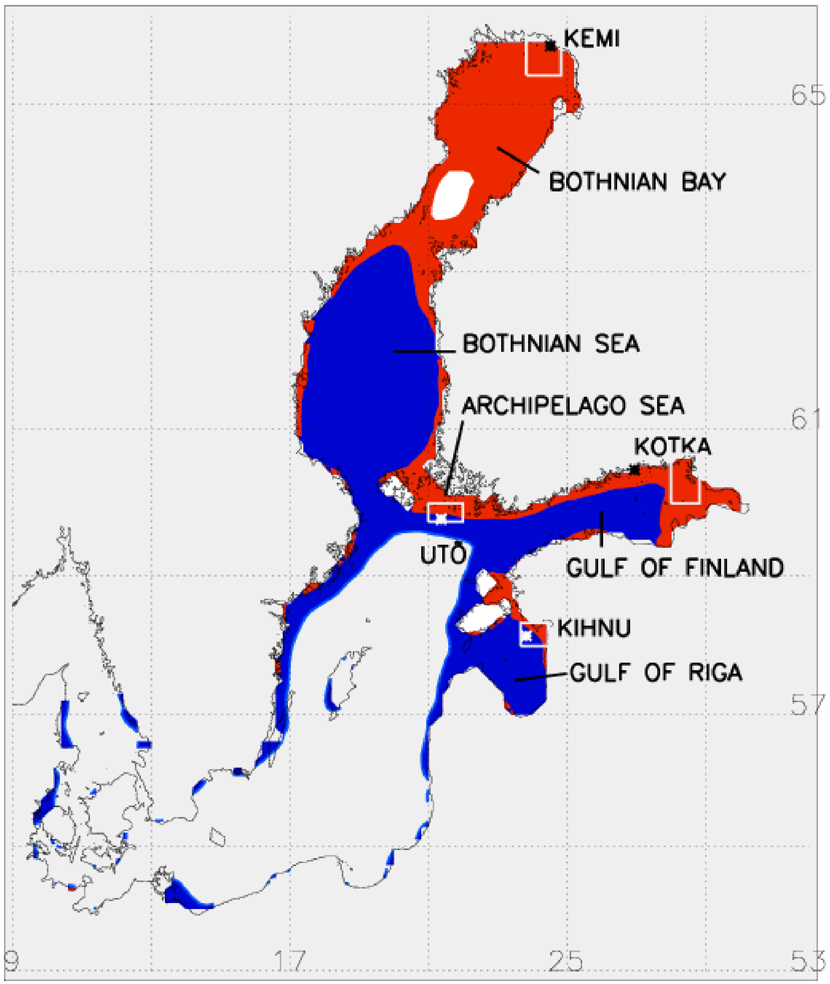
Changes in the ice-ocean



Annual mean sea surface temperature change:
+ 2-4°C

Seasonal mean SST differences between the ensemble average scenario and simulated present climate (in °C): DJF (upper left), MAM (upper right), JJA (lower left), and SON (lower right) (Meier, 2006).

Mean maximum ice cover in control (blue) and scenario (red)



Mean maximum ice extent change: - 60-70%

(Meier et al., 2004c)

