Physical oceanography of the Baltic Sea and seas around Sweden

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Overview:

1. History of Baltic Sea research
2. Development of the Baltic Sea
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4. Water balance
5. Heat balance
6. Currents
7. Sea level
8. Temperature, salinity, density, and oxygen
9. Sea ice
10. Processes
11. Climate variability (long-term)
12. Comparison with other seas
13. Baltic Sea models
14. The major Baltic inflow in January 2003
15. Spreading of juvenile freshwater
16. On the Baltic conveyor belt
17. Causes of climate variability
18. Scenarios of temperature, salinity, and sea ice for the end of the 21st century

References:

- Fonselius, S., 1996: Västerhavets och Östersjöns Oceanografi. SMHI, Oceanografiska laboratoriet, Nya varvet, S-42 671 Västra Frölunda
- Magaard, L. and G. Rheinheimer (eds.), 1974: Meereskunde der Ostsee. Springer, 1st edition, 240 pp
- Rheinheimer, G. (ed.), 1996: Meereskunde der Ostsee. Springer, 2nd edition, 338 pp

References:

- Leppäranta, M. and K. Myrberg, 2009: Physical Oceanography of the Baltic Sea, Springer, 378 pp
- Meier, H.E.M., R. Feistel, J. Piechura, L. Arneborg, H. Burchard, V. Fiekas, N. Golenko, N. Kuzmina, V. Mohrholz, C. Nohr, V.T. Paka, J. Sellschopp, A. Stips, and V. Zhurbas, 2006: Ventilation of the Baltic Sea deep water: A brief review of present knowledge from observations and models. Oceanologia, 48(S), 133-164.

1. History of Baltic Sea research

- earliest explored sea, many observations, source area for oceanography
- long records of historical observations, e.g.:

1. totally ice covered Baltic, e.g. 1323, 1333, 1349, 1399, 1690
2. flooding events, e.g. 13 Nov 1872 (271 dead persons in Denmark and Germany)
3. periods of lacking oxygen causing fish death in German fjords were known before industrial times
4. Anders Celsius (Prof in Uppsala) noticed 1724 land rise in the Bothnian Sea (but gave wrong explanation)

- old universities with oceanographic research: St. Petersburg, Helsingfors, Uppsala, Königsberg, Kiel, Kopenhagen, Göteborg, (Krakau)

Carta Marina (1539)

(map of Scandinavia from Olaus Magnus (1490-1557))

(source: James Ford Bell Library, University of Minnesota)

Highest sea level in Kiel 1904

Zum Jahreswechsel 1904 stand die Flut nach einem starken Orkan in allen Straßen

Als Kiel im Wasser versank

Ruhe und Frieden wünschten sich die Kieler Ende 1904 für das kommende Jahr – doch stattdessen wurde ihnen ein turbulenter Jahreswechsel beschert, der als „Dezember-Katastrophe" in die Annalen eingehen sollte. Vor 90 Jahren erlebte Kiel das verheerendste Hochwasser dieses Jahrhunderts.

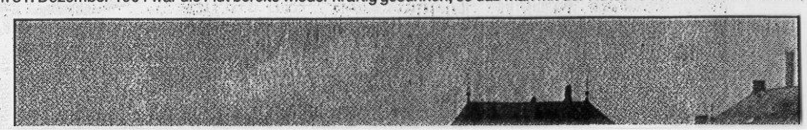
Bereits am 30. Dezember, einem Freitag, traute sich kaum jemand vor die Tür. Der seit Tagen andauernde Sturm wandelte sich zu einem kräftigen Orkan, abends peitschten Schneeschauer durch die Stadt. Als der Wind dann auf Nordost umsprang, wurden ungeheure Wassermassen in die Förde gedrückt. Während der Nacht stieg der Pegel immer mehr an, am letzten Altjahresmorgen waren die hafennahen Straßen vom Eisenbahndamm bis zum Seegarten überschwemmt. Durch die Holstenstraße zwischen Hafenstraße und Holstenbrücke wälzte sich die trübe Flut, auch das Hindenburgufer und die Gärten am Düsternbrooker Weg versanken im Wasser.

Fischer boten für zwei Groschen eine Bootsfahrt durch die Stadt an

Die Kieler Zeitung berichtete am Sonnabend über vollgelaufene Keller und Wohnräume: *In vielen Räumen hingen die Möbel an den Zimmerdecken. Es war unmöglich, sie herauszuschaffen.* Insbesondere die älteren Menschen saßen in ihren Häusern wie in einer Falle. Behelfsstege, vor allem aber Boo-

Beim Wäschehaus Meislahn: Am 31. Dezember 1904 war die Flut bereits wieder kräftig gesunken, so daß man mit der Kutsche durchs Wasser fahren konnte. Abbildungen Archiv Niebergall

wieder hat es auch an der Ostsee verheerende Sturmfluten gegeben. Unvergessen war Ende 1904 insbesondere die gewaltige Flut vom 13. November 1872. Sie versetzte die Küstenbewohner der



tuationen noch, wenn bei Vollmond an der Westküste eine Springflut entsteht und das Hochwasser der Nordsee mit höherem Wasserstand durch Skagerrak und Kattegat zwischen den dänischen

(Kieler Nachrichten, 17. December 1994)

Important dates of Baltic Sea research

- 1576: weather and ice observations by Tycho Brahe (1546-1601) on the island Vers in the Öresund
- 1697: Samuel Reyher's "experimentum novum" in the harbor of Kiel (measurements of salinity)
- since 1869: monitoring in the Baltic (Denmark, Germany)
- 1871: "Pommerania" expedition from Kiel (Meyer, Möbius, Karsten, Hensen)
- 1877: Swedish expedition (G. Ekman, O. Petterson)
- 1892: resolution on international cooperation (DK, S, D, SF, Russia)
- 1898: agreement on simultaneous investigations on a regular basis at a few selected deep stations
- 1902: start of the International Council of the Exploration of the Sea (ICES)
- 1937: foundation of the Institute of Marine Research in Kiel
- 1957: first Conference of the Baltic Oceanographers (CBO) in Helsinki

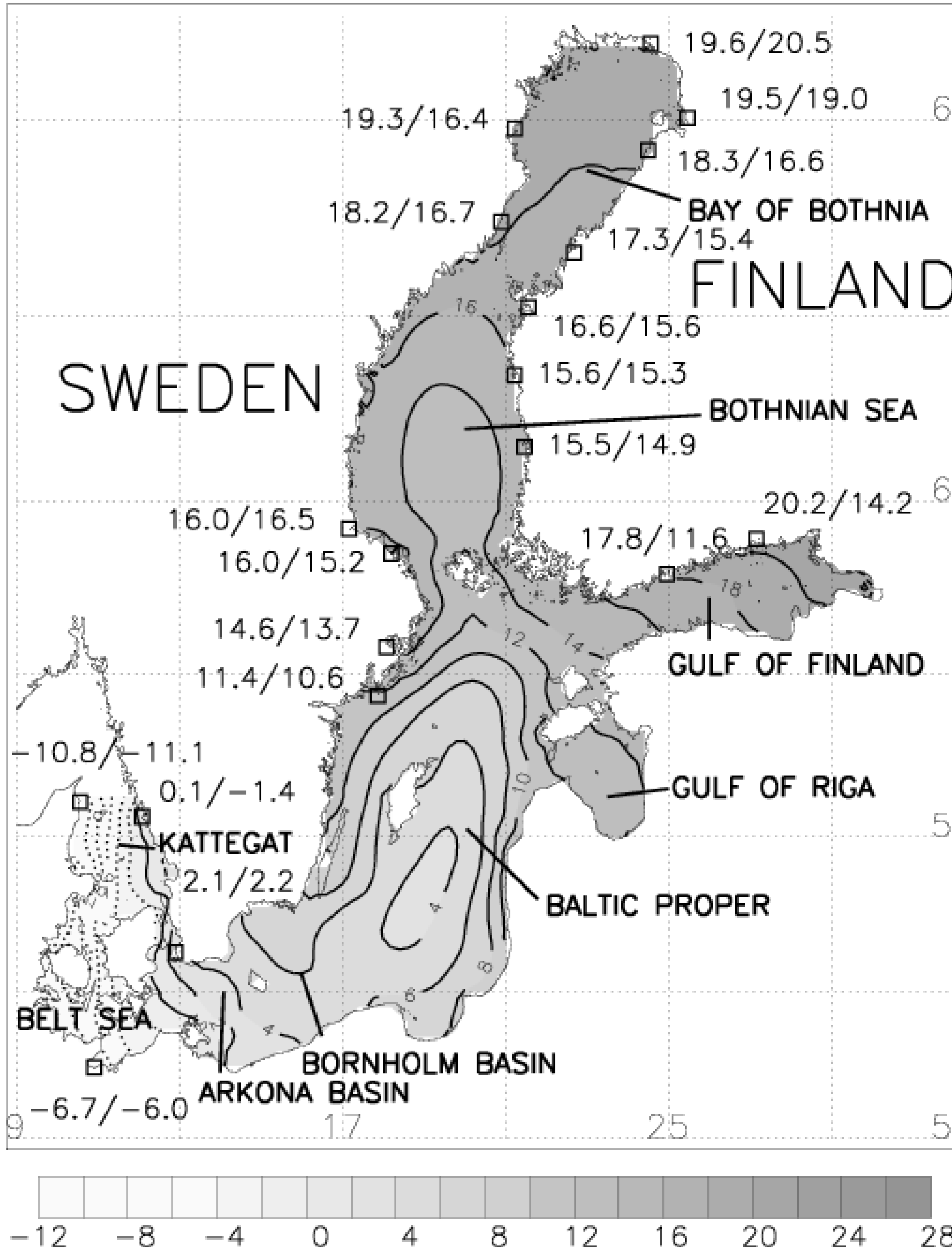
2. Development of the Baltic Sea

- today: fjord or estuary with brackish water

Factors affecting sea level change on long time scales

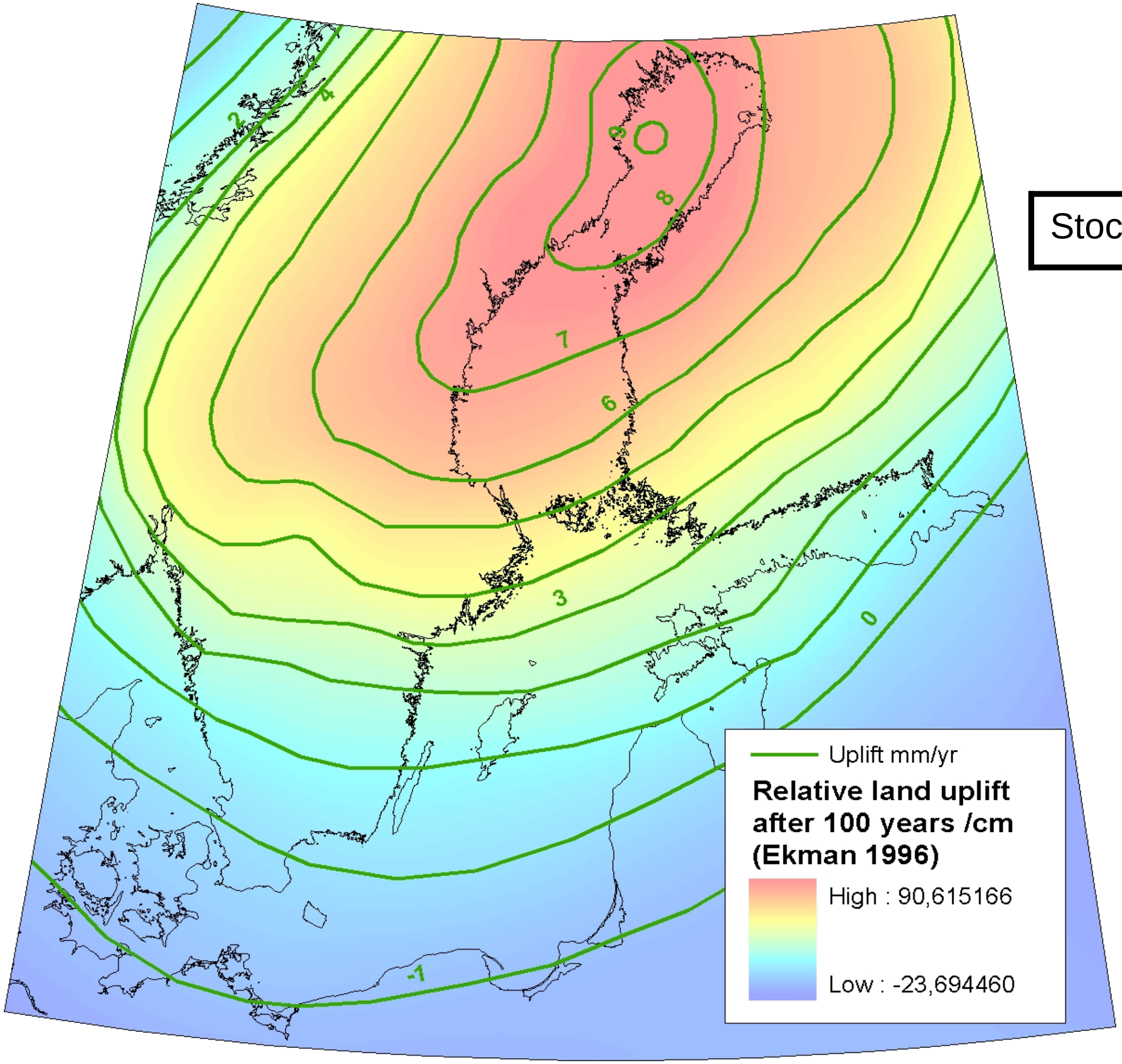
- Land uplift (glacio-hydro-isostatic effect)
- Eustatic sea level rise (thermal expansion, glaciers, etc.)

Mean sea level



(Meier et al., 2004a)

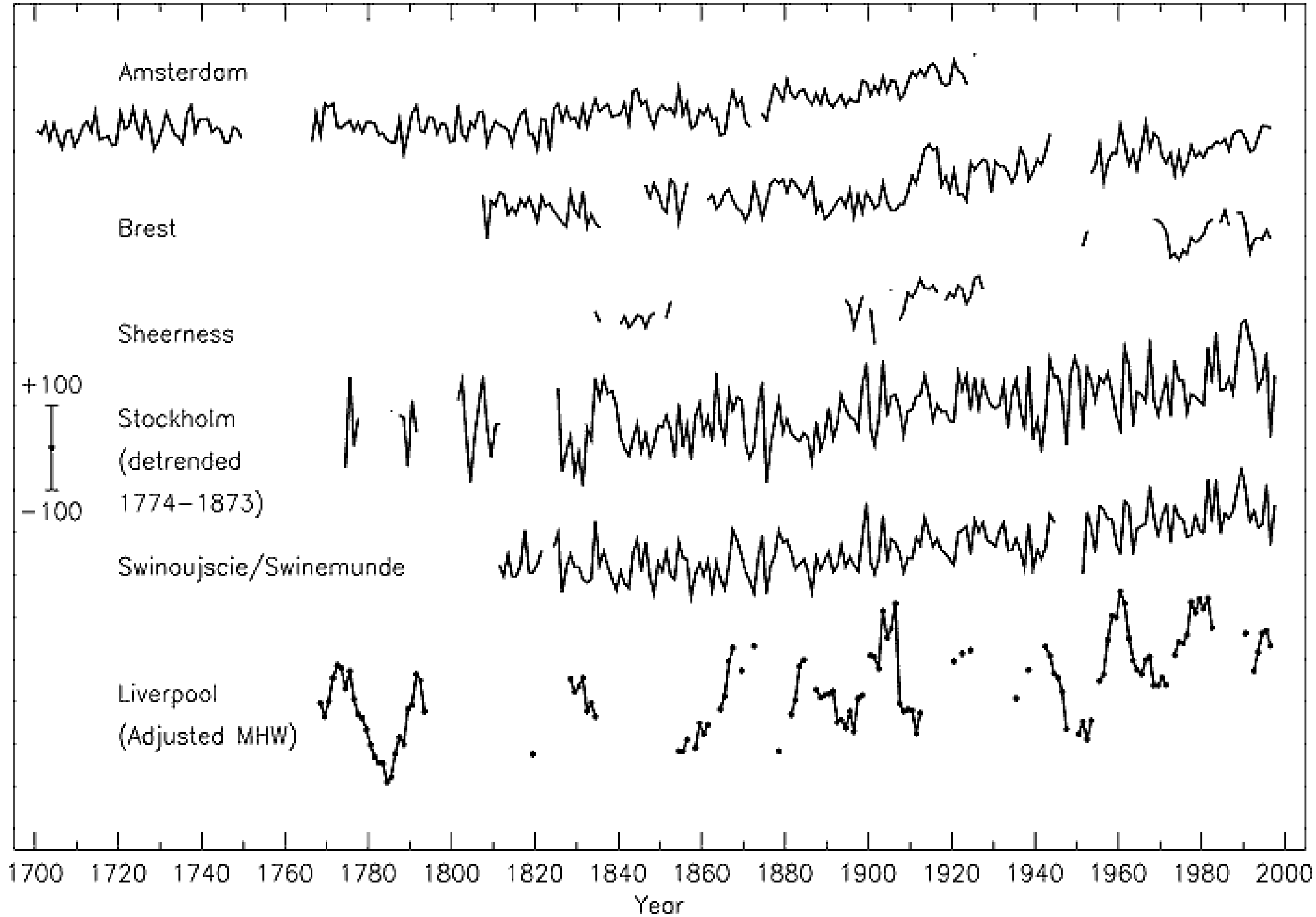
Land uplift relative to the mean sea level



Stockholm	4 mm/yr

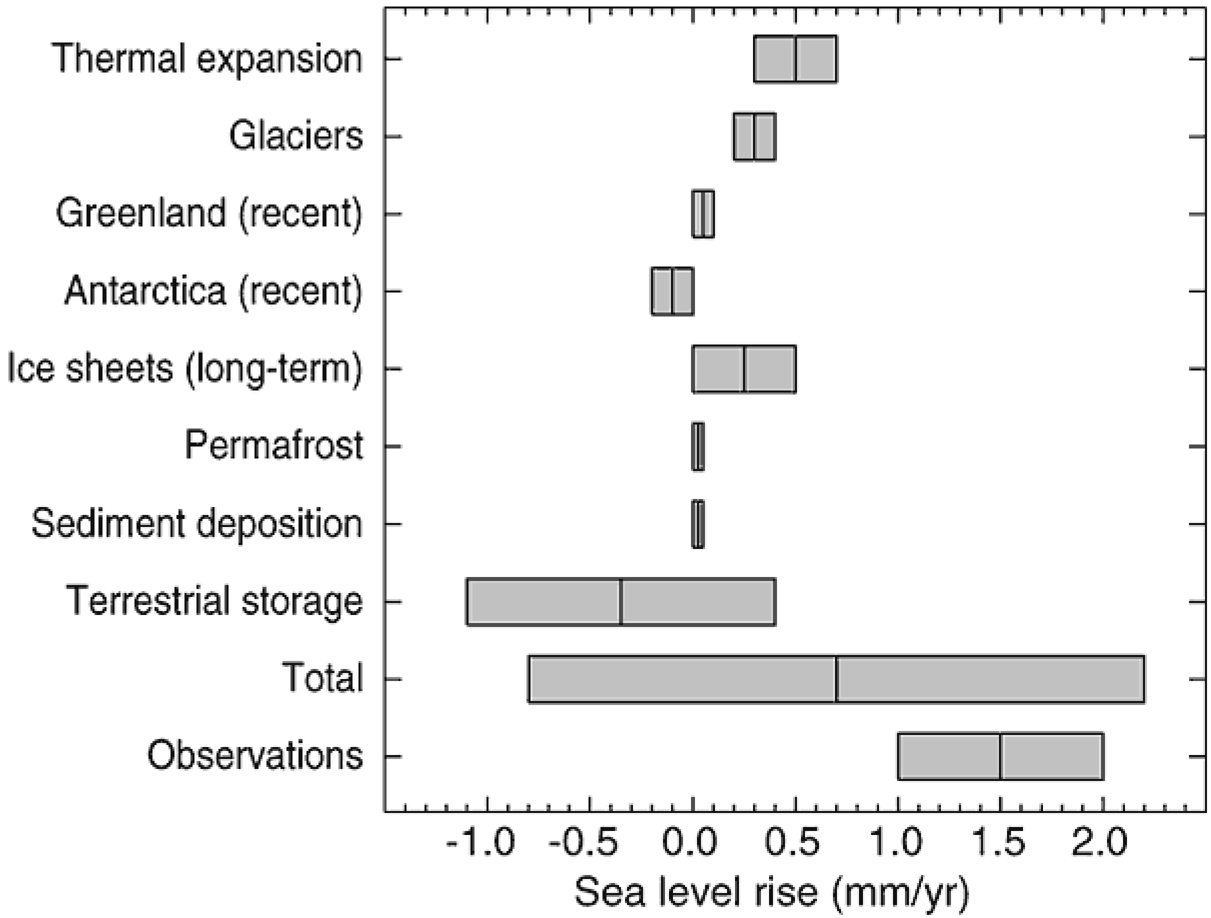
(Ekman, 1996)

Past eustatic sea level rise

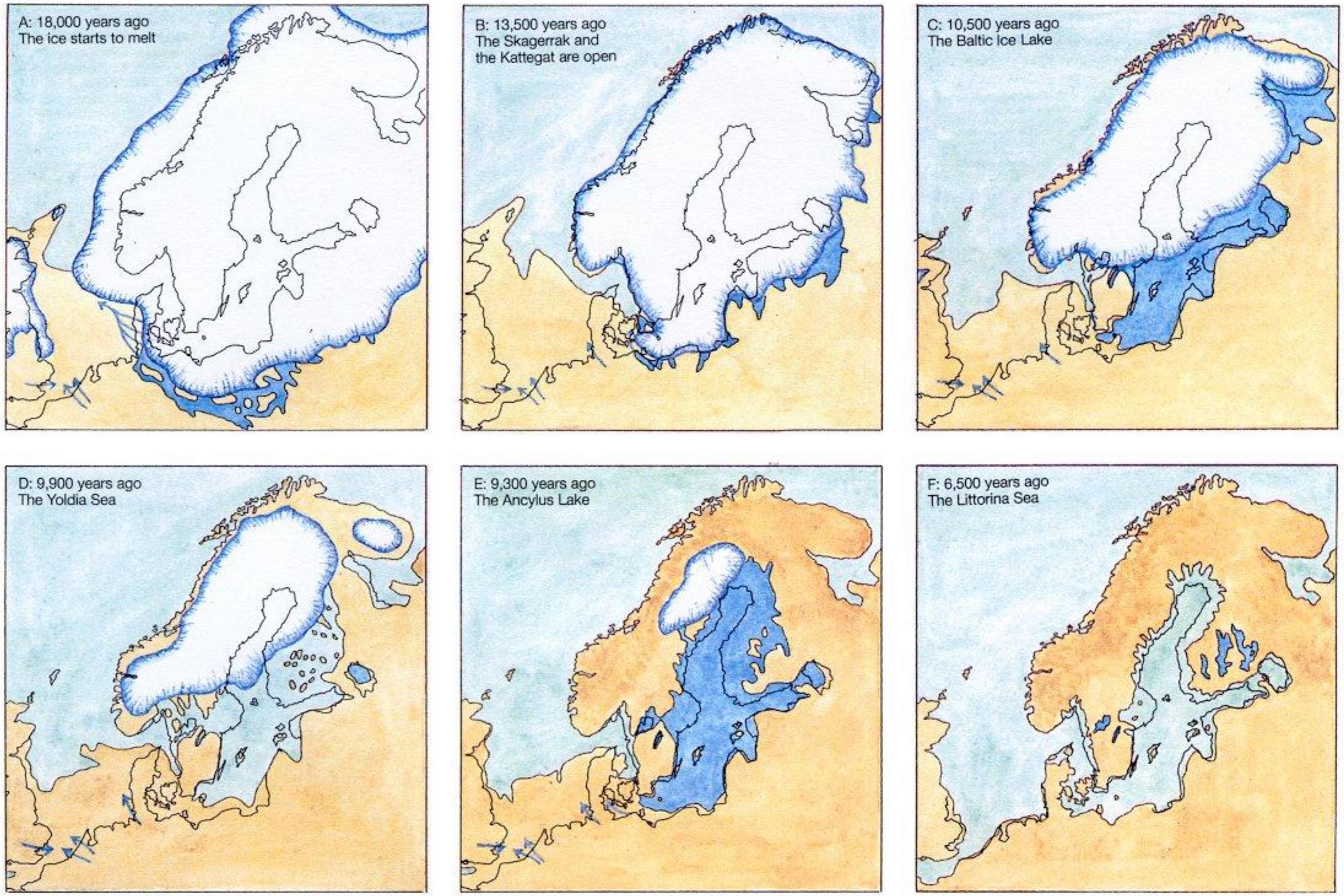


(IPCC, 2001)

Sea level changes during the 20th century



(IPCC, 2001)



A. The latest glaciation—the Weichel—had its greatest extent in northern Europe at this time. At the same time the surface of the oceans was at its lowest level, about 130 m lower than today.

B. The ice margin retired and the Skagerrak, Kattegat and parts of Skåne became ice-free. The surface of the oceans was at that time about 100 m lower than today.

C. During a period with colder climate, the melting of the ice ceased and terminal moraines were formed along the edge of the ice in southern Norway, central Sweden and Finland. The Baltic Ice Lake, dammed up by the ice, probably drained through the Sound to the oceans.

D. When the margin of the ice retired from the northern point of Billingen and the water level in the Baltic Ice Lake sank to that of the oceans (about 60 m lower than today), brackish water was able to enter the Baltic Basin through the Central Swedish Sounds.

E. The rapid isostatic upheaval caused the sill of the Baltic Basin in central Sweden to rise above the present level of the oceans and the Baltic returned to a freshwater state. Initially, it drained through Lake Vänern but later the outflow changed to the Great Belt.

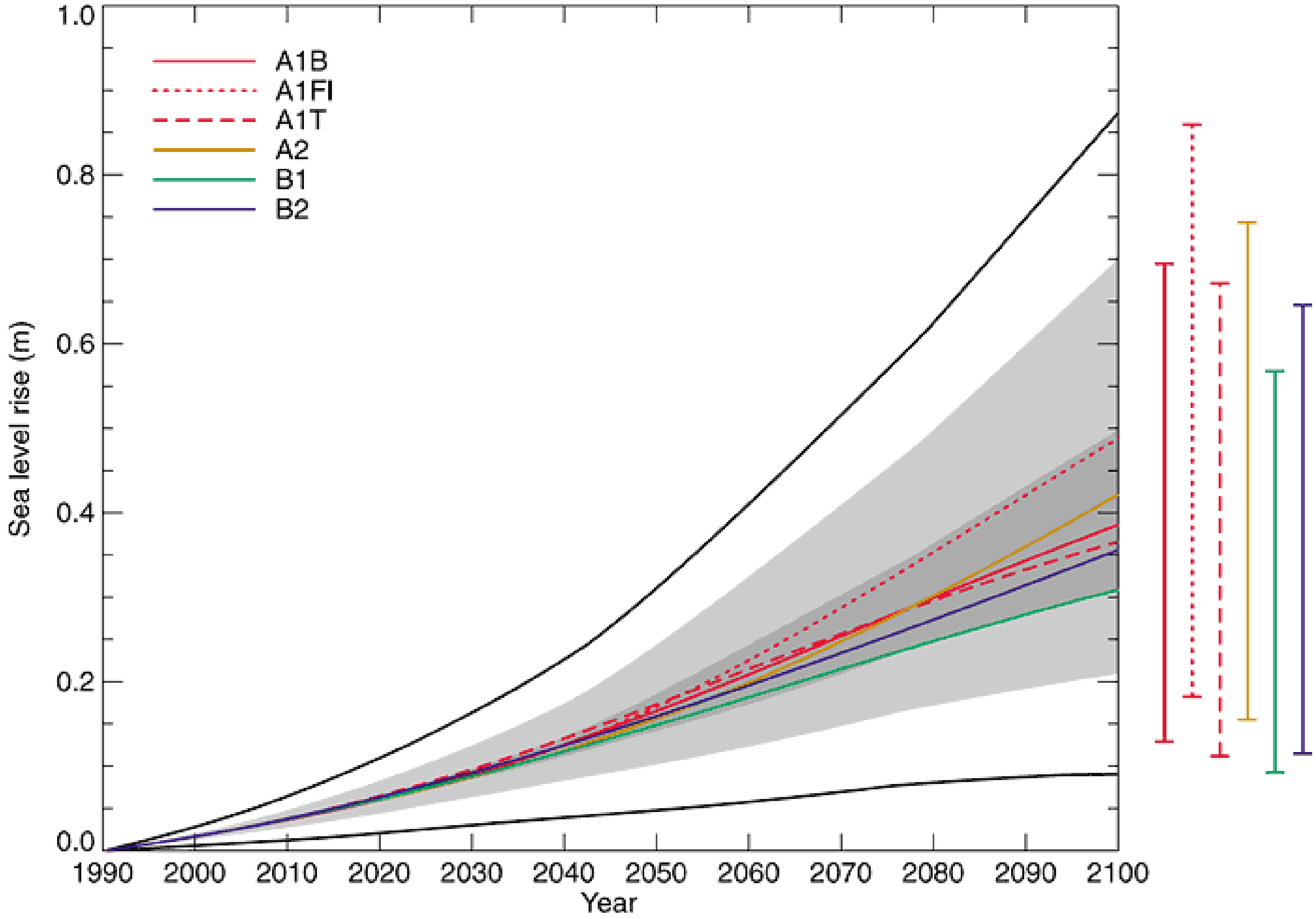
F. The ocean, the level of which still rose has penetrated through the Danish Sound and the Baltic Sea is again connected with the Skagerrak/Kattegat.

(National Atlas of Sweden)

Some numbers:

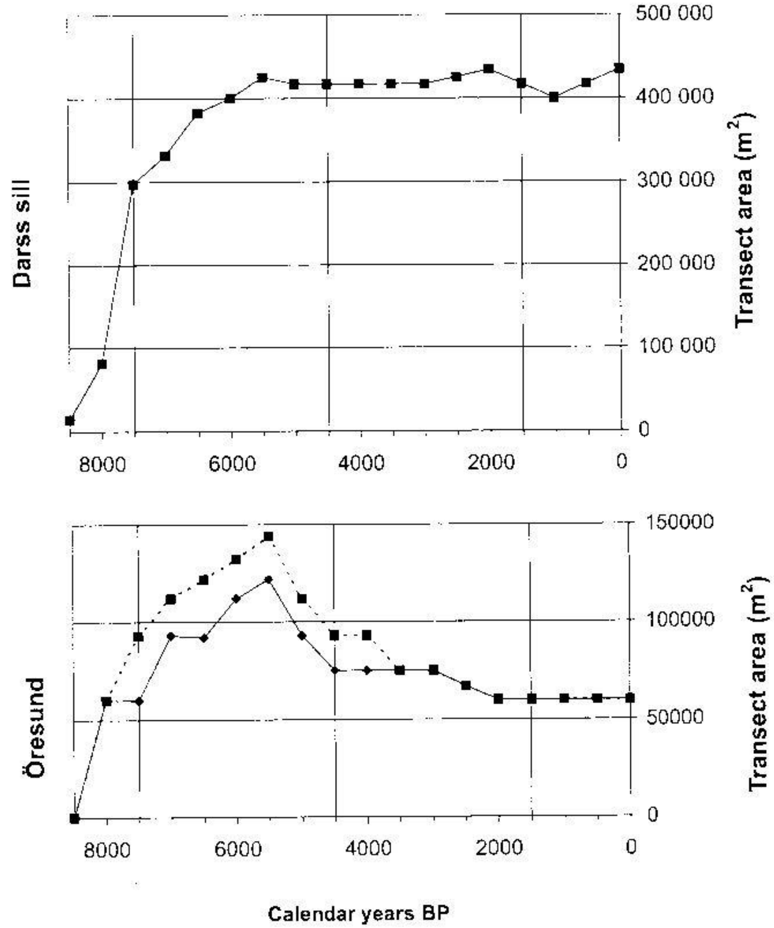
- during the last glaciation the global mean sea level was about 80-100 (120) m lower than today
- if all ice today is melting, the sea level would rise by 60 m
- deceleration of land uplift from 3 m/100 yr to 1 m /100 yr

Projections of global mean sea level rise with different emission scenarios



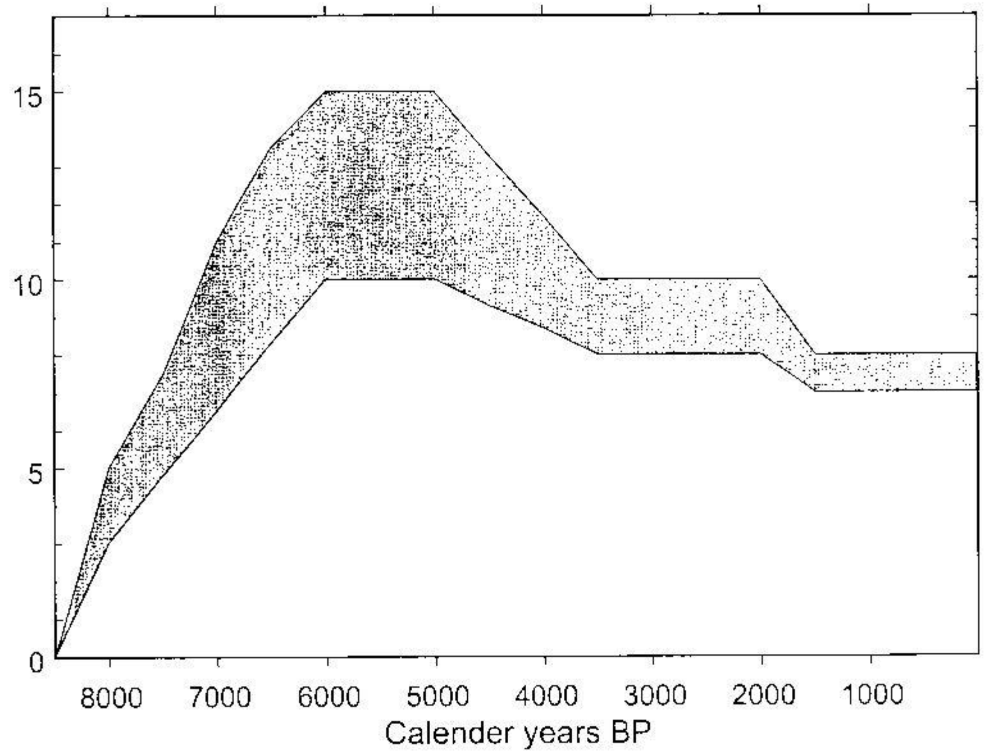
(IPCC, 2001)

Changes in inlet transect areas
(Gustafsson and Westman, 2002)



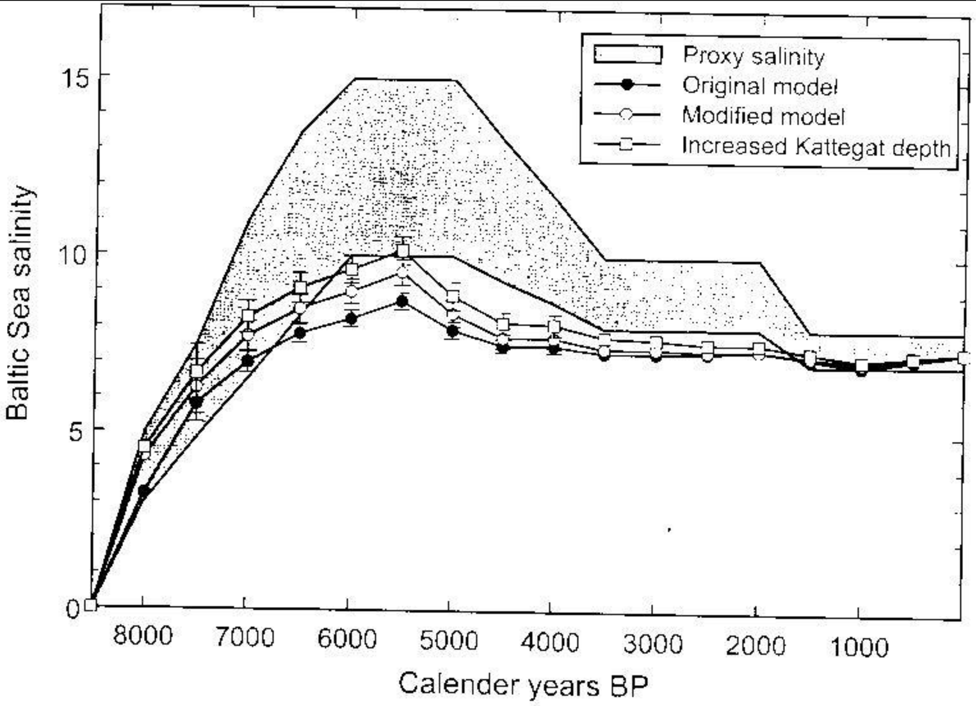
Estimated salinity for the Litorina Sea Stage based on proxy data

(Gustafsson and Westman, 2002)



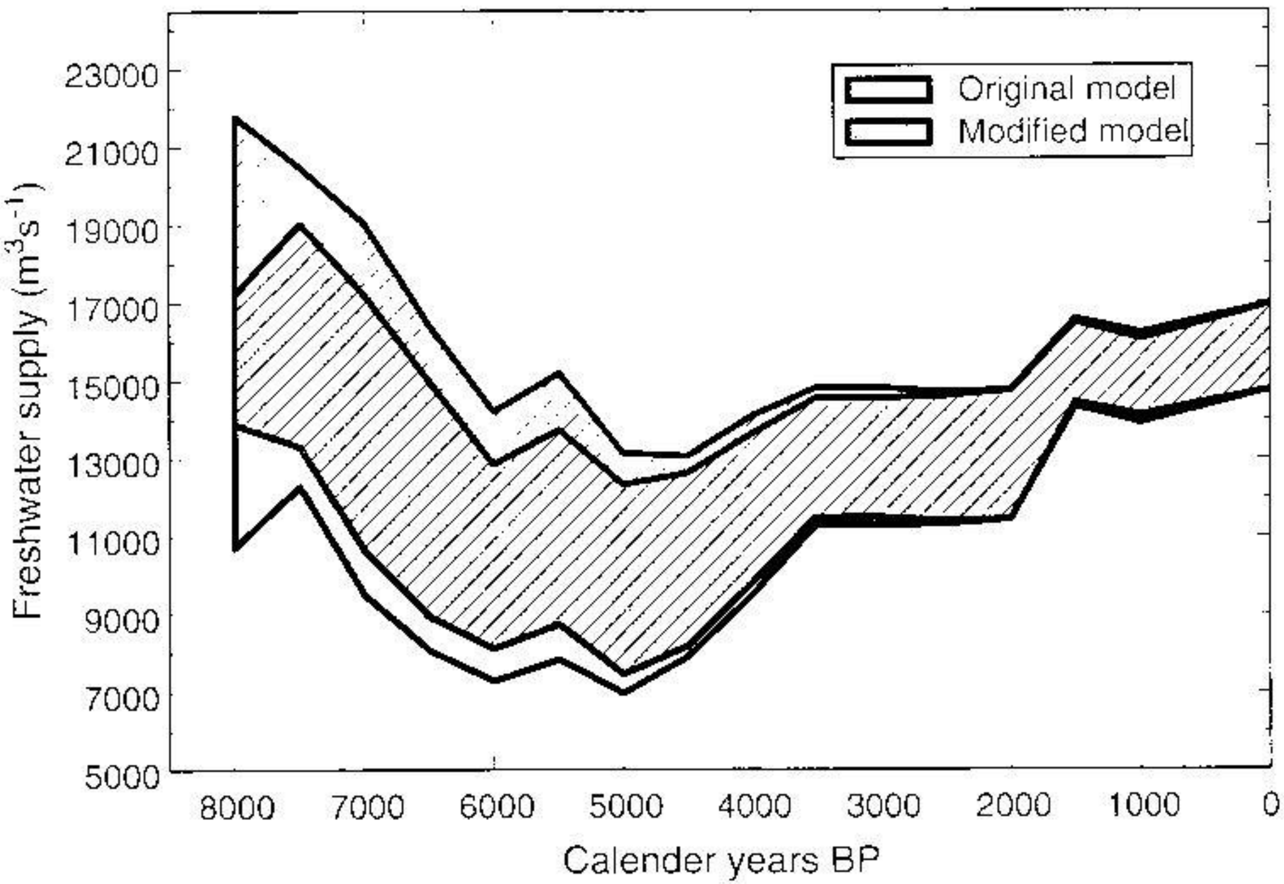
Simulated salinity for the Litorina Sea stage

(Gustafsson and Westman, 2002)

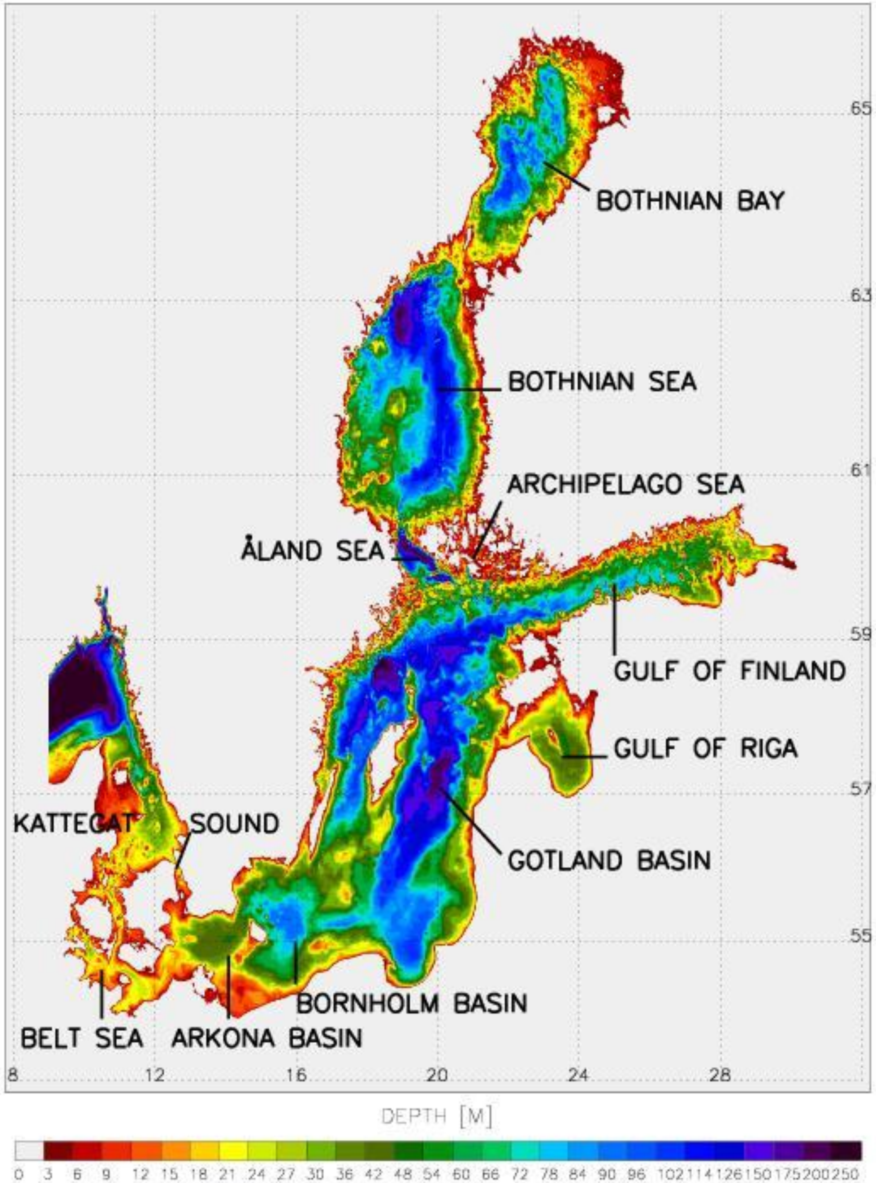


Variations in freshwater supply that is necessary to explain salinity variations derived from proxy data

(Gustafsson and Westman, 2002)



3. Bottom topography of the Baltic Sea



Reference topography data:

www.io-warnemuende.de/research/de_iowtopo.html

(Seifert and Kayser, 1995)

Mean depth: 52 m

Maximum depth (Landsort Deep): 459 m

Resolution of gridded data: 2   1
(Belt Sea 1   0.5)

4. Water balance

$$Q = Q_F + P - E = Q_{out} - Q_{in}$$

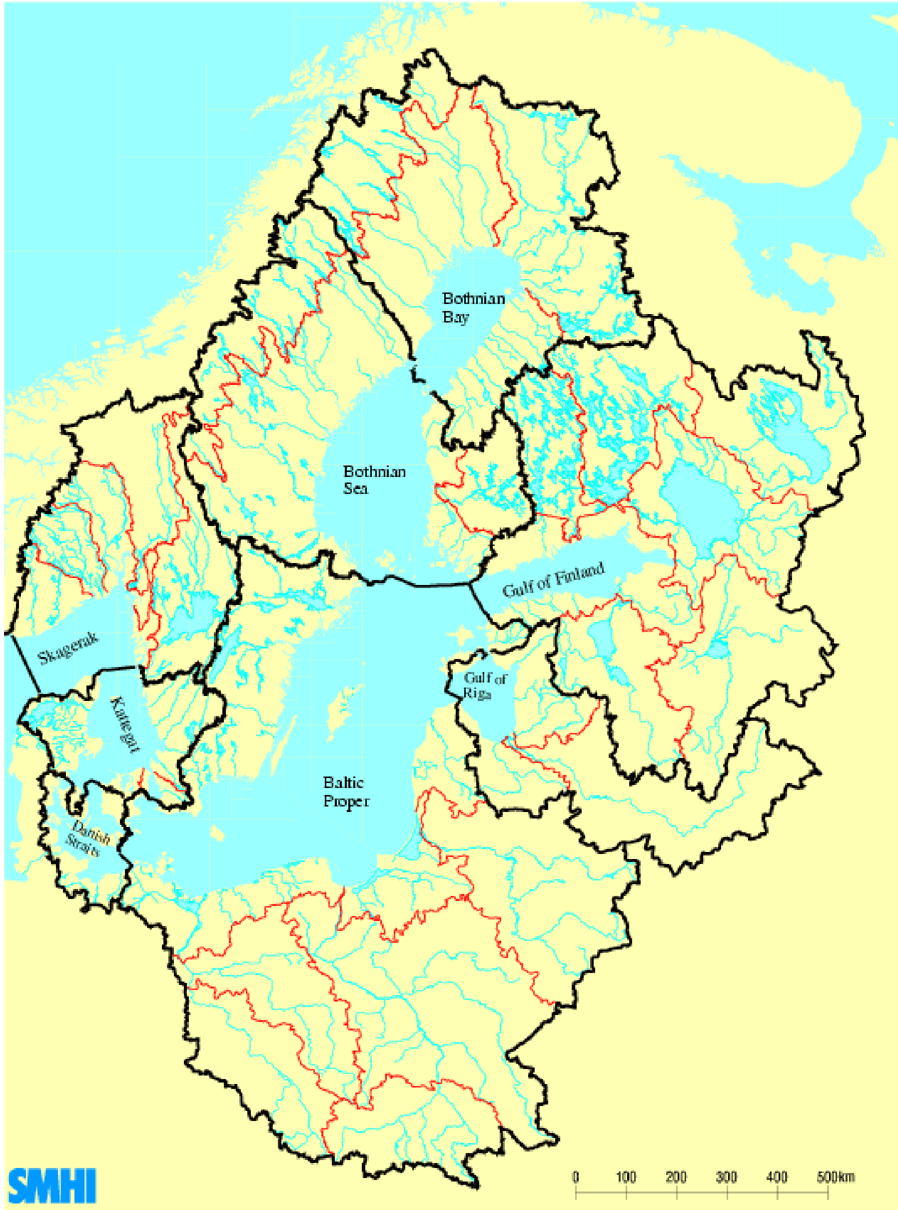
$$Q_F = 15\,310\,\mathrm{m^3 s^{-1}} = 483\,\mathrm{km^3 yr^{-1}} \quad (1950\text{-}1990)$$

$$\text{interannual variability} = \pm 30\,\mathrm{km^3 yr^{-1}}$$

$$\text{NEVA}: \quad Q_F = 2\,460\,\mathrm{m^3 s^{-1}} = 77.6\,\mathrm{km^3 yr^{-1}}$$

(Bergström and Carlsson, 1994)