Salinity at Gotland Deep

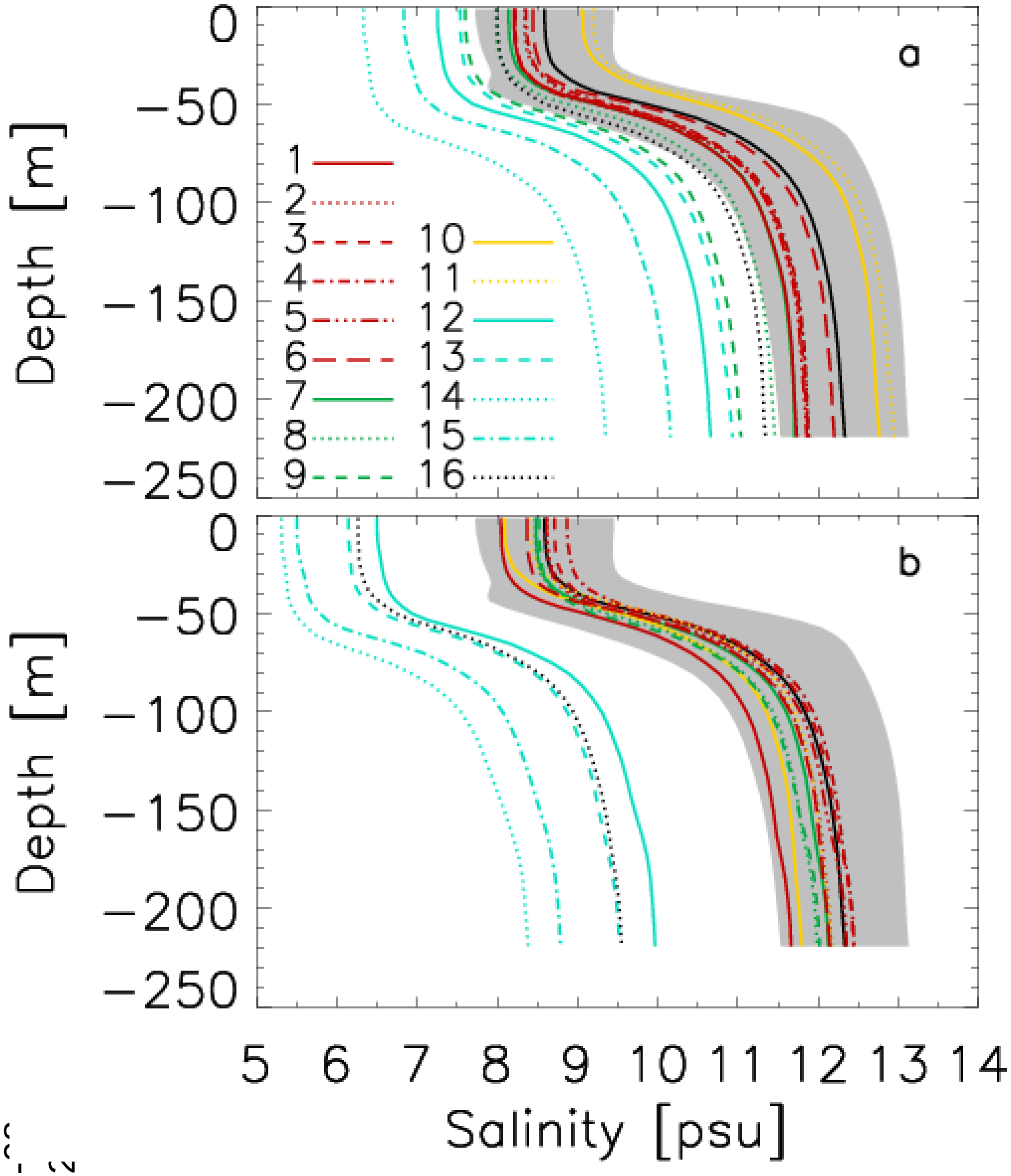
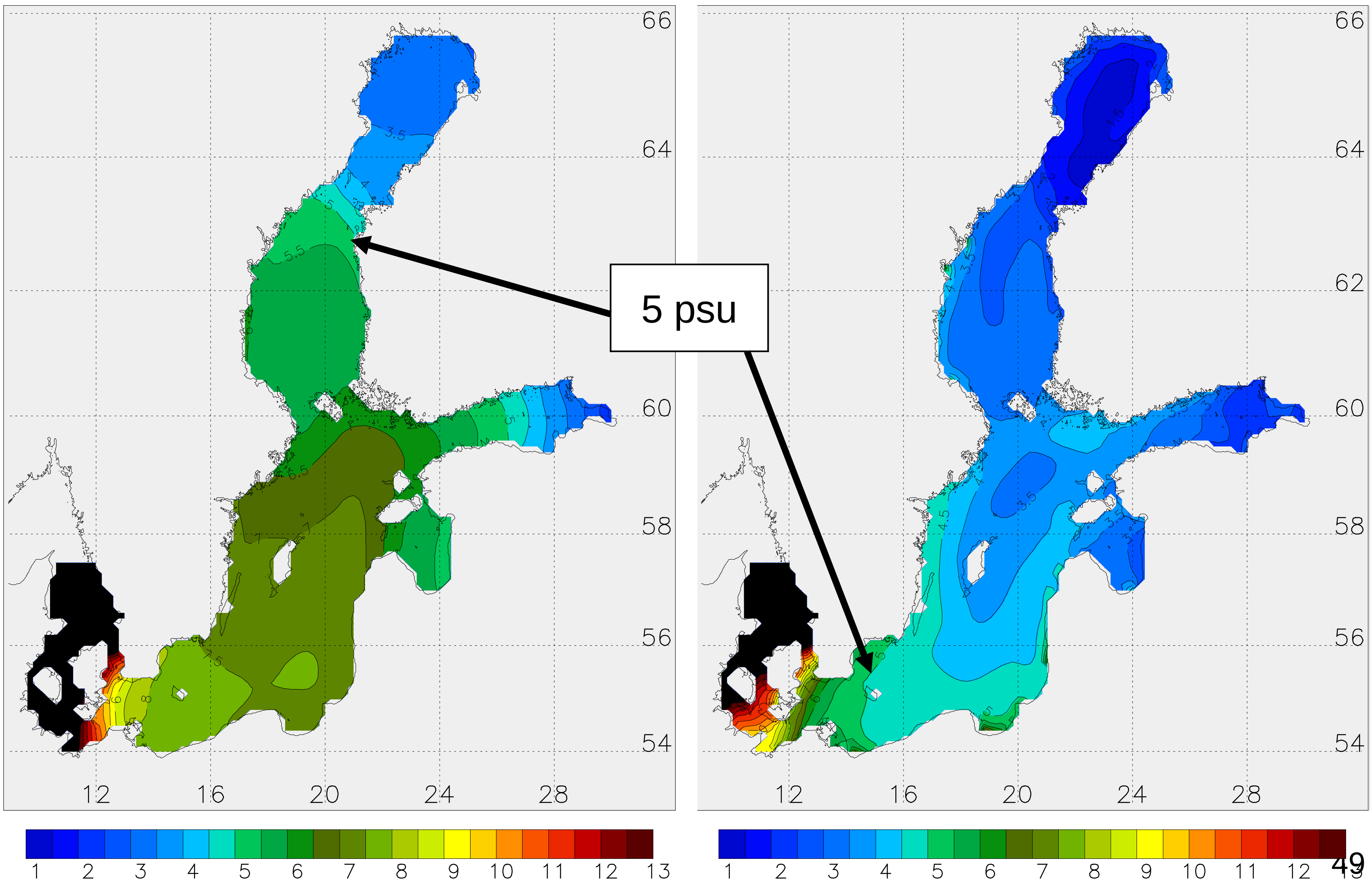


Figure 1. Median profiles of salinity at monitoring station BY15 for present climate 1961-1990 (black solid line, shaded areas indicate the +/- 2 standard deviation band calculated from two-daily values for 1903-1998) and in projections for 2071-2100 (colored lines). In (a) only effects from wind changes are considered whereas in (b) projections based upon wind and freshwater inflow changes are shown. Numbers in the legend correspond to the different scenario runs (see Tab.1). The figure is taken from Meier et al. (2006, Fig.2).

Sea surface salinity

Present climate

Projection with the largest change
RCAO-ECHAM4/A2



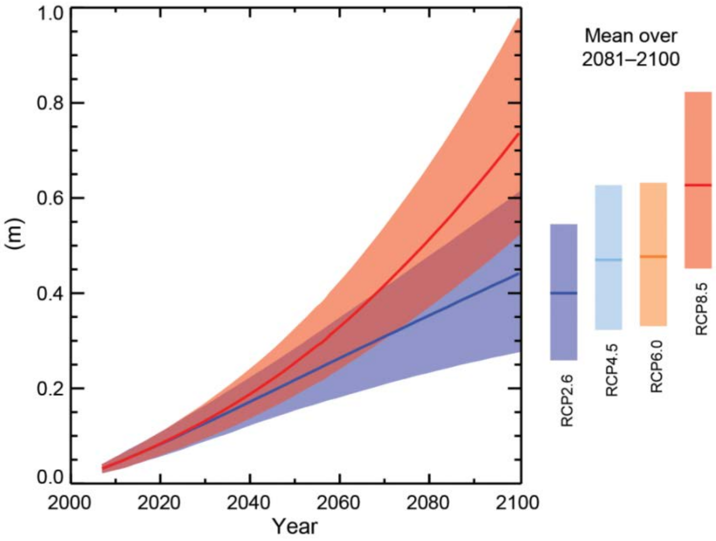
Meier et al. (2006)

What are the drivers of salinity?

What are the drivers of salinity?

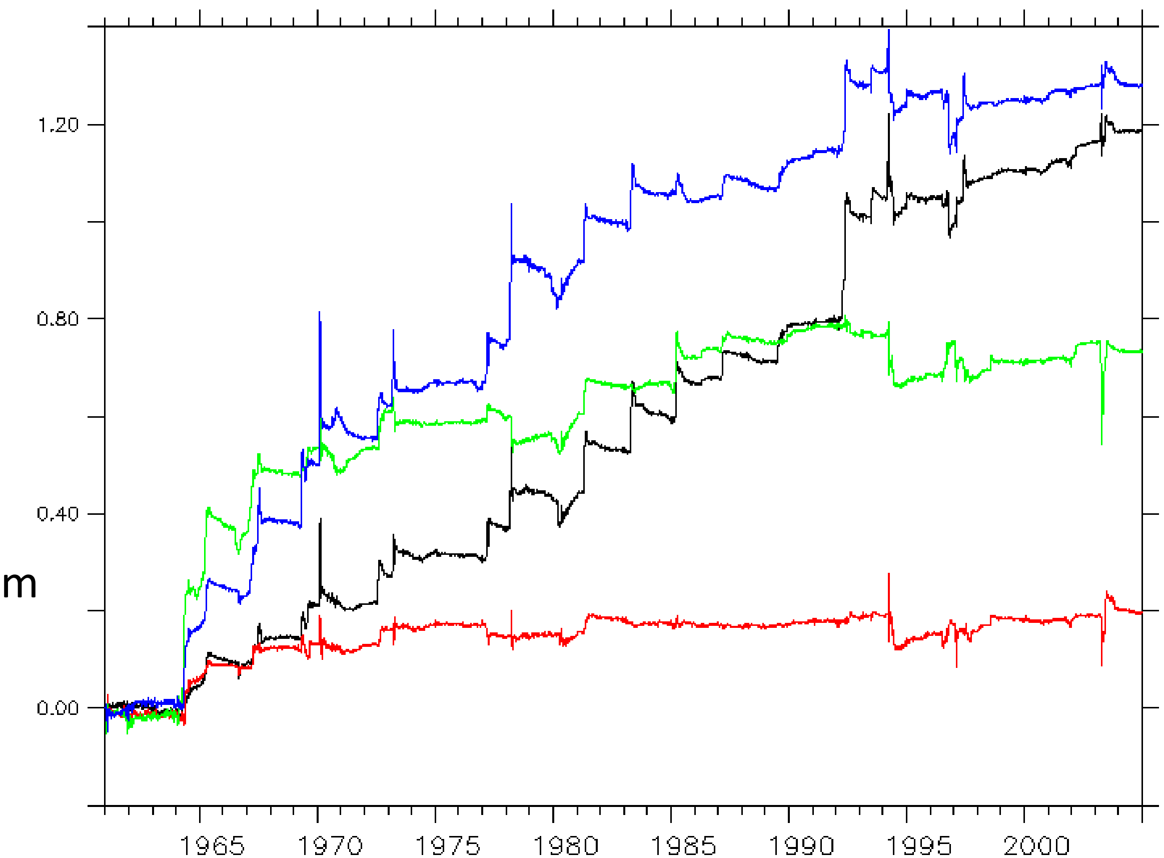
- Runoff
- Zonal wind
- Saltwater inflows
- Global mean sea level

Impact of accelerated future global mean sea level rise on the volume averaged salinity difference in the Baltic Sea



(Source: IPCC 2013)

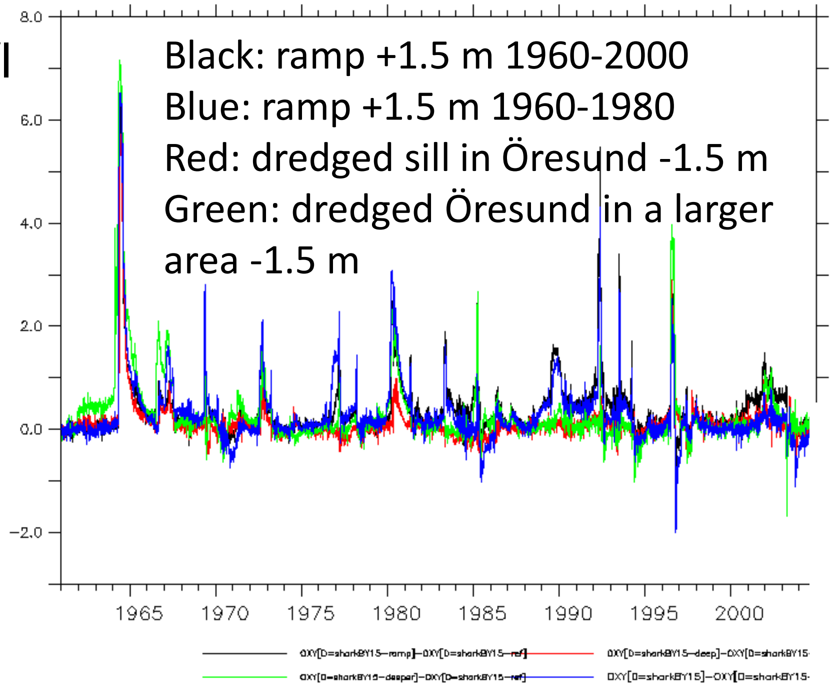
Black: ramp +1.5 m 1960-2000
Blue: ramp +1.5 m 1960-1980
Red: dredged sill in Öresund -1.5 m
Green: dredged Öresund in a larger area -1.5 m



(Source: Meier et al., in prep.)