Baltic Sea catchment area

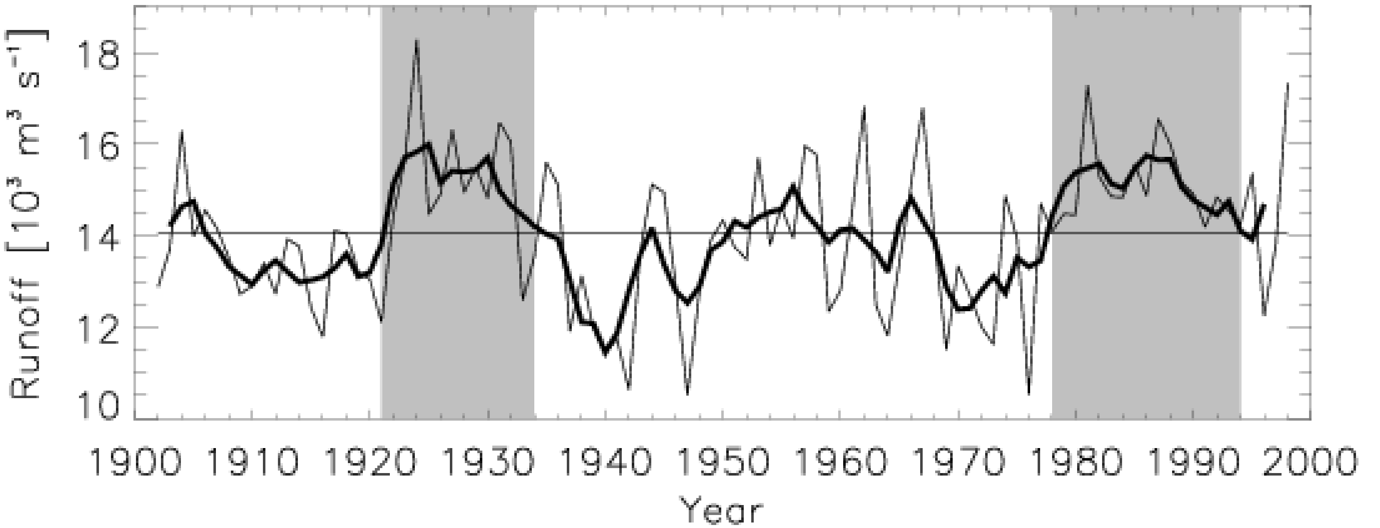


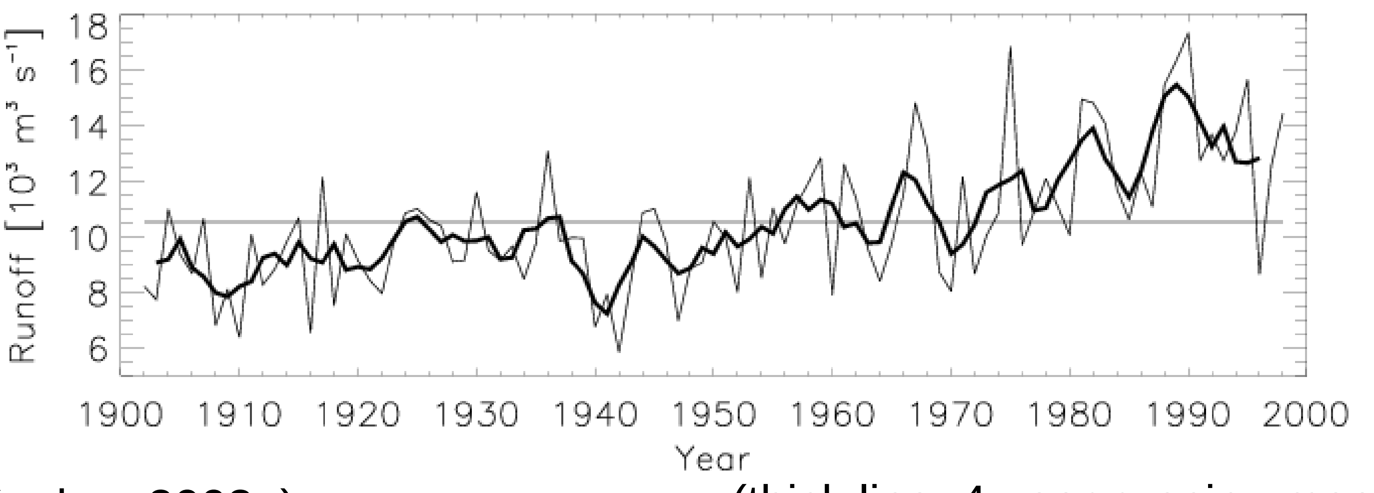
with Kattegat (without Skagerrak):
1 729 000 km^2 =
4 times Baltic Sea surface

Baltic surface (without Kattegat) = 398 470 km^2

Baltic volume (without Kattegat) = 21 500 km^3

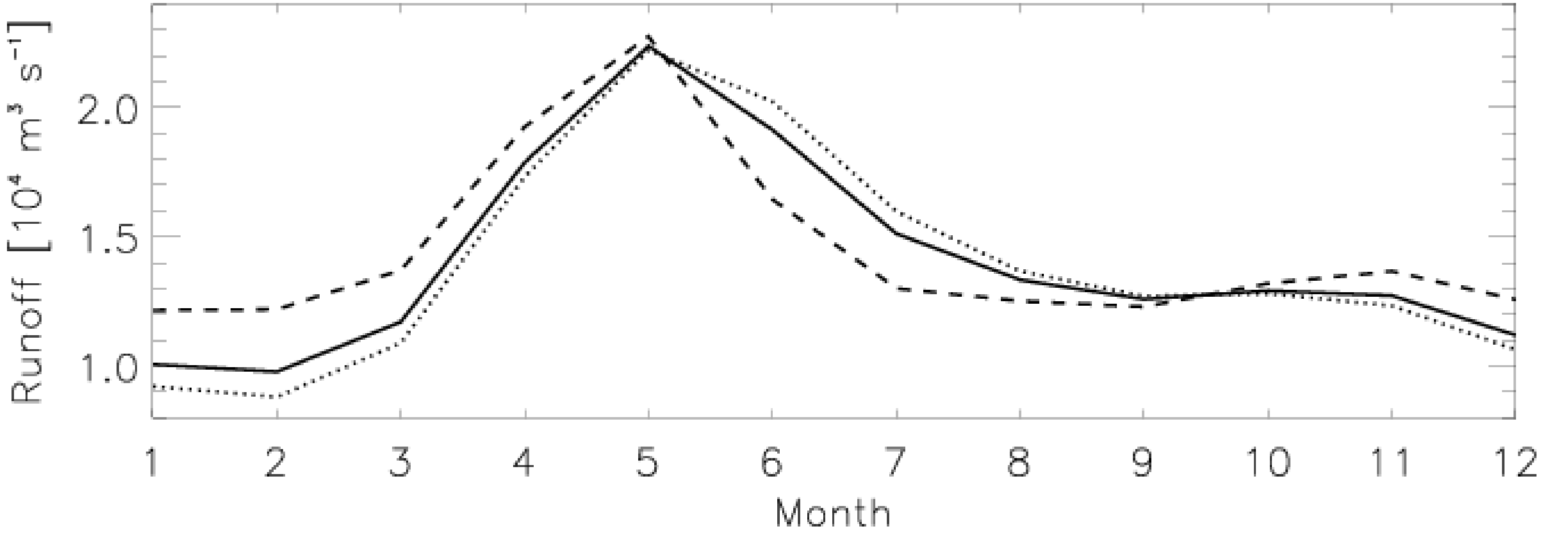
Annual and winter (JFM) mean runoff





(Meier and Kauker, 2003a) (thick line: 4-year running mean runoff)

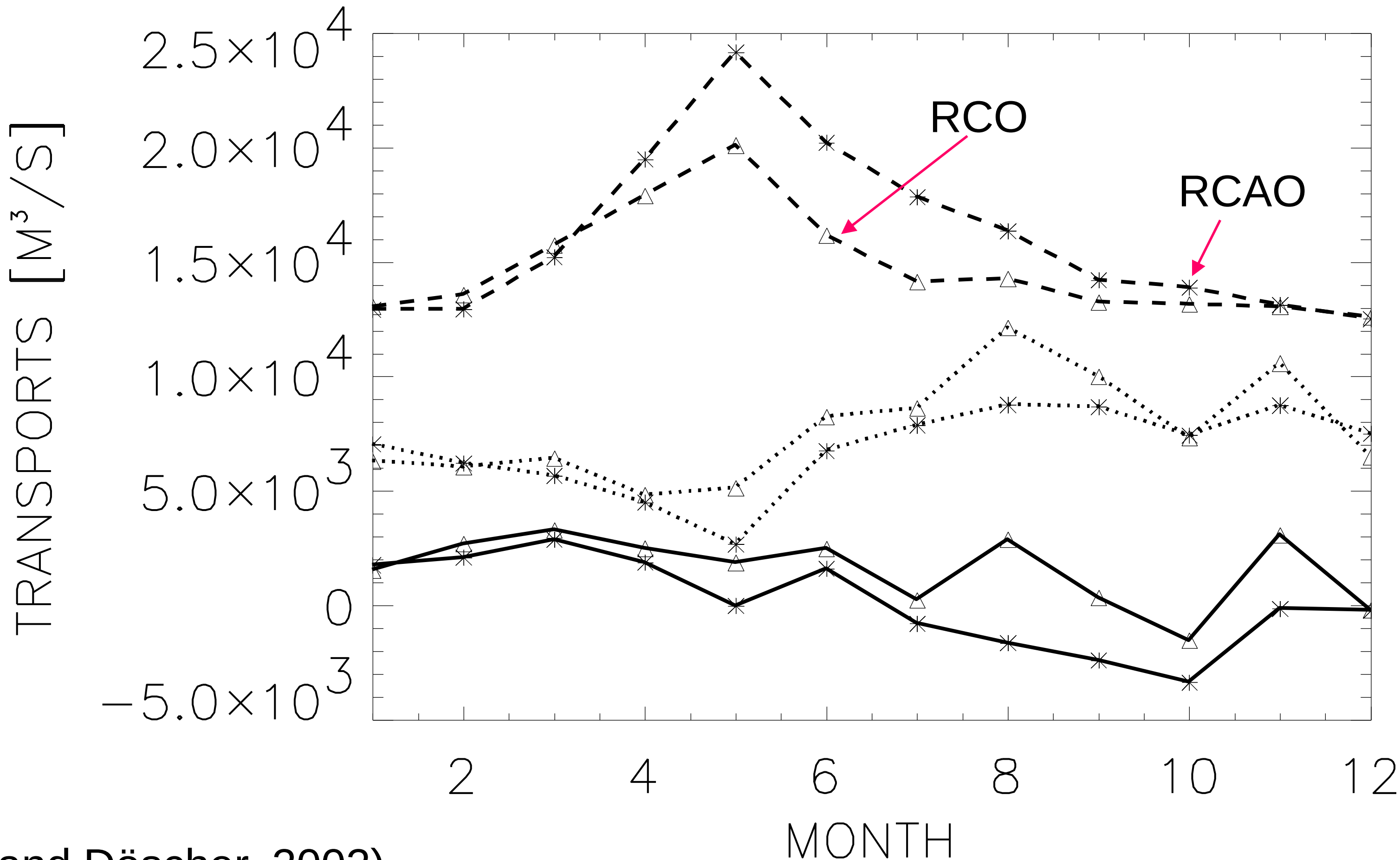
Monthly mean runoff to the Baltic without Kattegat



(solid line: 1902-1998, dotted line: 1902-1970, dashed line: 1971-1998)

(Meier and Kauker, 2003a)

Monthly mean runoff (dashed), precipitation (dotted), and net precipitation (solid) for Sep 1988 to Aug 1993



(Meier and Döscher, 2002)

5. Heat balance

$$Q_a = Q_{SW} + Q_{LW} + Q_S + Q_L$$

$Q_{SW} = 90\,\mathrm{Wm}^{-2}$ short-wave radiation

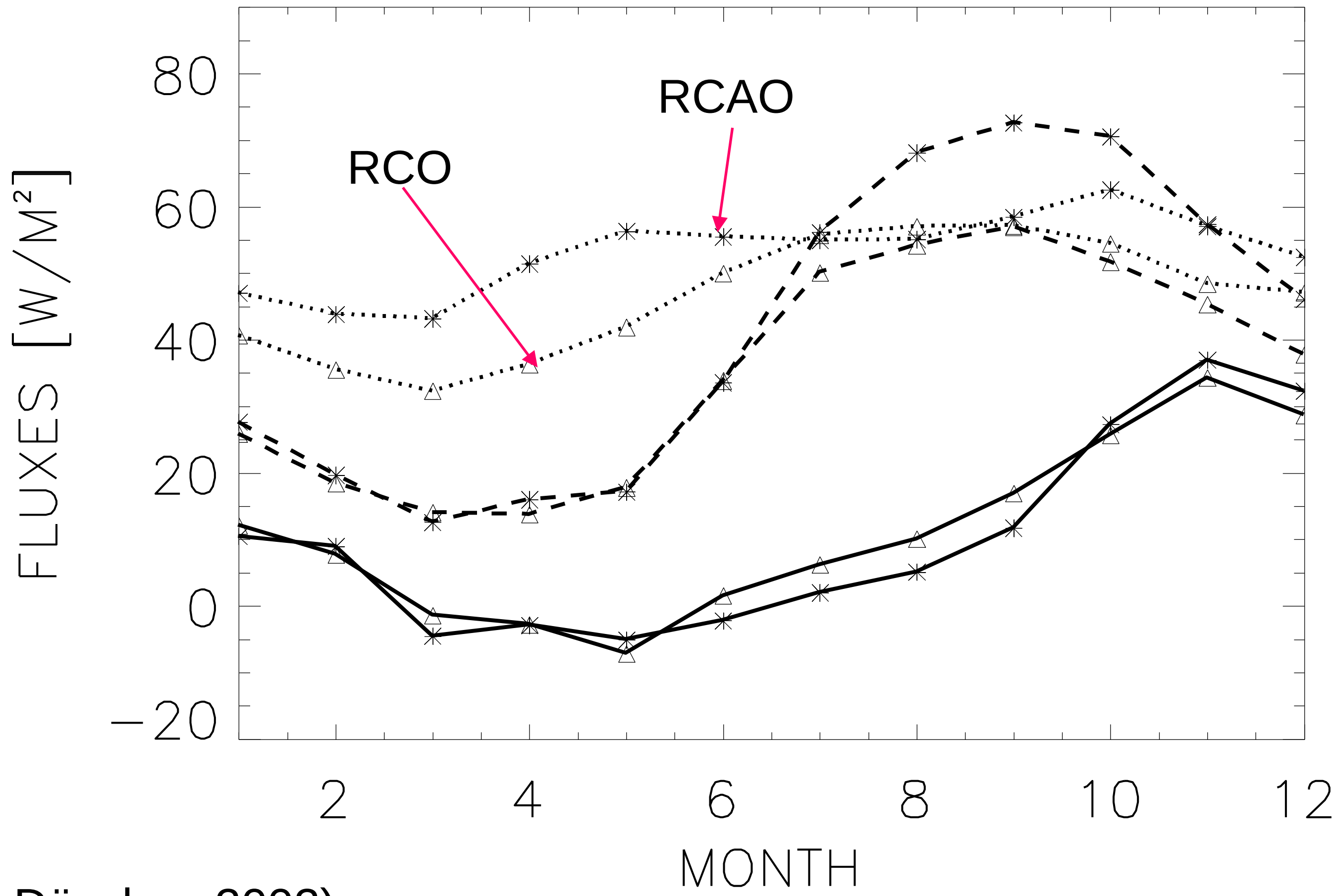
$Q_{LW} = -45\mathrm{Wm}^{-2}$ long-wave radiation

$Q_S = -12\mathrm{Wm}^{-2}$ sensible heat flux

$Q_L = -32\mathrm{Wm}^{-2}$ latent heat flux

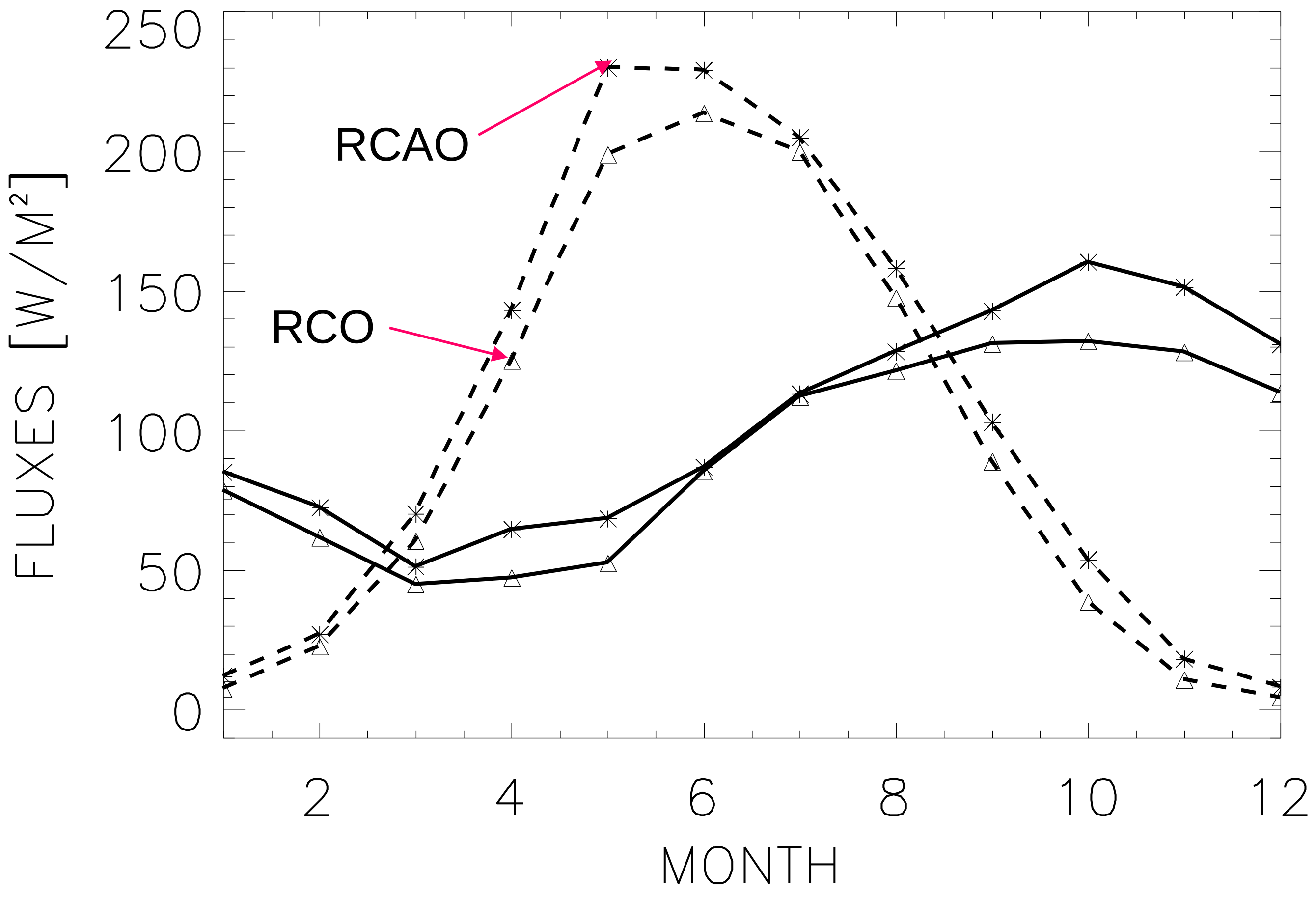
$Q_a = 1\mathrm{Wm}^{-2}$ net atmospheric heat flux

Monthly mean sensible (solid) and latent (dashed) heat flux, and long-wave radiation (dotted)



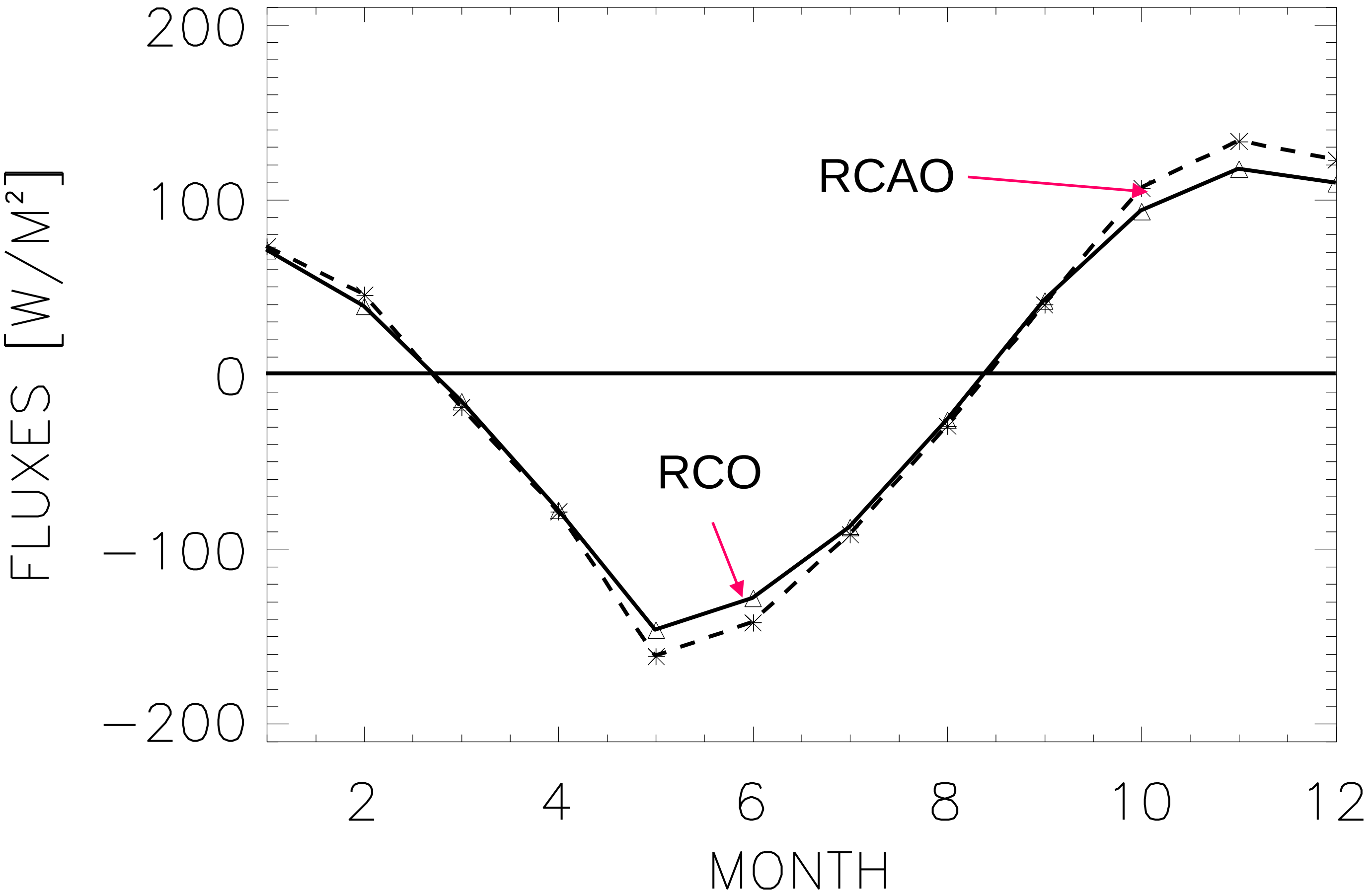
(Meier and Döscher, 2002)

Heat loss to the atmosphere (solid) and solar radiation (dashed)



(Meier and Döscher, 2002)

Monthly mean total heat flux

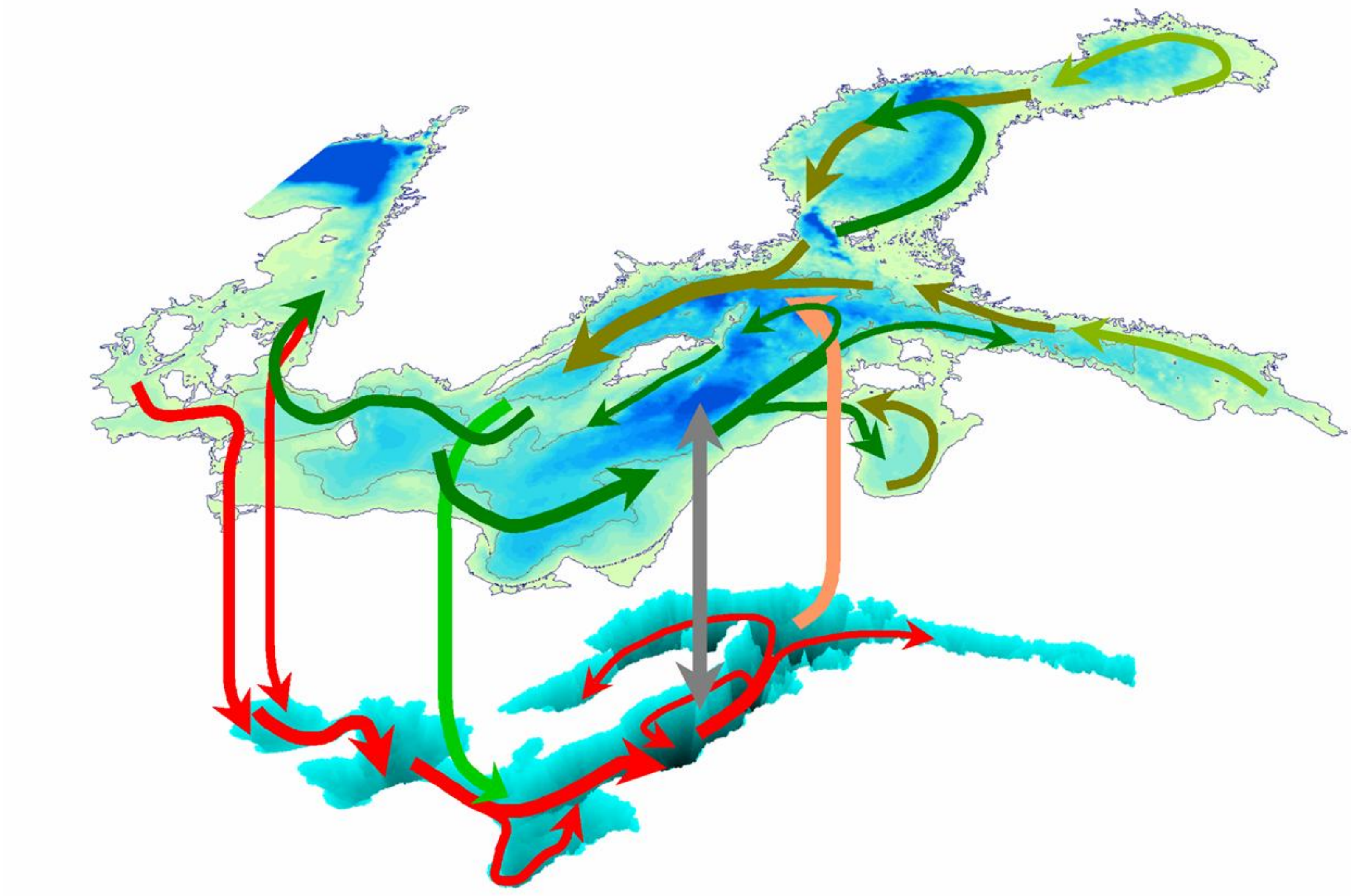


(Meier and Döscher, 2002)

6. Currents

- There is only one permanent current in the Baltic Sea, i.e. the Baltic current in the Kattegat.

Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2007)



10-year mean stream function of the vertical integrated flow

(Lehmann and Hinrichsen, 2000)

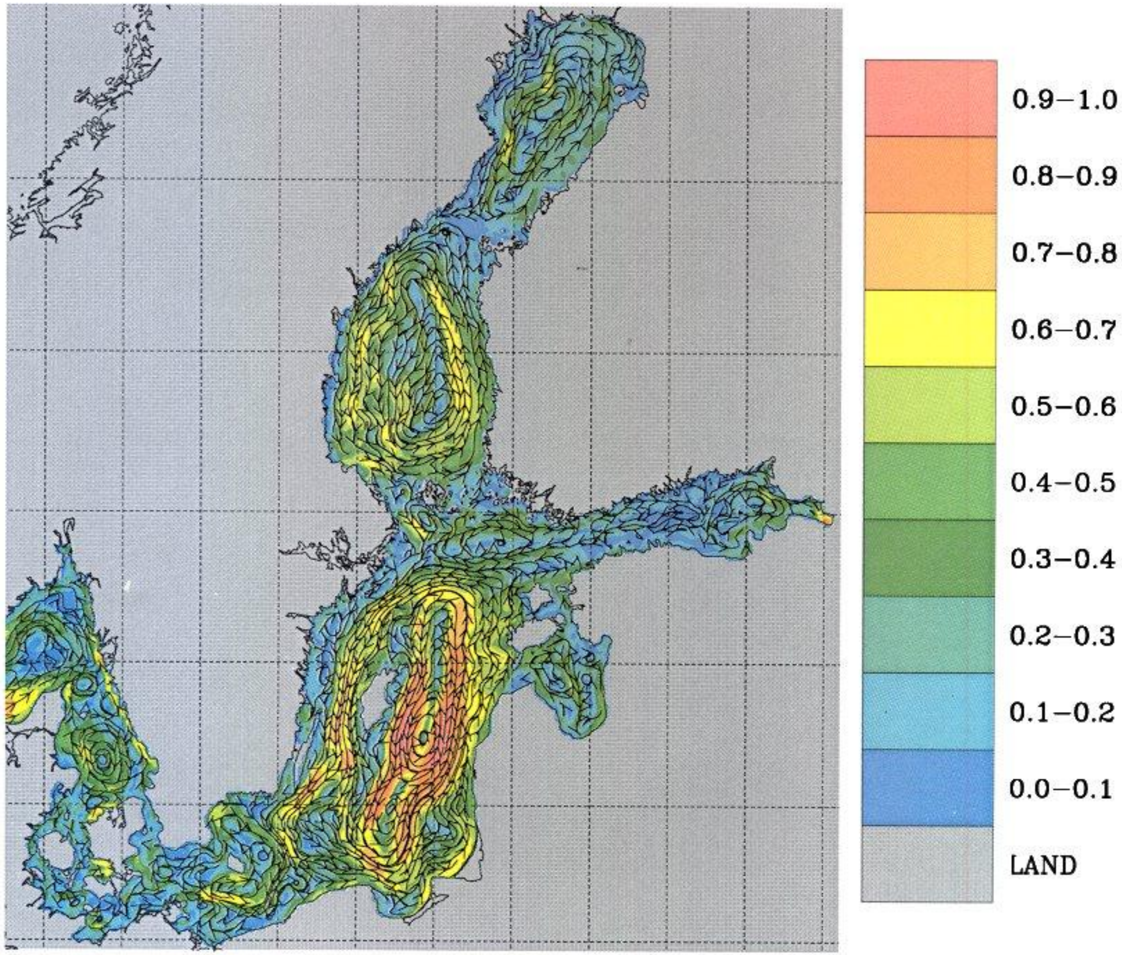
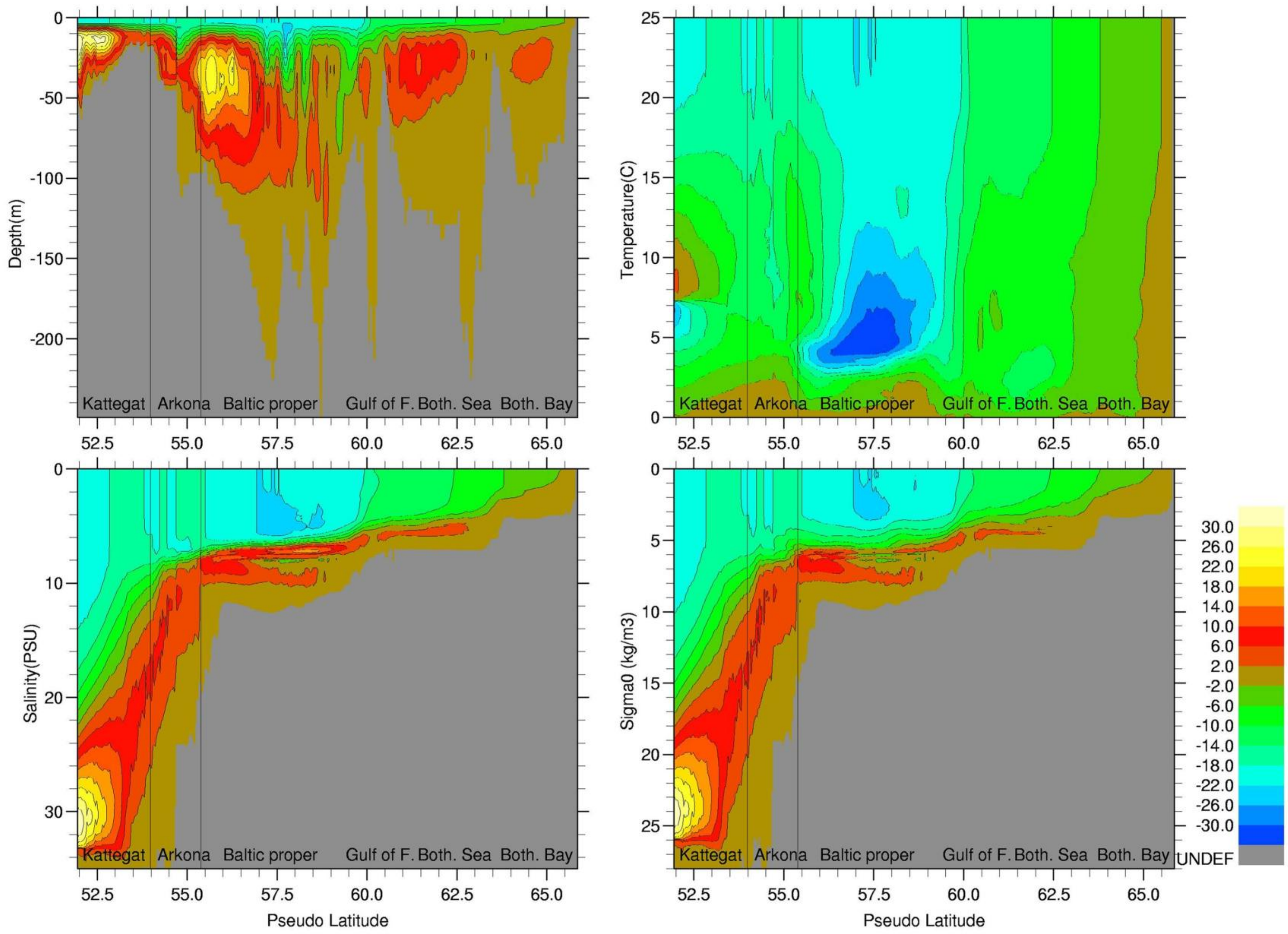


Figure 2: Streamlines representation of the 10-years average of the barotropic circulation underlayed with the stability of the barotropic flow. Colour bar represents stability values 0-1.



Overturning stream function (Döös et al., 2004)

Satellite image of SST (IOW)

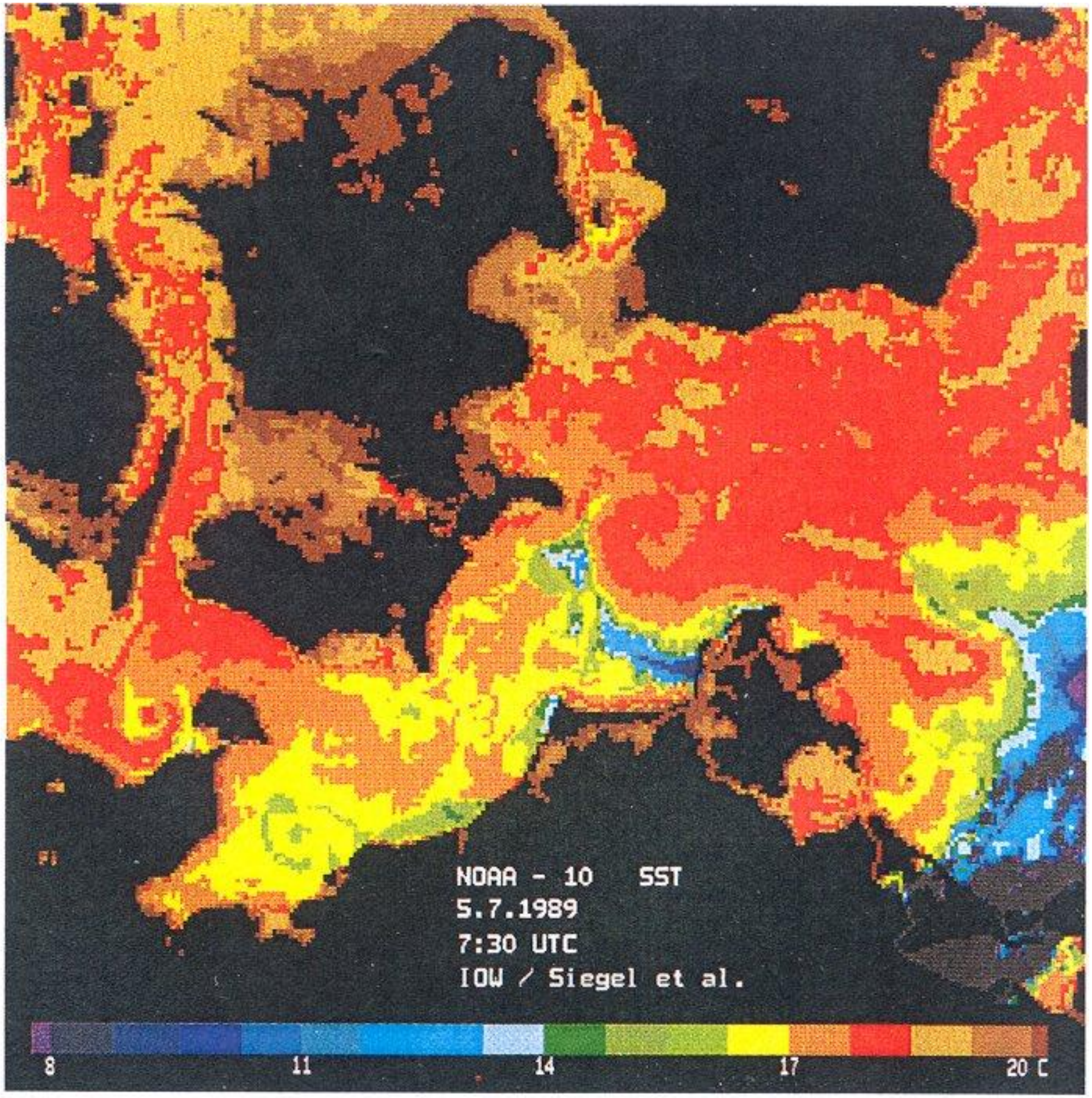


Abb. 25. Satellitenaufnahme der Wasseroberflächentemperatur in der westlichen Ostsee

(Rheinheimer, 1996)

Satellite image of chlorophyll (IOW)

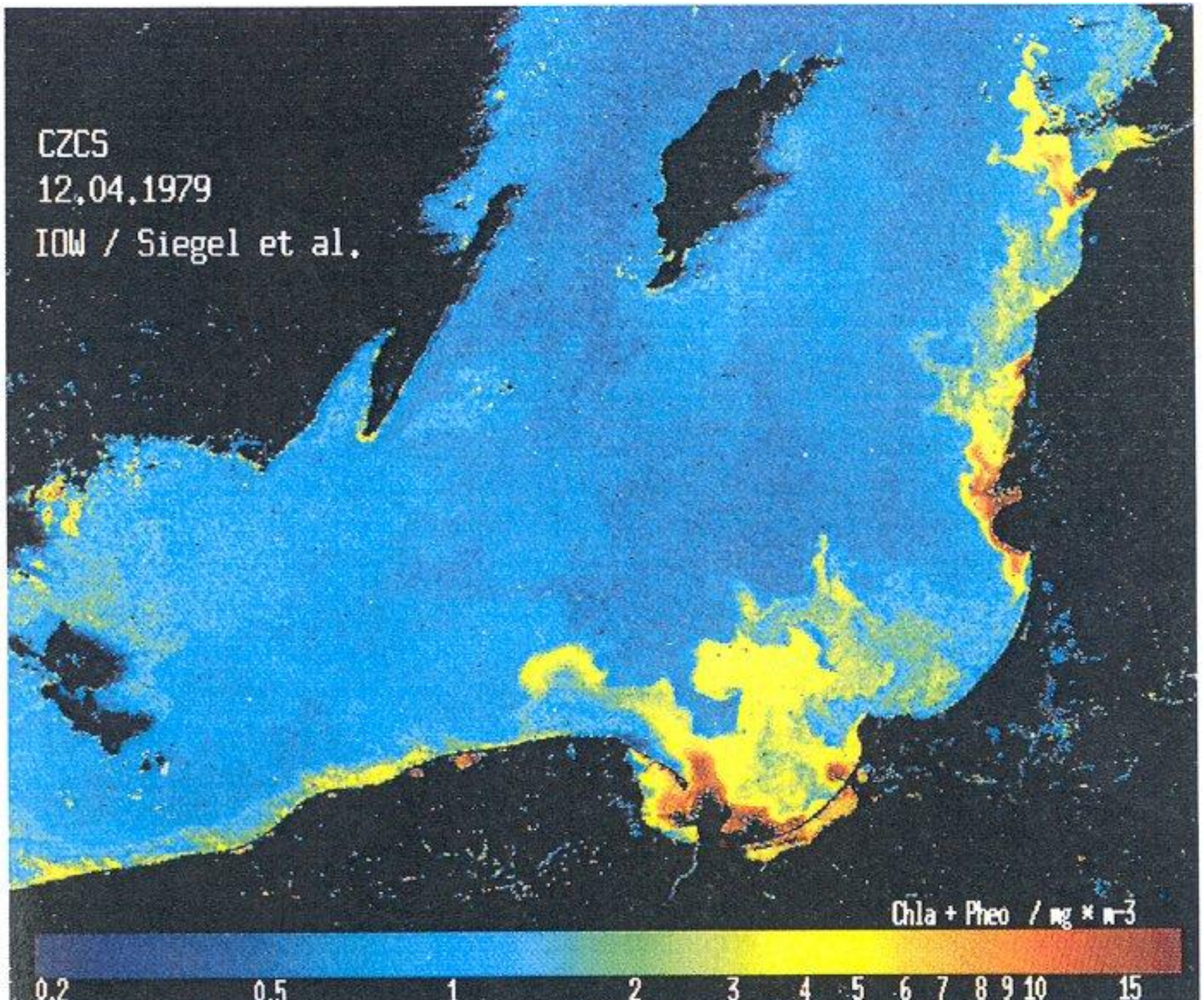


Abb. 26. Satellitenaufnahme der Chlorophyll-Verteilung in der eigentlichen Ostsee

(Rheinheimer, 1996)

7. Sea level

Forcing of the sea level in the Baltic Sea:

- tides:

  S_2 (12.00 h), M_2 (12.42 h),

  K_1 (23.93 h), O_1 (25.82 h)
- seiches
- wind stress and sea level pressure gradient

Semi-diurnal tides

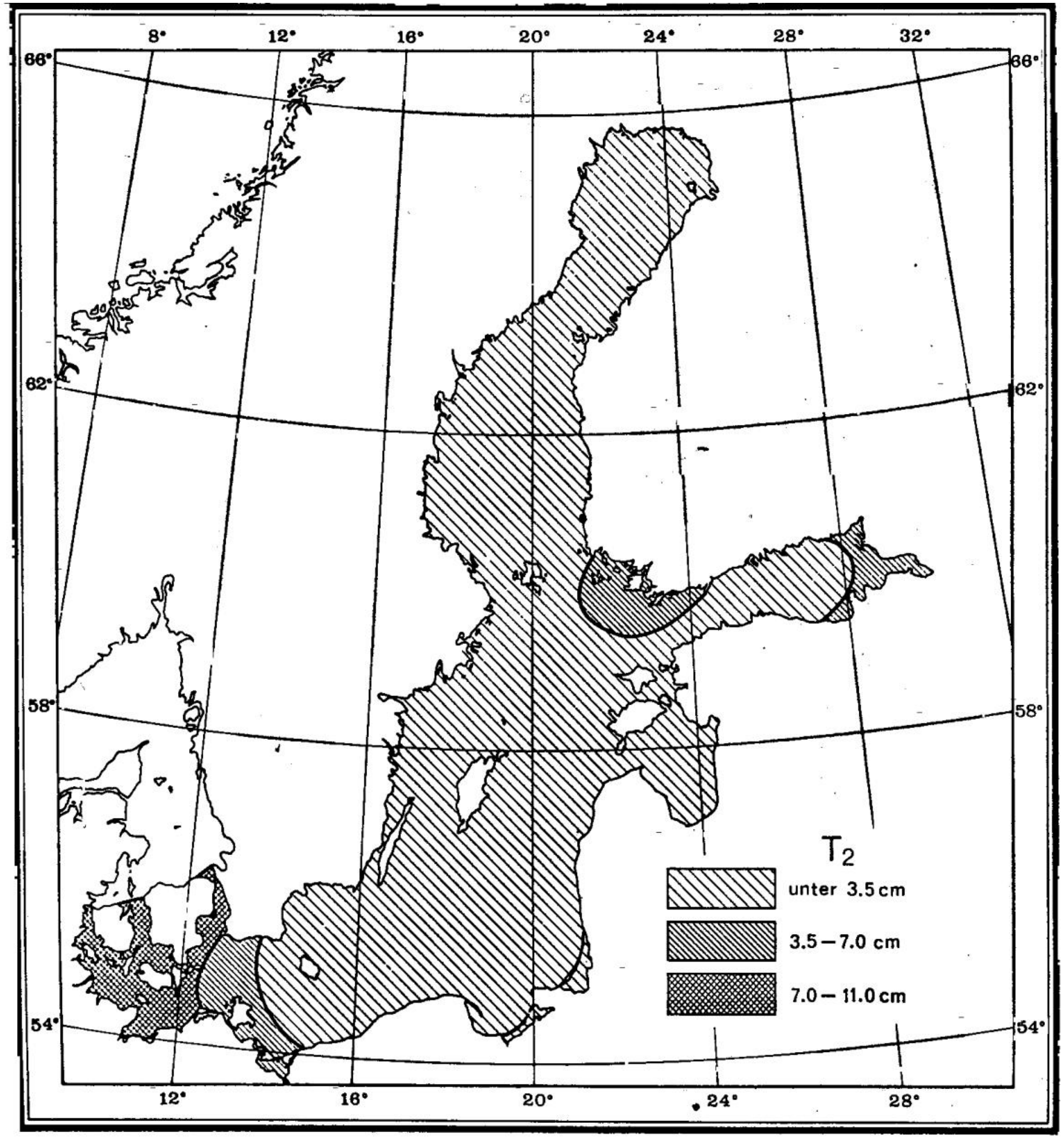


Abb. 2. Geographische Verteilung des Springtidenhubs T_2 der halbtägigen Gezeiten

(Magaard and Rheinheimer, 1974)