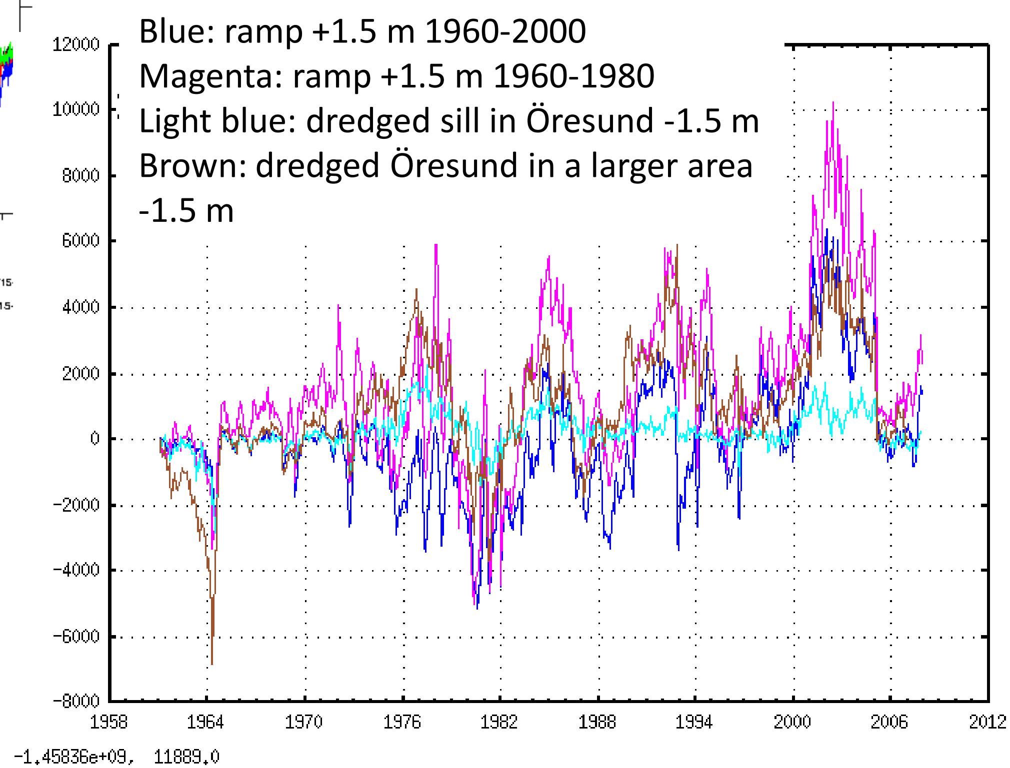
Bottom oxygen concentration difference at Gotland Deep

ml/l



km²

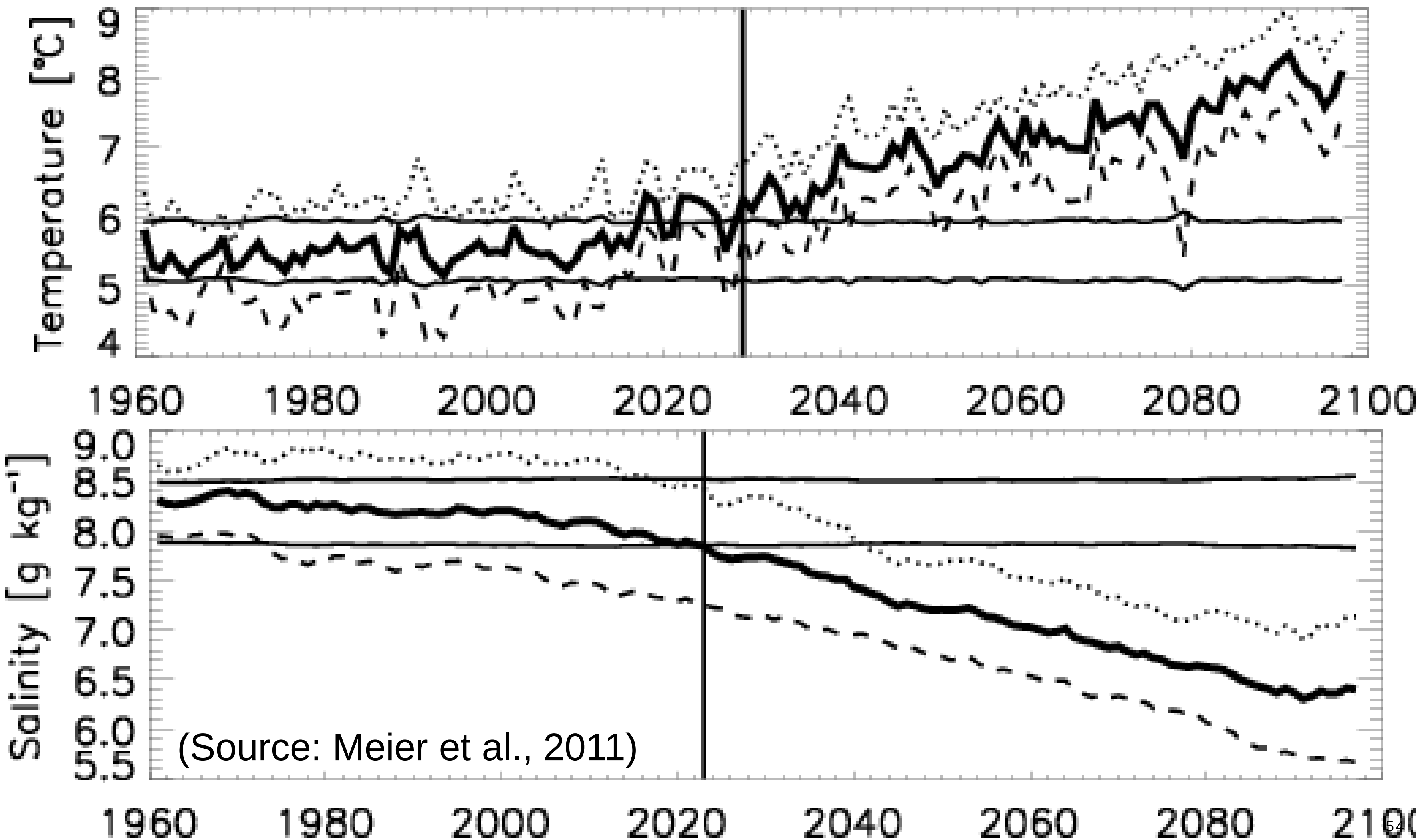
Anoxic area difference



Global sea level rise
⇒ stronger stratification
⇒ larger anoxic area
⇒ decreased phosphorus retention in the sediments
⇒ intensified cyanobacteria blooms

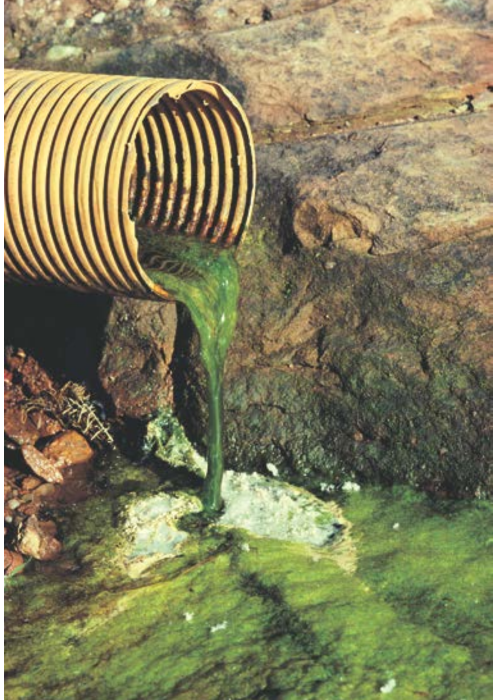
(Source: Meier et al., in prep.)

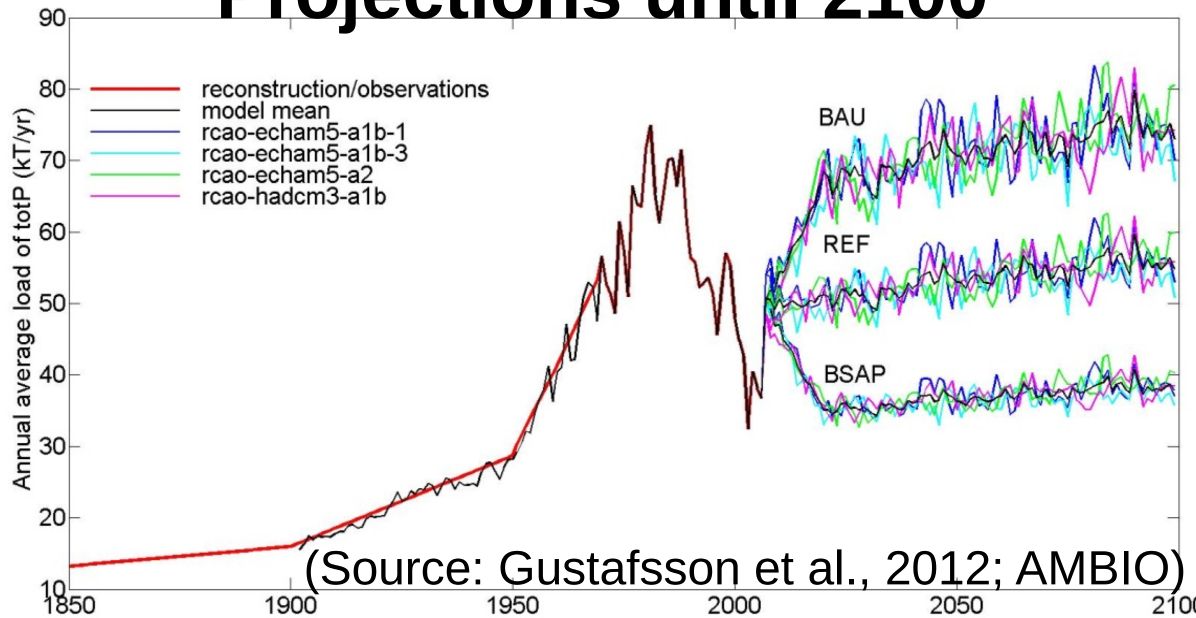
Ensemble mean volume averaged temperature and salinity

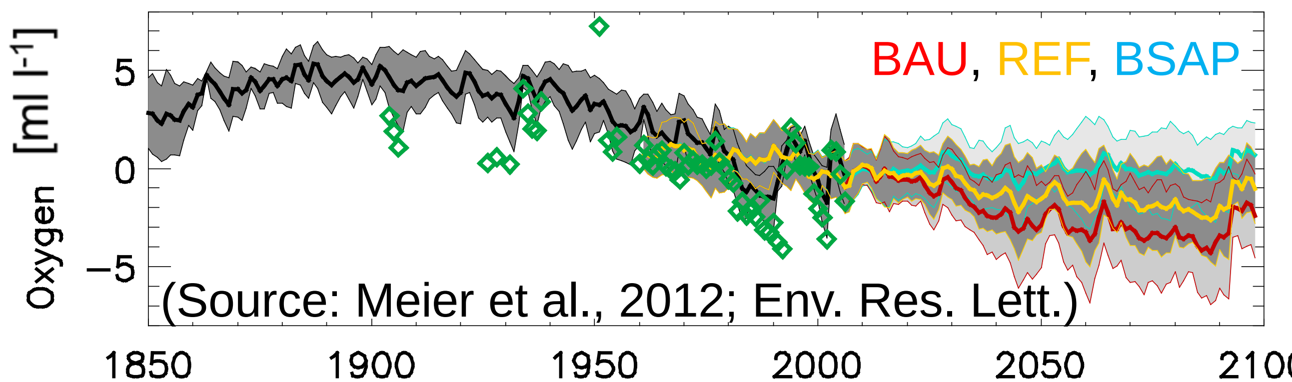


(Source: Meier et al., 2011)