Diurnal tides

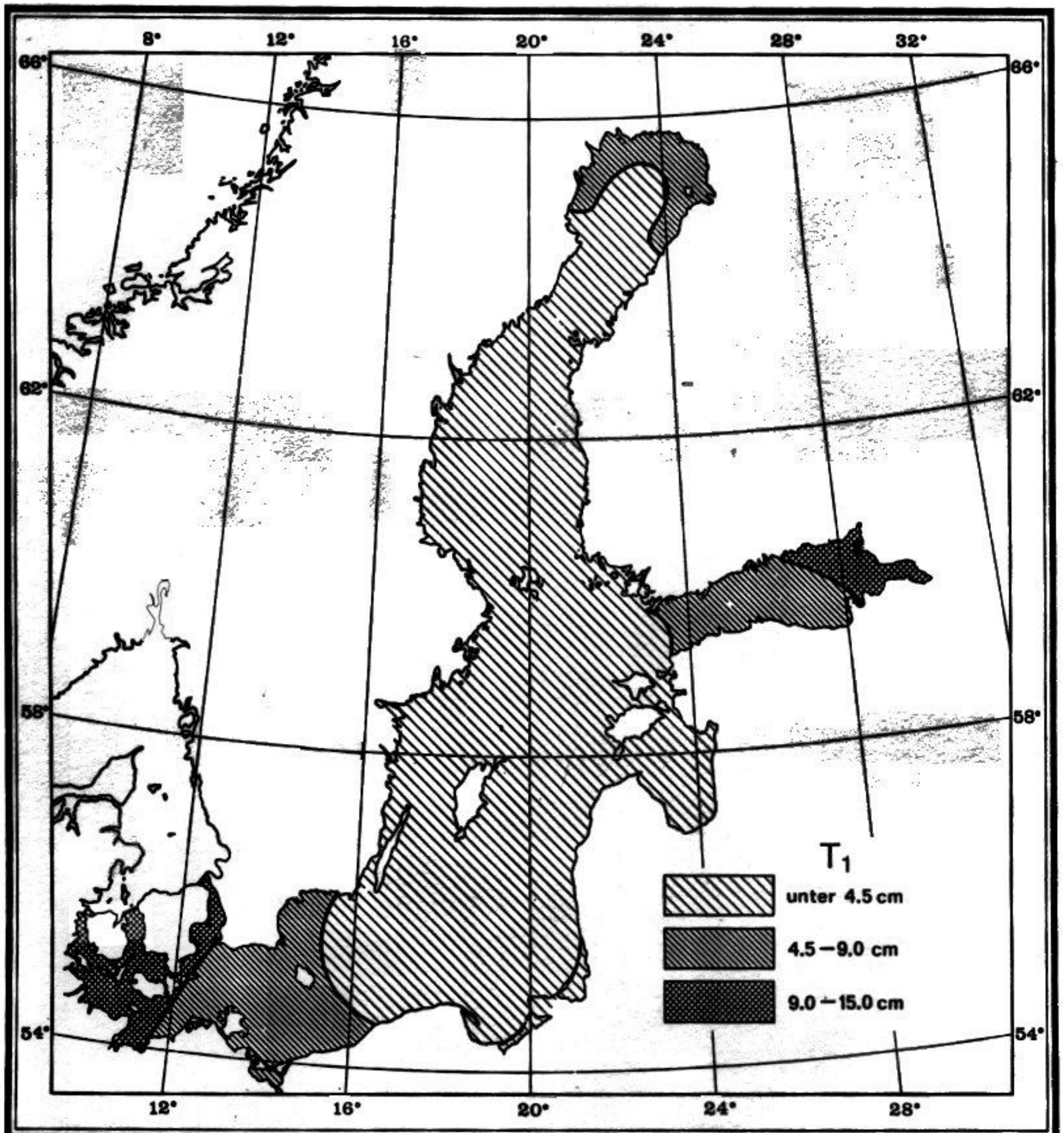


Abb. 3. Geographische Verteilung des Springtidenhubs T_1 der eintägigen Gezeiten

(Magaard and Rheinheimer, 1974)

Ratio between diurnal and semi-diurnal tides

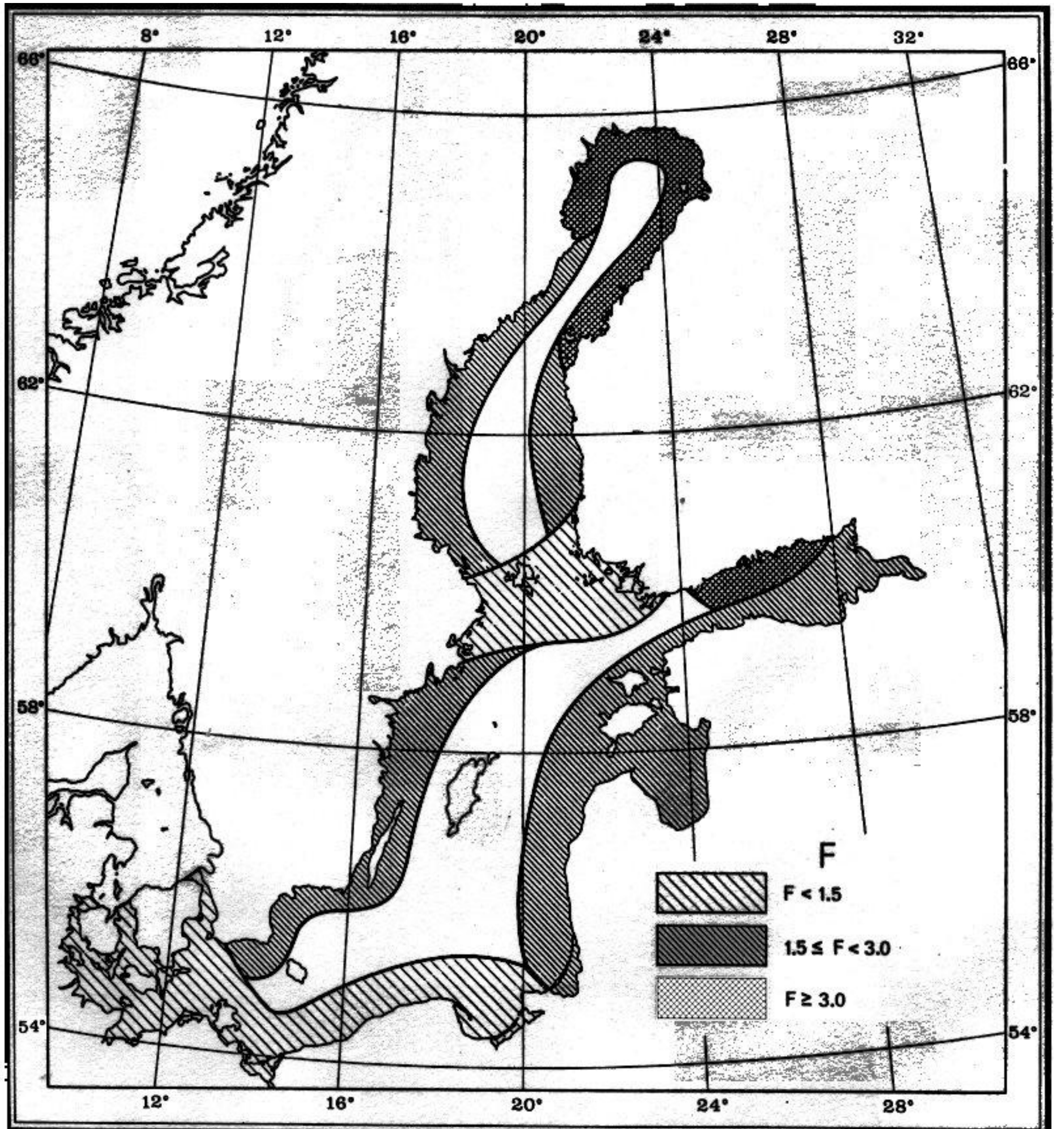


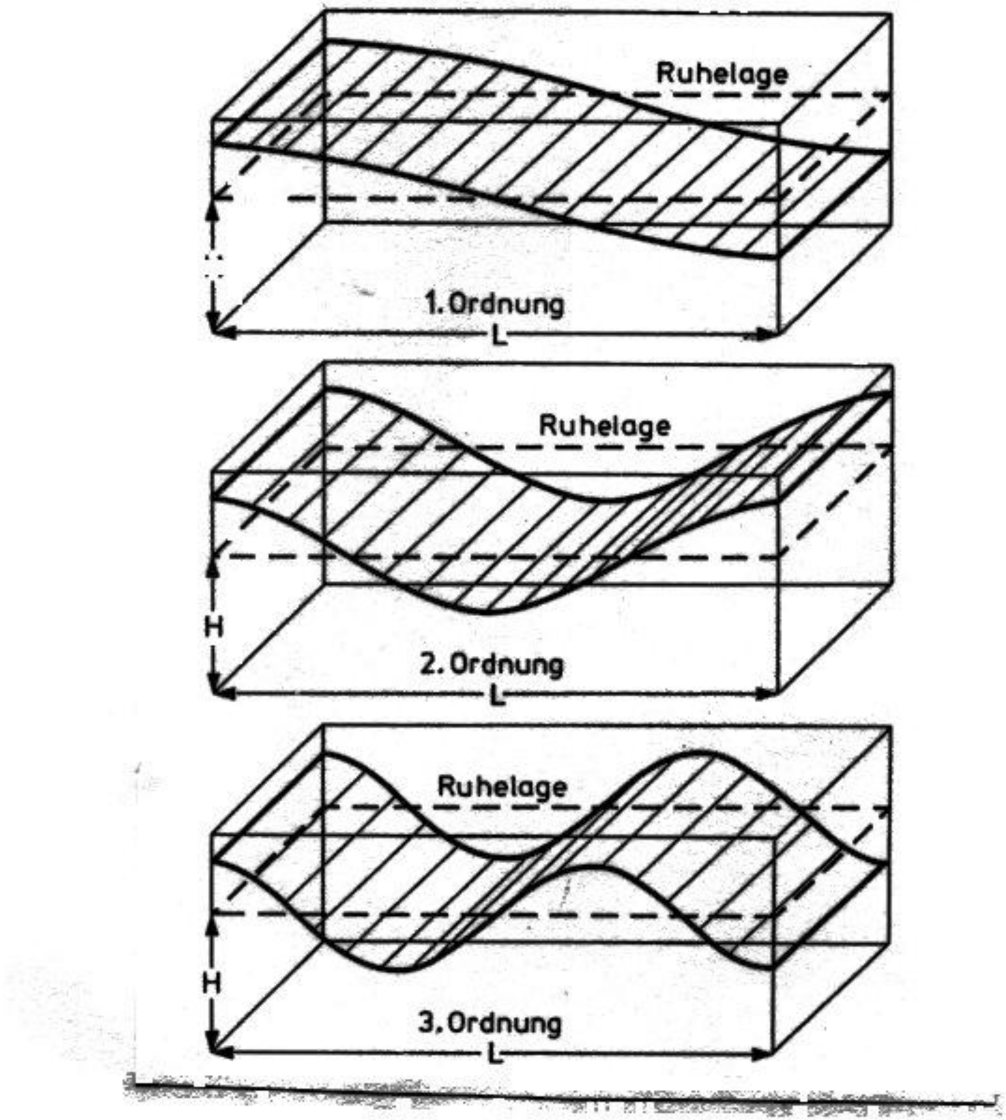
Abb. 4. Geographische Verteilung der Formzahl F

0<F<0.25: semi-diurnal tide

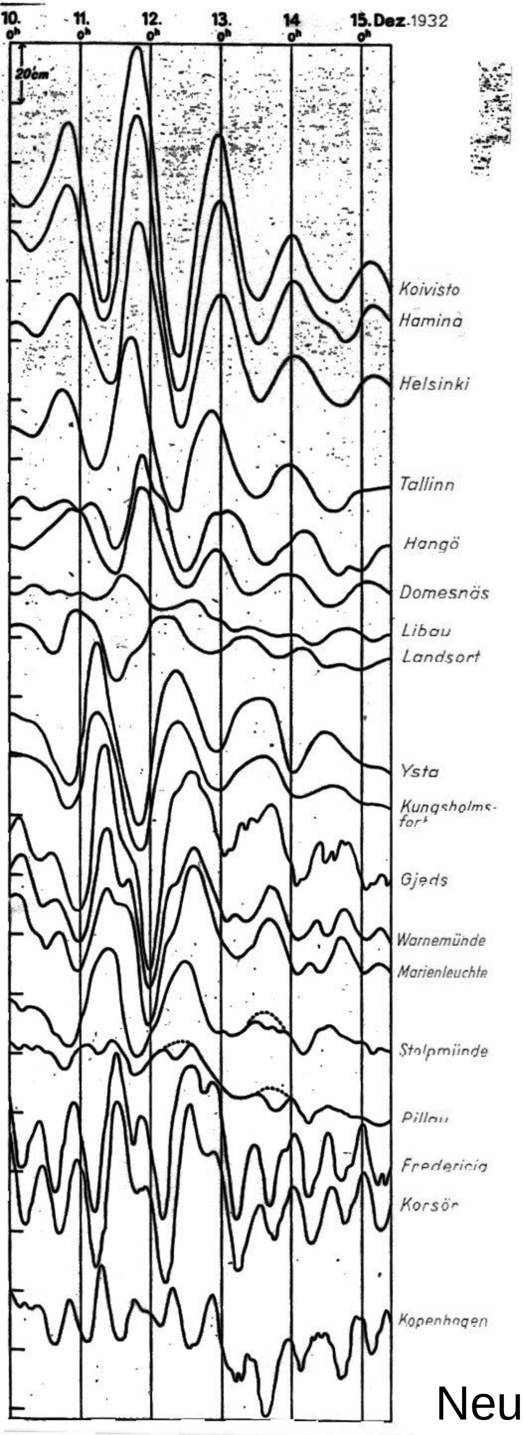
3<F: diurnal tide

(Magaard and Rheinheimer, 1974)

Schematic of seiches



(Magaard and Rheinheimer, 1974)



Neumann (1941)

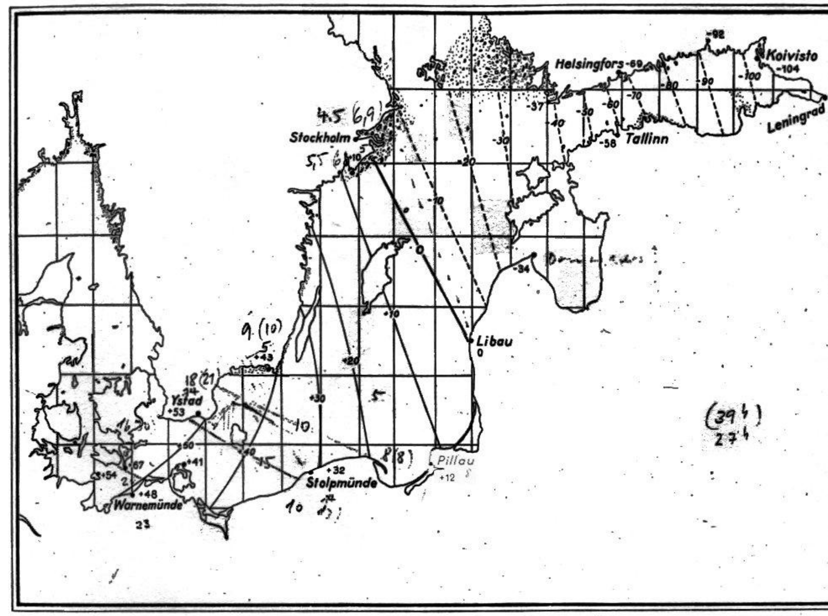


Abb. 4: Linien gleicher Hubhöhe für die Schwingung vom 11. bis 12. Dezember 1932. Die gestrichelten Linien geben den Senkungsbetrag des Wasserspiegels zwischen dem Maximum im Finnischen Meerbusen am 11. Dezember und dem Minimum am 12. Dezember an, die ausgezogenen Linien den Hebungsbetrag zwischen dem entsprechenden Minimum in der westlichen Ostsee und dem darauffolgenden Maximum. Die Zahlen bedeuten cm.

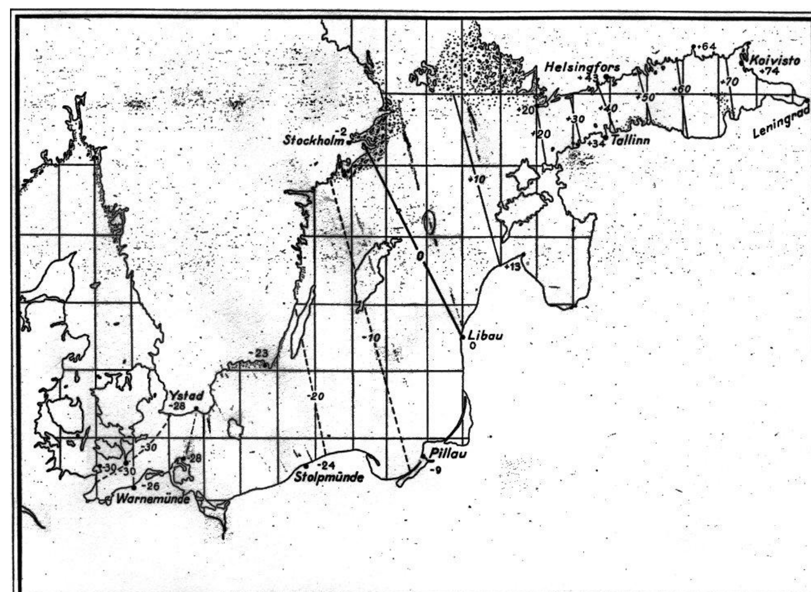
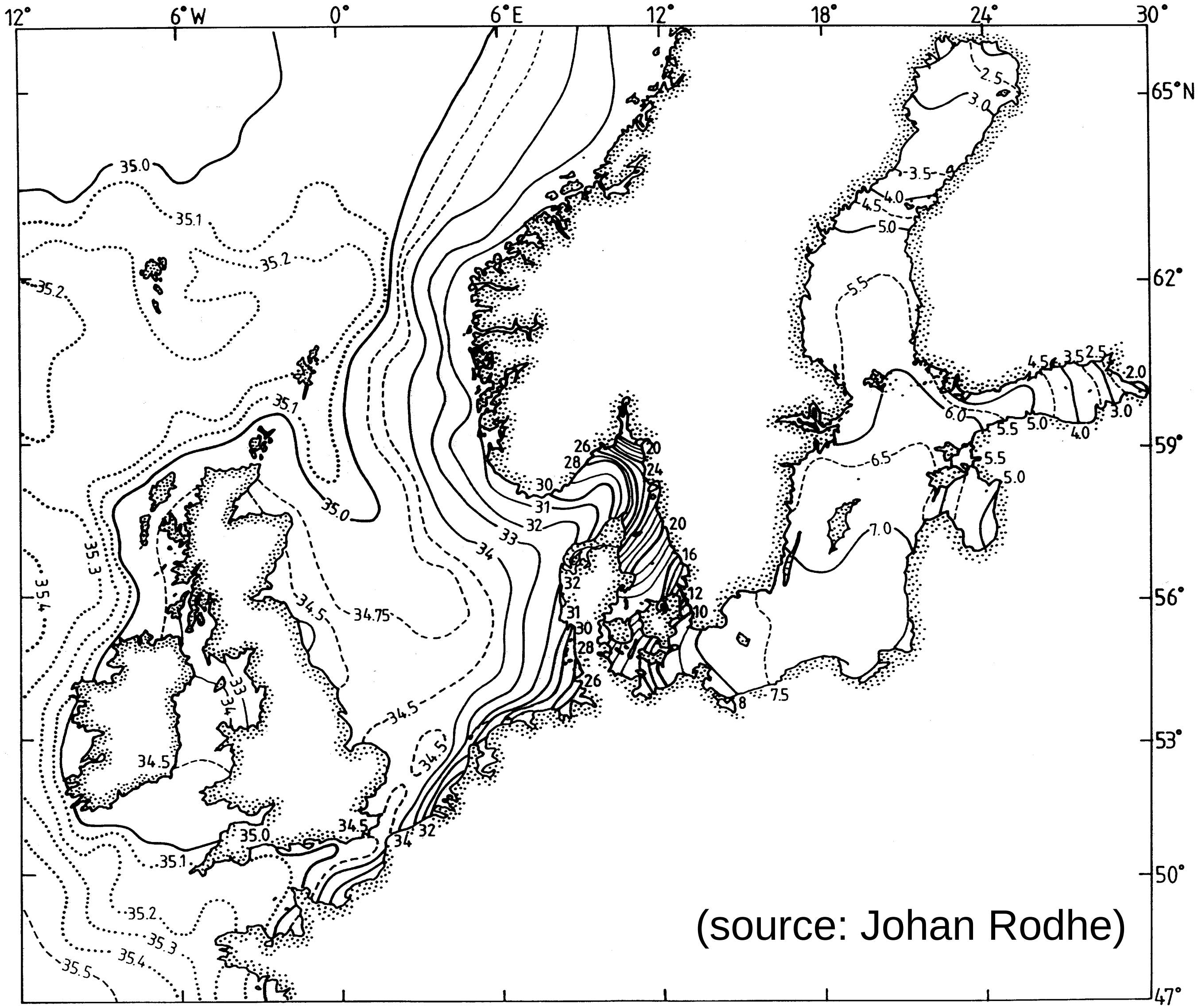


Abb. 5: Linien gleicher Hubhöhe für das Zurückschwingen der Wassermasse am 12. Dezember 1932 im Anschluß an Abb. 4. Die gestrichelten Linien geben den Senkungsbetrag, die ausgezogenen Linien den Hebungsbetrag des Wasserspiegels an. Die Zahlen bedeuten cm.

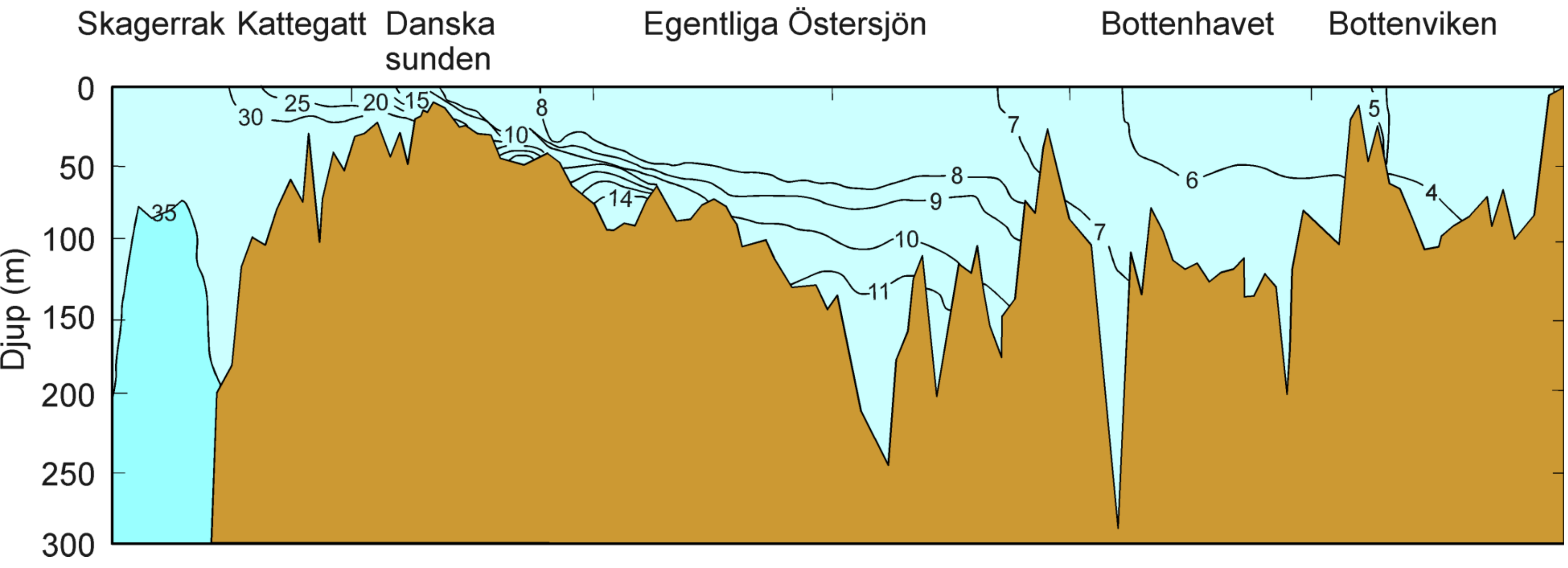
8. Temperature, salinity, density, and oxygen

Sea surface salinity



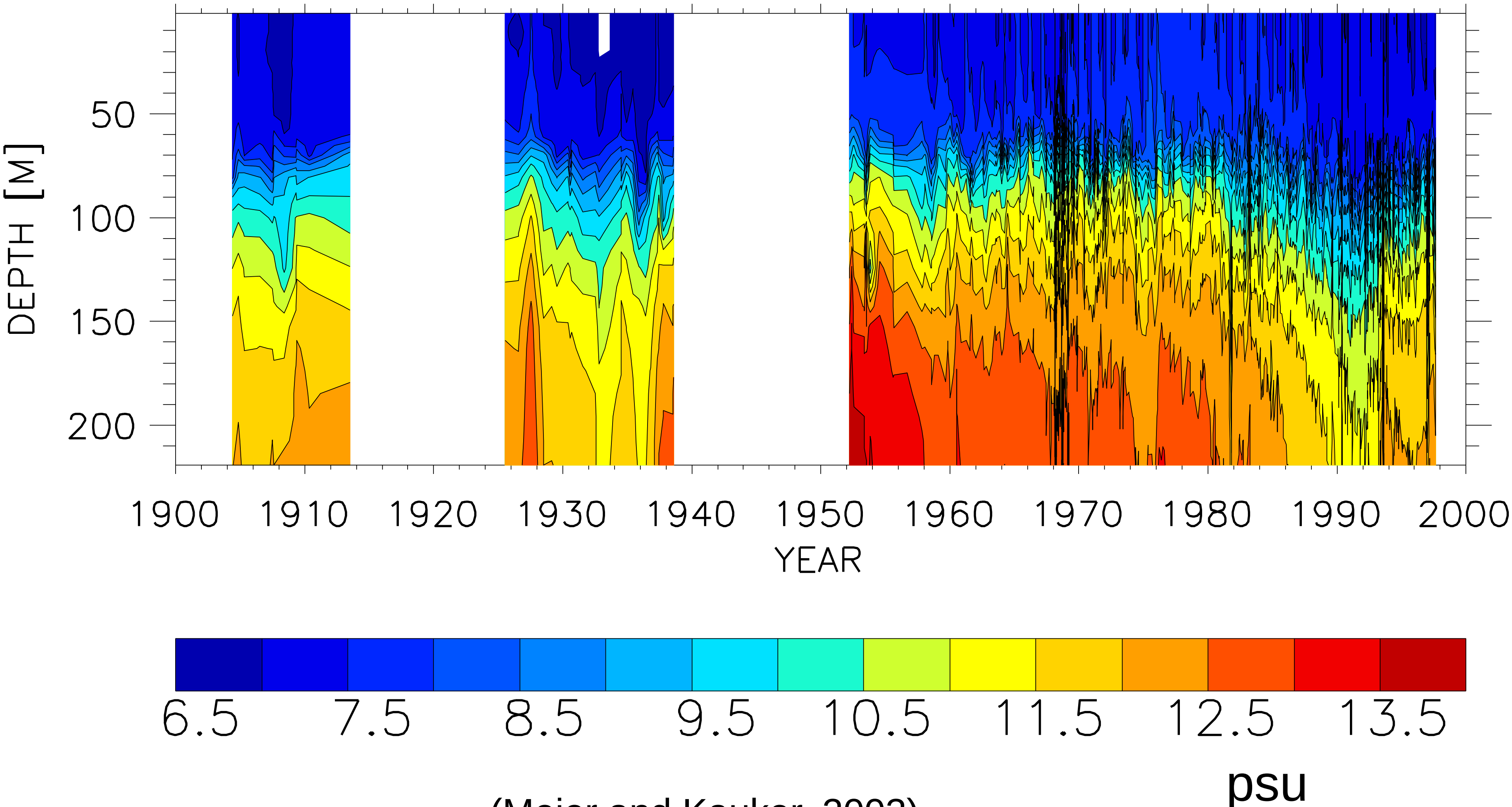
(source: Johan Rodhe)

Cross section of salinity



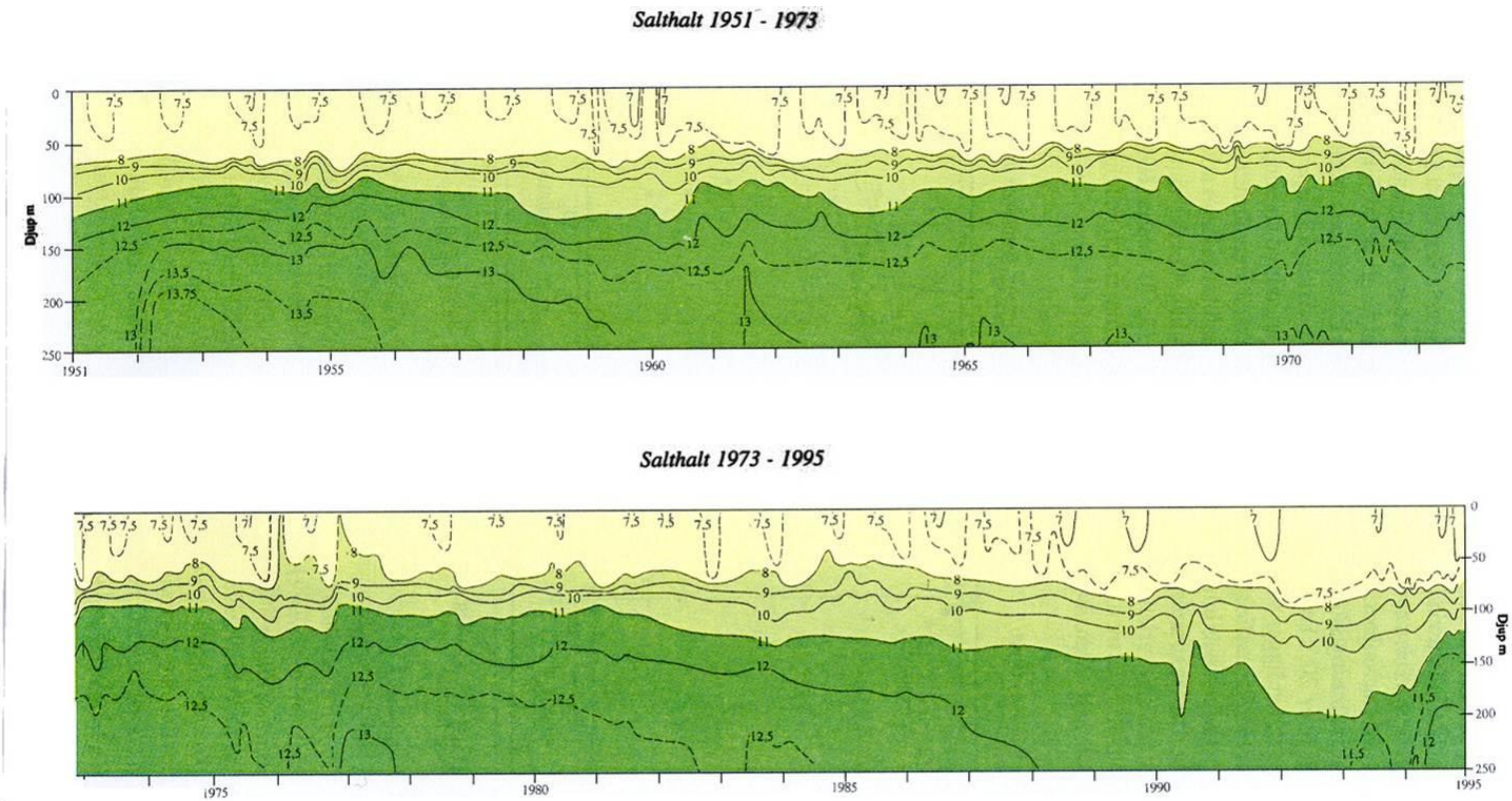
(source: Johan Rodhe)

Salinity as function of time and depth at Gotland Deep



(Meier and Kauker, 2003)

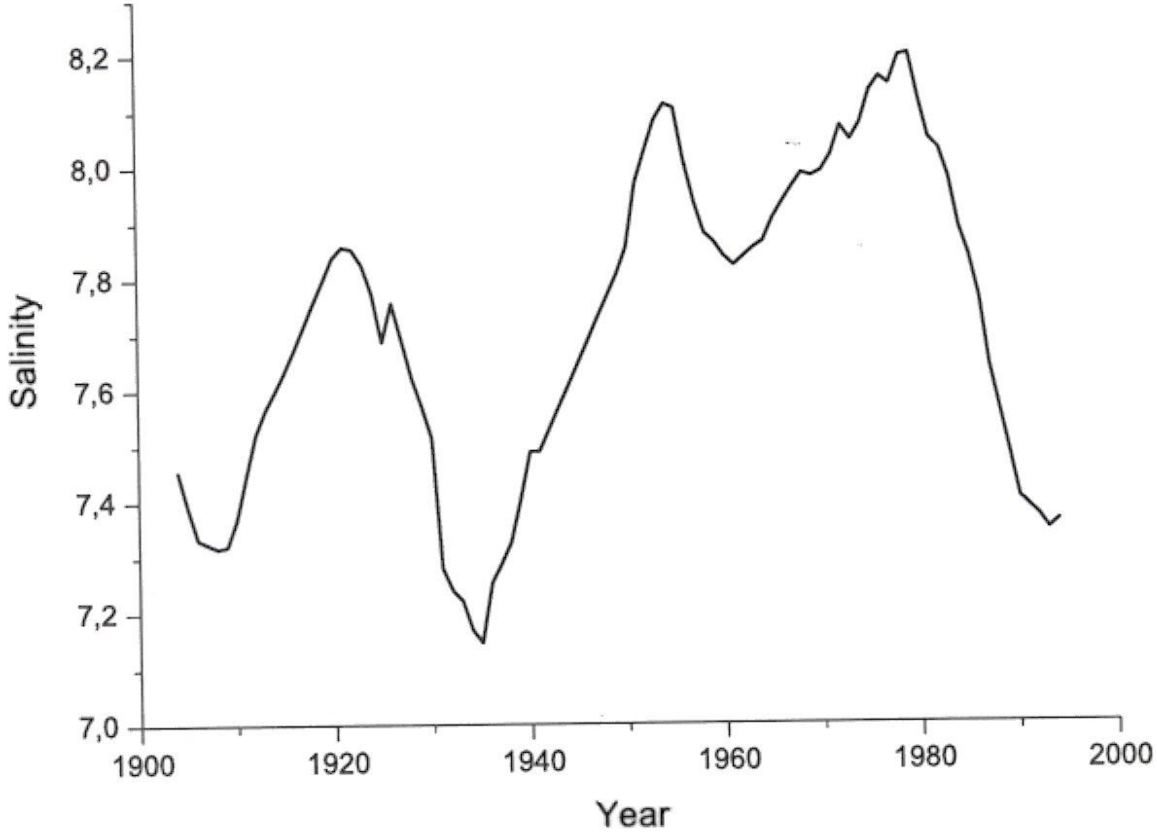
Salinity variability at Gotland Deep during 1951-1994



(Fonselius, 1996)

Fig. 3.18b. *Salthaltsvariationer i Gotlandsdjupet 1951 - 1994.*
I salthaltsfördelningen ser man tydligt det stora saltvatteninbrottet som nådde Gotlandsdjupet 1952 och höjde salthalten i bottenvattnet till över 13,75. Man kan också se flera smärre inbrott 1961, 1964, 1965, 1967, 1970 och 1977. Efter 1977 sker en nästan kontinuerlig minskning av salthalten och man kan också iakttaga en glesning av isohalinerna i djupvattnet, som tyder på en lägre stabilitet i vattenkolumnen. I ytvattnet kan man se årstidsvariationer med lägre salthalt under sommaren pågrund av ökad tillrinning av älvvatten under snösmältningen på våren. I april 1993 förnyades bottenvattnet på grund av ett nytt större inflöde av saltare vatten till Östersjön.

Average salinity of the Baltic Sea



(Winsor et al., 2001; 2003)

Cross section of temperature

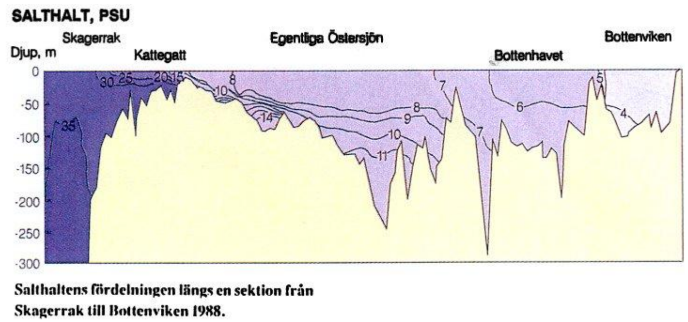


Fig. 3.10. Salthaltsfördelningen i ett vertikalsnitt från Skagerrak till Bottenviken. Skagerrakfronten, Bältfronten, Bottenhavsfronten och Bottenviksfronten kan ses som skarpa förändringar i salthalten[30].

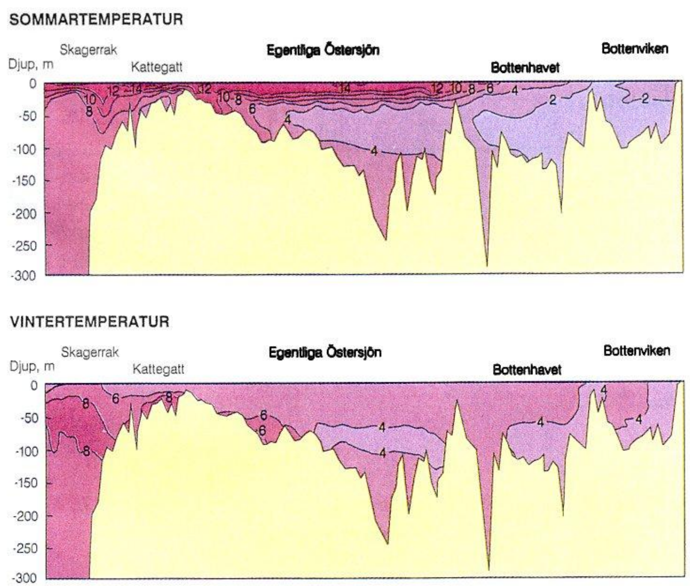


Fig. 3.11. Temperaturfördelningen i ett vertikalsnitt från Skagerrak till Bottenviken[30].

a) Sommartemperaturer i ytvattnet med kallt vintervatten under detta och haloklinenoch varmare djupvatten.

b) Vinterförhållanden med nästan homogen temperatur i vattenpelaren.

(Fonselius, 1996)

Temperature, salinity, density profiles in the Baltic proper

(Rheinheimer, 1996)

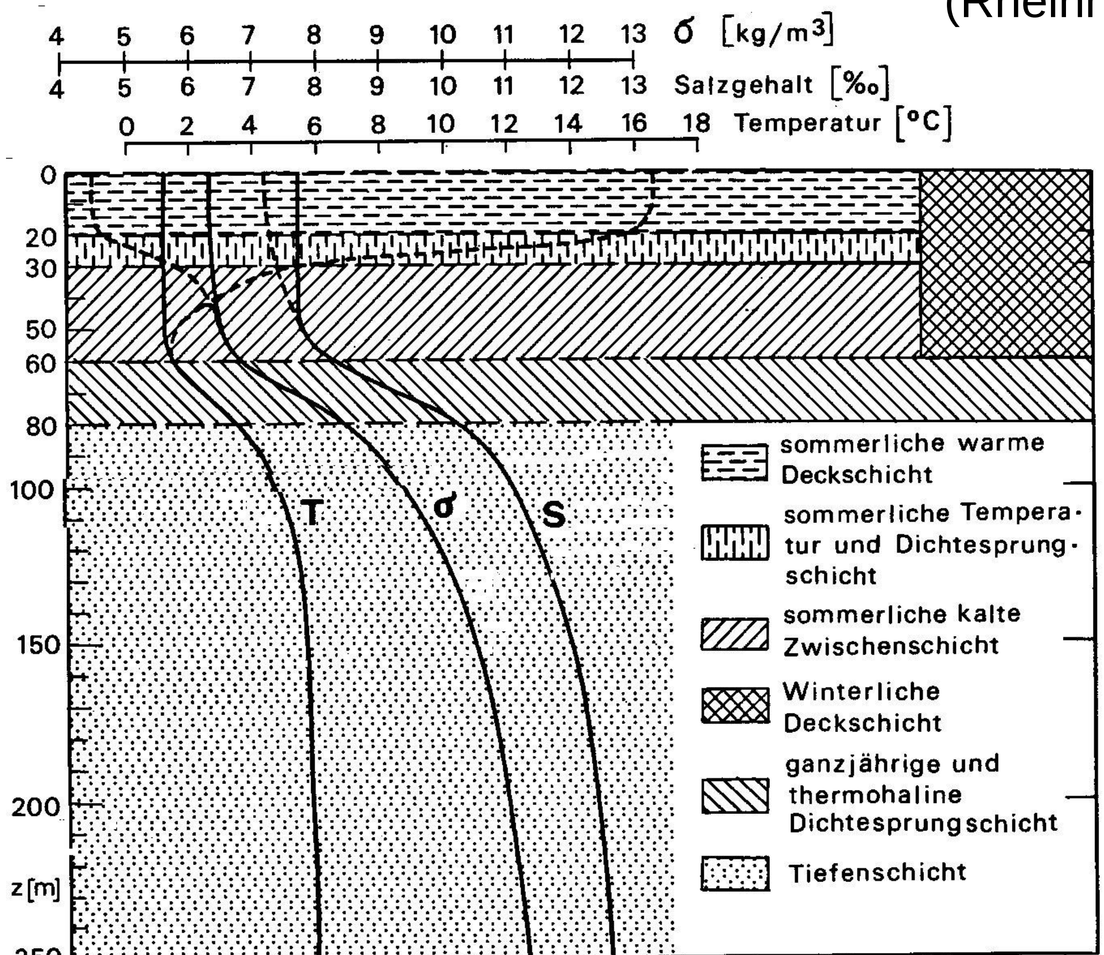


Abb. 32. Typische thermohaline Schichtungsstruktur in der zentralen Ostsee im Winter (ausgezogen) und im Sommer (teilweise gerissen)

Temperature in Arkona, Bornholm, Gotland Sea

(Rheinheimer, 1996)

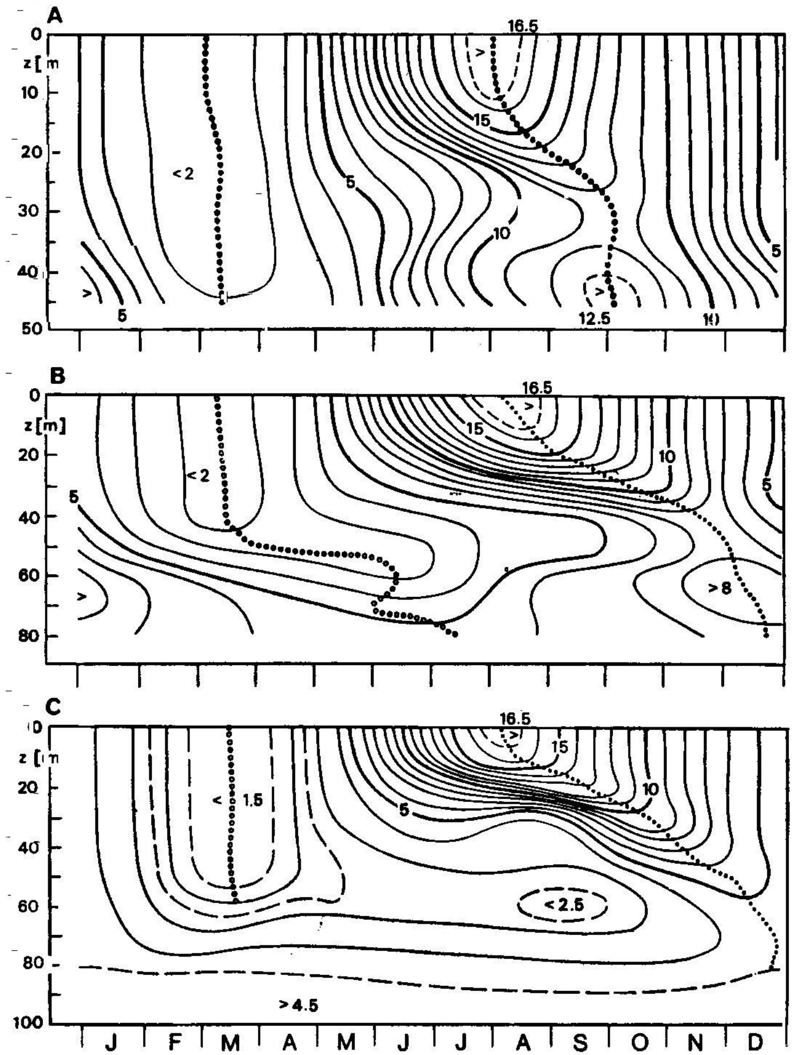
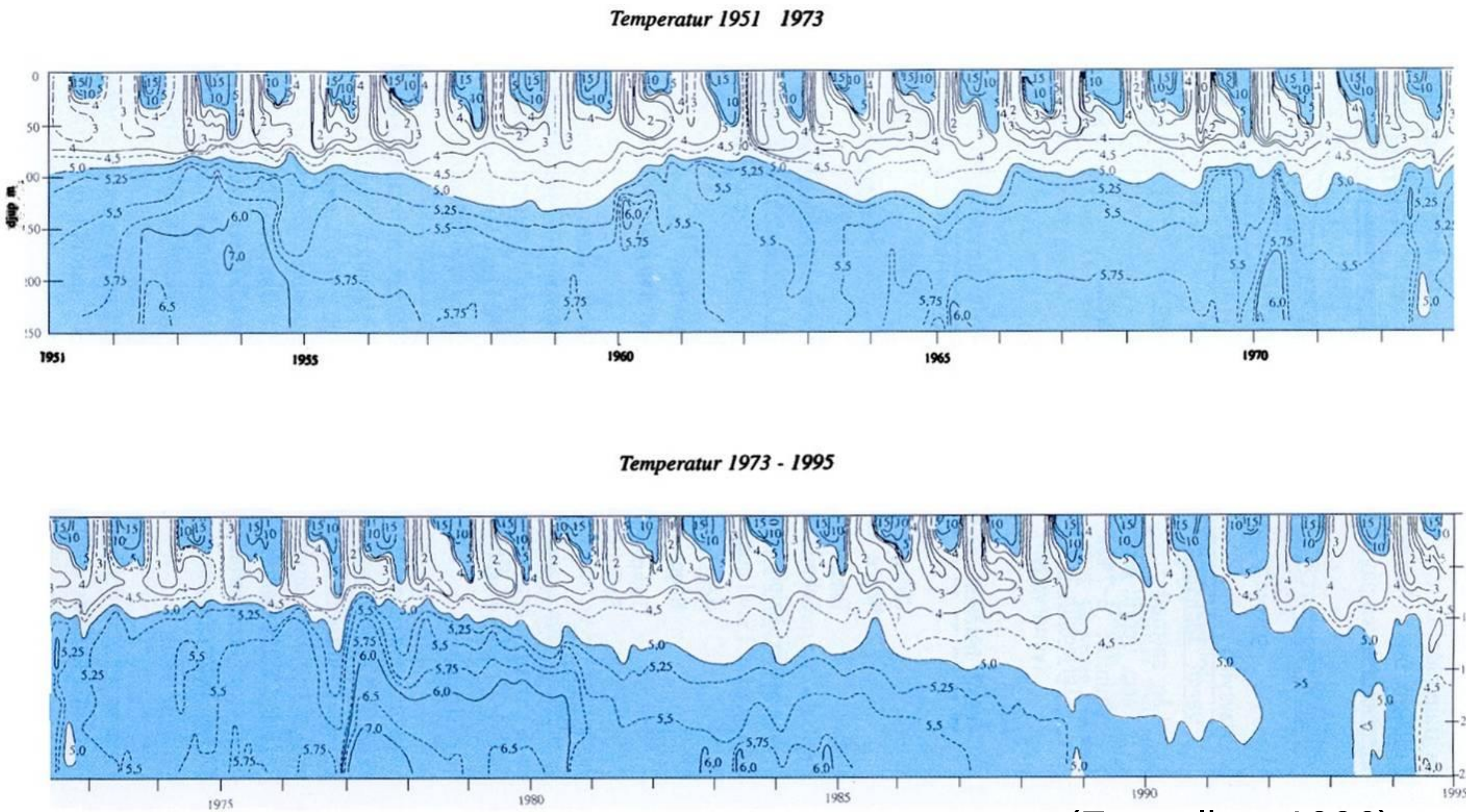


Abb. 33A–C. Mittlerer Jahresgang der thermischen Schichtung im Arkona- **(A)**, Bornholm- **(B)** und östlichen Gotlandbecken **(C)** in °C. **(Nach Matthäus 1977)**

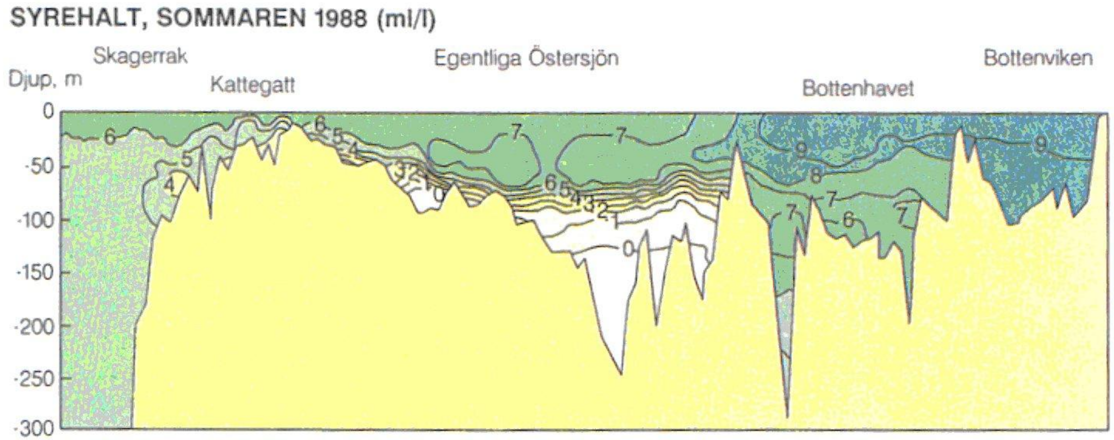
Temperature variability at Gotland Deep during 1951-1994



(Fonselius, 1996)

Fig. 3.18a. **Temperaturvariationer i Gotlandsdjupet 1951 - 1994.**
Temperaturvariationerna från ytan till botten vid Gotlandsdjupet har studerats mera i detalj. I ytvattnet kan man se årstidsvariationerna med varmt vatten under sommaren. I djupvattnet under den permanenta haloklinen kan man inte finna några årstidsvariationer, men man kan se perioder med varmare vatten, som beror på inströmning av nytt saltare vatten genom De danska sunden. Speciellt kan man lägga märke till den ovanligt höga temperaturen efter saltvattens inbrotten 1952, 1970 och 1977. Vid saltvattensinbrottet 1977 var bottenvattens temperaturen över 7°C, den högsta som någonsin uppmätts i Gotlandsdjupet.