Projections until 2100



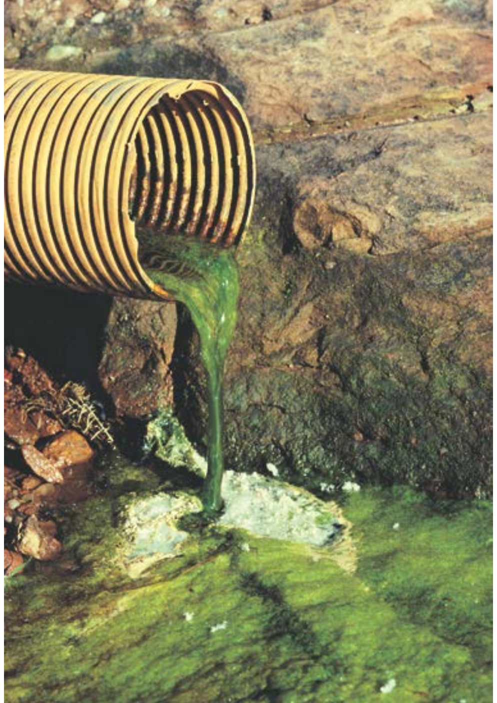


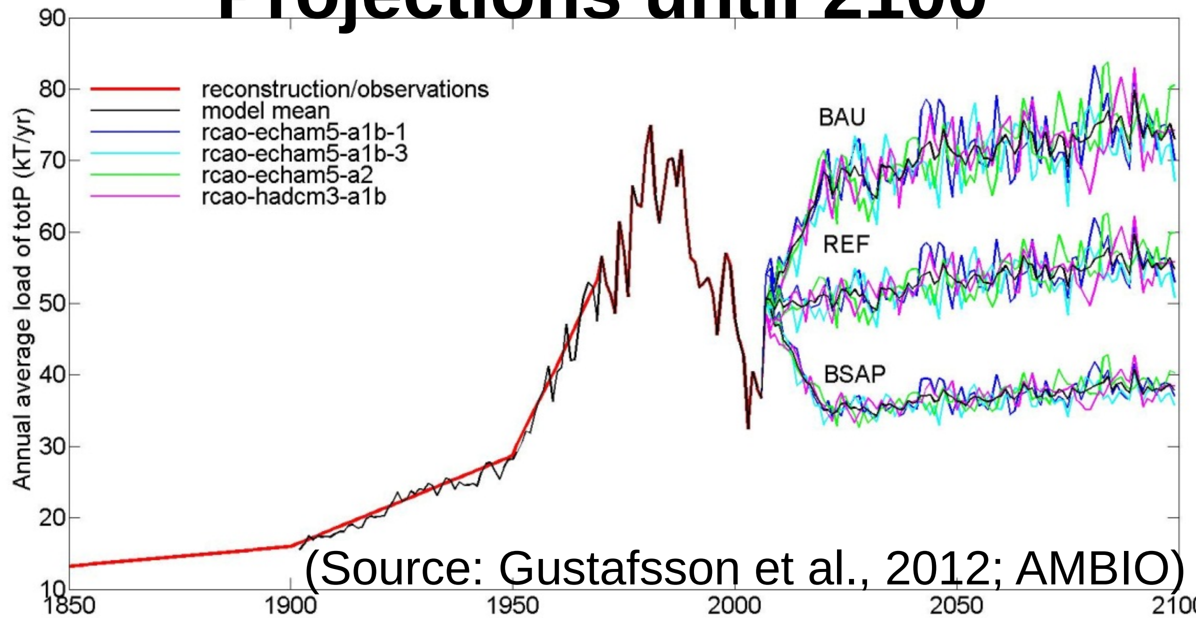


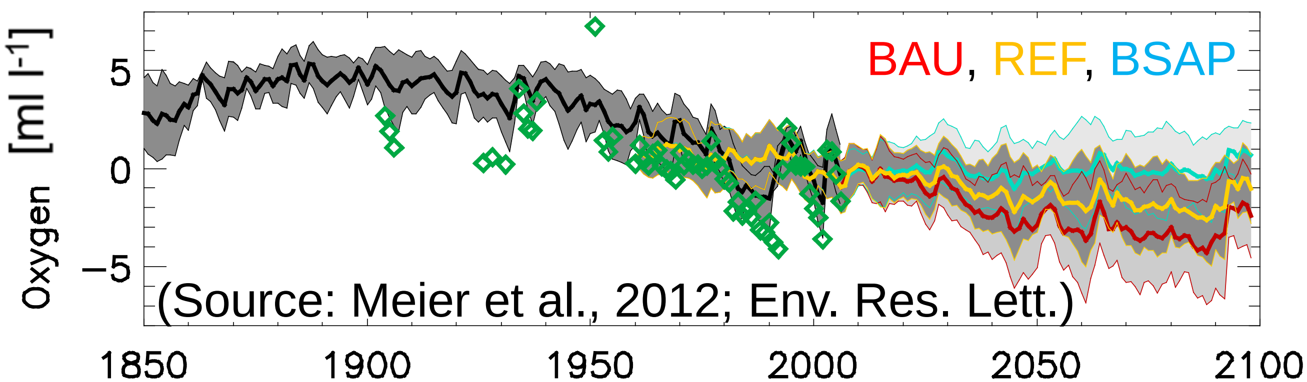
Ensemble mean and standard deviation of oxygen concentration at Gotland Deep (200 m)

ECO SUPPORT

Projections until 2100





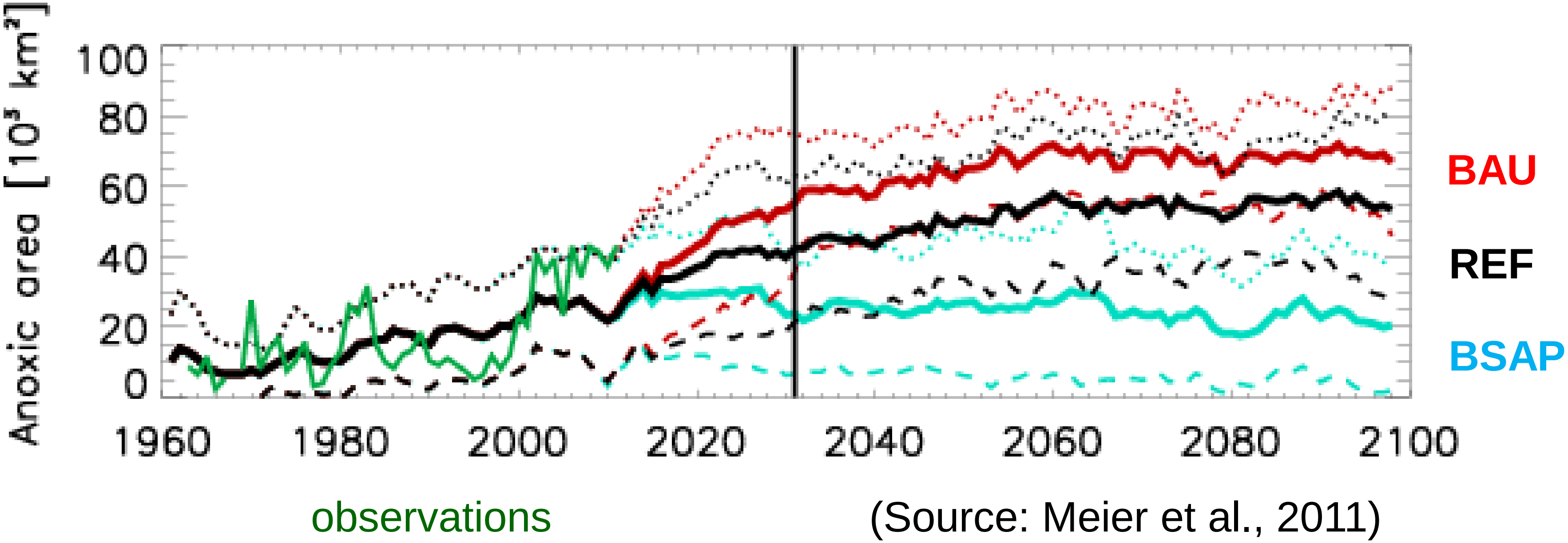


Ensemble mean and standard deviation of oxygen concentration at Gotland Deep (200 m)