Cross section of oxygen



a) Sommarförhållanden

(Fonselius, 1996)

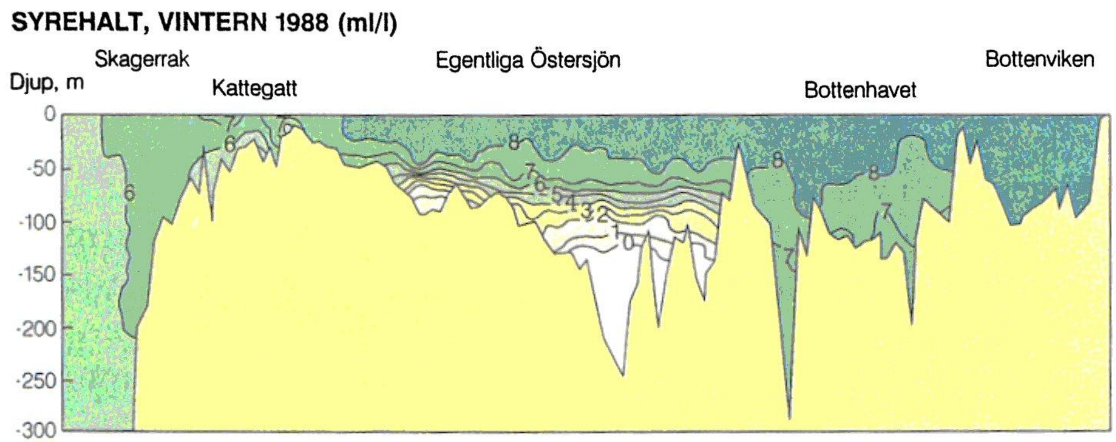


Fig. 7.1 *Syrgaskoncentrationen i ml/l under sommar- och vinterförhållanden i ett längdsnitt från Skagerrak till Bottenviken[30]*

Oxygen variability at Gotland Deep during 1951-1994

(Fonselius, 1996)

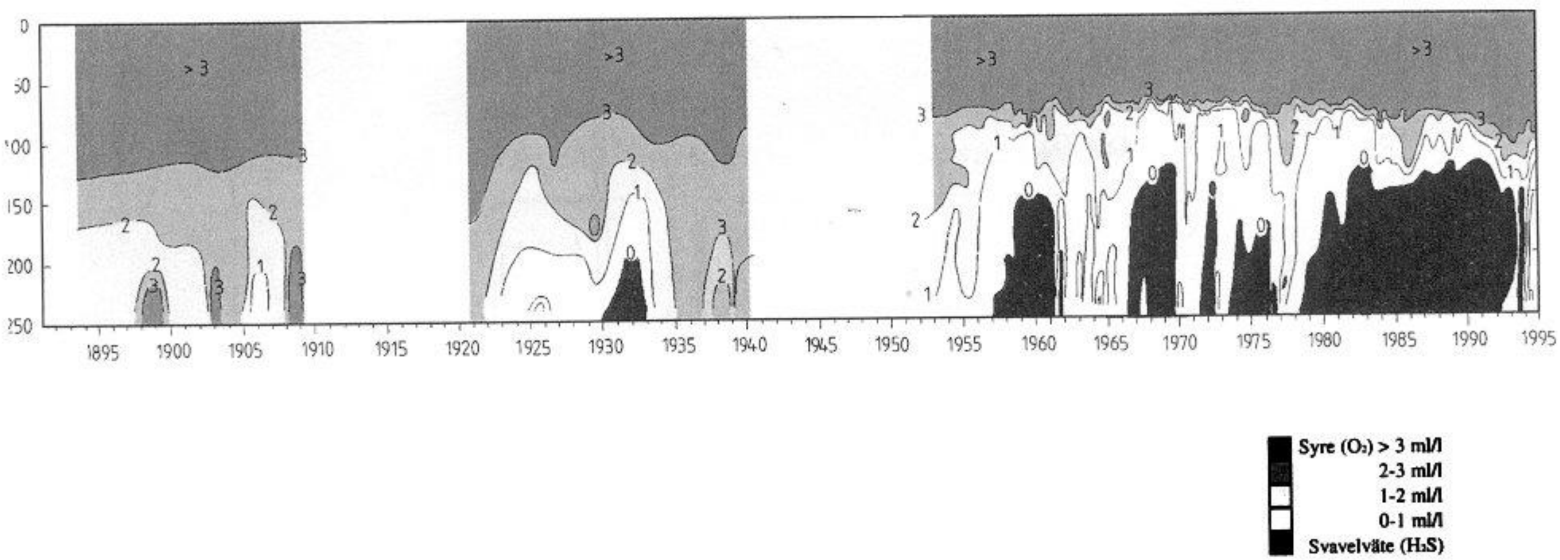
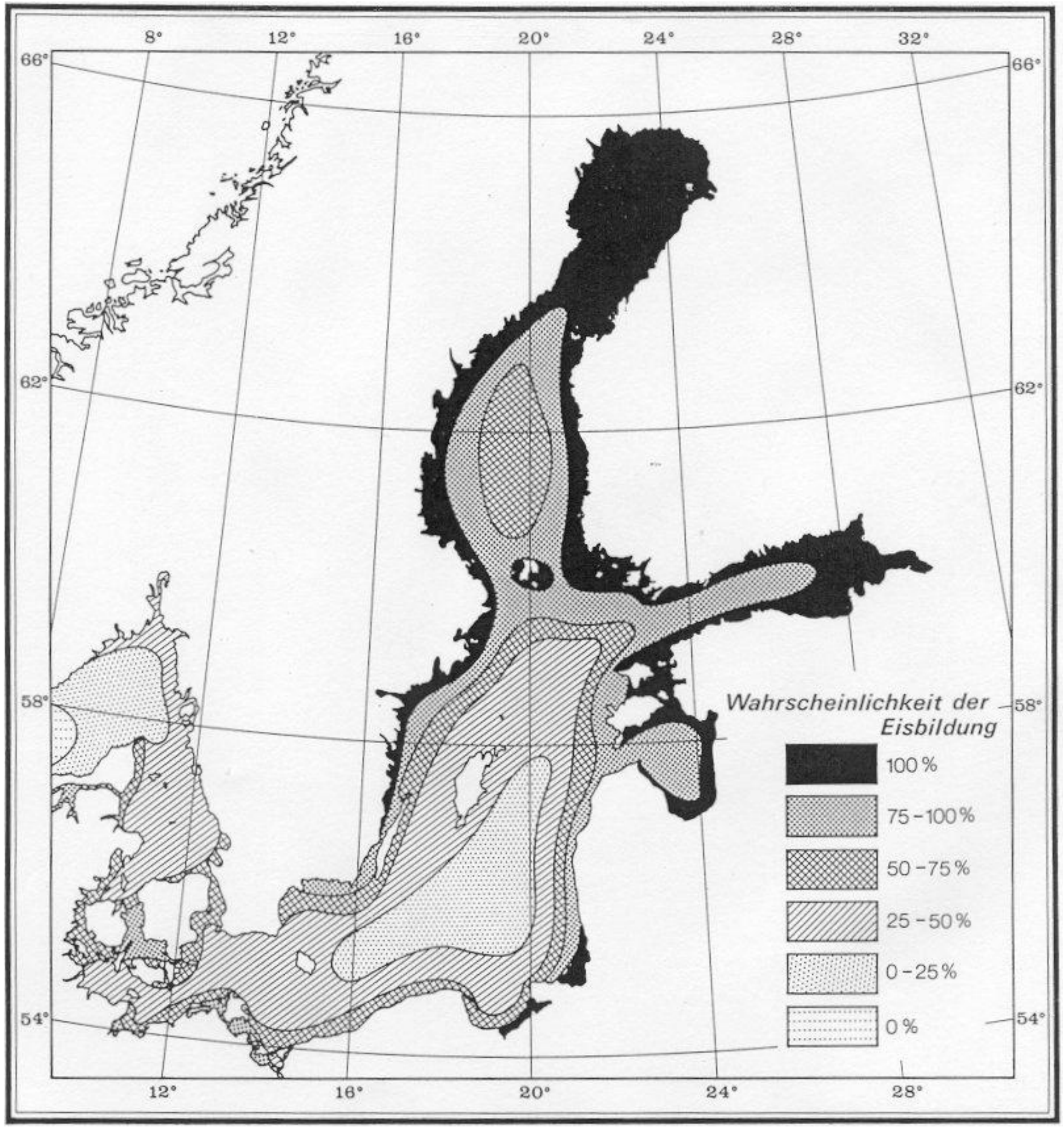


Fig. 9.14. *Syrgas- och svavelvätevariationerna i Gotlandsdjupet 1893 - 1994. De svarta områdena betecknar svavelväteförekomst. Bottenvattnet förnyades 1993 och svavelvätet försvann. Syret i ml/l.*

9. Baltic sea ice

(Courtesy of Seppo Keränen)

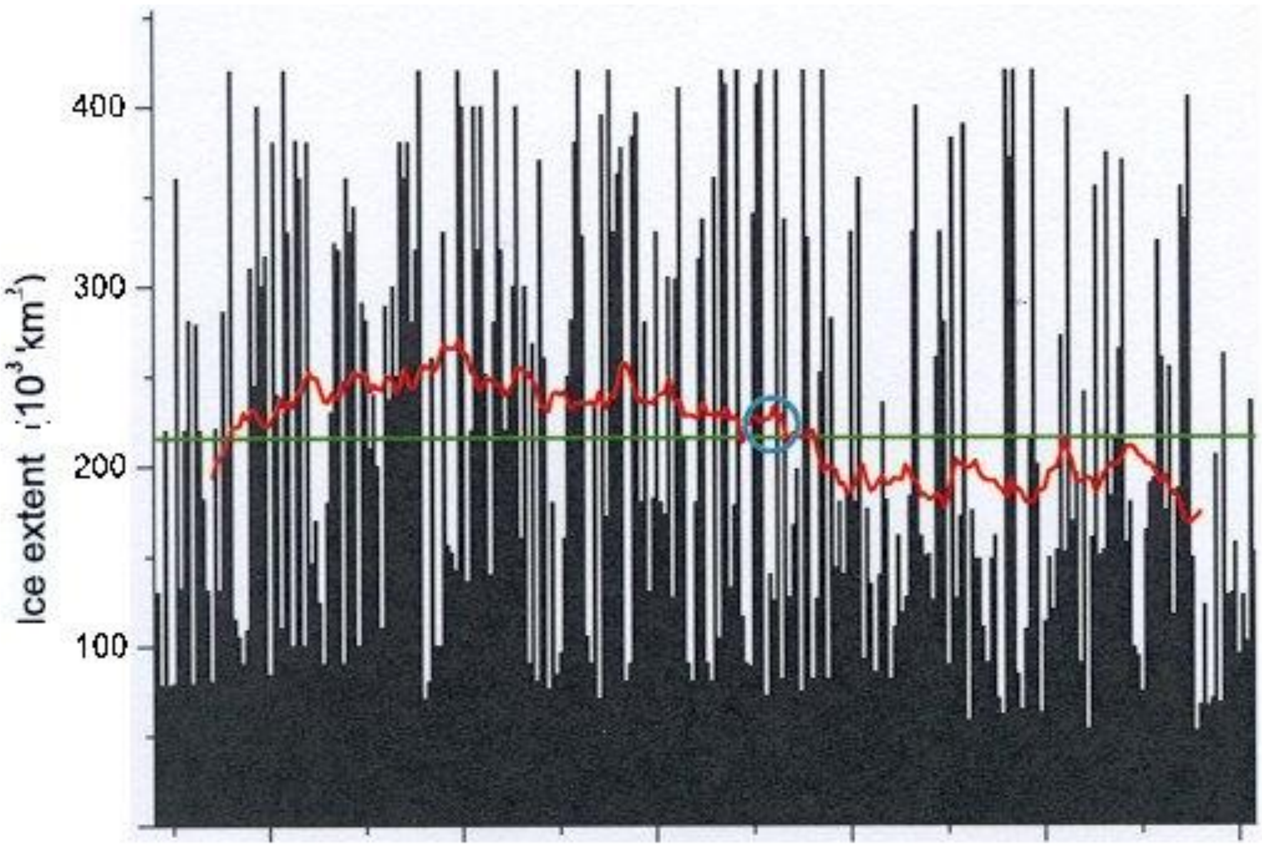
Probability of ice occurrence 1931-1960



(Magaard and Rheinheimer, 1974)

Abb. 1. Wahrscheinlichkeit der Eisbildung, berechnet für den Zeitraum 1931-1960 (nach PALOSUO, 1966).

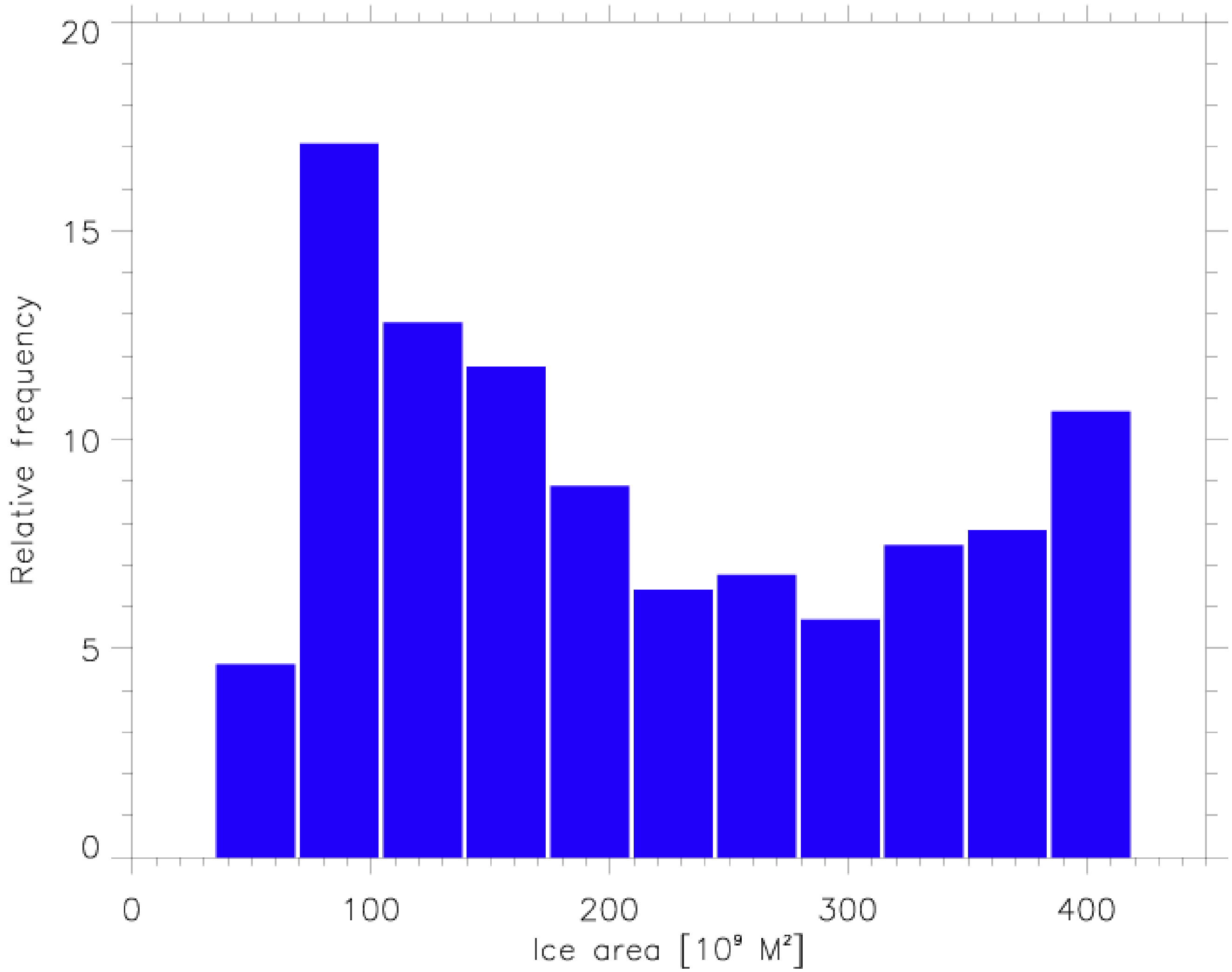
Maximum ice extent



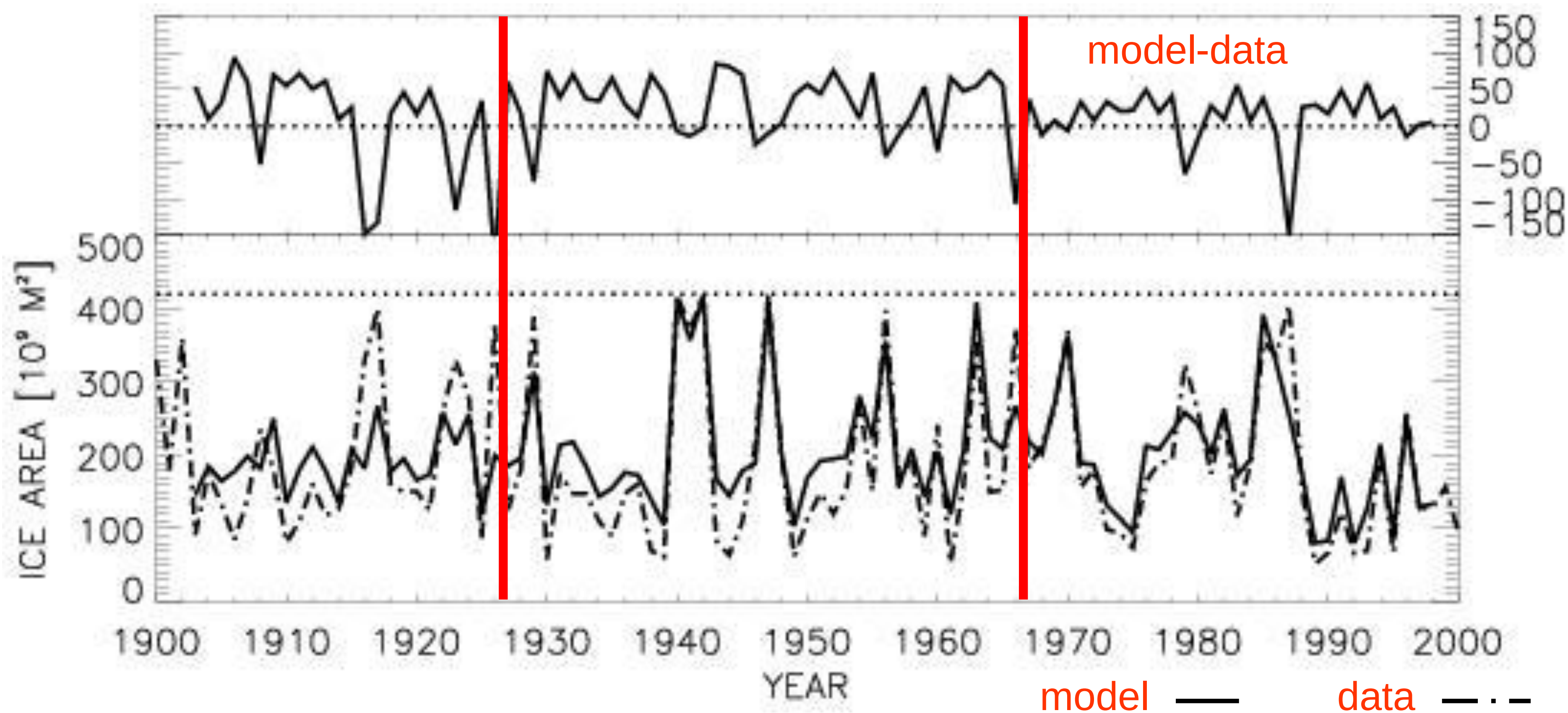
1750 1800 1850 1900 1950 2000

(Omstedt and Chen, 2001)

Relative frequency of maximum ice extent during 1720-2000



Annual maximum ice extent



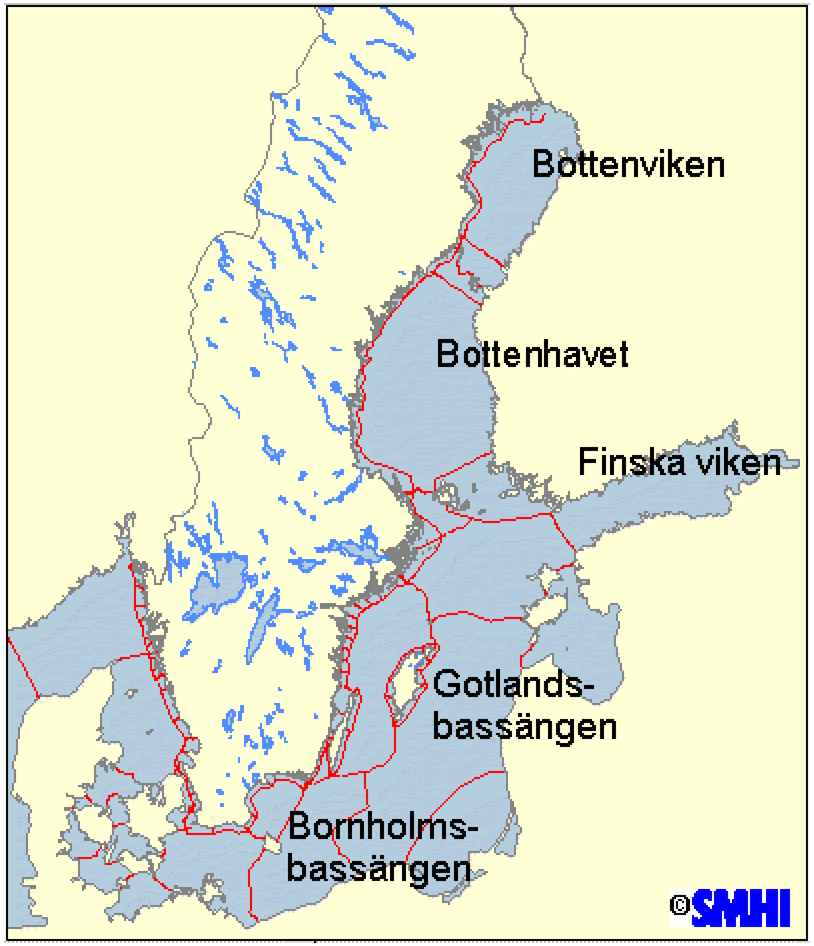
Period	ME	RMSE	R	VAR
1903-98	16.8	55.2	0.87	0.71
1903-26	3.9	73.9	0.66	0.37
1927-66	29.1	52.8	0.94	0.79
1967-98	11.1	39.5	0.93	0.83

Model biases:
ME=mean error in 10^9 m^2,
RMSE=root mean square error in 10^9 m^2,
R=correlation coefficient,
VAR=explained variance

(Meier and Kauker, 2003a)

10. Processes

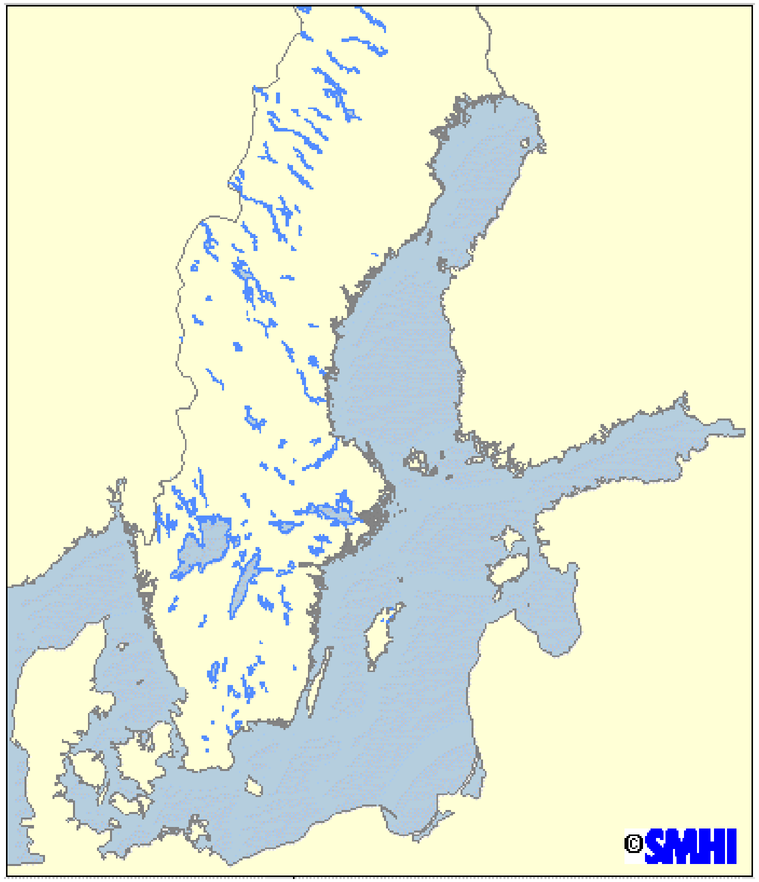
Östersjön



- medeldjup är 56 m och maximala djupet är 451m
- Is 5-7 månader
- vattenutbytet mellan Östersjön och Nordsjön sker via trånga passager och trösklar vid de Danska sunden
- högst varierande bottentopografi - bassänger
- stratifierad- en övre homogen zon och lägre delar skiktade
- vattenutflödet från landytorna varierar kraftigt

SWECLIM
SWEDISH REGIONAL CLIMATE MODELLING PROGRAMME

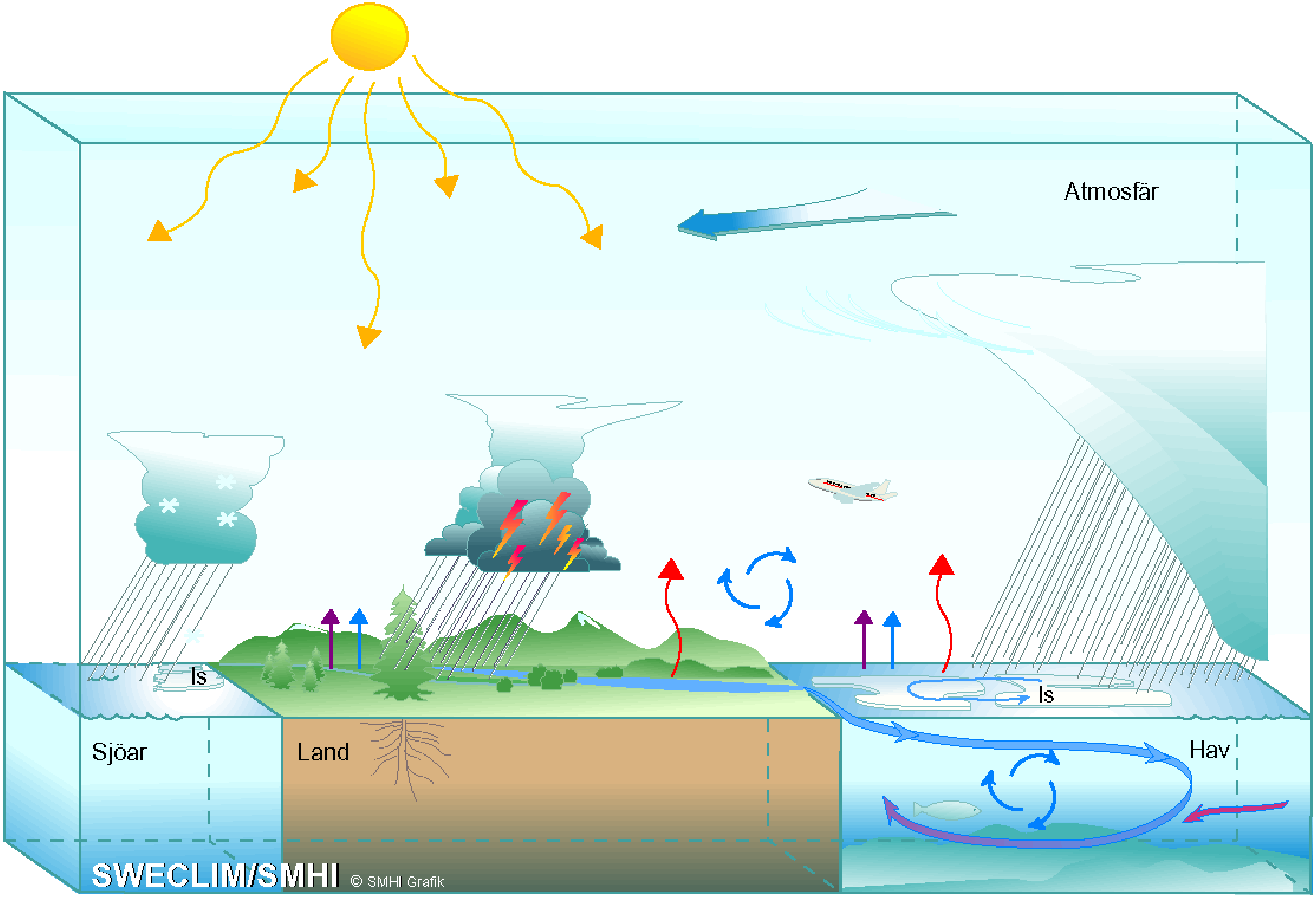
Cirkulationen i Östersjön bestäms av:



- vattenutbytet genom de Danska sunden
- bottentopografin
- utflöde av färskvatten från vattendragen
- interaktionen mellan atmosfär-is-hav

SWECLIM
SWEDISH REGIONAL CLIMATE MODELLING PROGRAMME

Atmosphere-ice-ocean-land surface system



Freezing point temperature and temperature of maximum density as function of salinity

Fragile climatological niche:

impact on convection,
Baltic Sea winter water
(Eilola, 1997),

buoyancy production of juvenile freshwater
(Eilola and Stigebrandt, 1998; Stipa and Vepsäläinen, 2002)

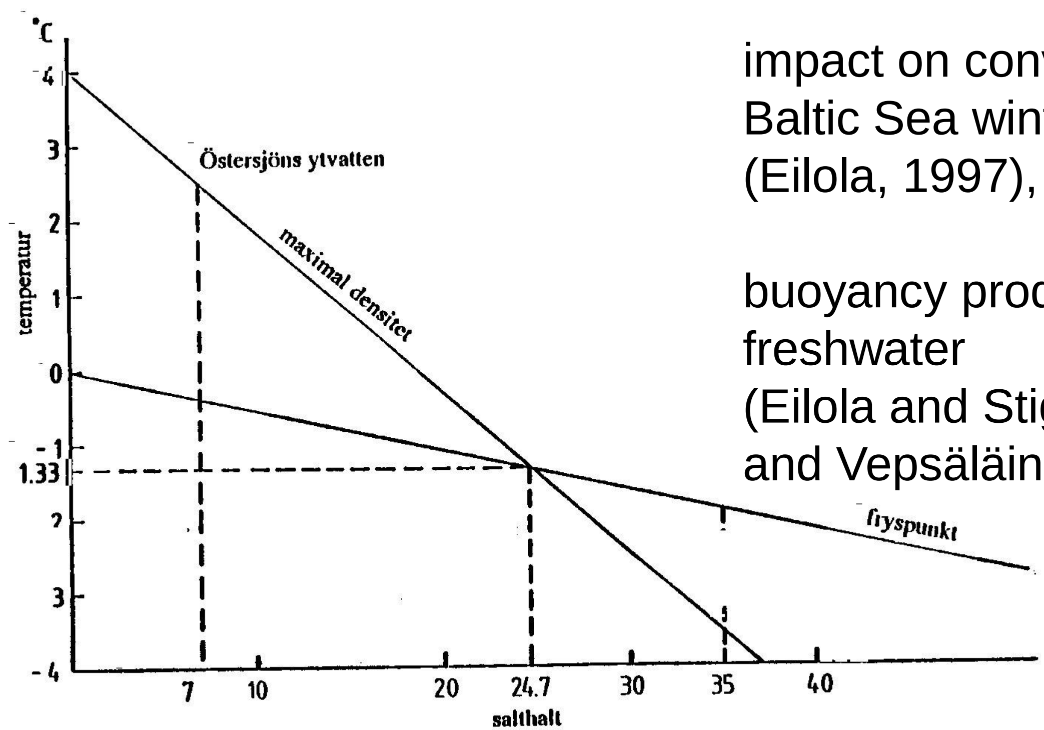
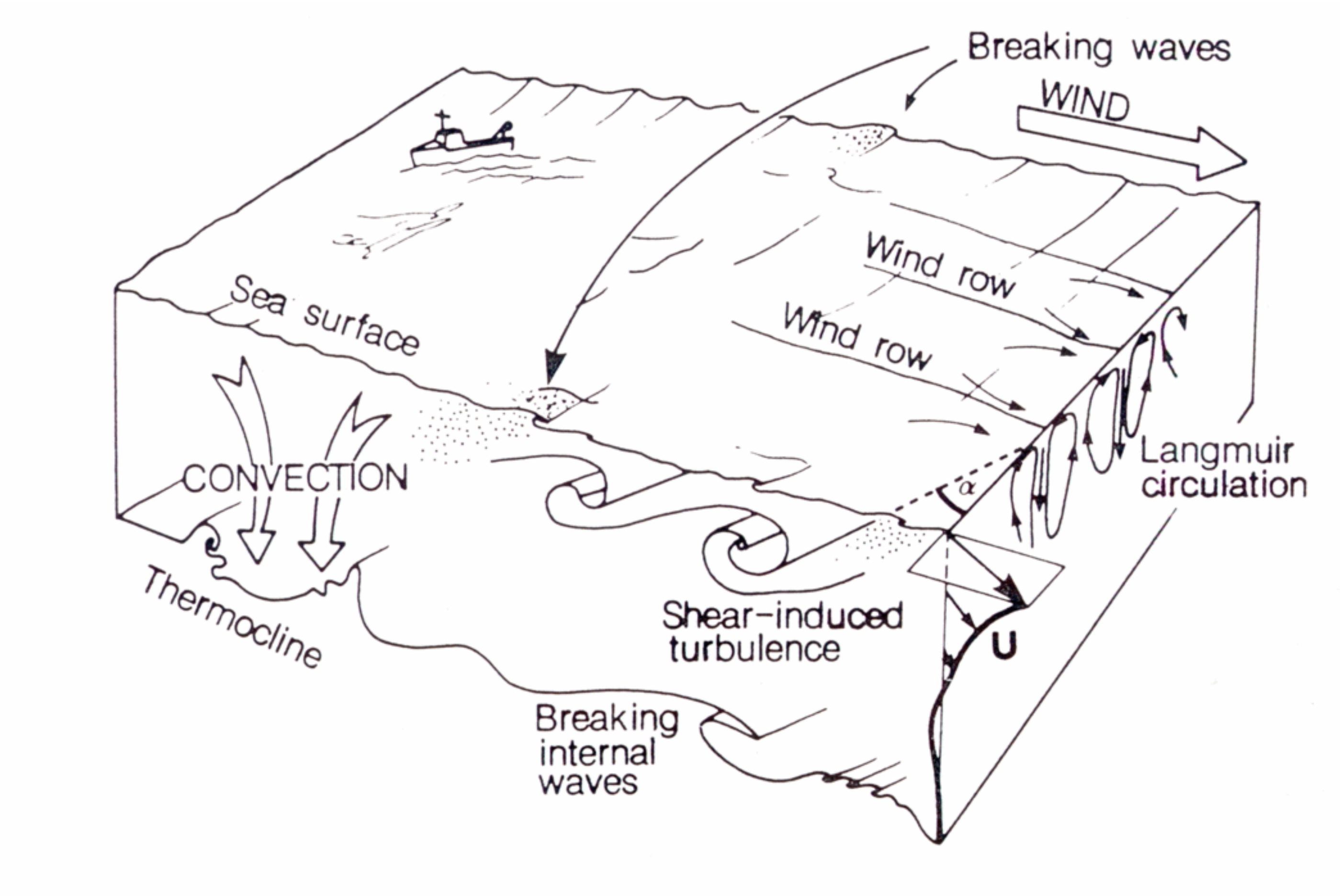


Fig. 3.1. *Förhållandet mellan temperaturen för maximal densitet och fryspunkt för vatten med olika salthalter.*

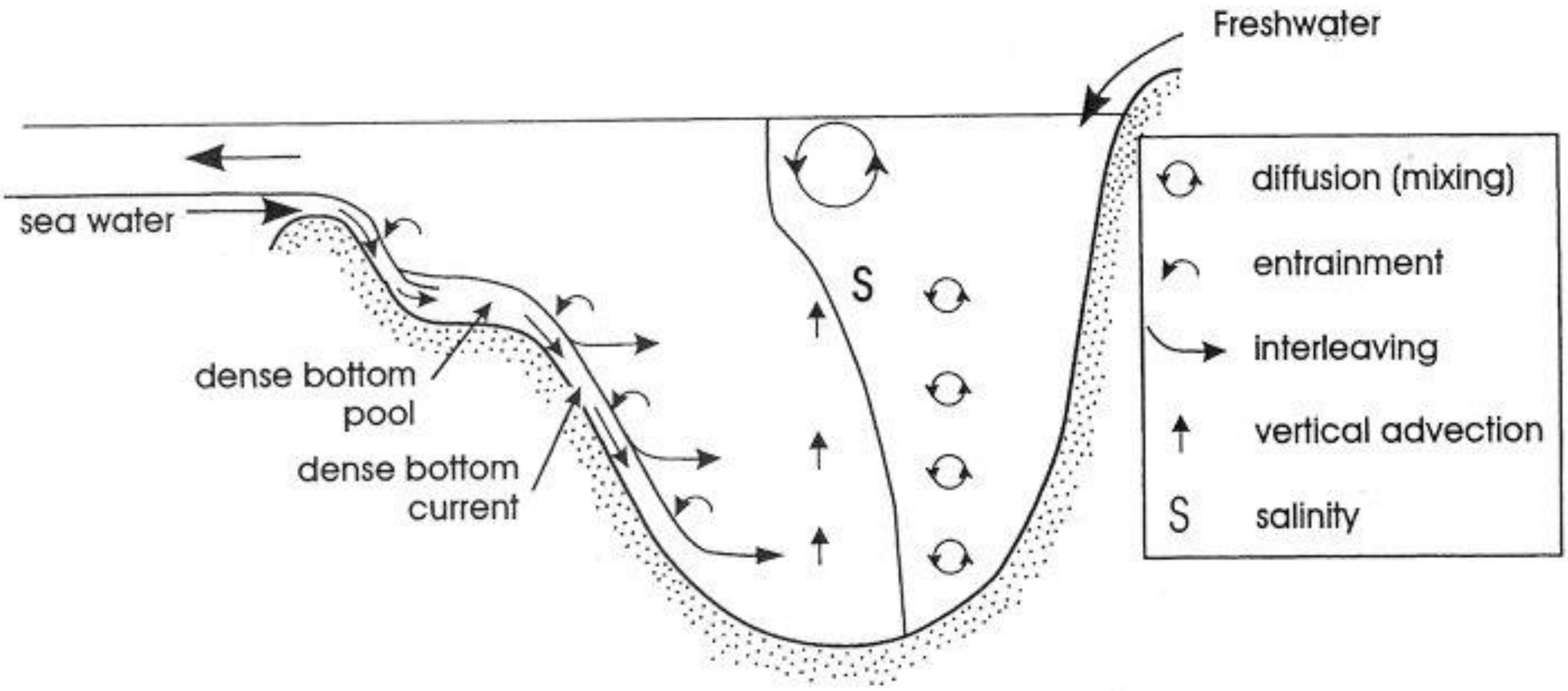
(Fonselius, 1996)

Processes in the surface boundary layer



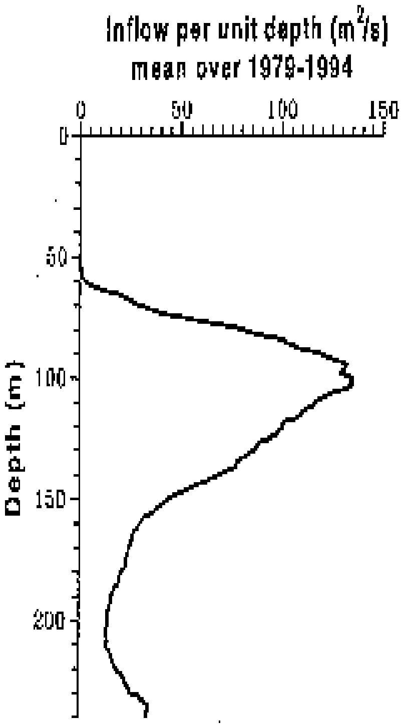
(Thorpe, 1985)

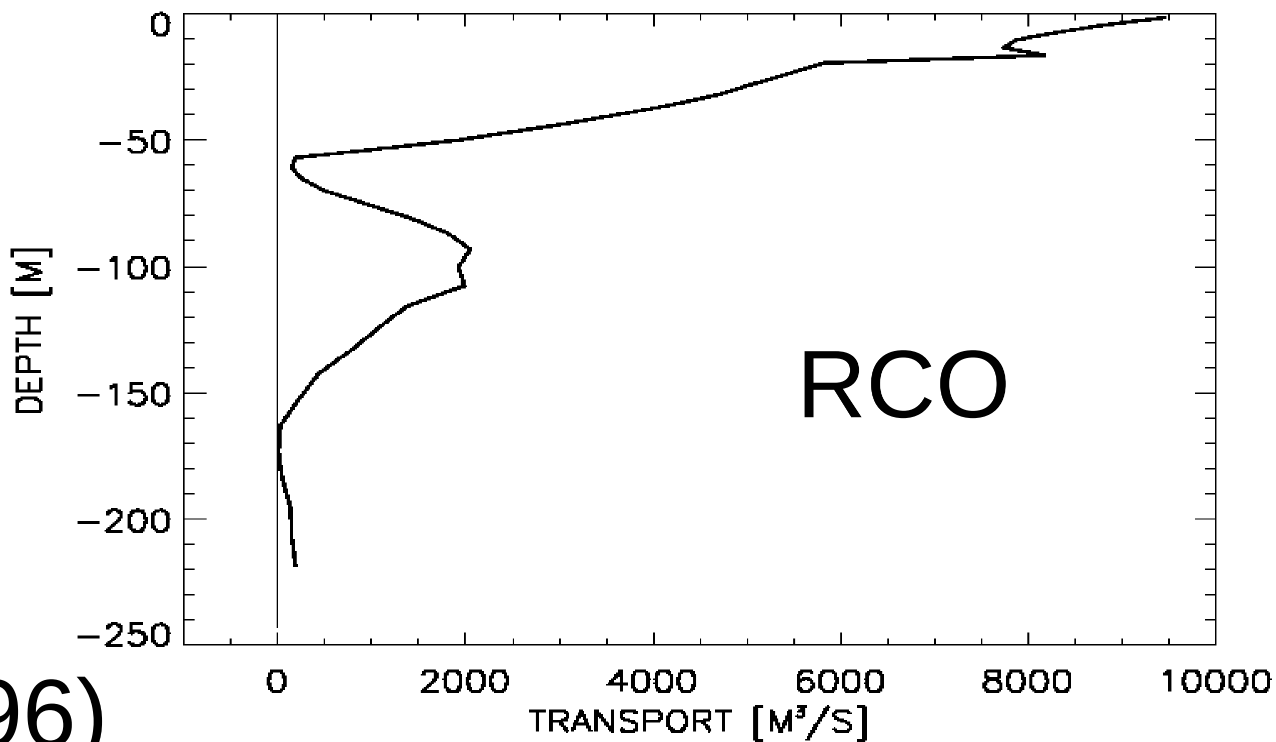
Ventilation of the Baltic Sea deepwater



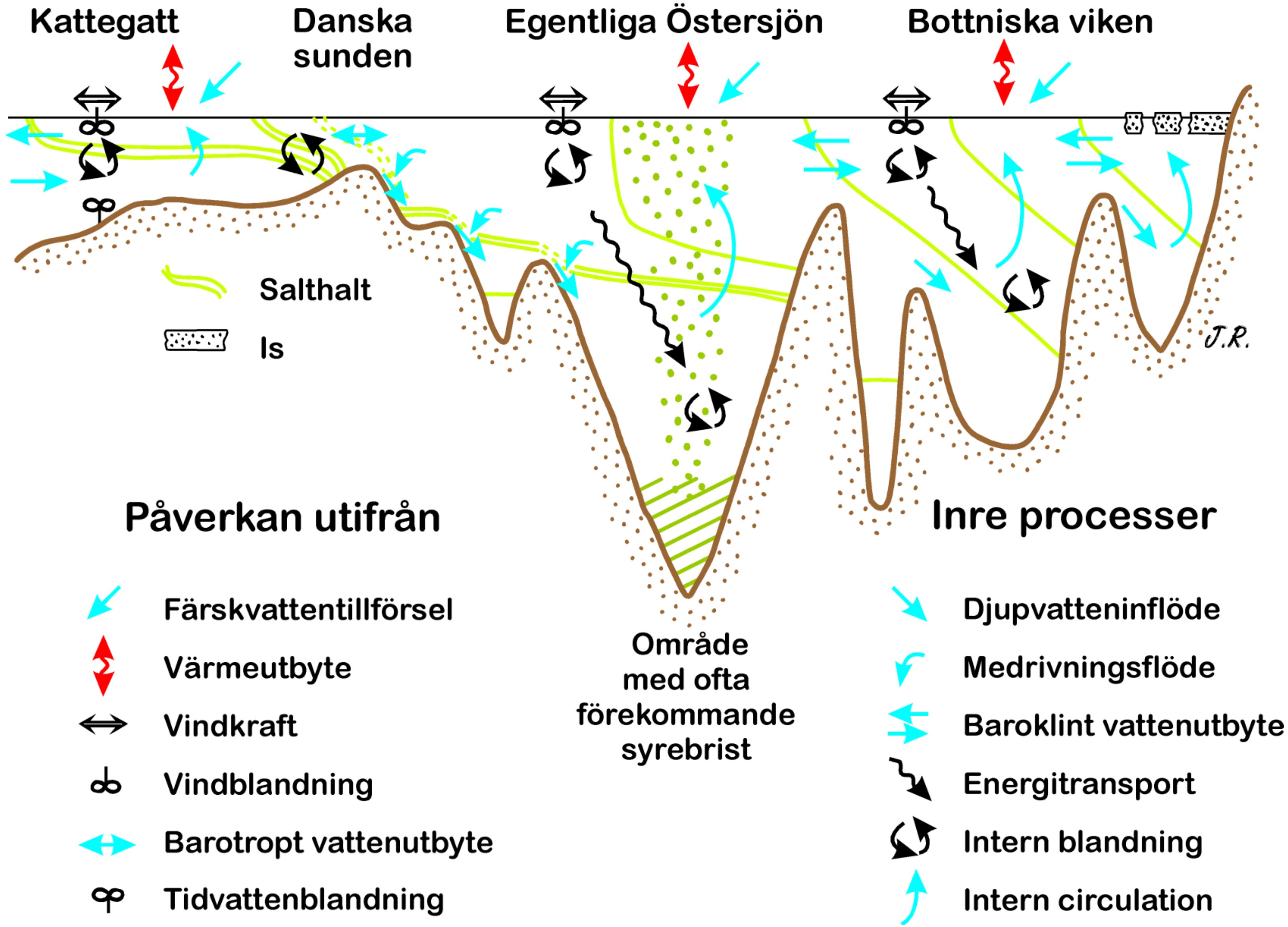
(Stigebrandt, 2001)

Horizontally integrated transport at the Gotland Deep section



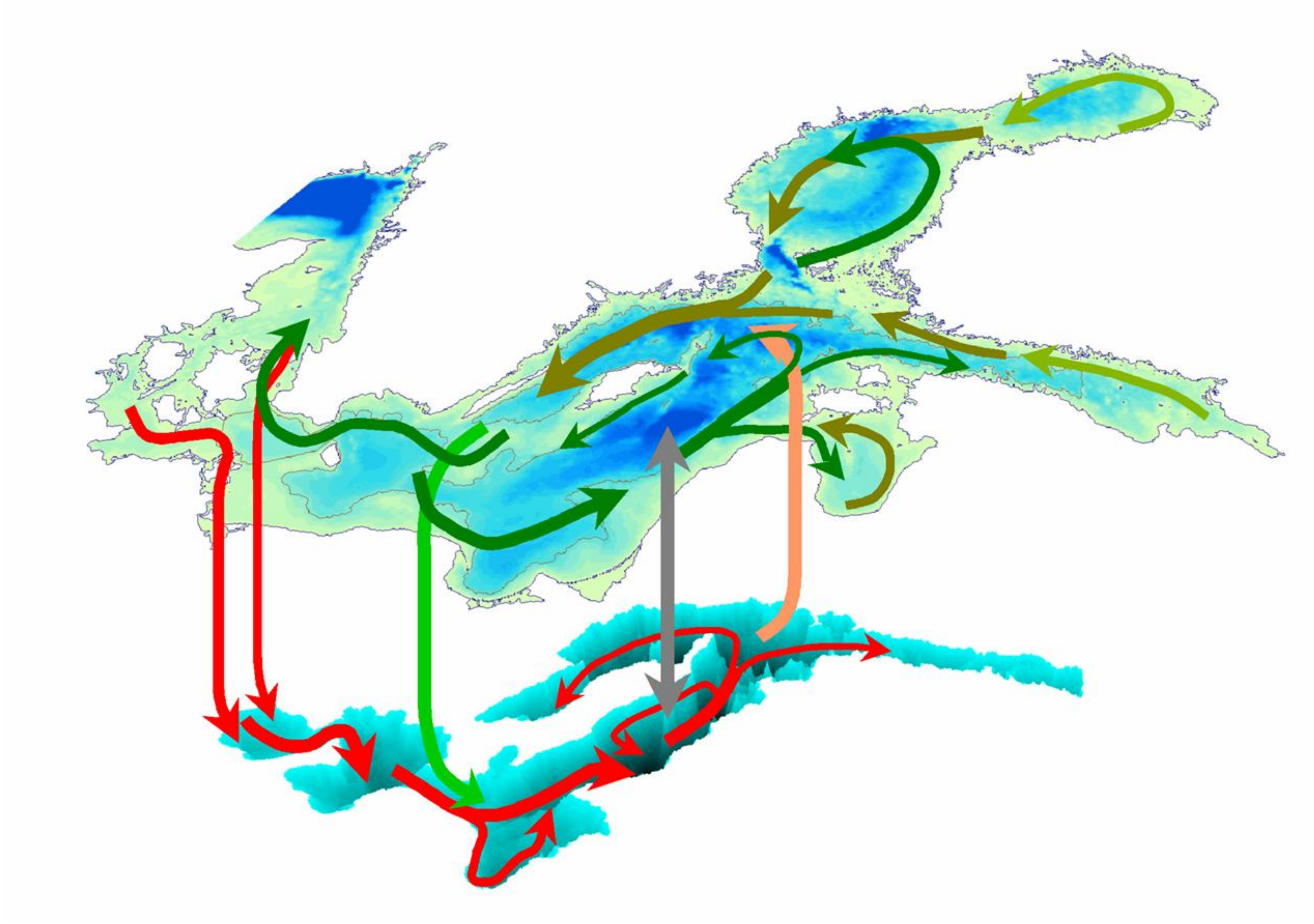


Elken (1996)



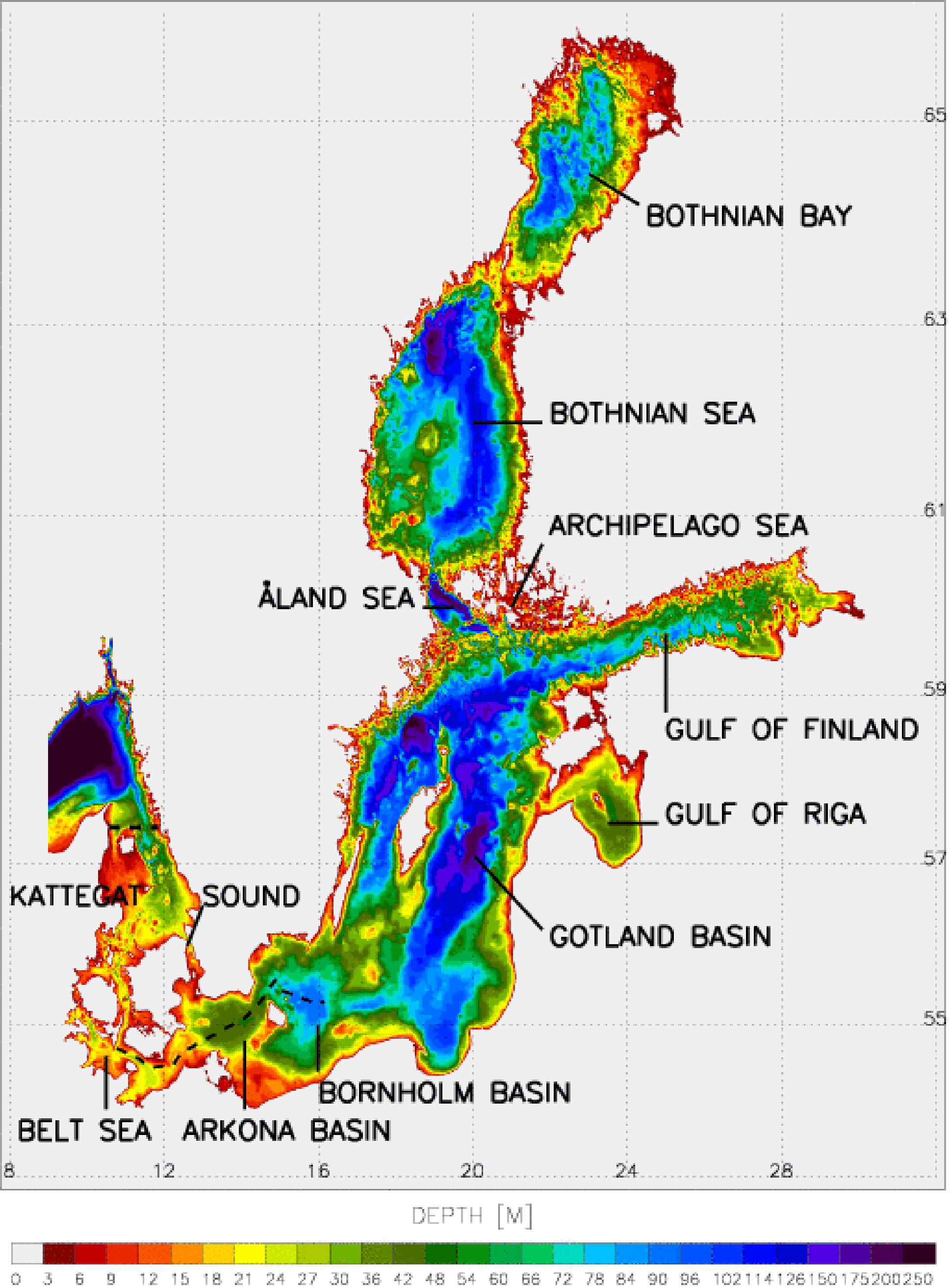
(source: Johan Rodhe)

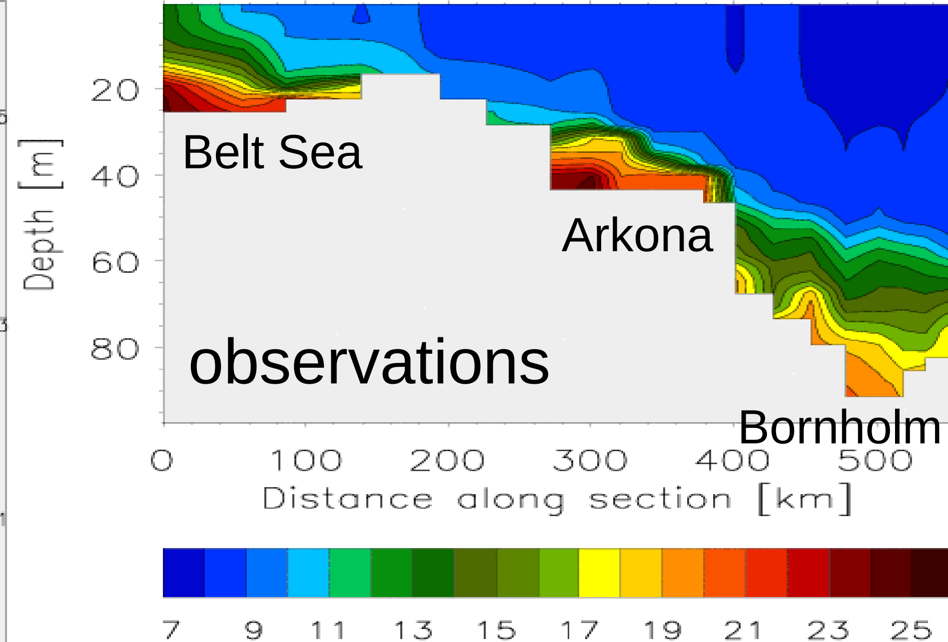
Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2007)

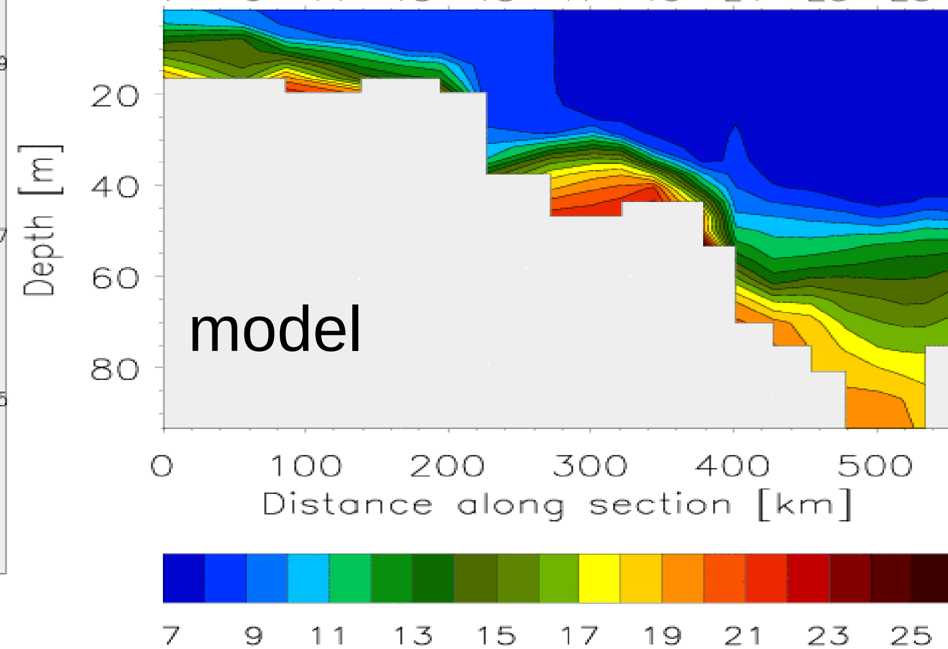


Saltwater inflows

- major Baltic inflows (e.g. Matthäus and Franck, 1992; Fischer and Matthäus, 1996)
- randomly at intervals of one to several years
- most probable between November to January
- forced by a sequence of easterly winds lasting about 20 days followed by strong to very strong westerly winds of similar duration
- since the mid-1970s the frequency and intensity has decreased
- latest inflow events: 1983, 1993, 2003

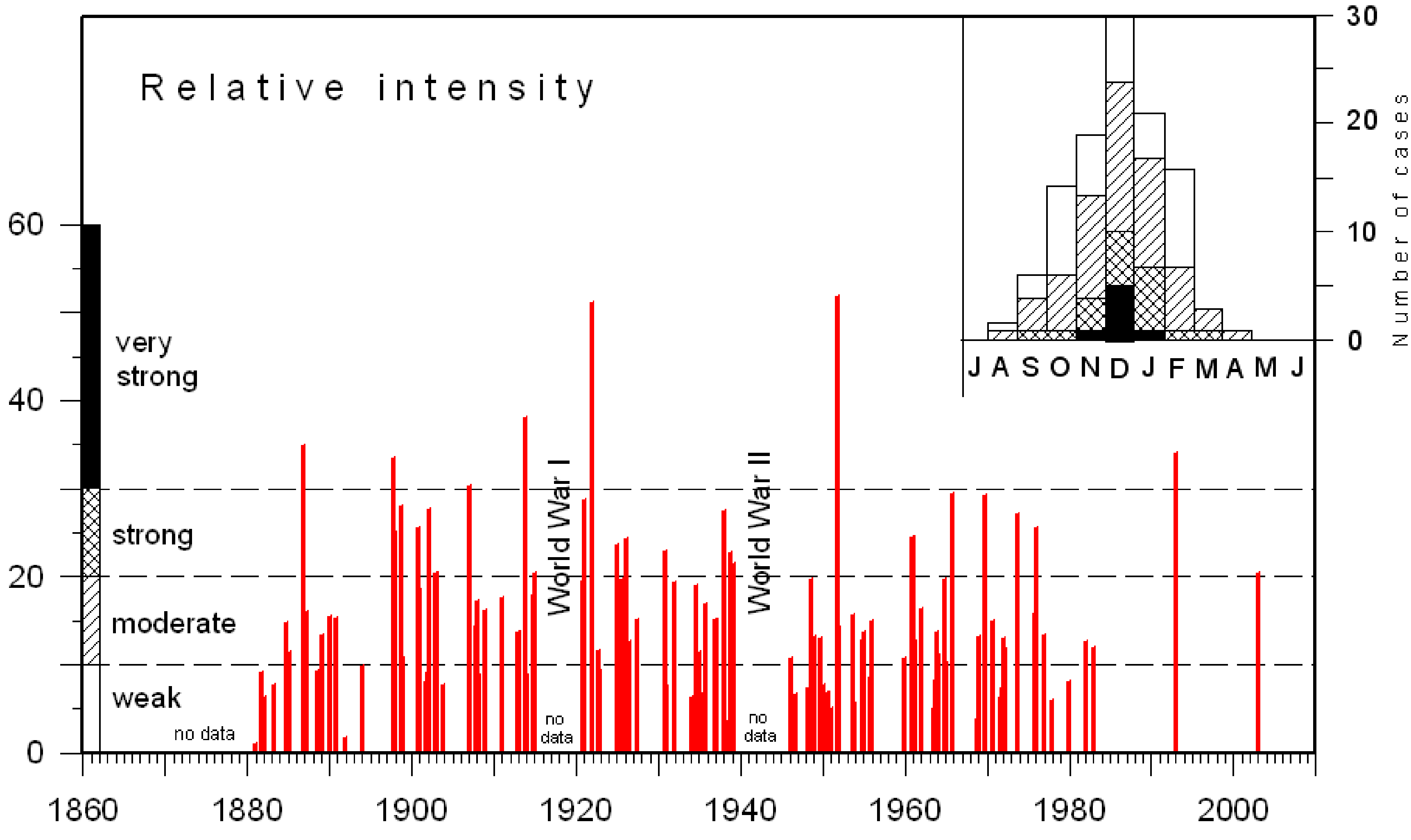

BOTHNIAN BAY
BOTHNIAN SEA
ARCHIPELAGO SEA
ÅLAND SEA
GULF OF FINLAND
GULF OF RIGA
KATTEGAT
SOUND
GOTLAND BASIN
BORNHOLM BASIN
BELT SEA
ARKONA BASIN
65
63
61
59
57
55
8
12
16
20
24
28
DEPTH [M]
0 3 6 9 12 15 18 21 24 27 30 36 42 48 54 60 66 72 78 84 90 96 102 114 126 150 175 200 250


Depth [m]
20
40
60
80
Belt Sea
Arkona
observations
Bornholm
0 100 200 300 400 500
Distance along section [km]
7 9 11 13 15 17 19 21 23 25


Depth [m]
20
40
60
80
model
0 100 200 300 400 500
Distance along section [km]
7 9 11 13 15 17 19 21 23 25

inflow 1993

Saltwater inflows during 1898-2008



(Matthäus & Franck 1992, Fischer & Matthäus 1996)

Characteristic periods of major Baltic inflows

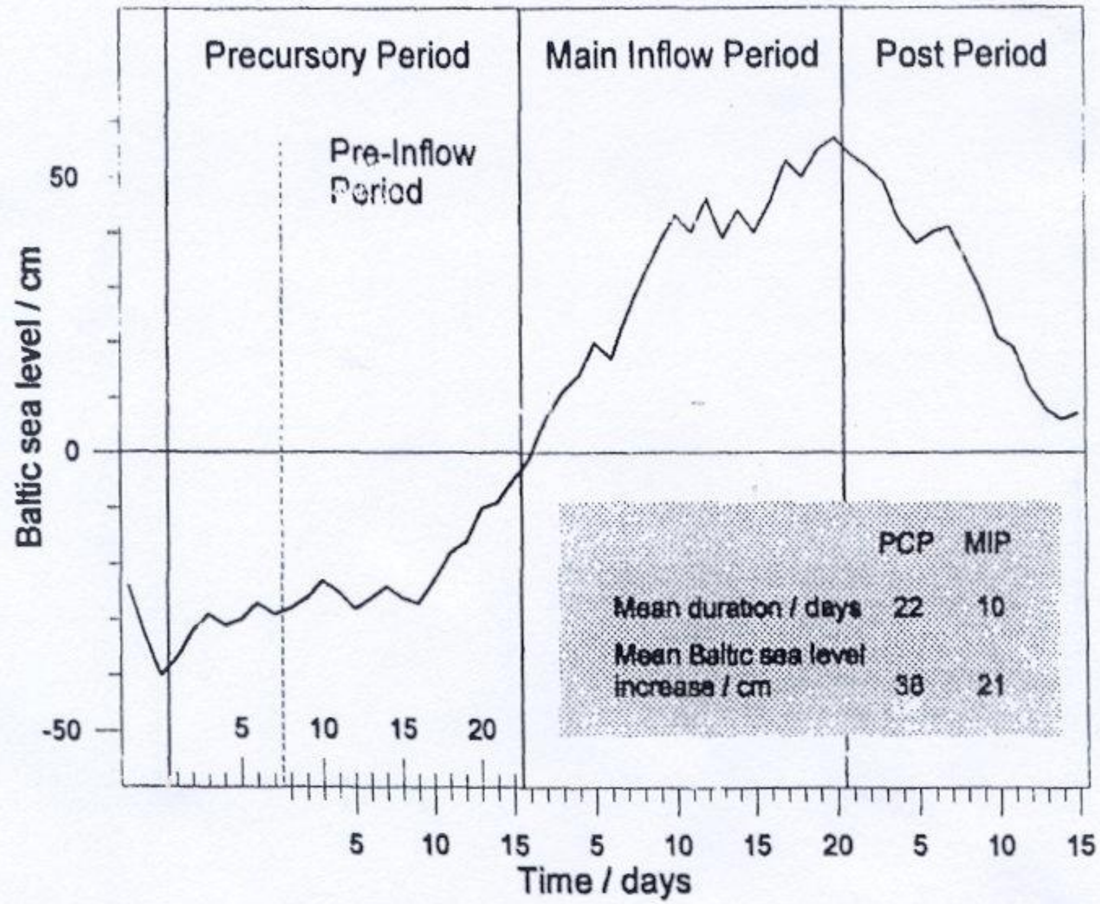


Fig. 4. Characteristic periods for major Baltic inflows, illustrated by Baltic sea level variations, and their mean characterization.

(Fischer and Matthäus, 1996)

11. Climate variability

Positive trend of salinity and temperature during the 20th century at almost all stations and depths (Fonselius and Valderrama, 2003)

Atmospheric CO_2 during 1750-1990

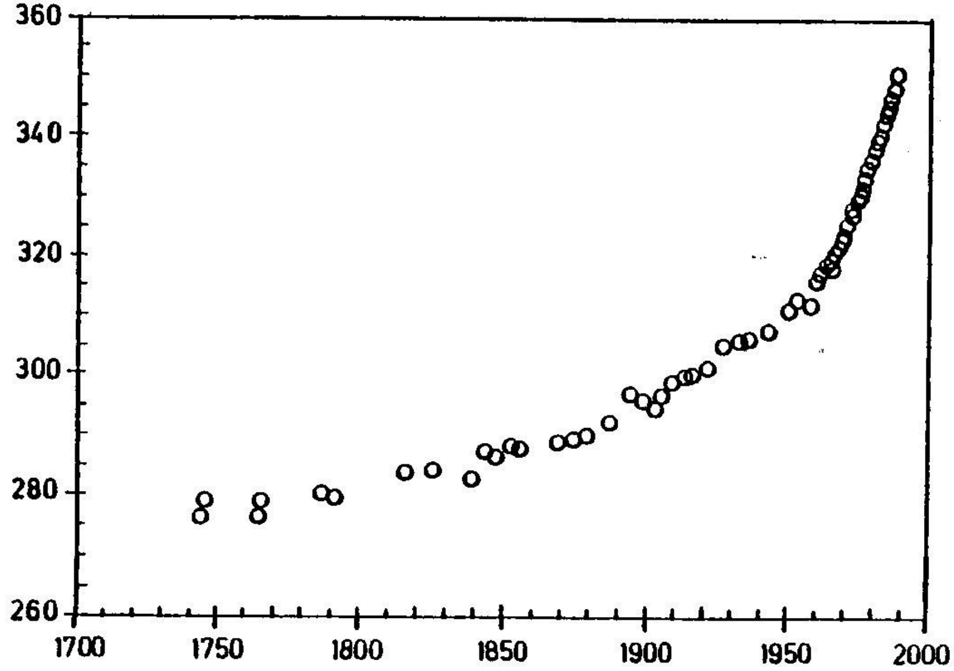


Fig. 9.2. *Ökningen av koldioxid i atmosfären från 1750 till 1990. Koldioxidhalten ges i miljondedelar, d.v.s. ml/m³. Värden fram till 1950 visar värden erhållna från is-kärnor i Antarktis. Värden från 1950 är aktuella mätningar på Mauna Loa på Hawaii* [109]

(Fonselius, 1996)

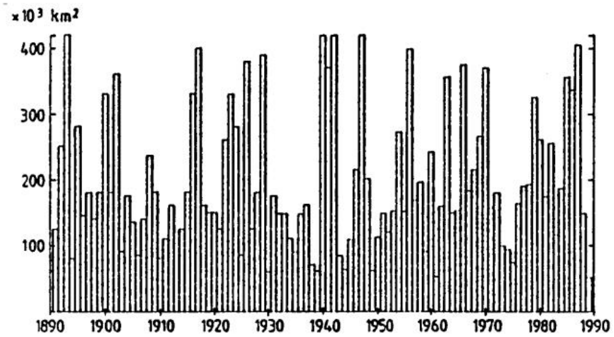


Fig. 9.5. *Tidsserie för utbredningen av årligt maximalt istäcke i Östersssjön från 1890/1891 till 1988/1989*[111].

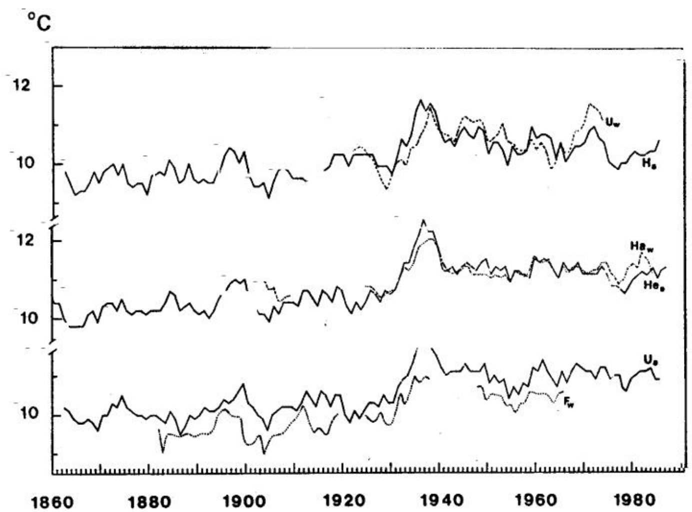


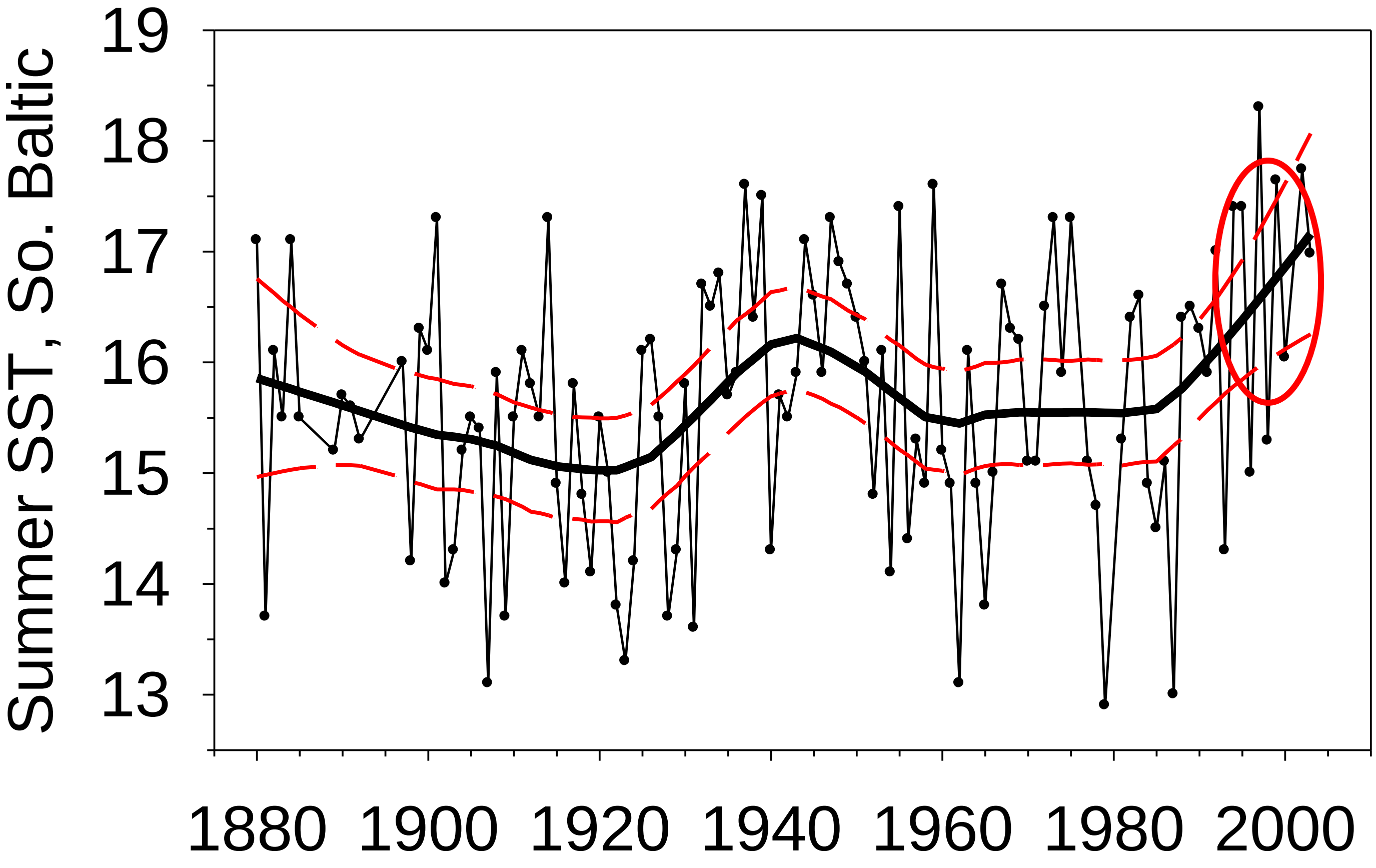
Fig. 9.6. *Långtidsserier för lufttemperatur och yttemperatur i vattnet*[111]

U_w = *vattentemperaturen vid Ulkokalla (juni - oktober)*
H_a = *lufttemperaturen i Haparanda (juni - oktober)*
Ha_w = *vattentemperaturen vid Harmaja (juni - november)*
He_a = *lufttemperaturen i Helsingfors (juni - november)*
F_w = *vattentemperaturen vid Finngrundet (juni - november)*
U_a = *lufttemperaturen i Uppsala (juni - november)*

Annual maximum maximum ice extent and SST/air temperature variations

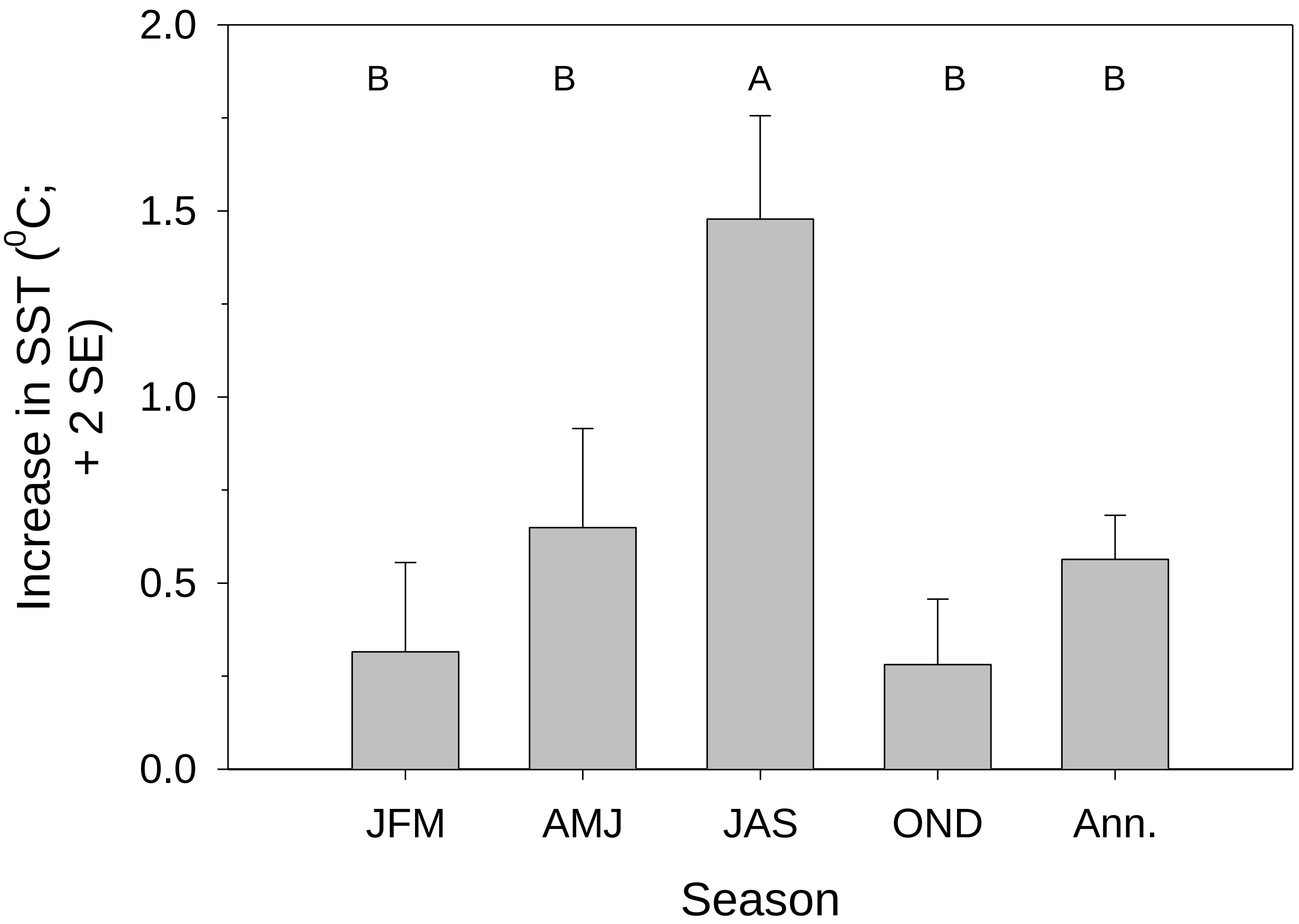
(Fonselius, 1996)

Summer (JAS) SST
1880-2003



warm conditions during 1990s-2000s

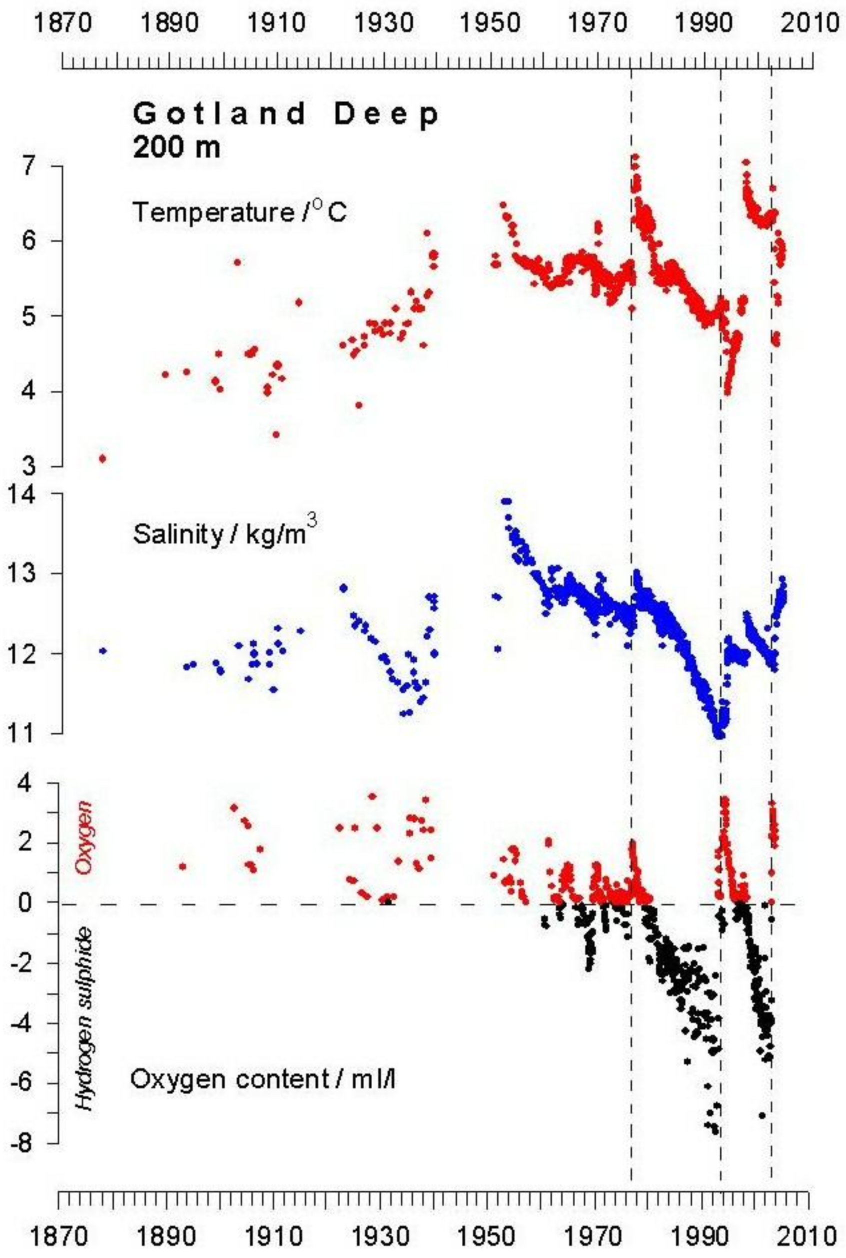
MacKenzie & Schiedek 2007
Global Change Biol.



warming rates differ significantly among seasons

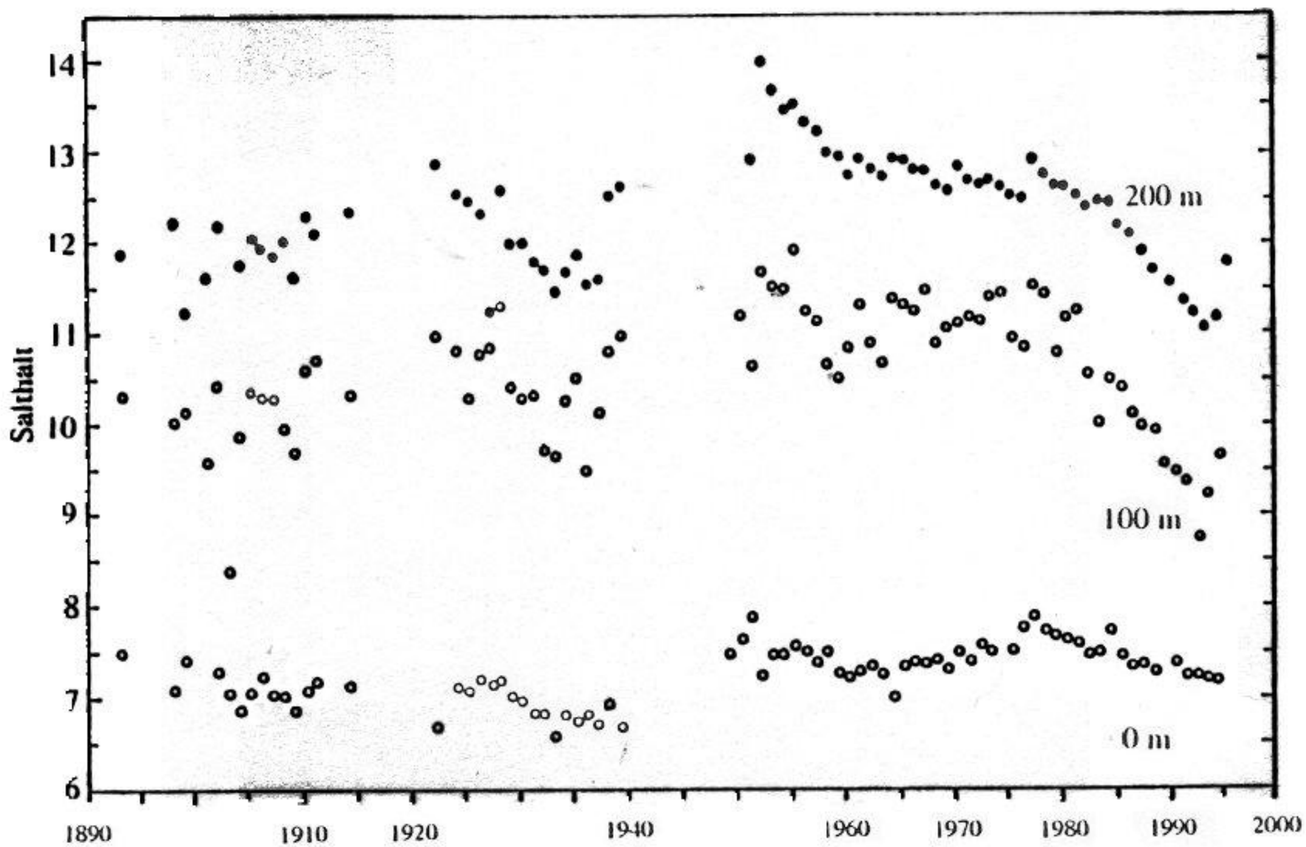
summers have warmed most (2-3x other seasons)

MacKenzie & Schiedek 2007
Global Change Biol.



Elken and Matthäus (2005)

Salinity variations at Gotland Deep



(Fonselius, 1996)

Fig. 9.10. Salthaltsvariationer på olika nivåer i Gotlandsdjupet 1890 - 1994.

Salinity variations of various sub-basins

(Fonselius, 1996)

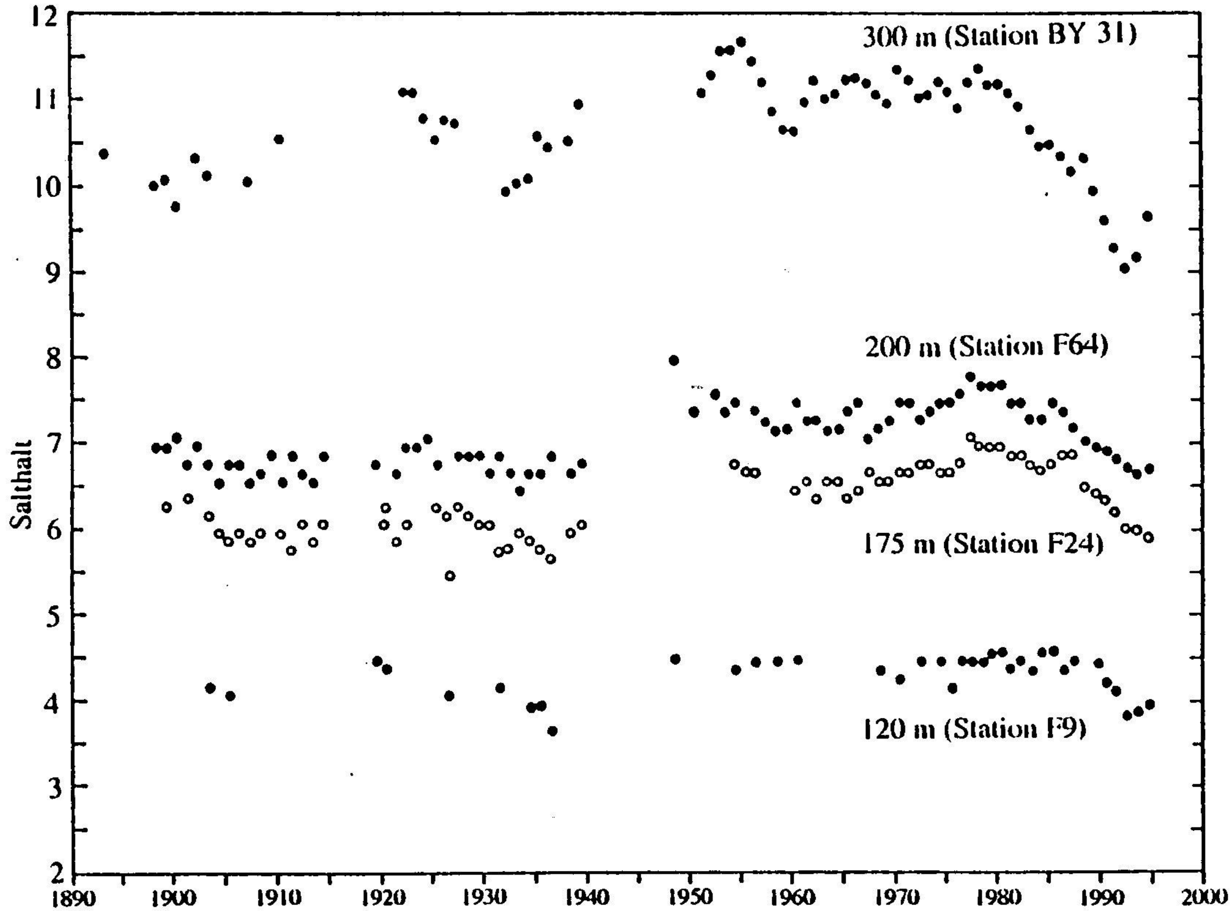


Fig. 9.9. *Salthaltsvariationer i djupvattnet i olika delar av Östersjön från 1890 - 1994* [113]. *St. BY31 Landsortsdjupet, F64 Ålandsdjupet, F24 Ulvödjupet, F9 Bjurödjupet.*

Oxygen concentration at Landsort Deep in 400 m depth

(Fonselius, 1996)

Hydrogensulfide observed 1970 and 1982

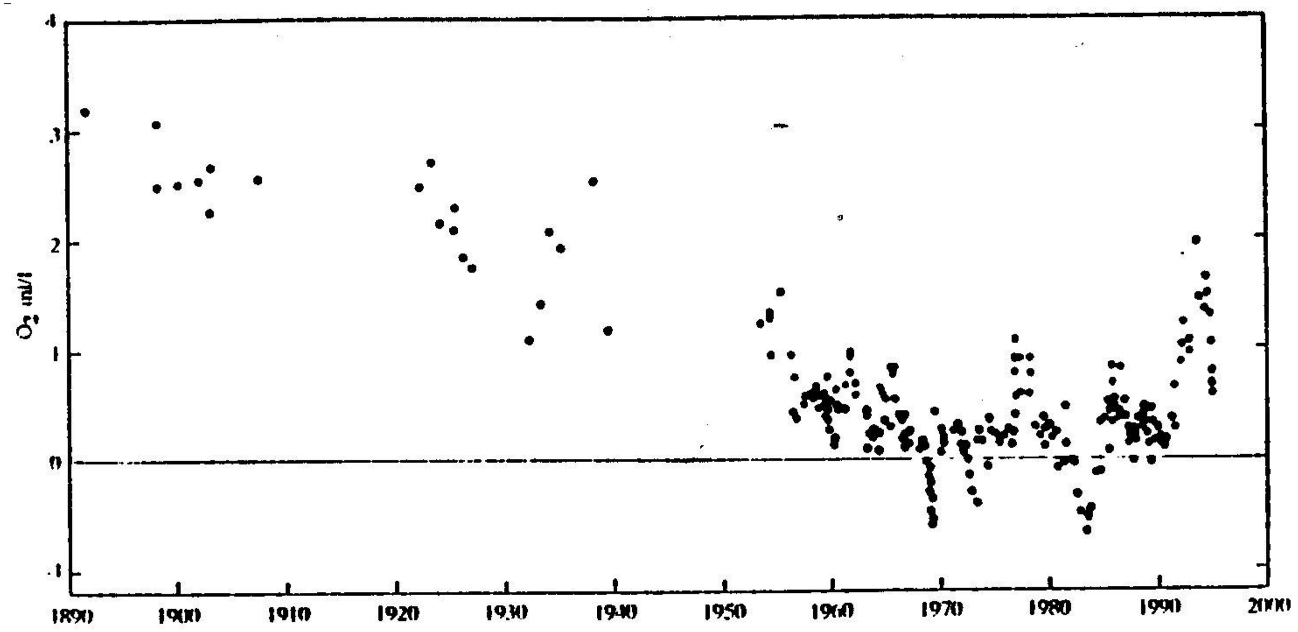
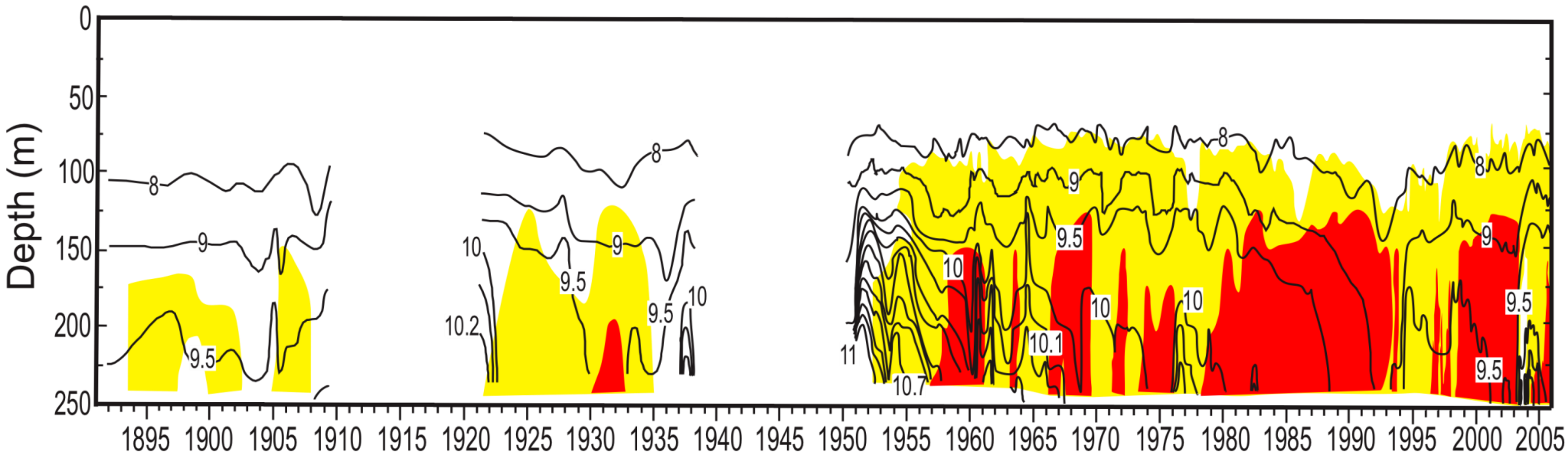


Fig. 9.15. Syrgas- och svavelvätevariationerna i Landsortsdjupet vid omkring 400 m djup 1891 - 1994 i ml/l. Svavelväte observerades för första gången 1968. Svavelvätet är uttryckt som negativt syre.