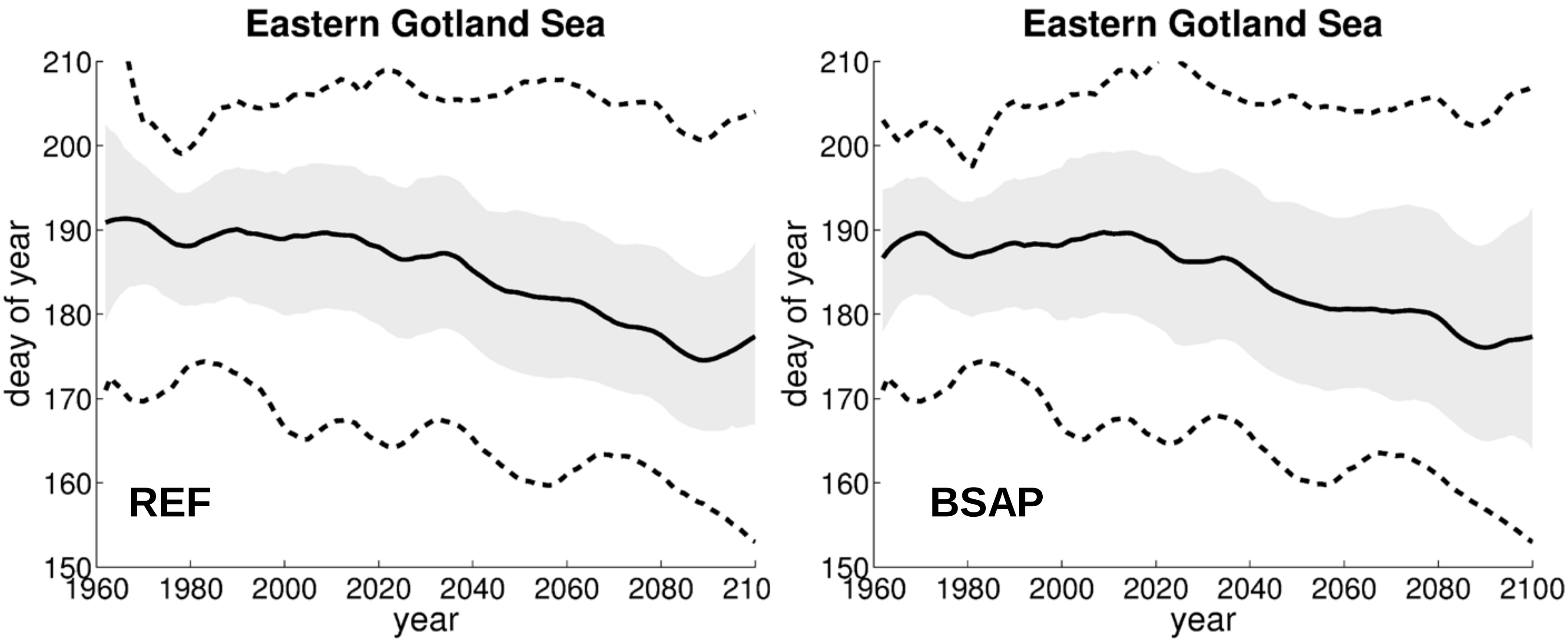
=> Hypoxia is projected to increase

ECO SUPPORT

Anoxic areas



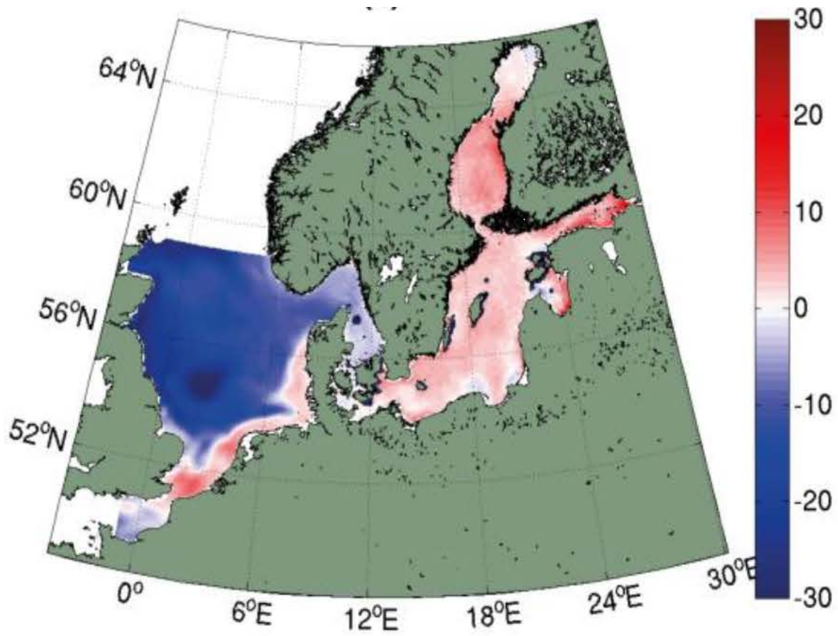
(Source: Meier et al., 2011)



Day of the first occurrence of a cyanobacteria bloom. The dotted lines are minimum and maximum values in the ensemble. The left panel shows results from the reference simulations and the right panel results from the BSAP nutrient load scenario. The solid line is the ensemble mean and the shaded area shows the 95% ensemble spread of the mean. (Source: Neumann et al., 2012)

Net primary production in the North Sea

Ensemble mean projected primary production change from a 3-member ensemble forced by RCP4.5



(Source: Pushpadas et al., submitted)

Lessons learned

- **Reconstructions of past climate variability help to constrain the sensitivity of biogeochemical models to nutrient load changes**

Lessons learned

- **Projections suggest unprecedented changes in the future ecosystem despite large uncertainties due to unknown nutrient loads, biases of the GCMs, biases of the biogeochemical models and natural variability**

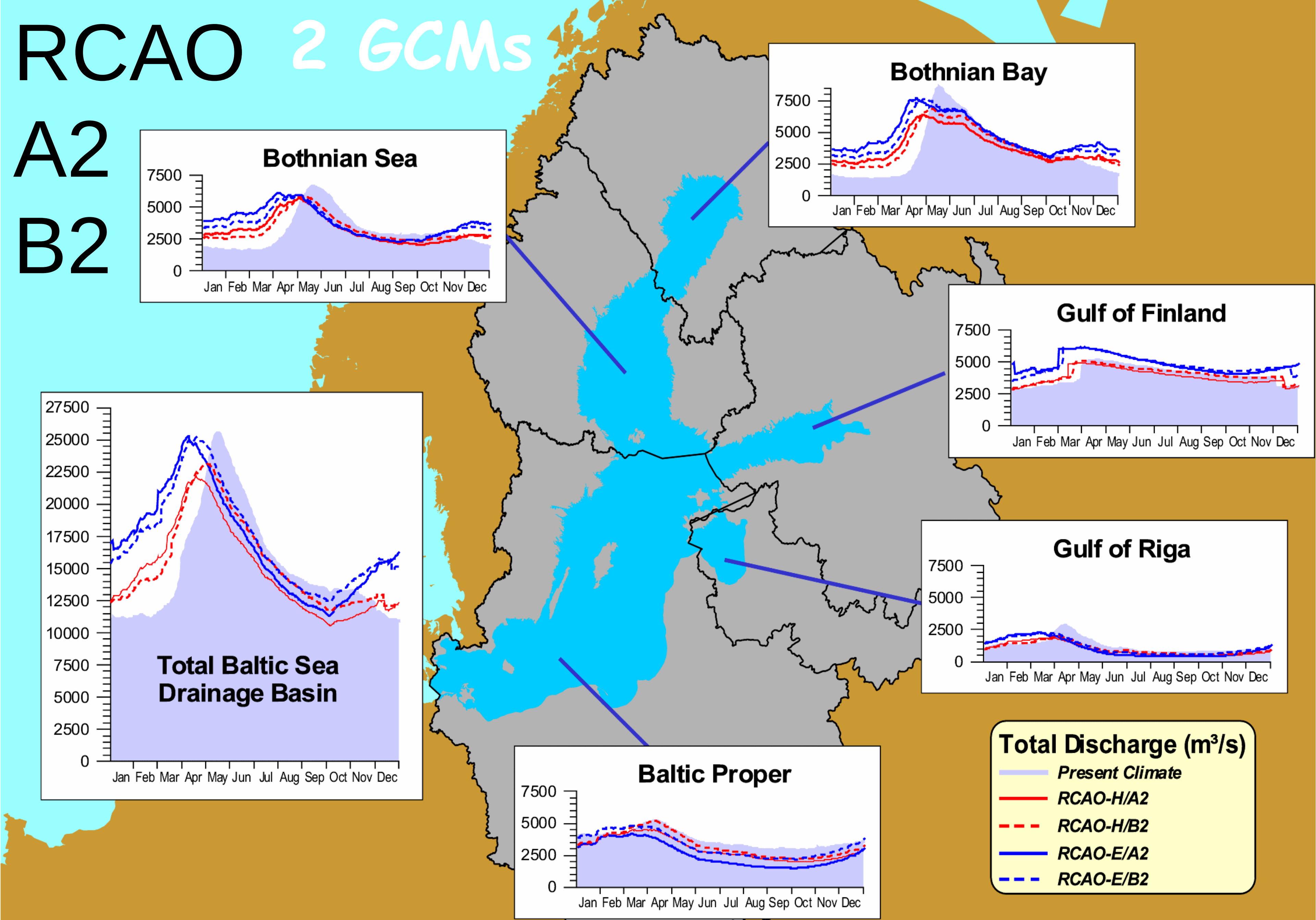
Lessons learned

- **In future climate, (1) enlarged nutrient loads due to increased runoff, (2) reduced oxygen flux from the atmosphere to the ocean due to increased temperature and (3) intensified internal nutrient cycling may result in substantial increases in both primary production of organic matter and oxygen consumption for its mineralization.**

Lessons learned

- **Without drastic nutrient load abatements hypoxic and anoxic areas are projected to increase.**

Thank you for your attention



Graham, 2004, *AMBIO*.