Oxygen and density at Gotland Deep 1890-2006



Isopyknen (– 1000 kg/m³)

Hypoxia (O2 Konzentration < 2 ml/l) gelb

Anoxia (O2 = 0) rot

(Conley et al. 2009)

Frequency distributions of sechi depths for 1914-1939 and 1969-1986

(Fonselius, 1996)

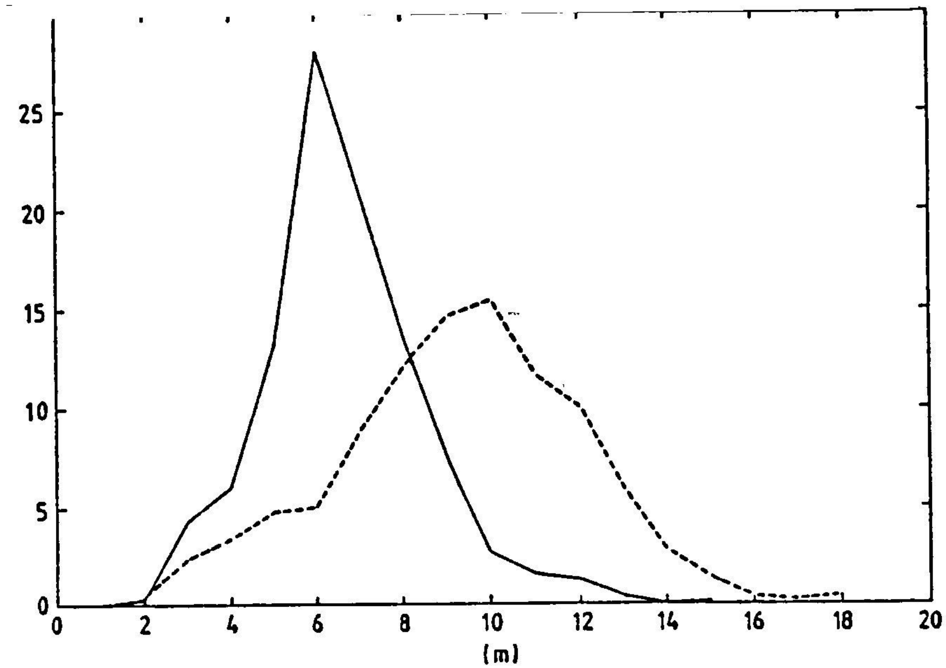


Fig. 9.17. Frekvensfördelningen av secchidiskobservationer i norra delen av egentliga Östersjön (111). Den streckade linjen visar fördelningen av siktdjupsobservationer i procent under perioden 1914 - 1939 och den heldragna linjen siktdjupsfördelningen 1969 - 1986. Siktdjupet har minskat med omkring 2 m.

12. Comparison with other seas

Schematic of different vertical circulation patterns

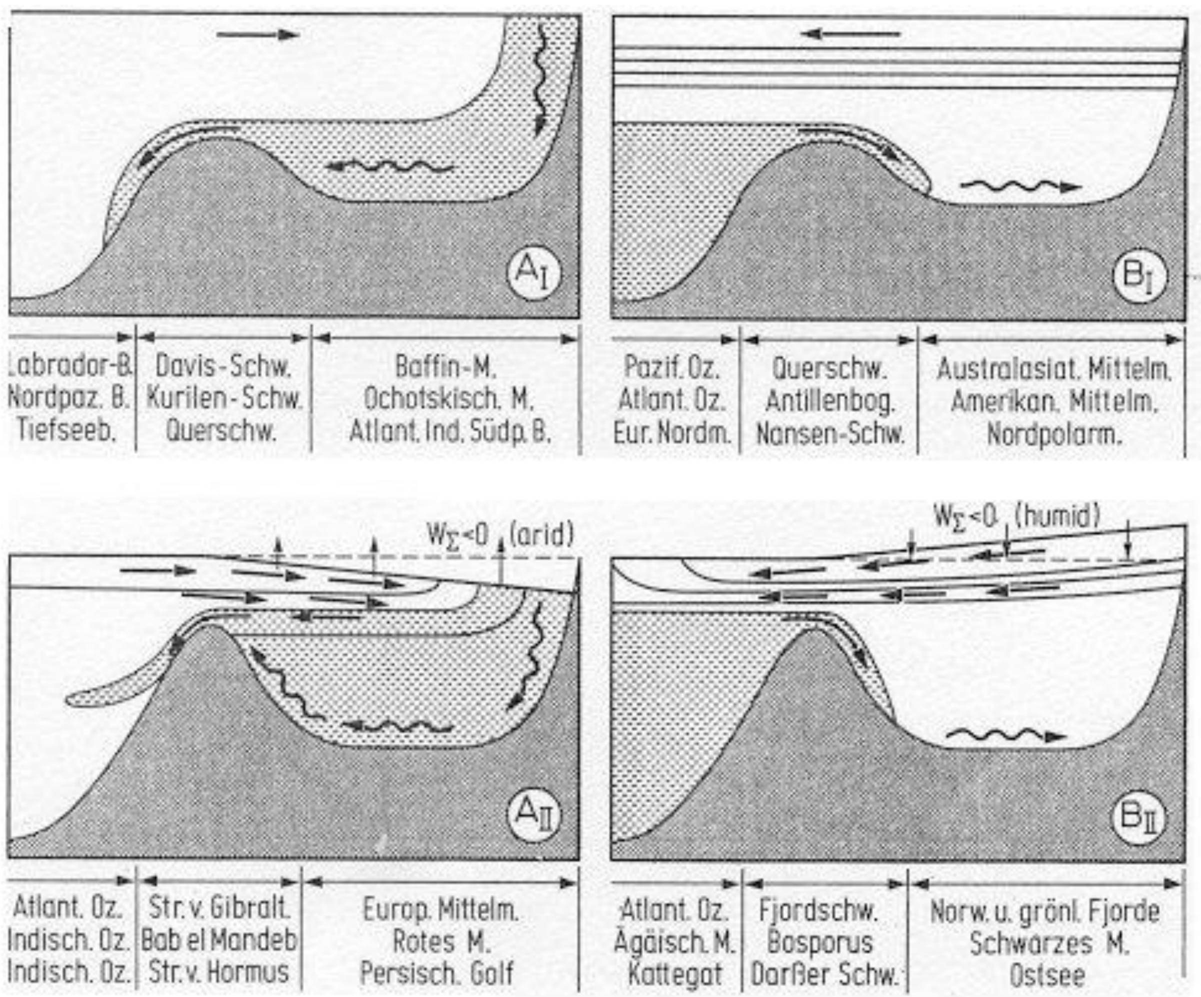
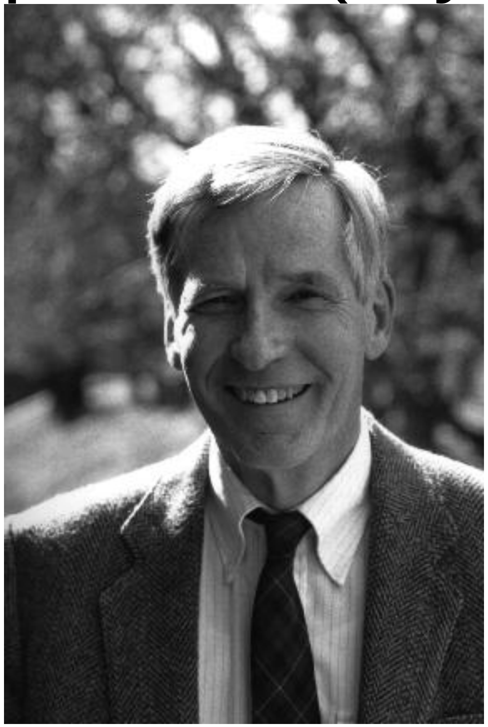


Abb. 10.17. Zirkulationsschemata für die Mittel- und Nebenmeere mit je drei Beispielen. A) *mit*, B) *ohne* tiefreichende thermohaline Konvektion. I: Bei kleinem V_S; II: bei großem V_S.

(Dietrich et al., 1975)

13. Baltic Sea models

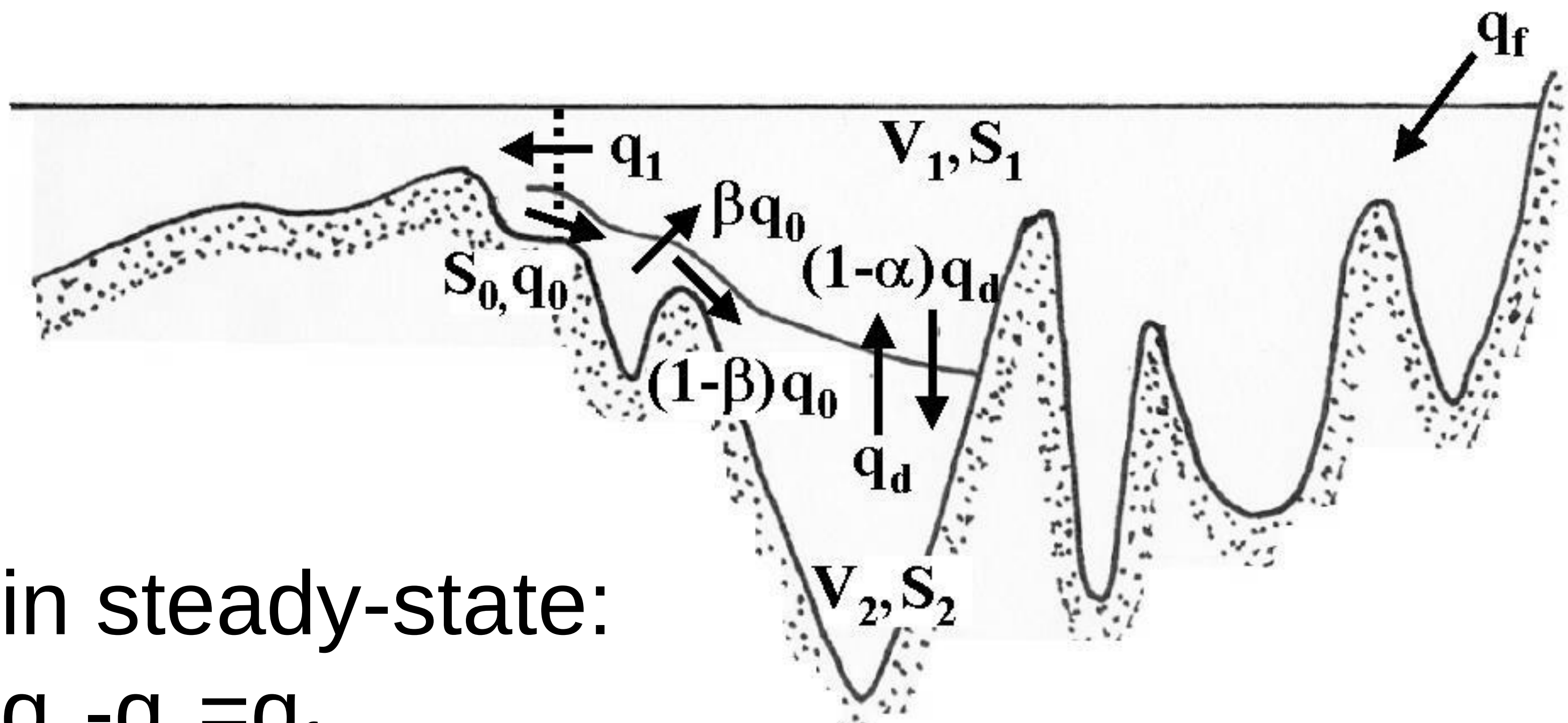
- process oriented models
- three-dimensional circulation models based upon the primitive equations (Bryan and Cox, 1968)



Kirk Bryan

http://www.aos.princeton.edu/WWWPUBLIC/kbryan/kbryan.html

Welander's model (1974)



in steady-state:

$q_1 - q_0 = q_f$

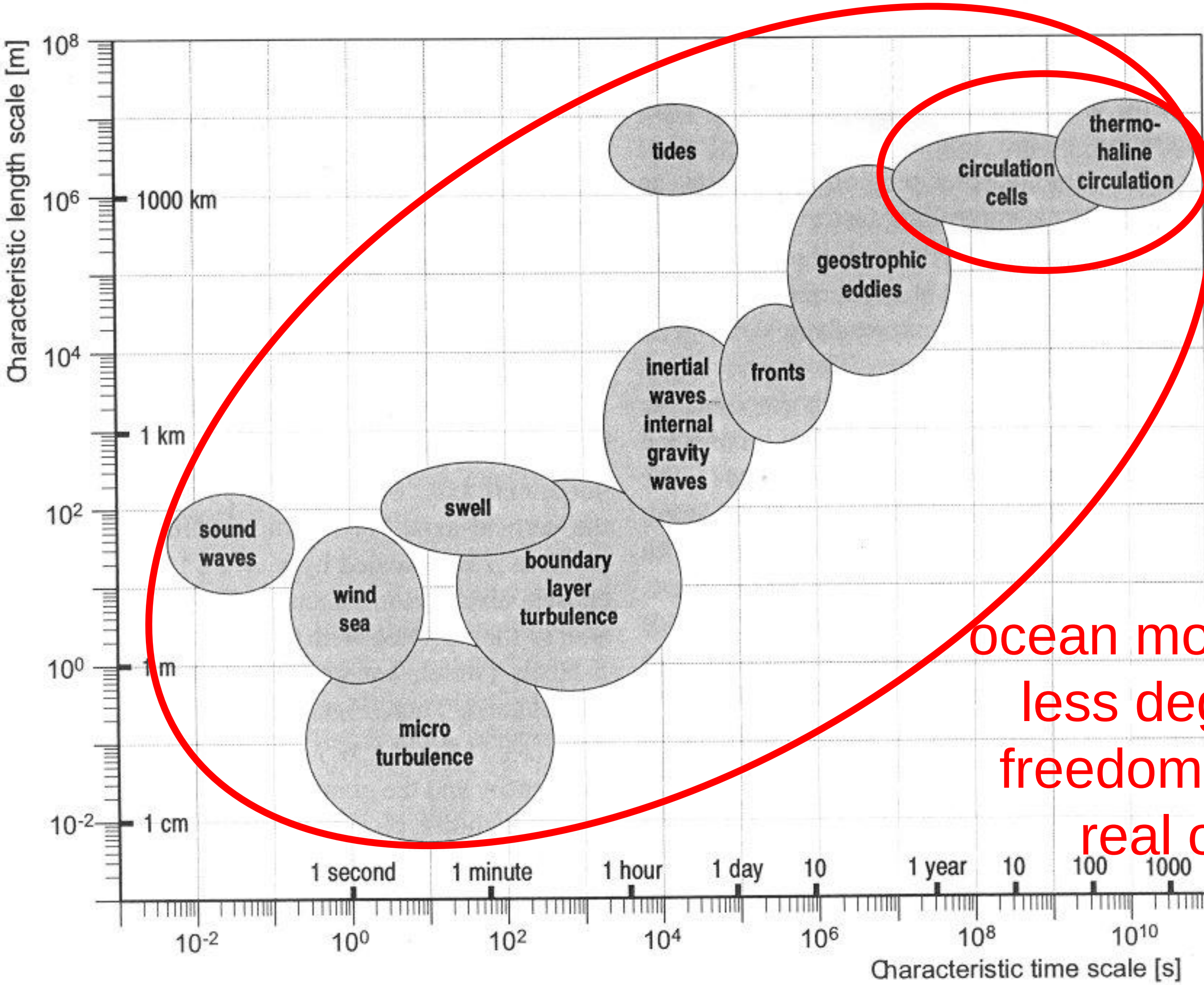
$S_0 q_0 = S_1 q_1$

(Knudsen,1900)

”Primitive equations” for large scale ocean circulation models = system of partial differential equations for salinity, potential temperature, and velocity plus equation of state for density

... follow conservation of mass, salinity, and momentum, and 1. and 2. fundamental theorem in thermodynamik

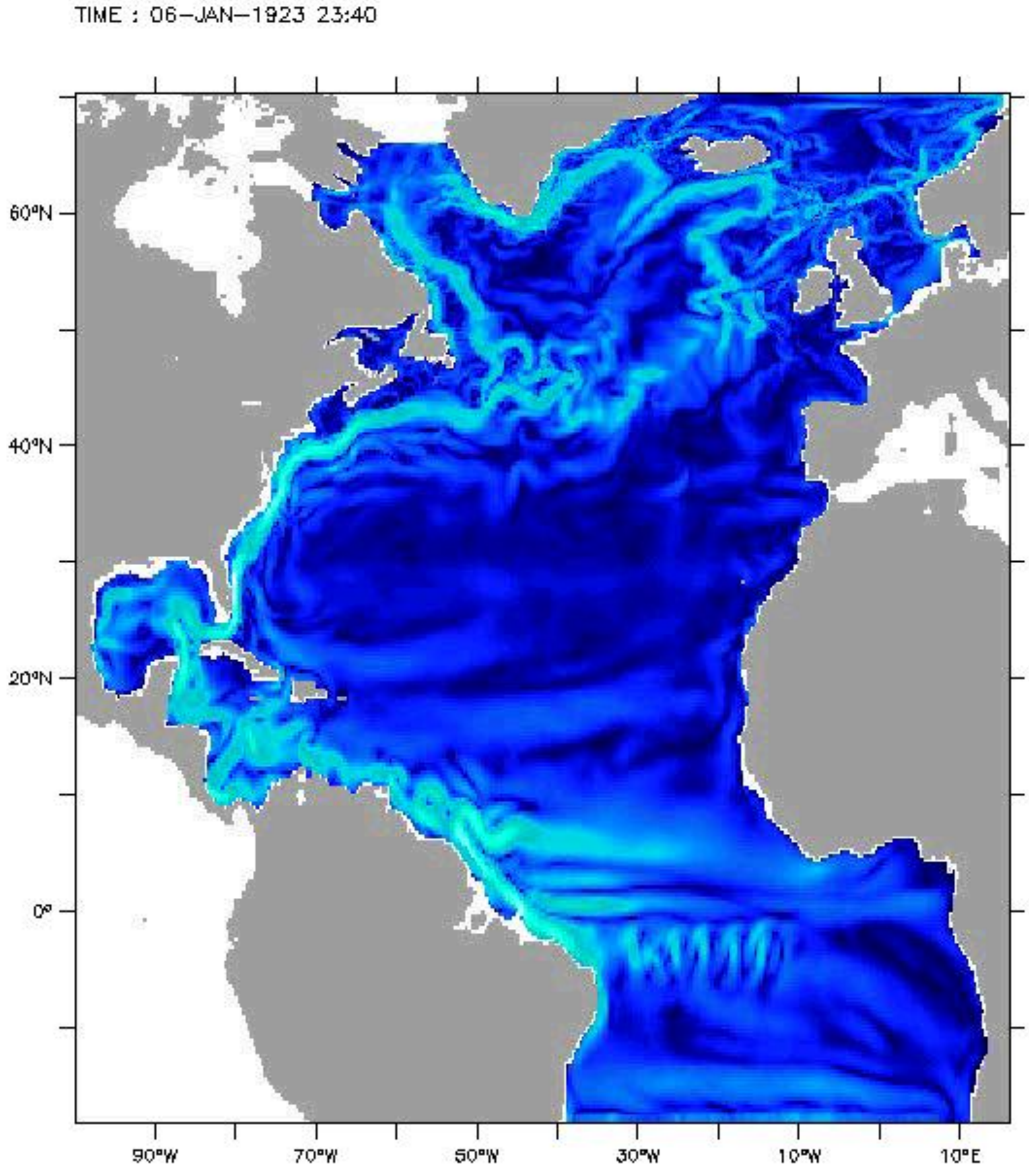
Time and length scales in the ocean



ocean models have less degrees of freedom than the real ocean

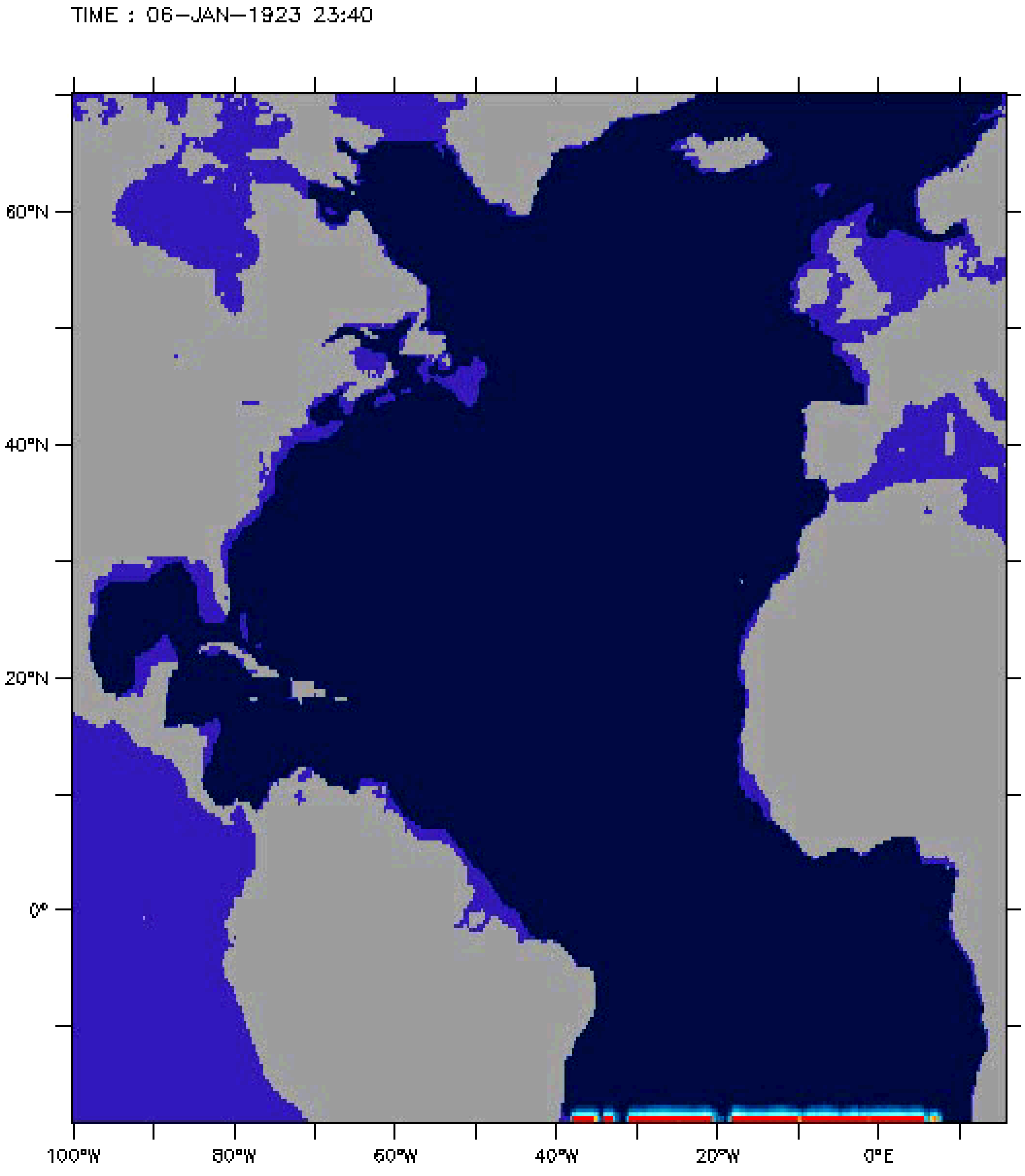
(von Storch and Zwiers, 1999)

FLAME-modellen: Hastighet på 100 m djup



(källa: J. Dengg)

Spårämne injicerat på 100 m djup på södra randen

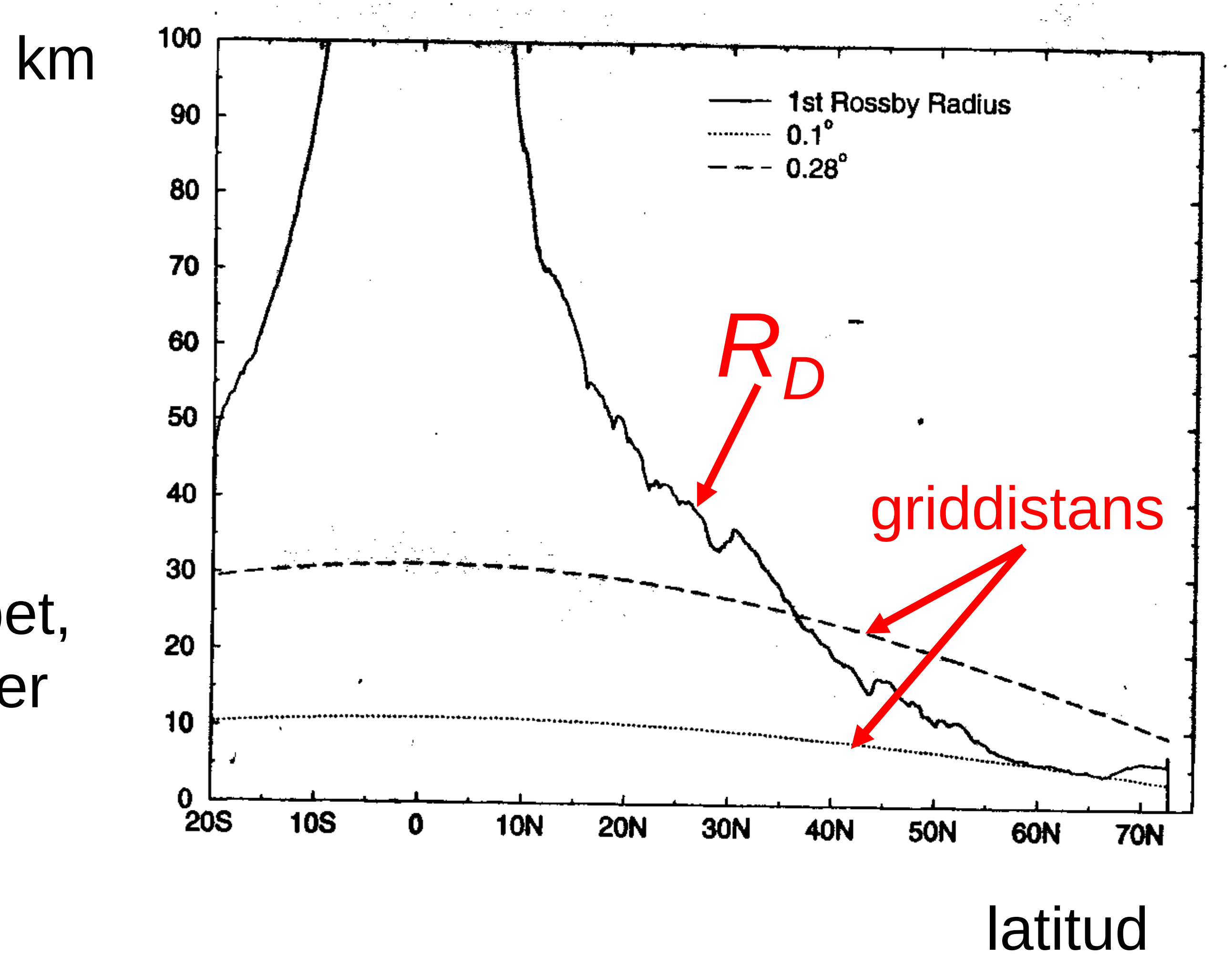


(källa: J. Dengg)

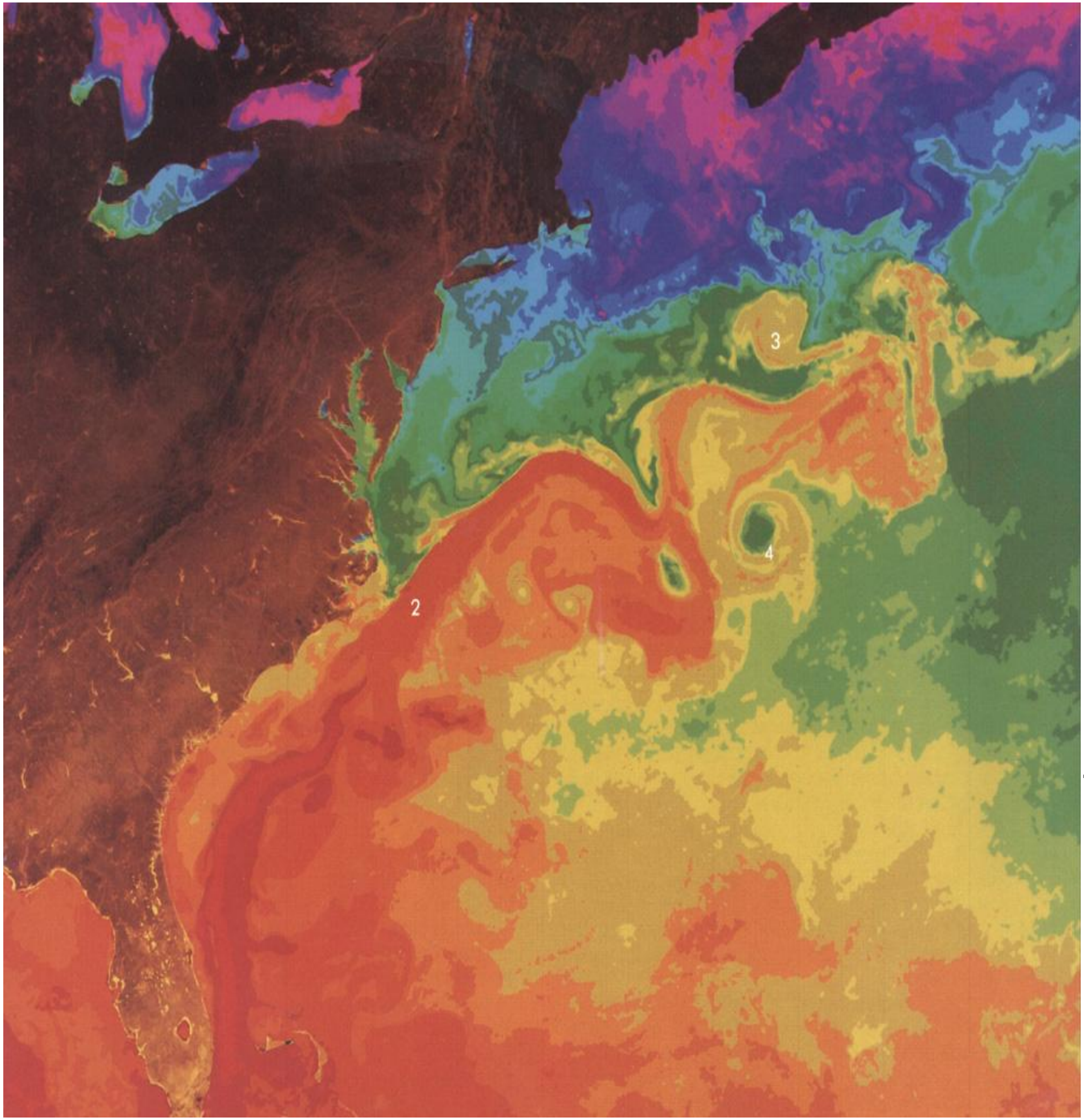
Rossbys deformationsradie i POP

$$R_D = \frac{\sqrt{gh_e}}{f}$$

g: gravitation,
h_e: ekvivalenta djupet,
f: Coriolis parameter



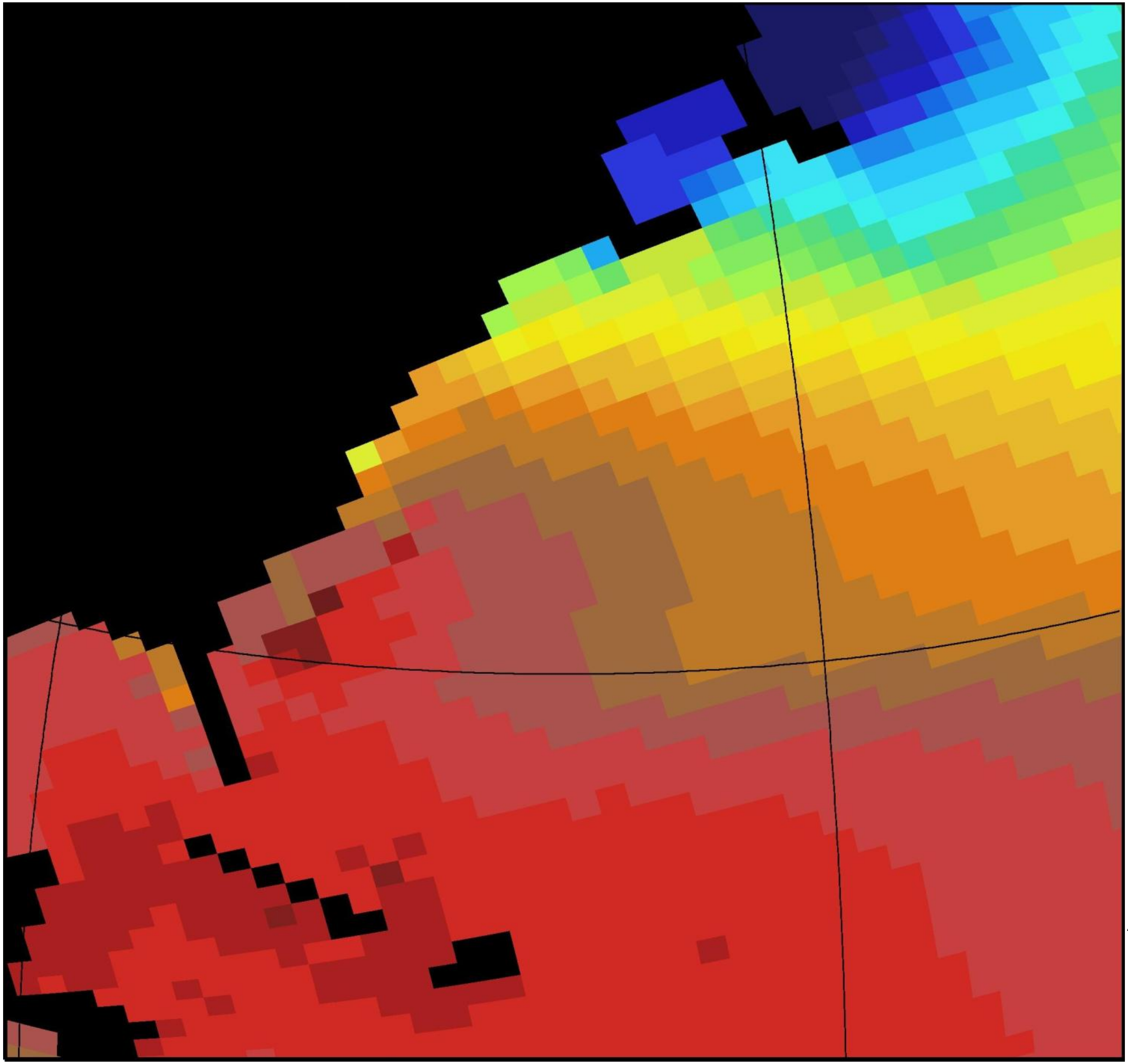
(källa: Smith et al., 2000)



satellit-
observationer

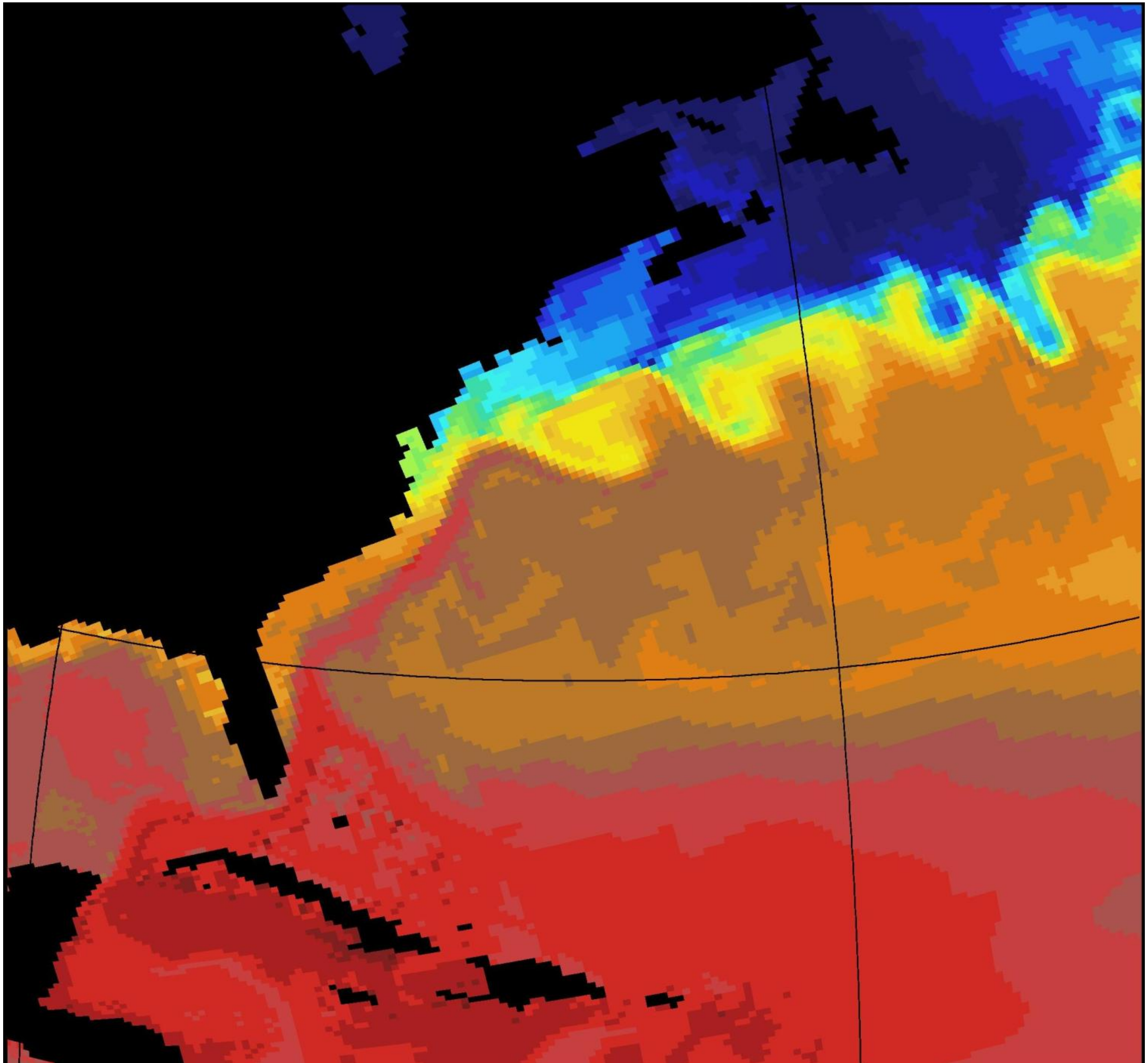
ytvatten-
temperatur

(källa:
A. Coward)



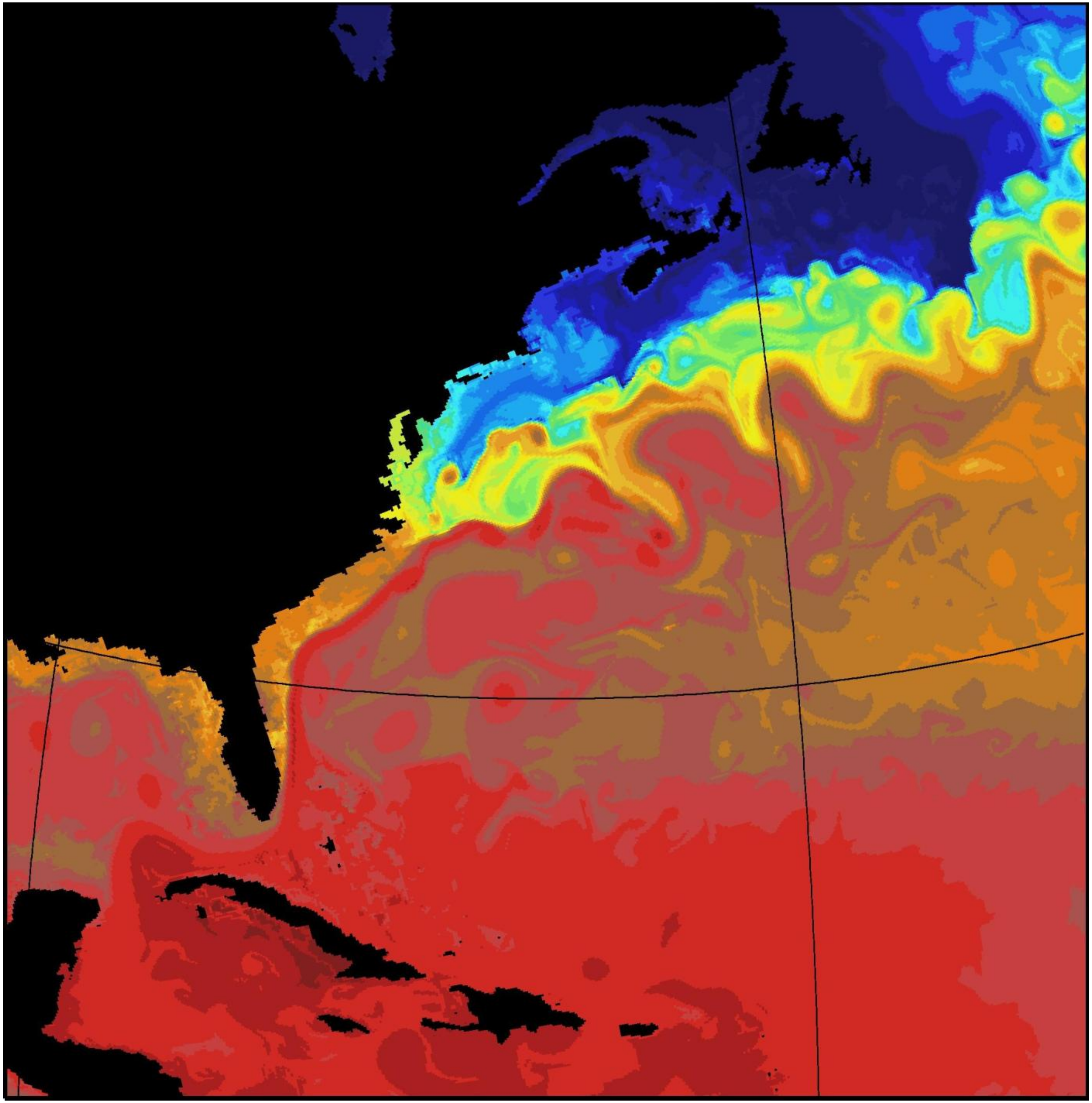
OCCAM
1º

(källa:
A. Coward)



OCCAM
1/4°

(källa:
A. Coward)

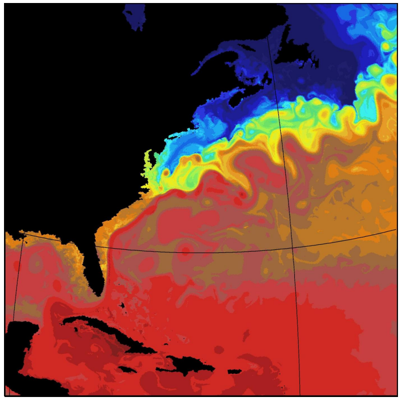


OCCAM
1/12°

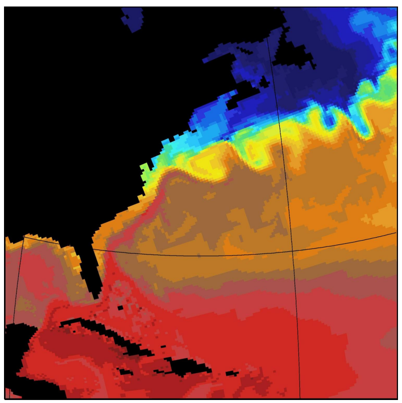
(källa:
A. Coward)

Ytvattentemperatur

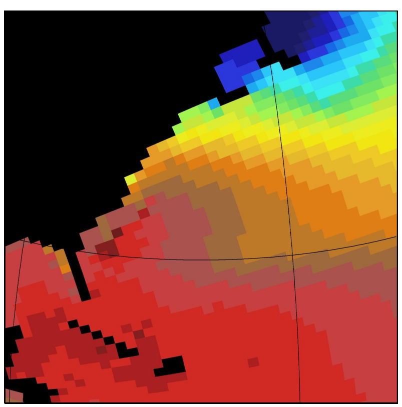
(källa:
A. Coward)



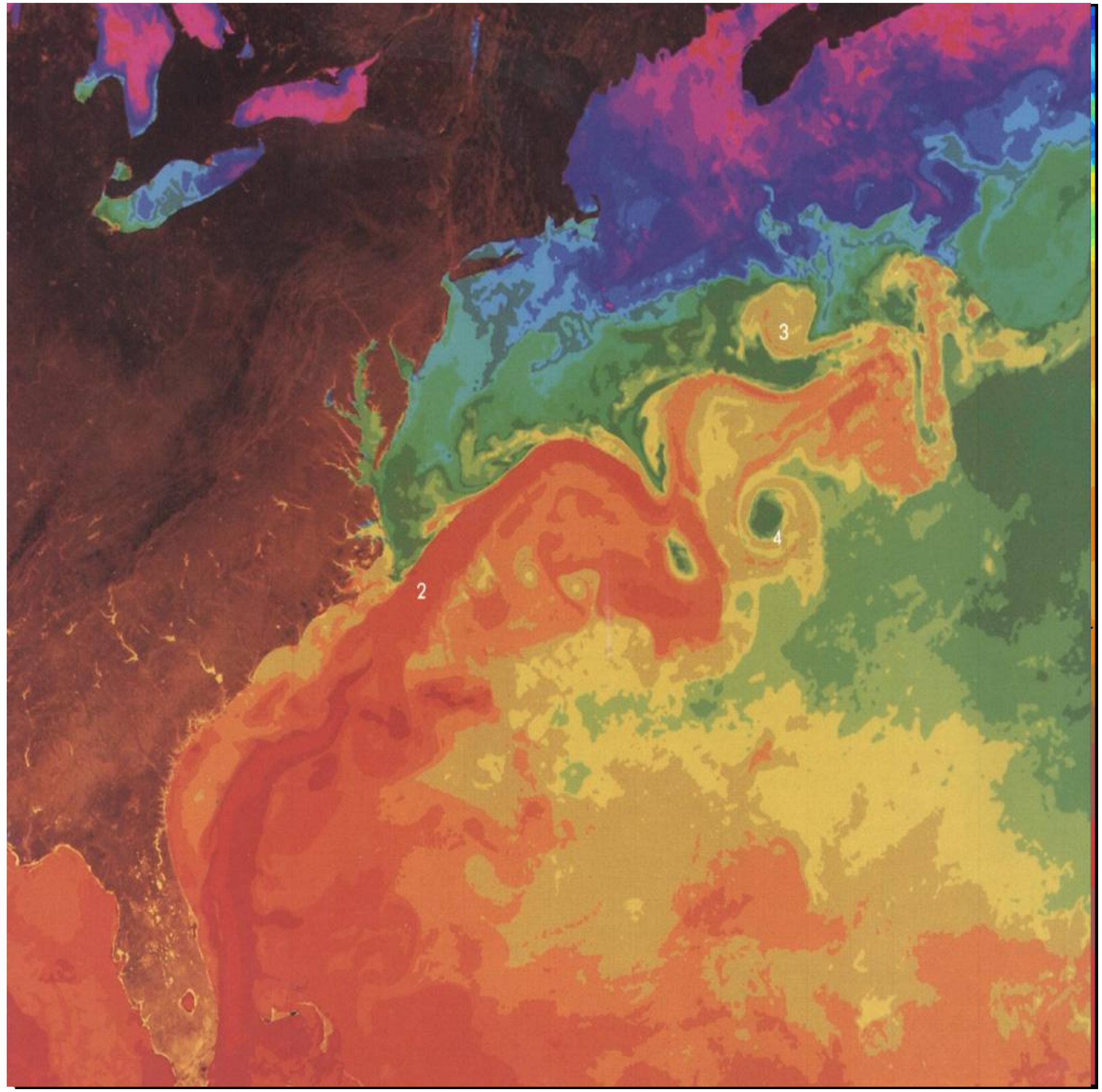
$1/12^o$



$1/4^o$



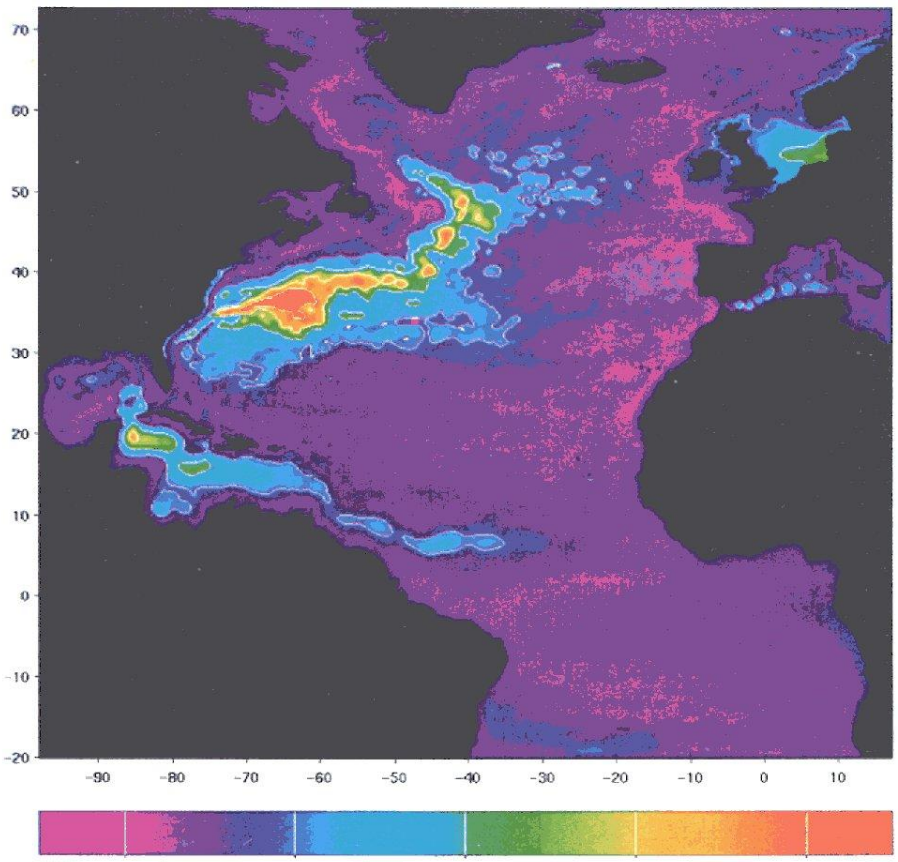
1^o



satellitobservationer

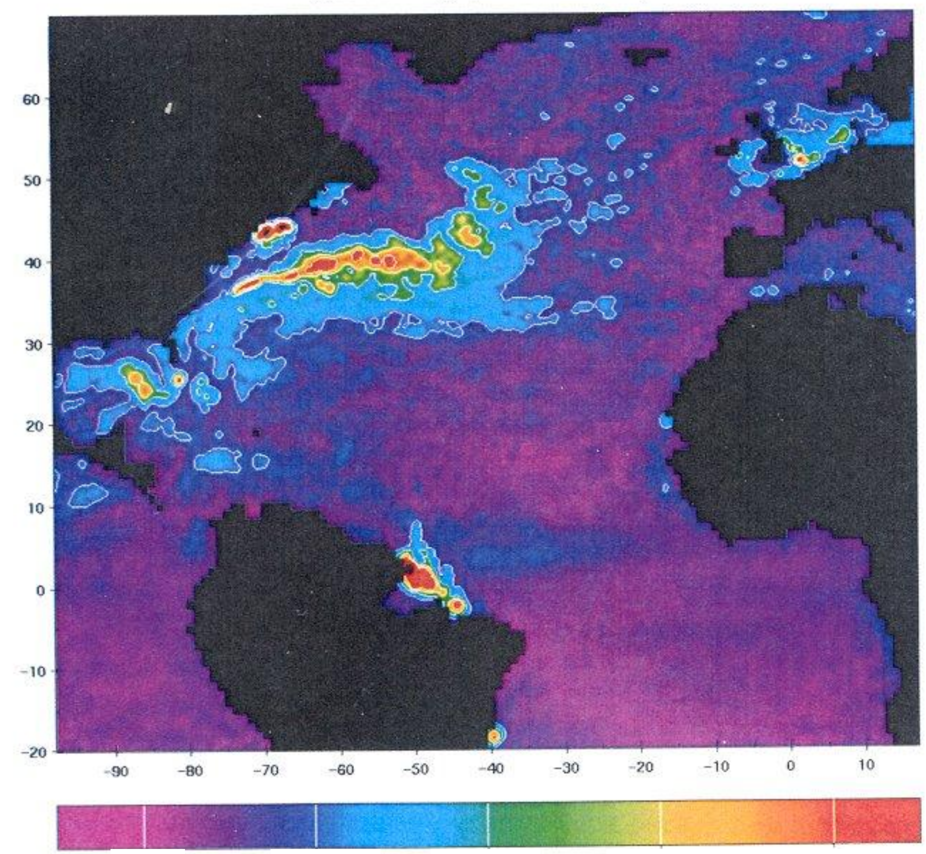
Vattenståndsvariabilitet $\sqrt{\overline{h'^2}}$

POP-modellen 0.1



0 10 20 30 40 cm

satellitobservationer

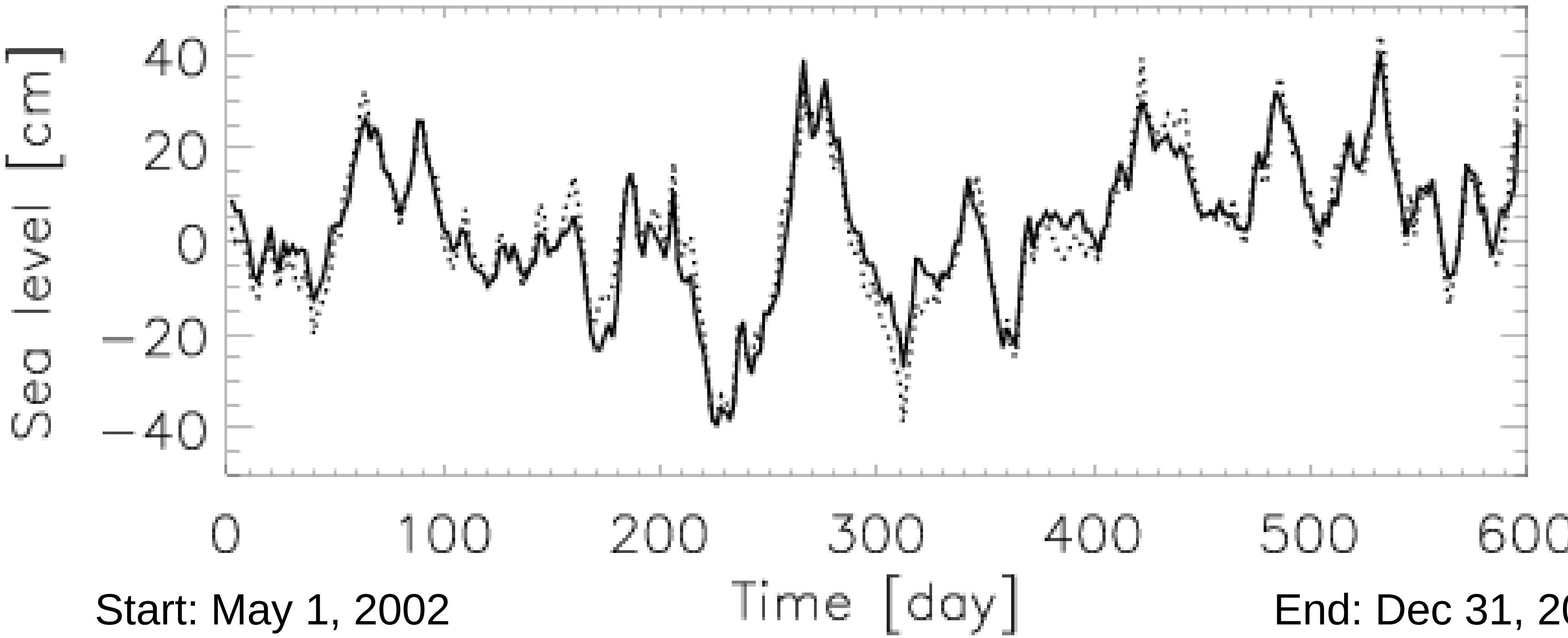


0 10 20 30 40

(källa: Smith et al., 2000)

14. The major Baltic inflow in January 2003 and preconditioning by smaller inflows in summer/autumn 2002

Sea level at Landsort: model (solid), observations (dotted)



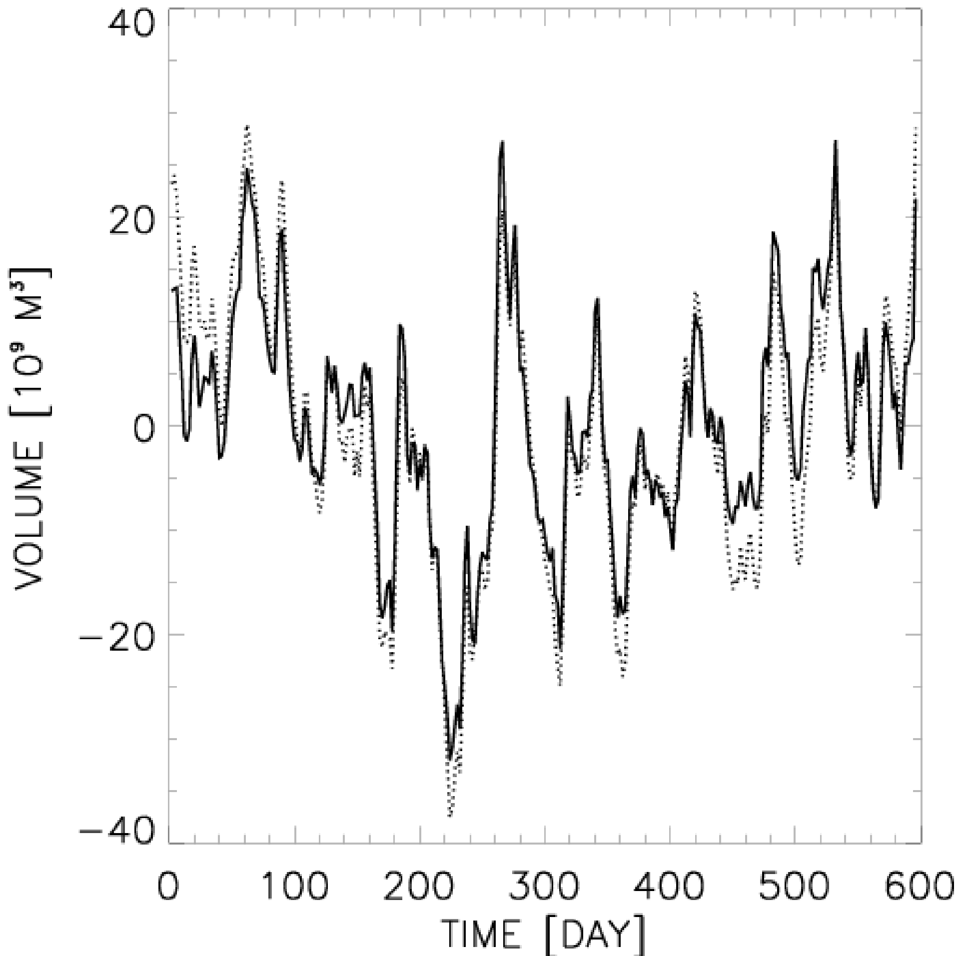
Start: May 1, 2002

End: Dec 31, 2003

ME=0.1 cm, RMSE=4.4 cm, R=0.96, VAR=0.92

(Meier et al., 2004b)

Detrended accumulated inflow through the Sound: RCO (solid), hydraulic model (dotted)

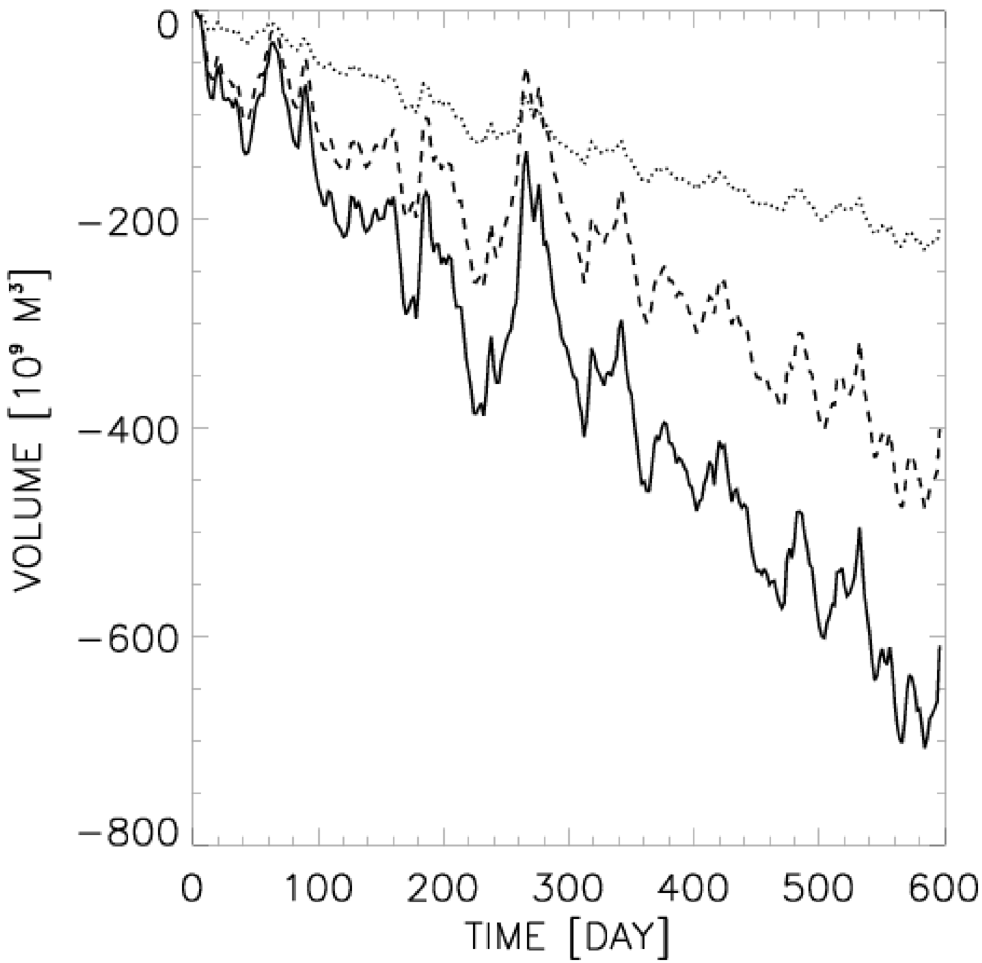


ME=0.9 km^3,
RMSE=4.1 km^3,
R=0.95,
VAR=0.89

Start: May 1, 2002

(Meier et al., 2004b)

Accumulated inflow: Sound (dotted), Darss Sill (dashed), sum (solid)



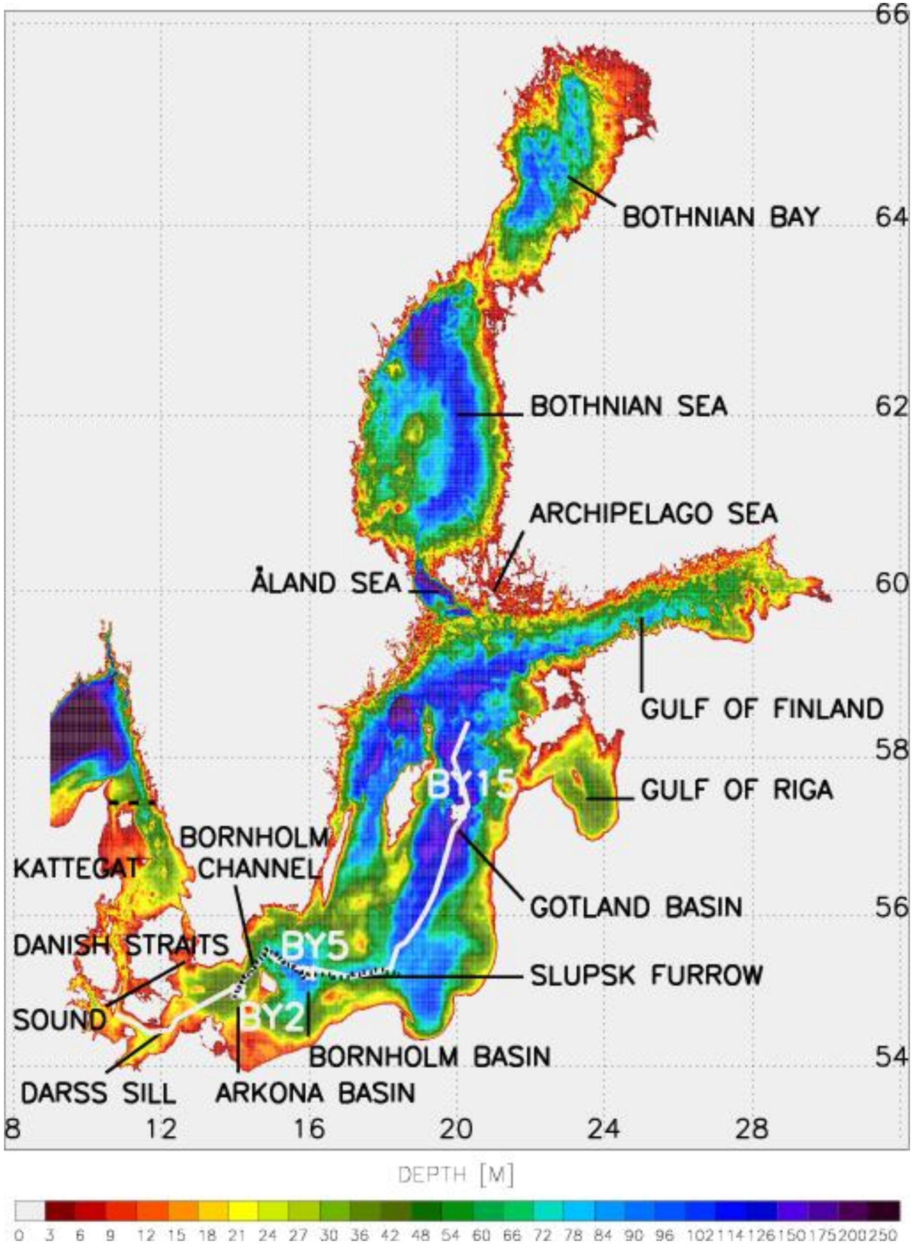
May 2002 - Dec 2003 (1993):
Sound: 35% (29%),
Darss: 65% (71%)

Start: May 1, 2002

(Meier et al., 2004b)

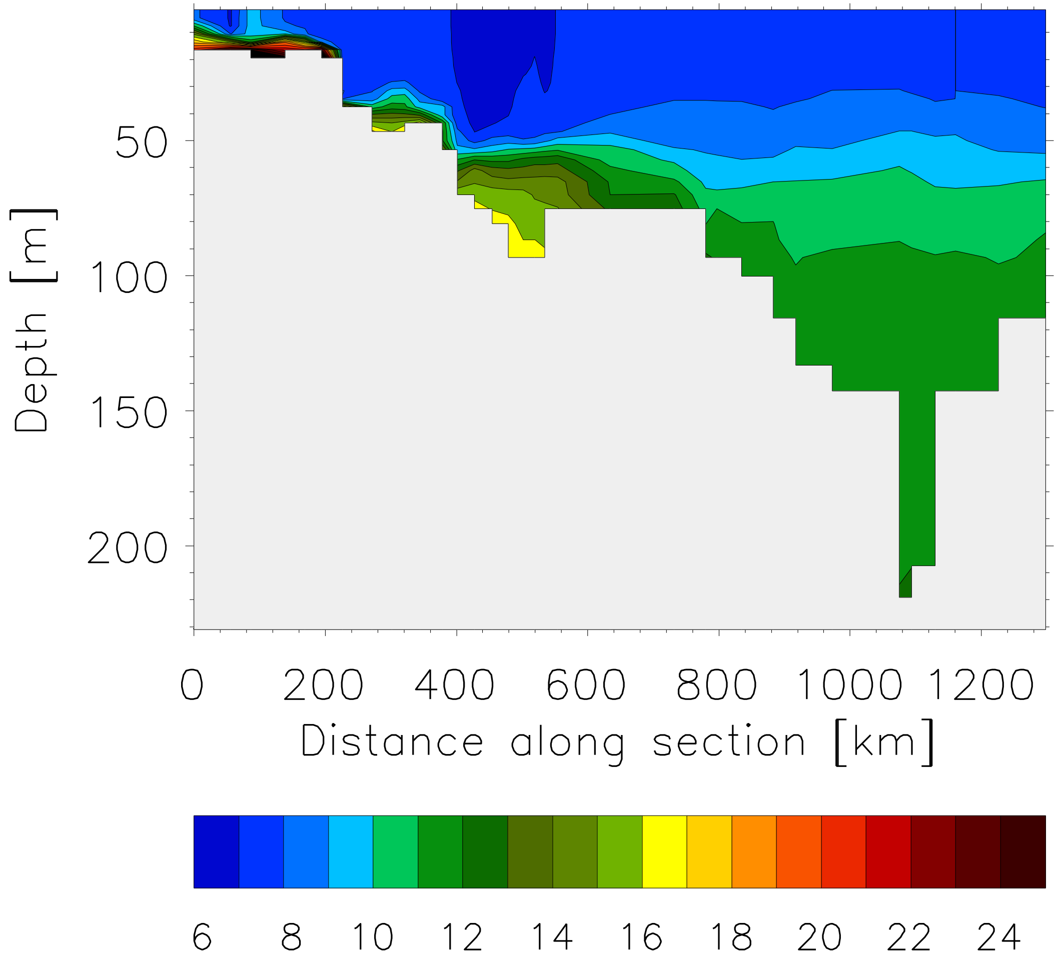
Regional model
RCO
1/30

Baltic Sea topography



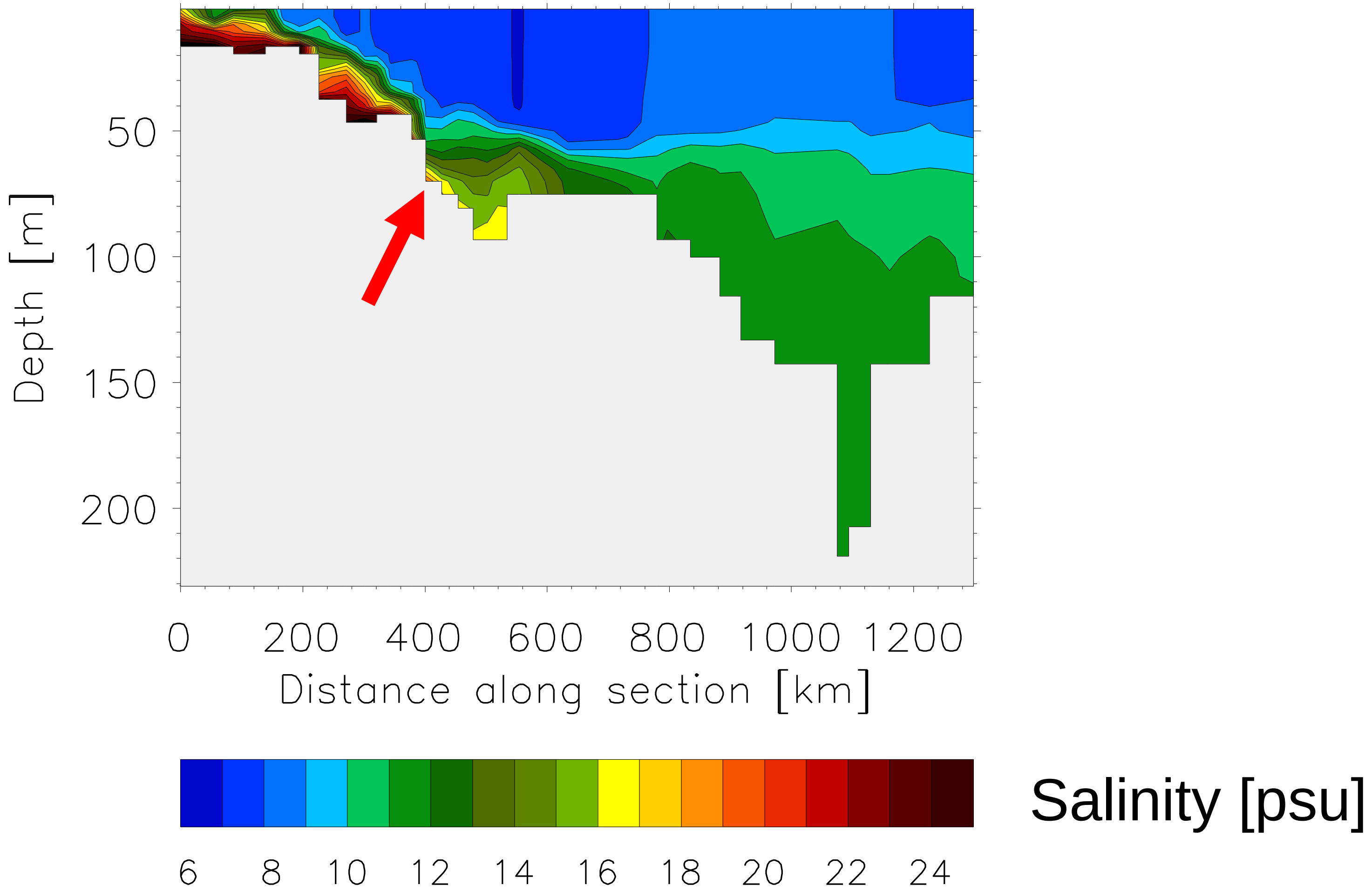
Depth [m]

15 December 2002



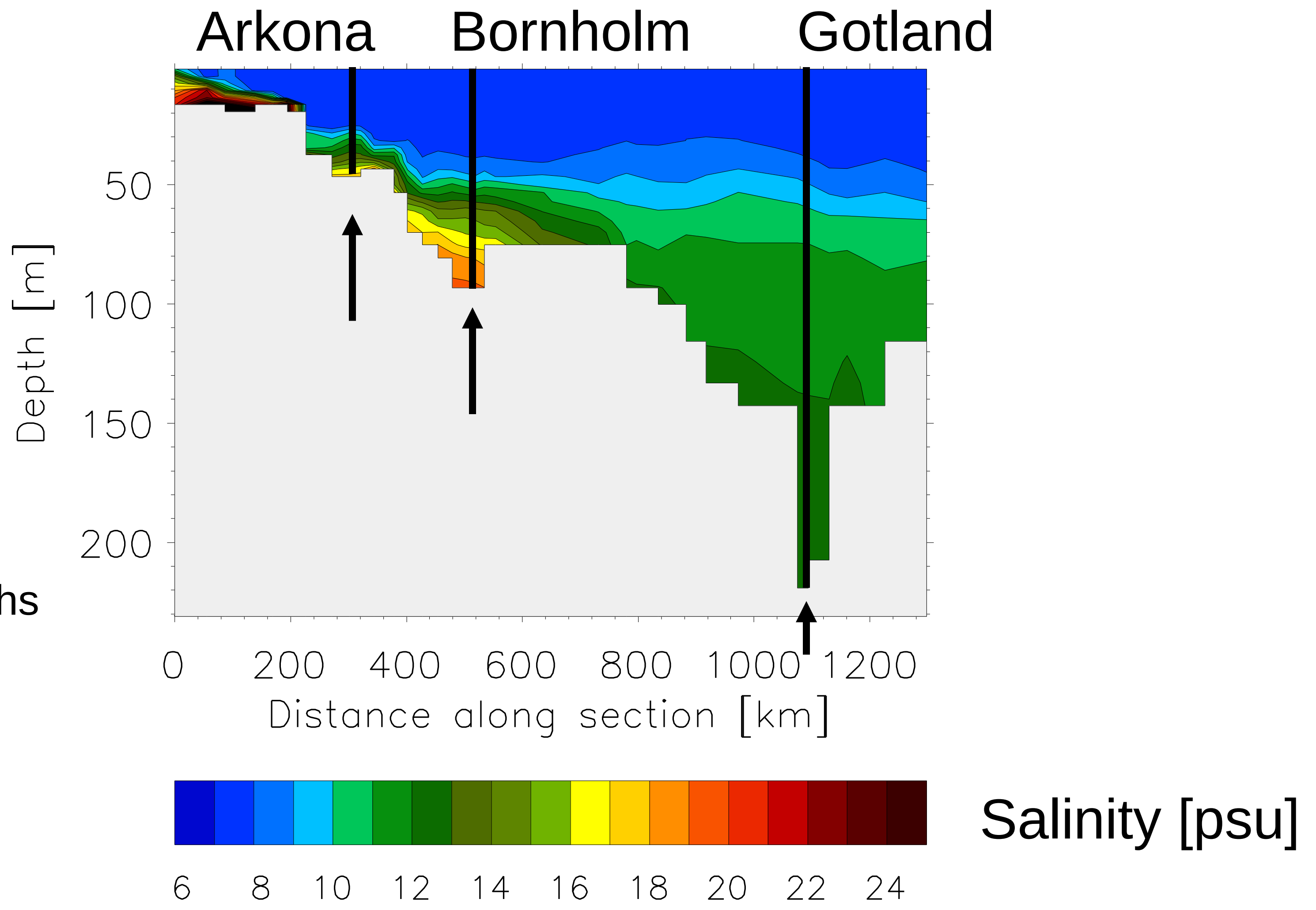
(Meier et al., 2004b)

24 January 2003



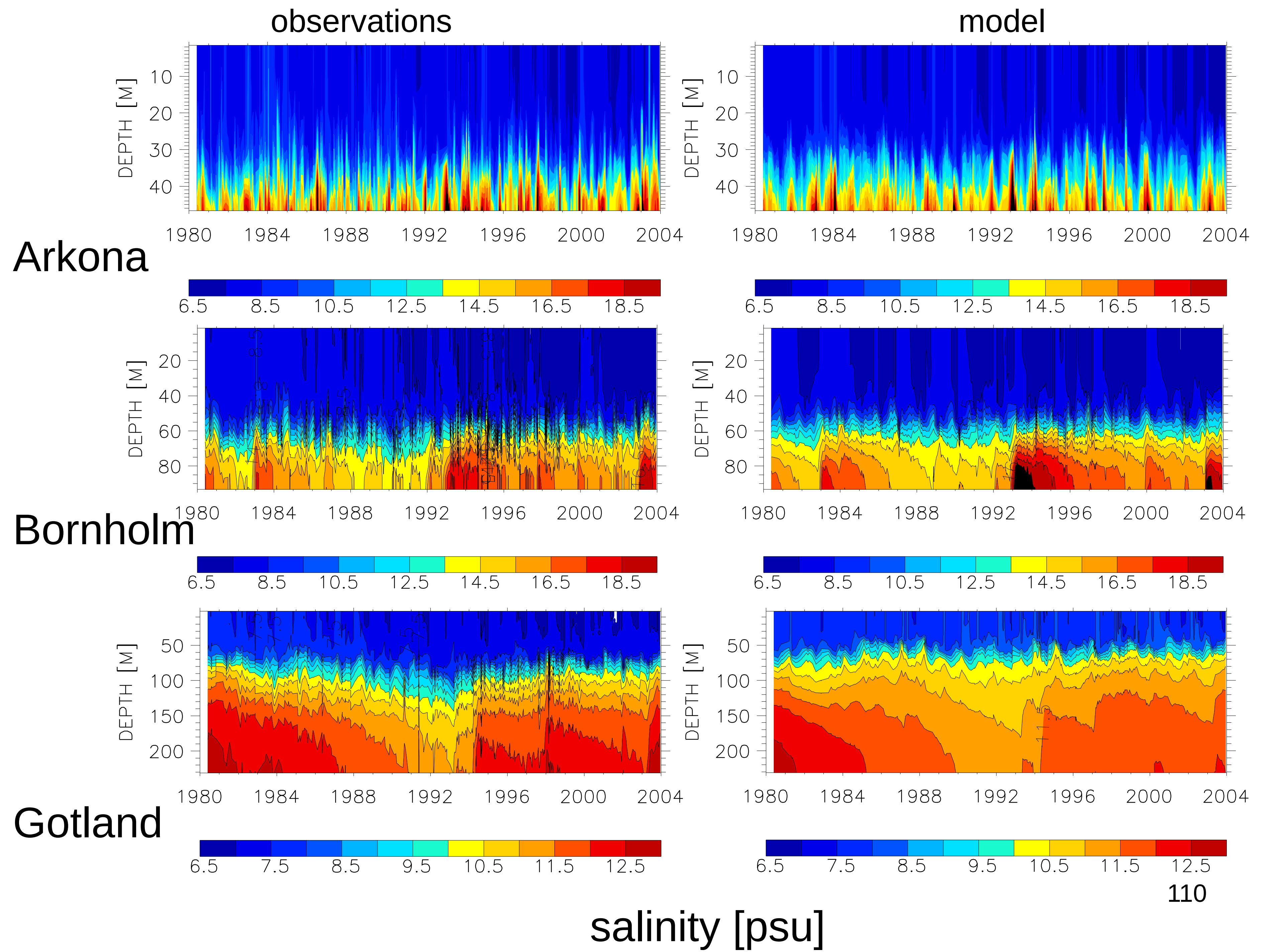
(Meier et al., 2004b)

29 October 2003

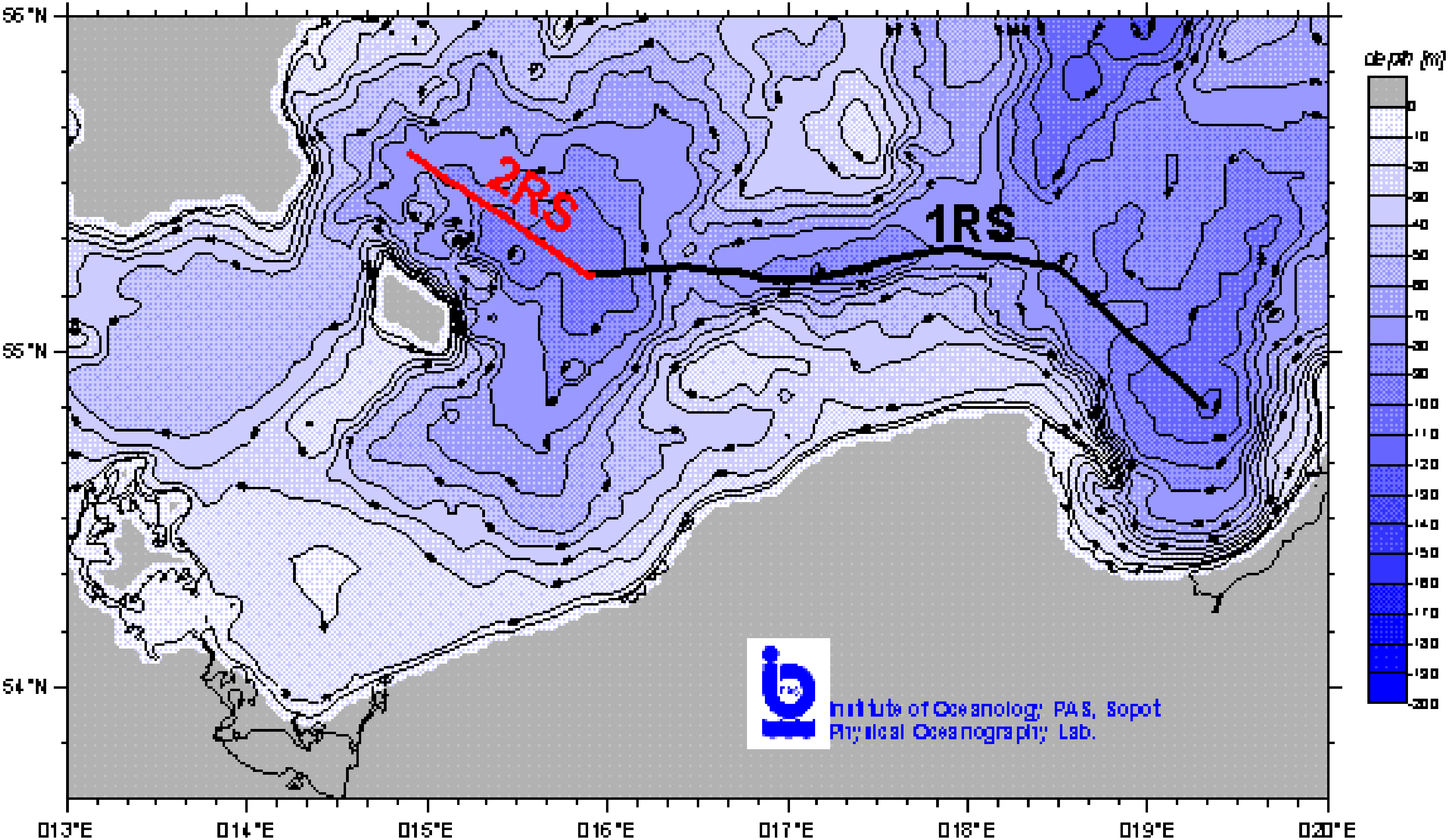


BY5: after 12 days,
BY15: after 3 months

(Meier et al., 2004b)

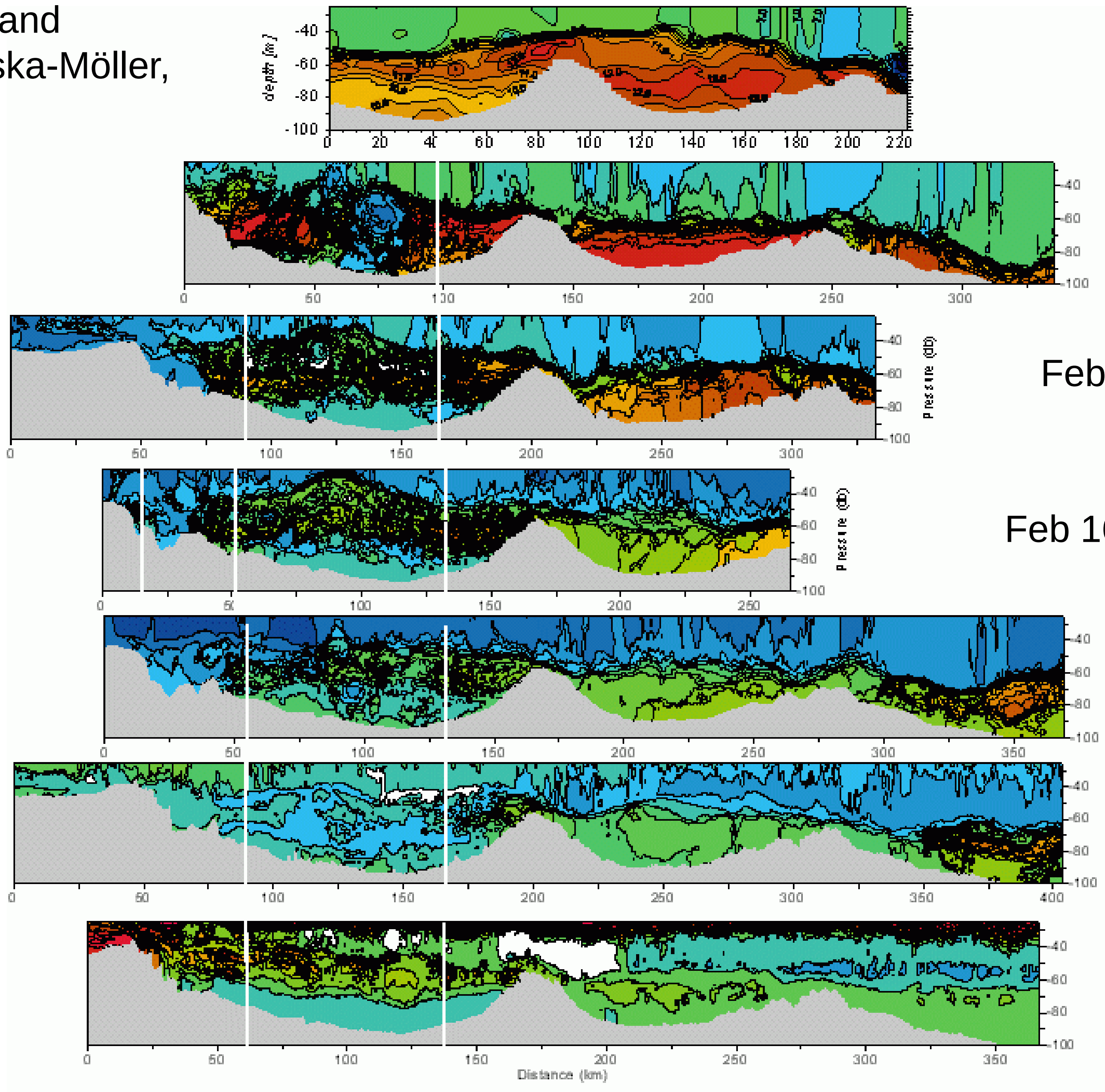

observations
model
Arkona
Bornholm
Gotland
DEPTH [M]
1980
1984
1988
1992
1996
2000
2004
6.5
8.5
10.5
12.5
14.5
16.5
18.5
7.5
9.5
11.5
salinity [psu]

temperature observations:

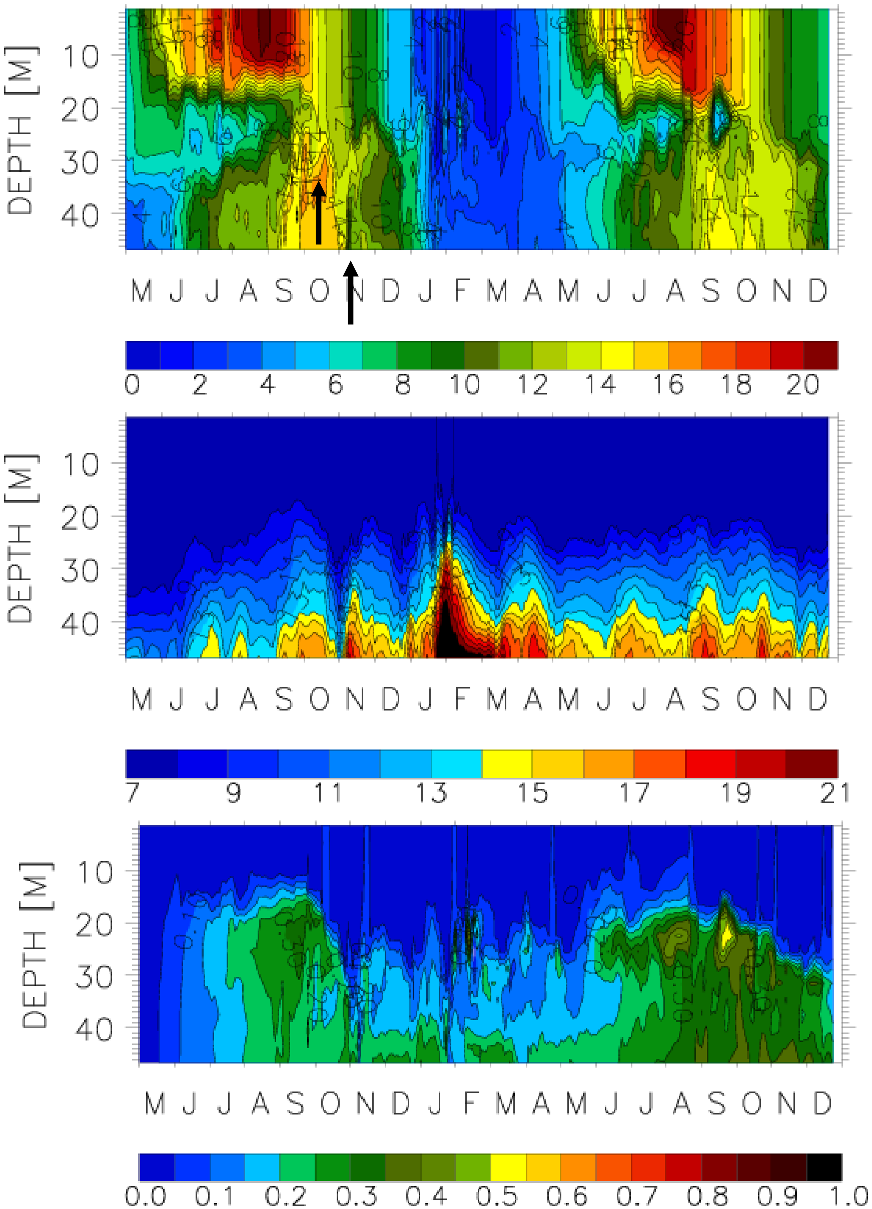


(Piechura and Beszczynska-Möller, 2003)

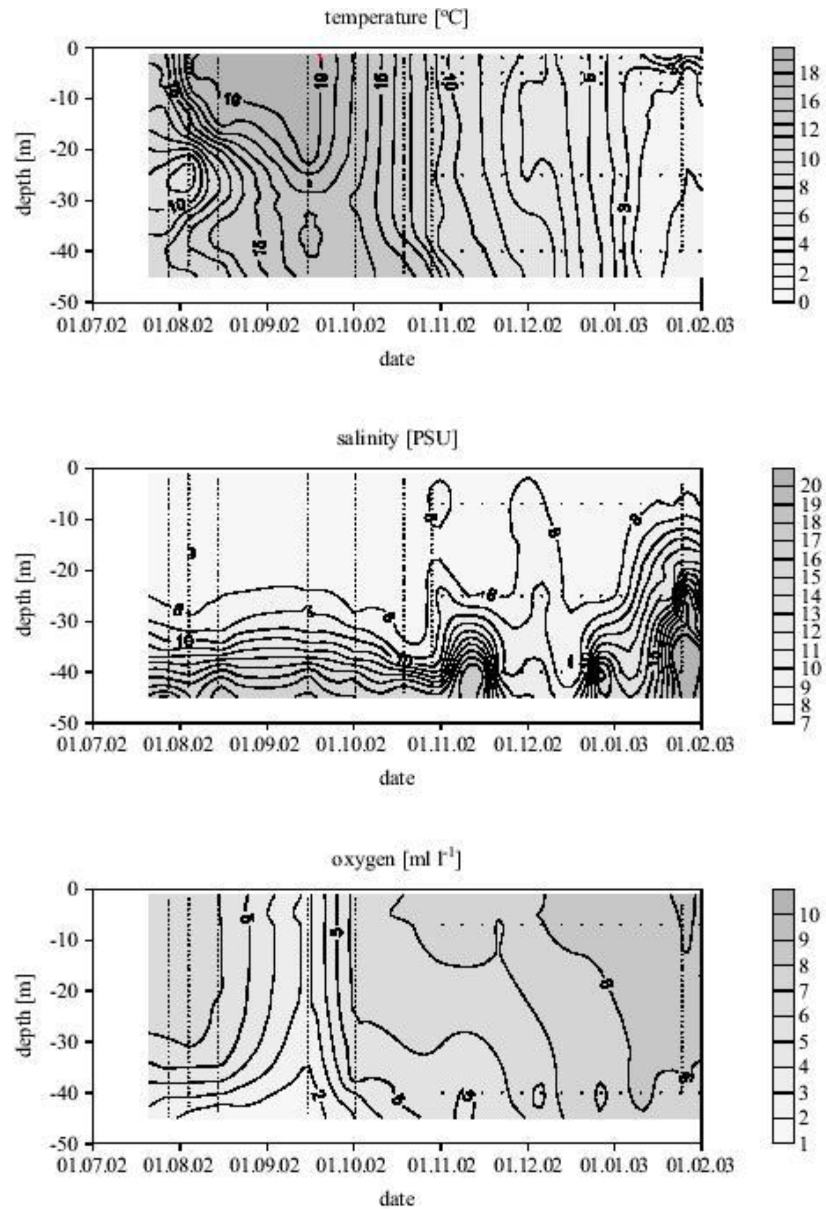
(Piechura and Beszczynska-Möller, 2003)



Temperature, salinity, and age at BY2

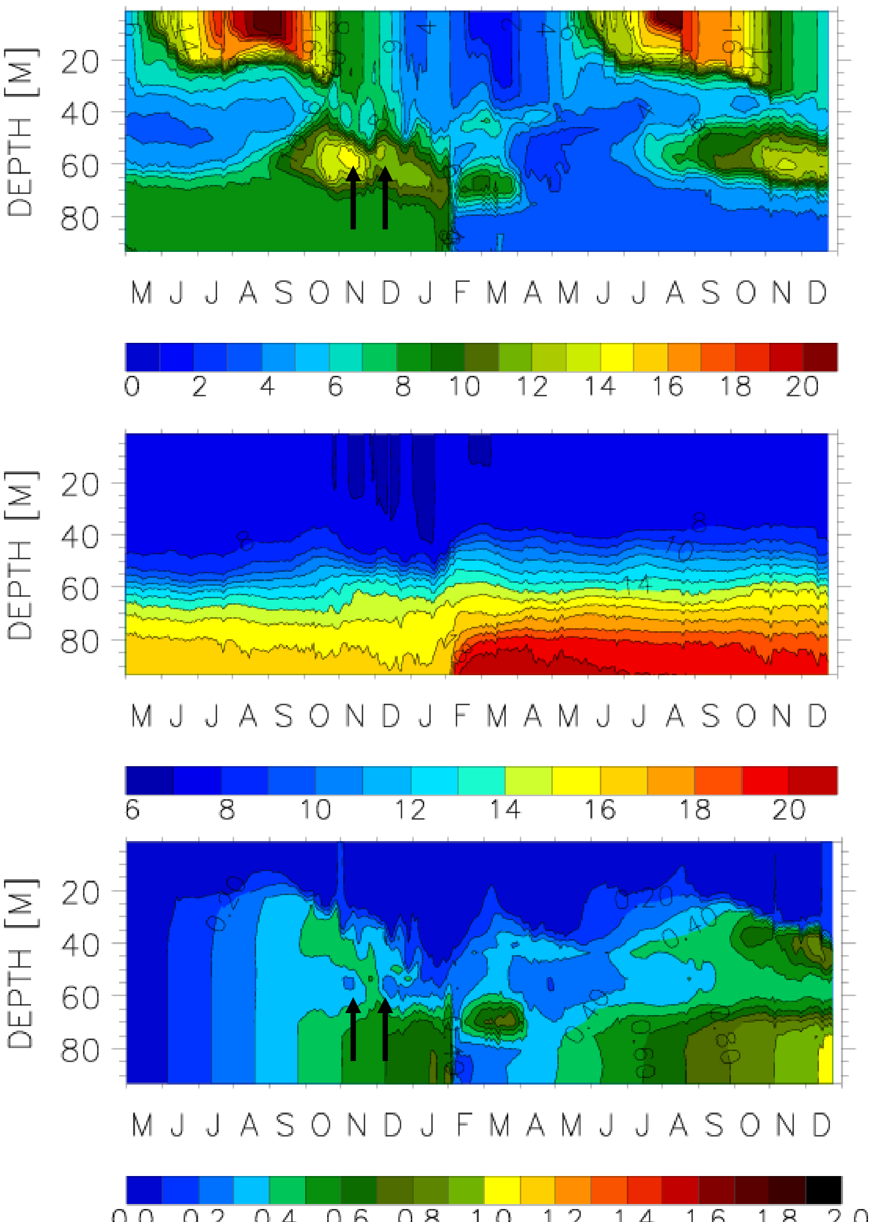


(Meier et al., 2004b)

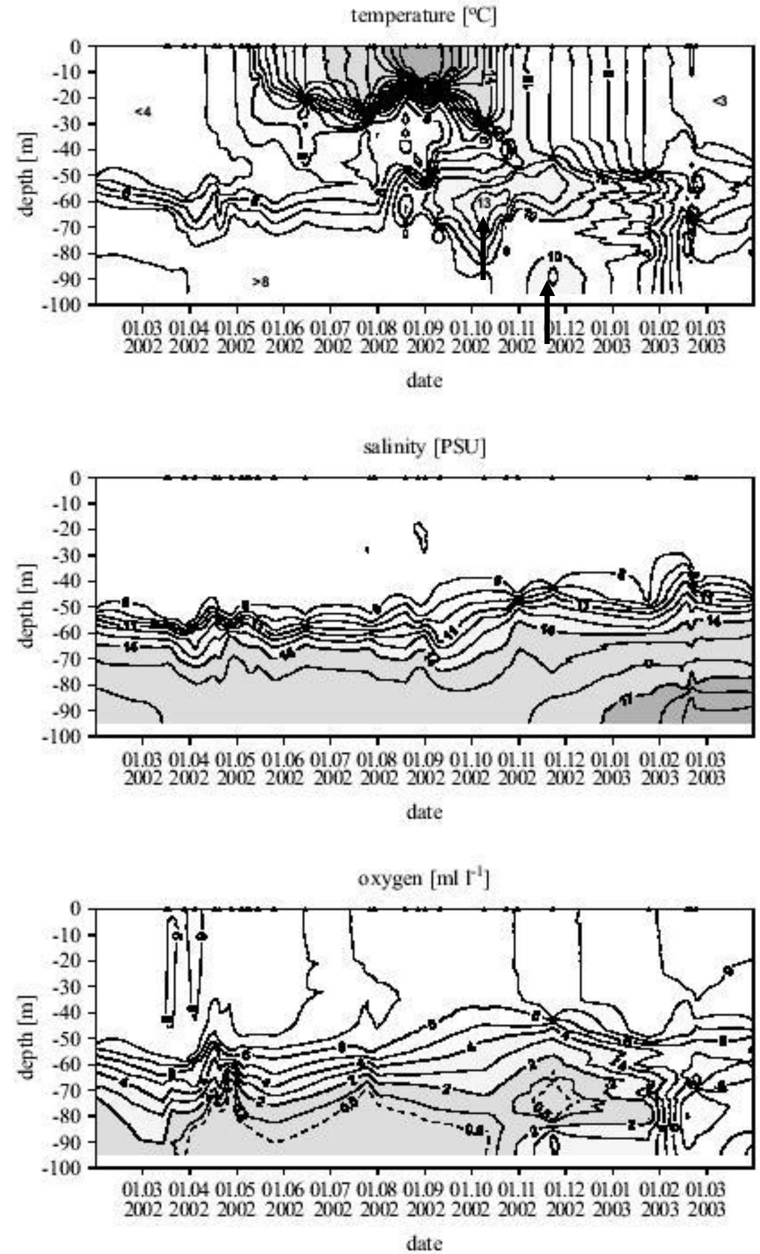


(Feistel et al., 2003)

Temperature, salinity, and age at BY5

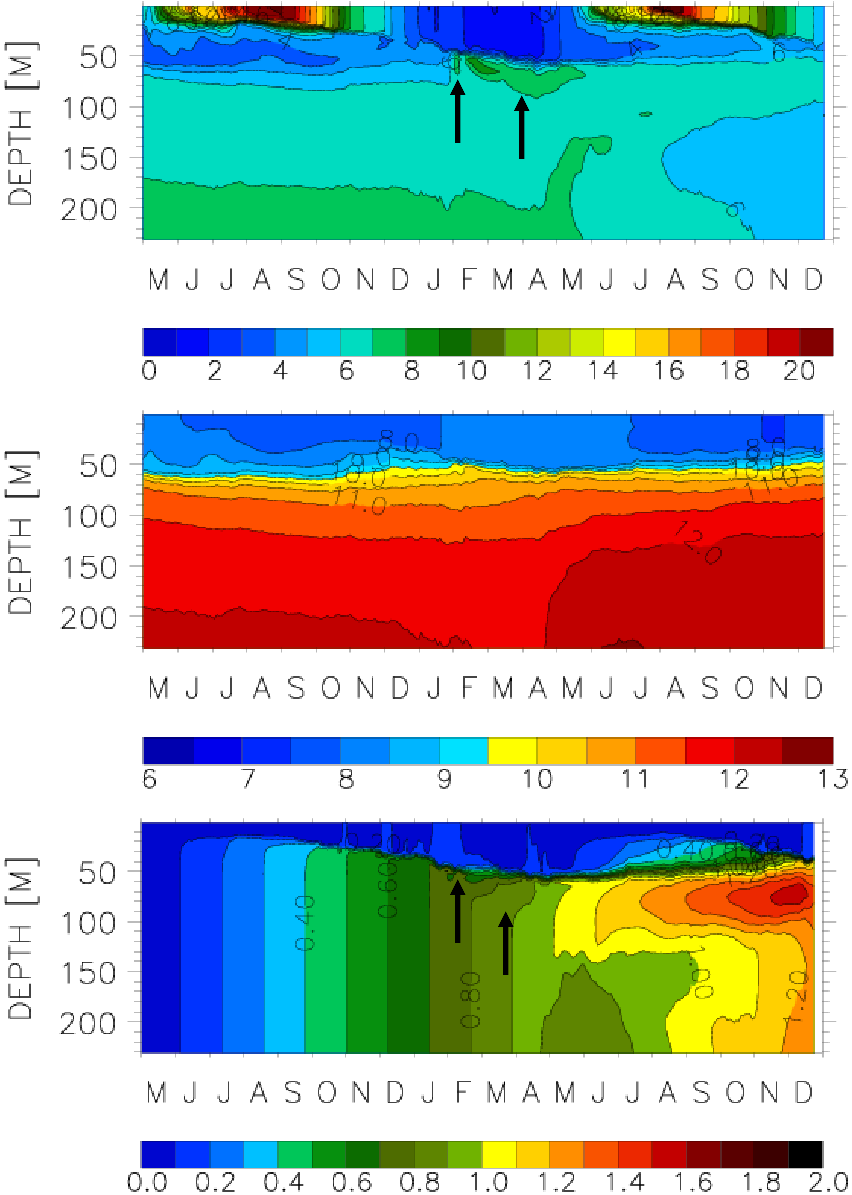


(Meier et al., 2004b)

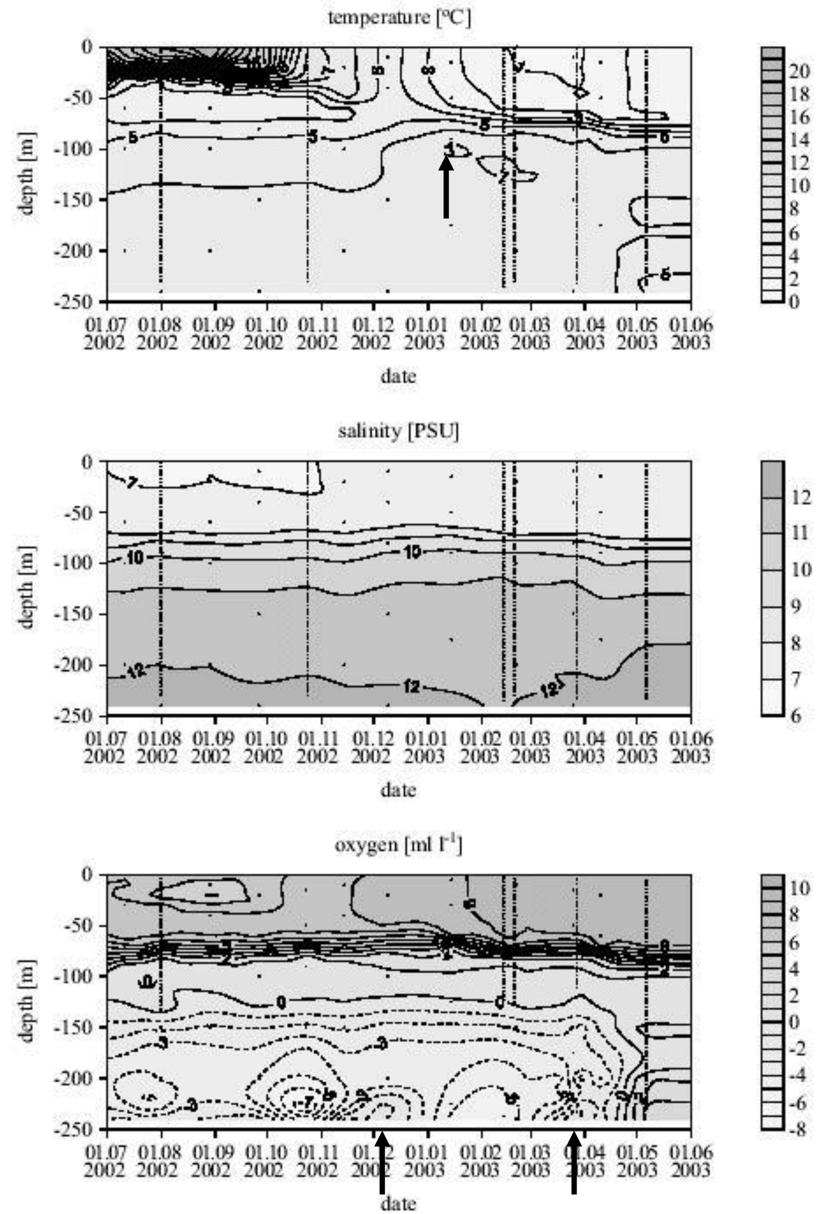


(Feistel et al., 2003)

Temperature, salinity, and age at BY15



(Meier et al., 2004b)

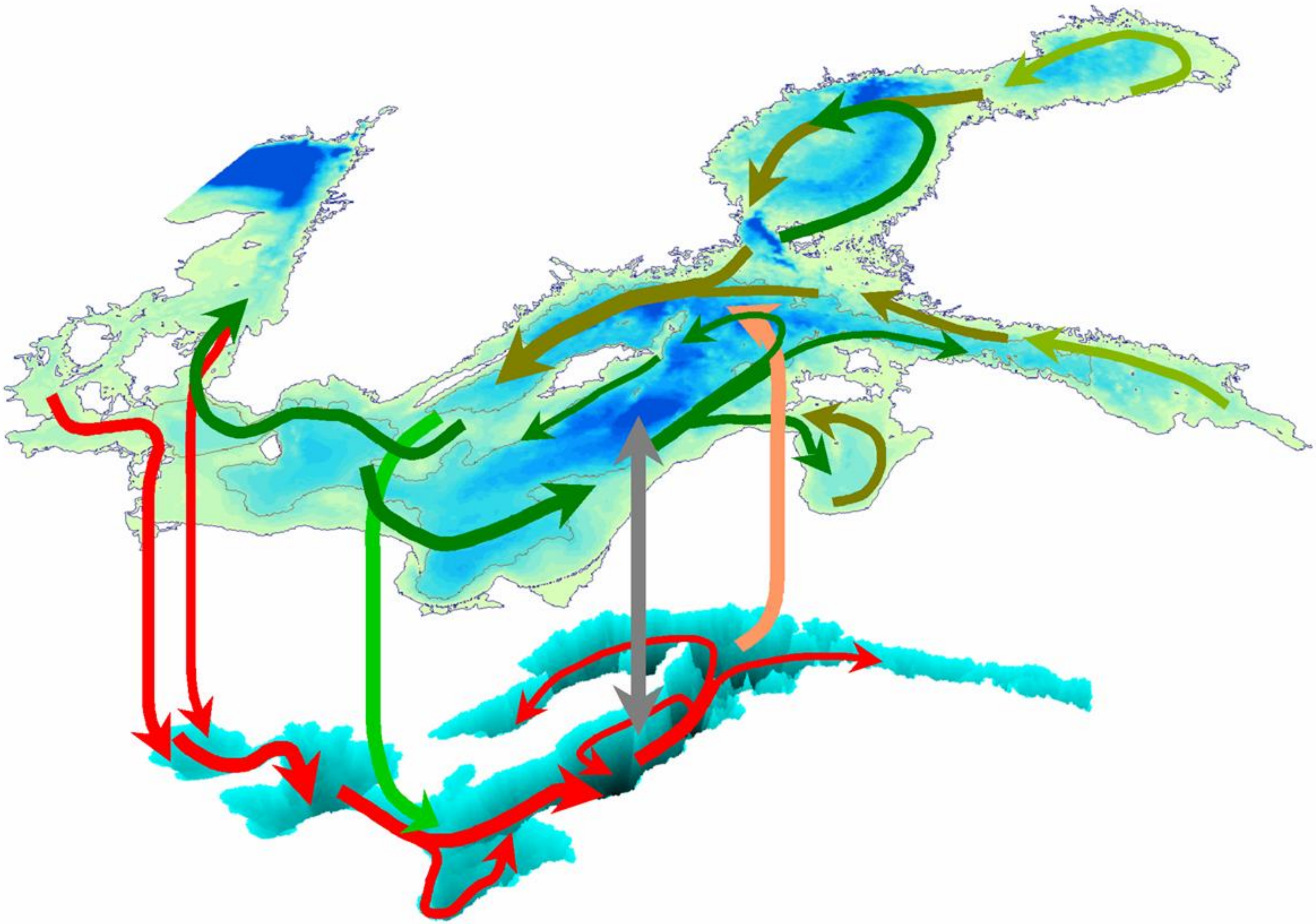


(Feistel et al., 2003)

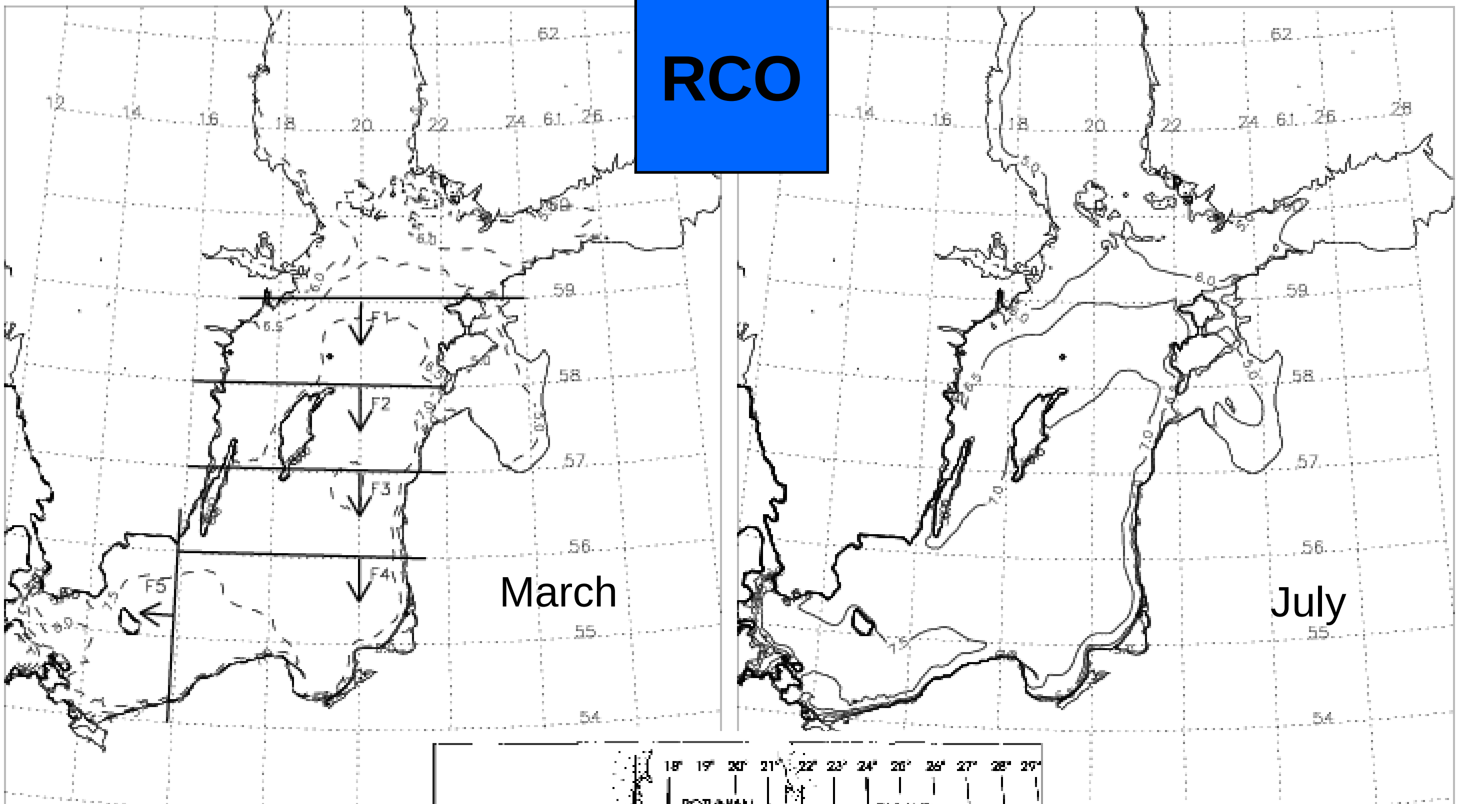
15. Spreading of juvenile freshwater in the Baltic Sea

(Hordoir and Meier 2009)

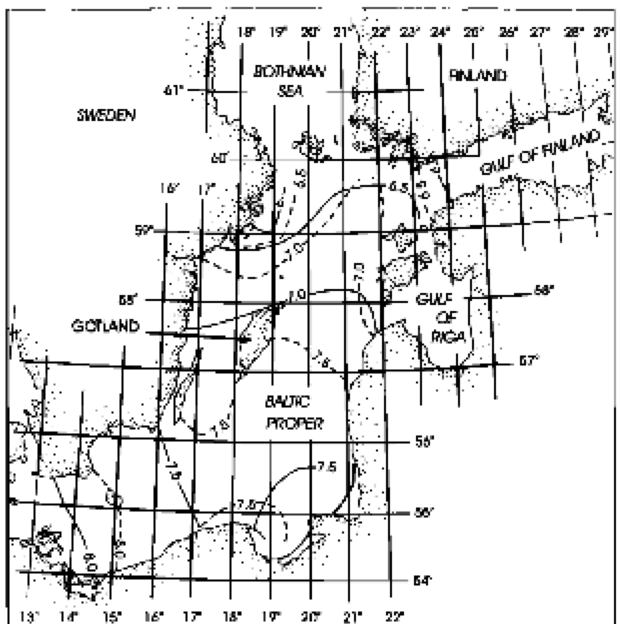
Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2007)



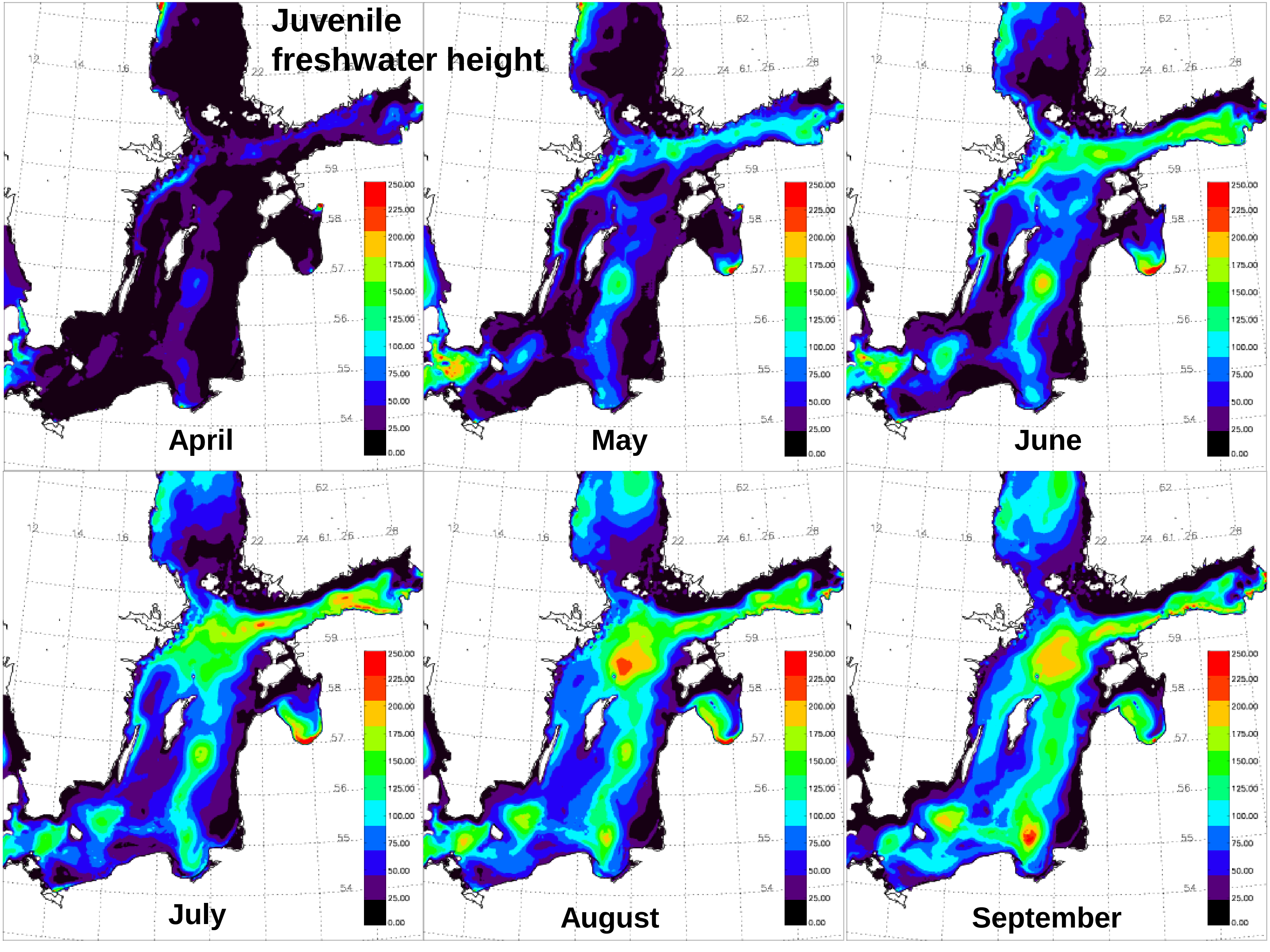
RCO



Sea surface salinity

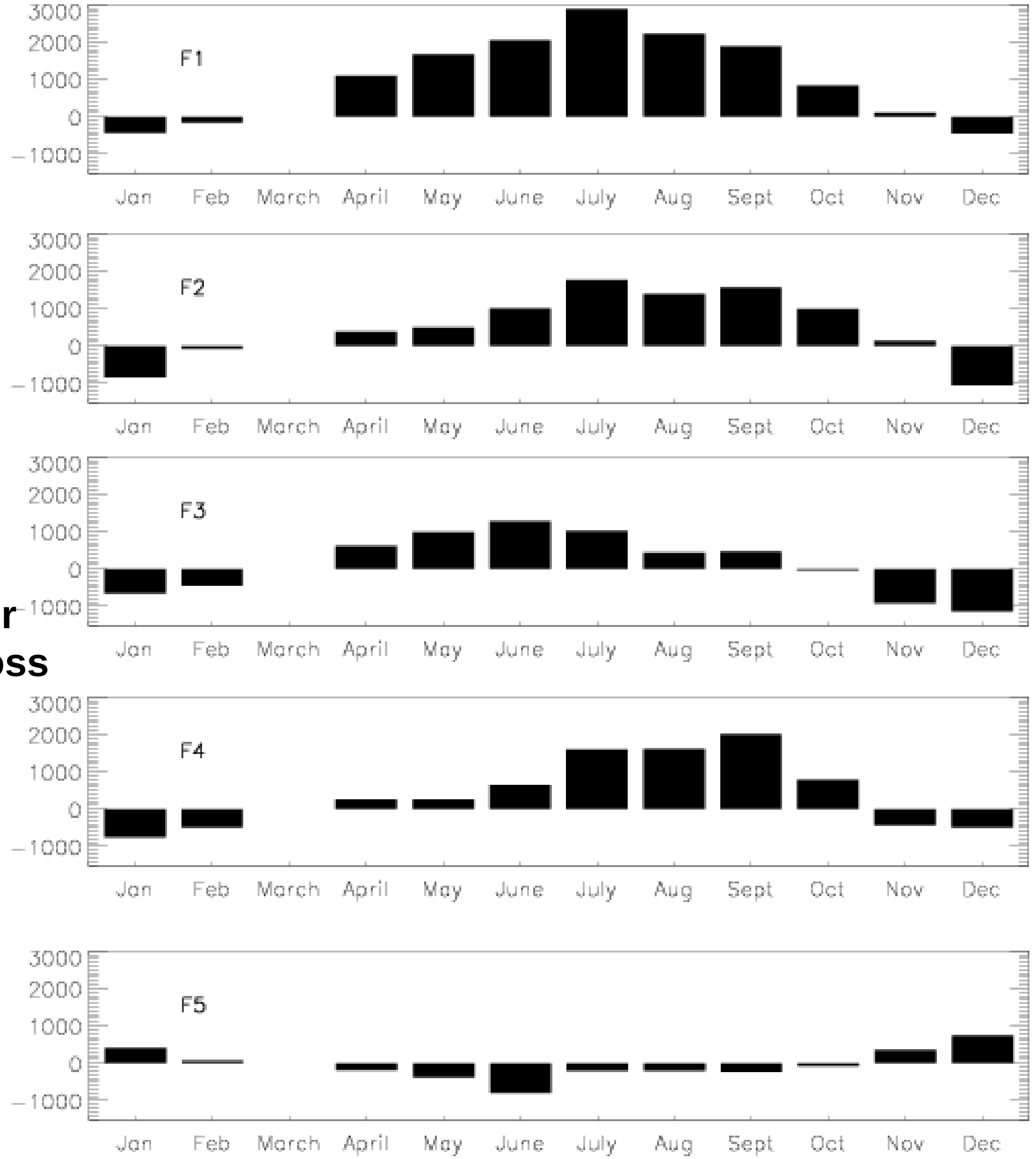


Observations
(Eilola and Stigebrandt, 1998)



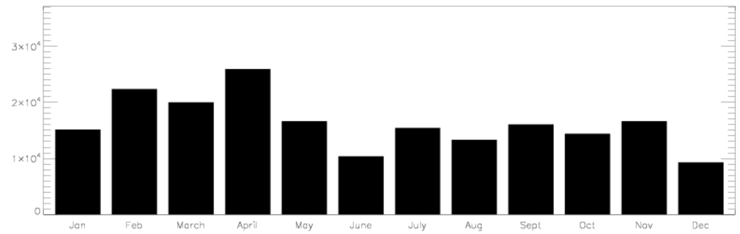
Juvenile freshwater height
April
May
June
July
August
September
250.00
225.00
200.00
175.00
150.00
125.00
100.00
75.00
50.00
25.00
0.00

Juvenile freshwater Fluxes through cross sections

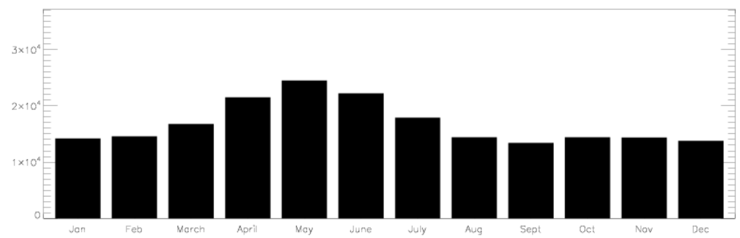


Monthly mean freshwater outflow, total freshwater input, volume outflow, and zonal wind stress over the Baltic

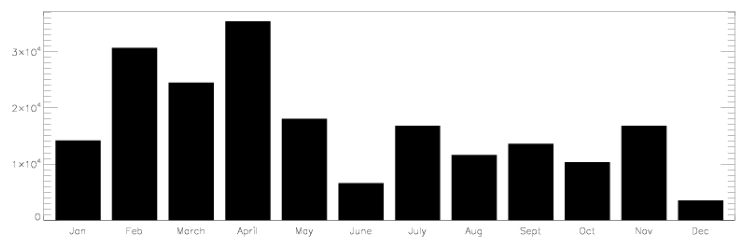
Freshwater outflow



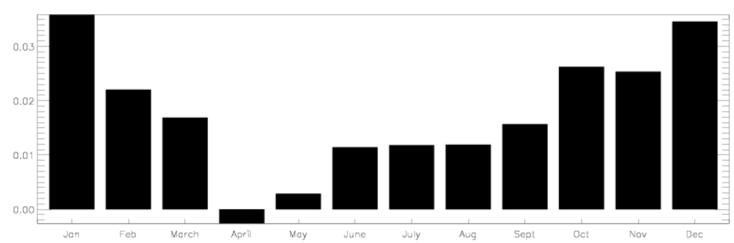
Net precipitation and runoff



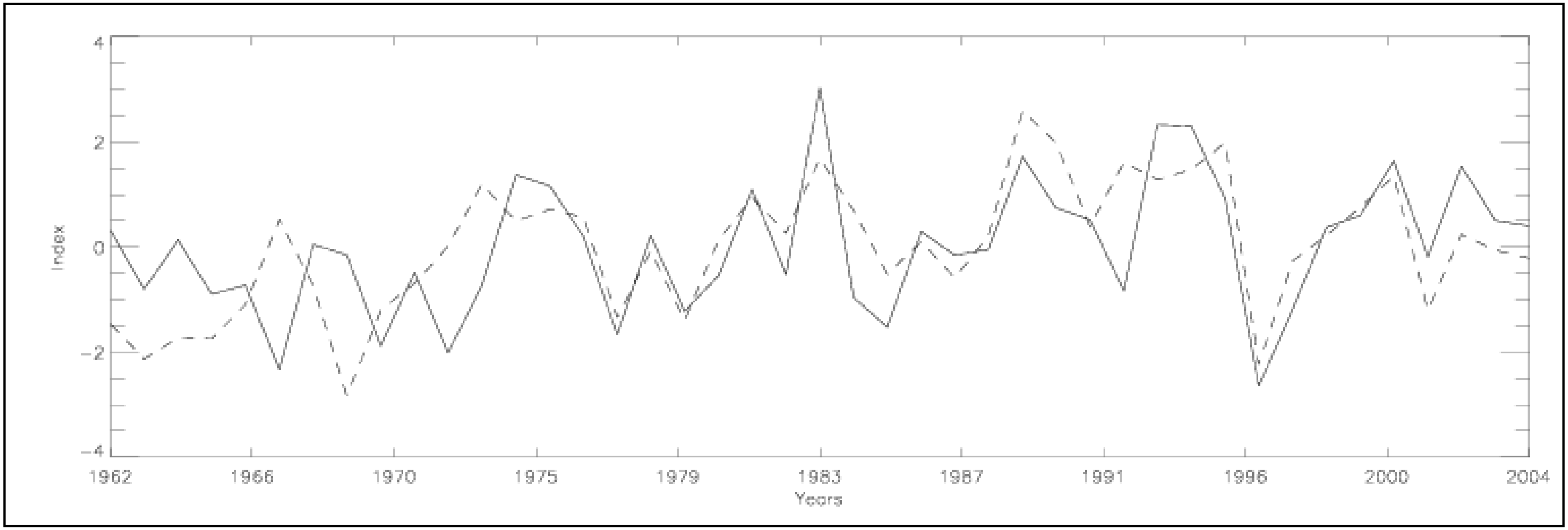
Volume outflow



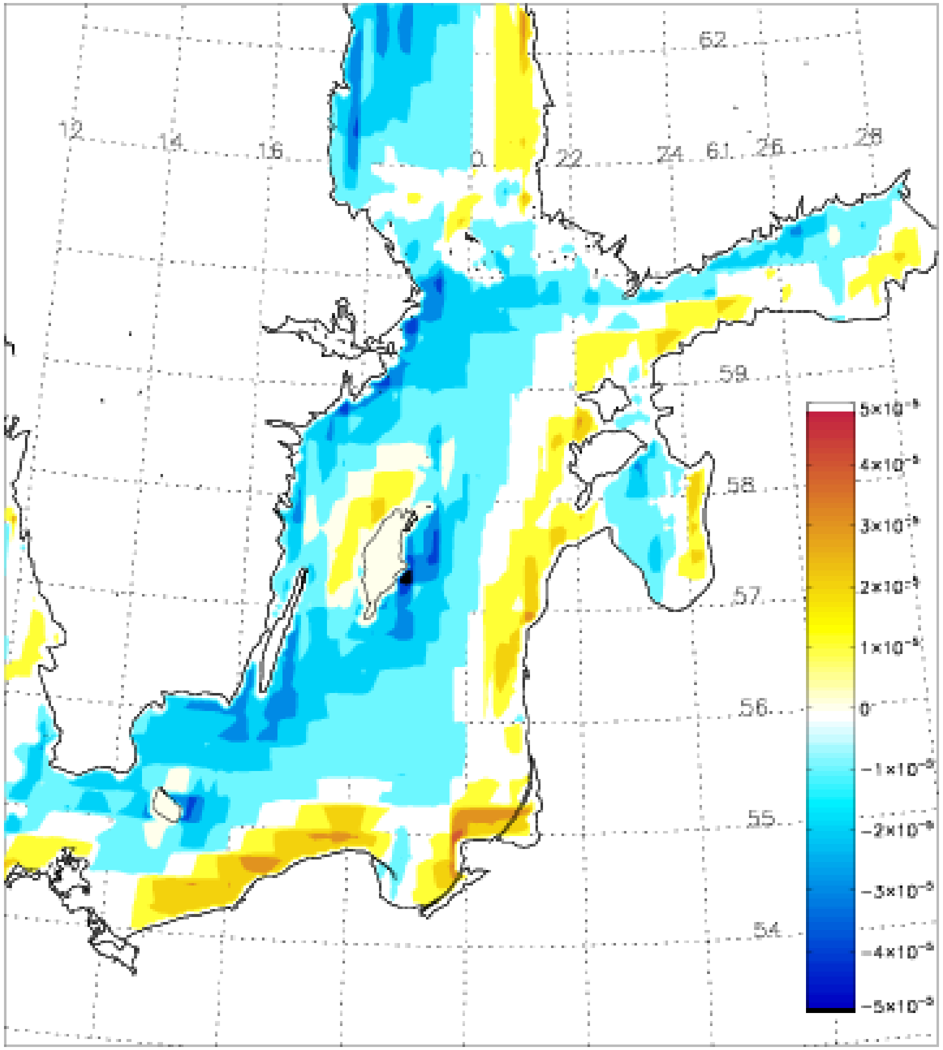
Zonal wind stress

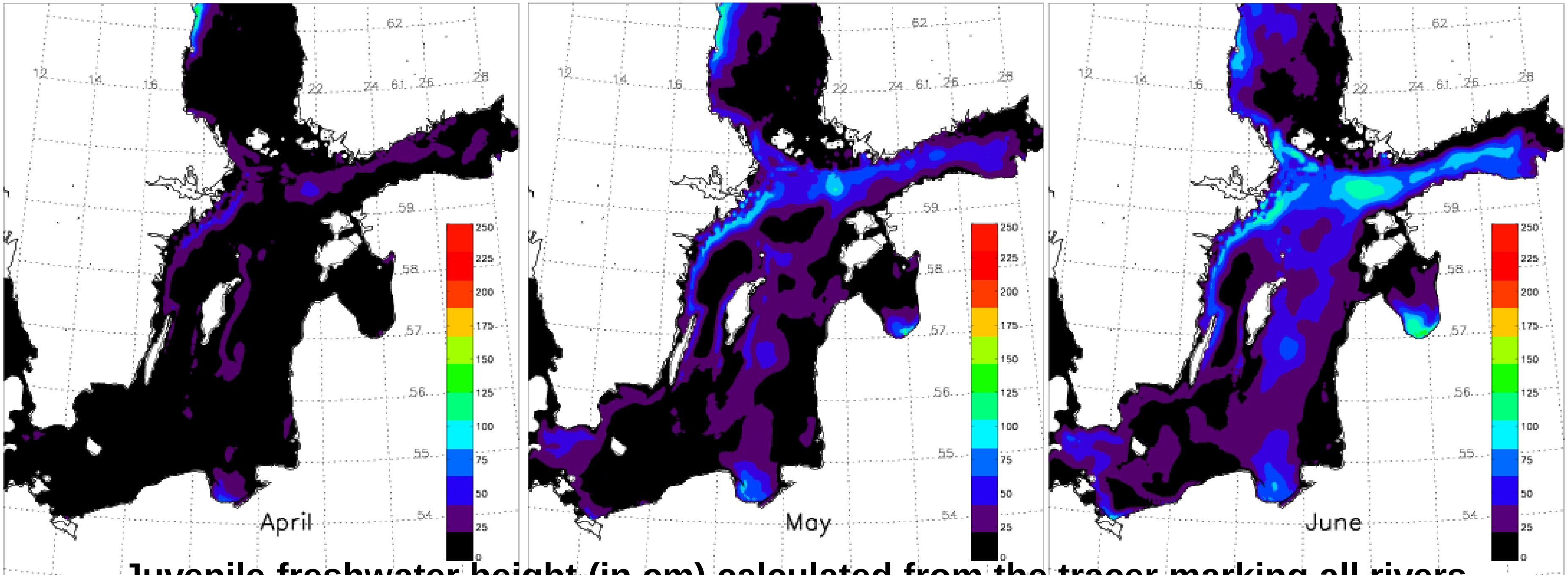


Winter mean freshwater outflow and NAO 1961-2004

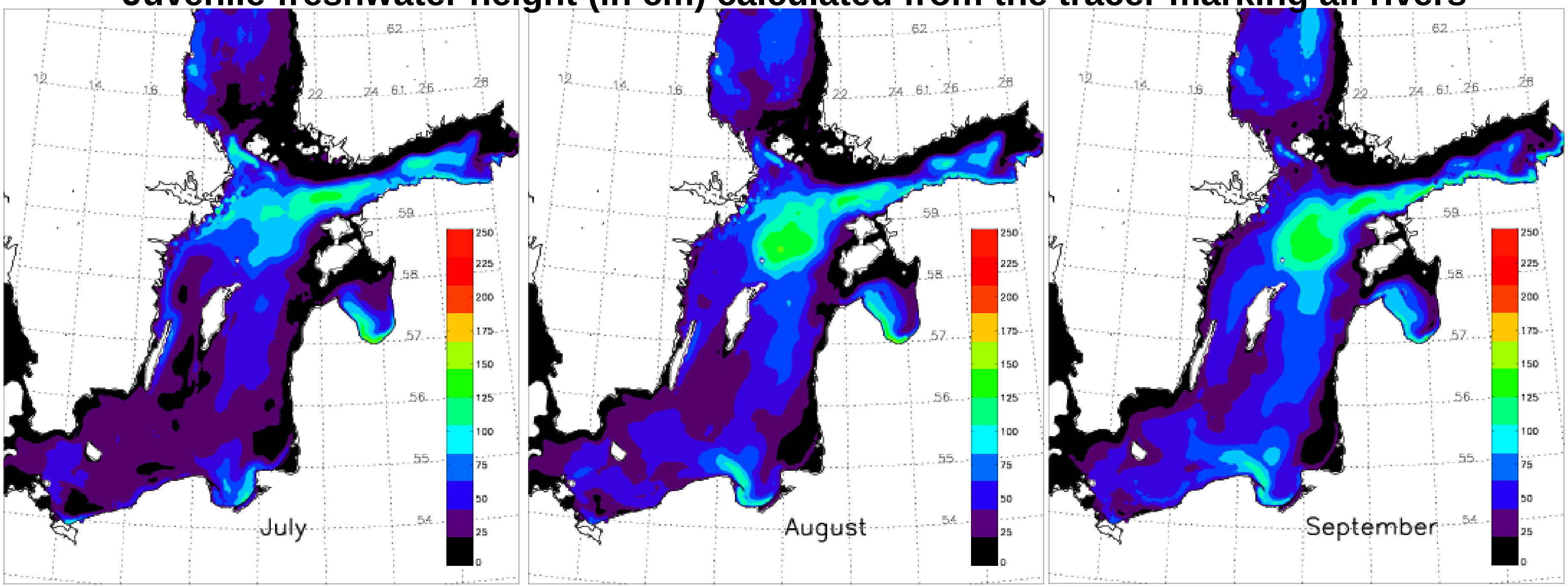


Vertical velocity difference between April and March due to Ekman pumping or suction calculated from the wind stress curl

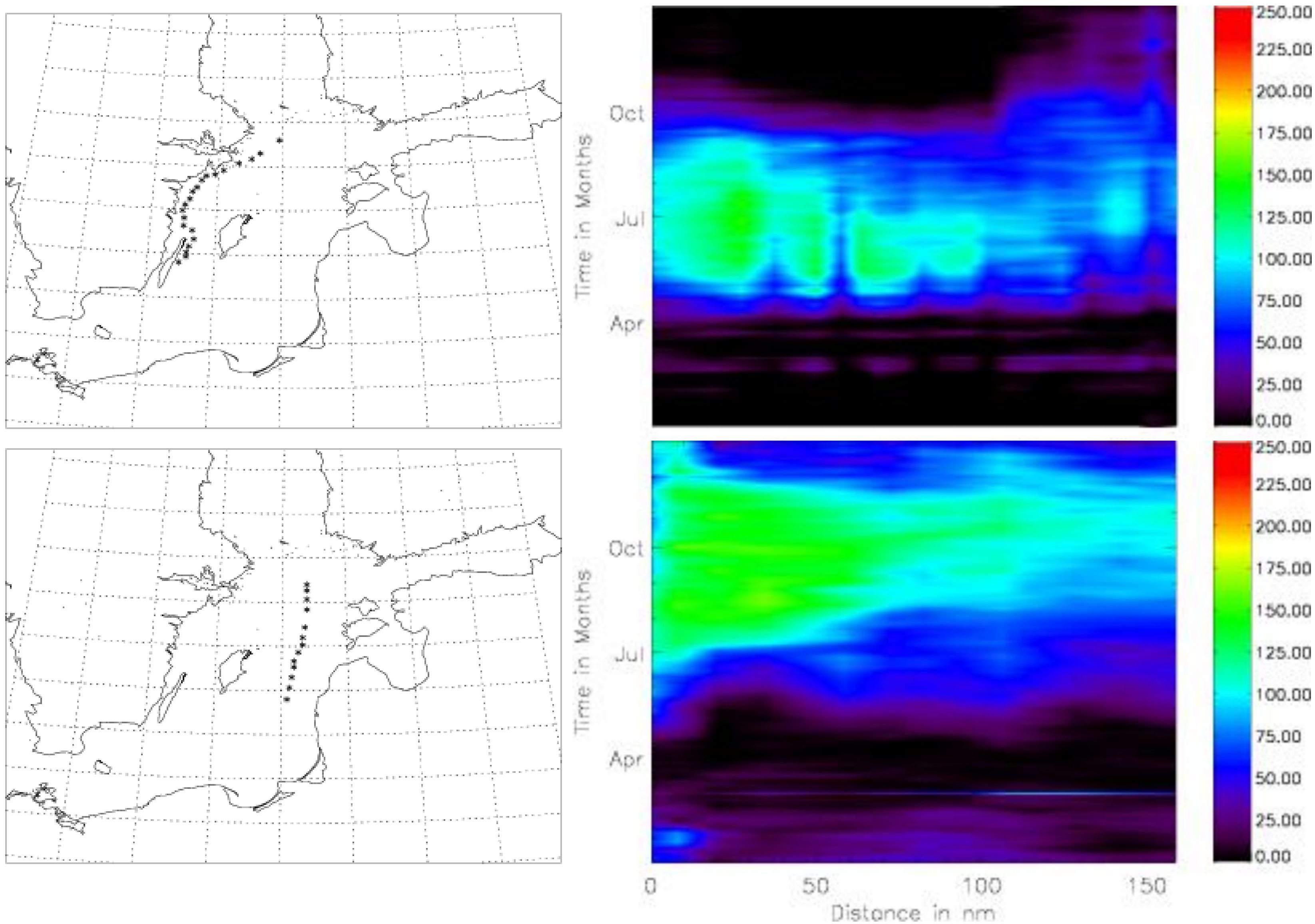




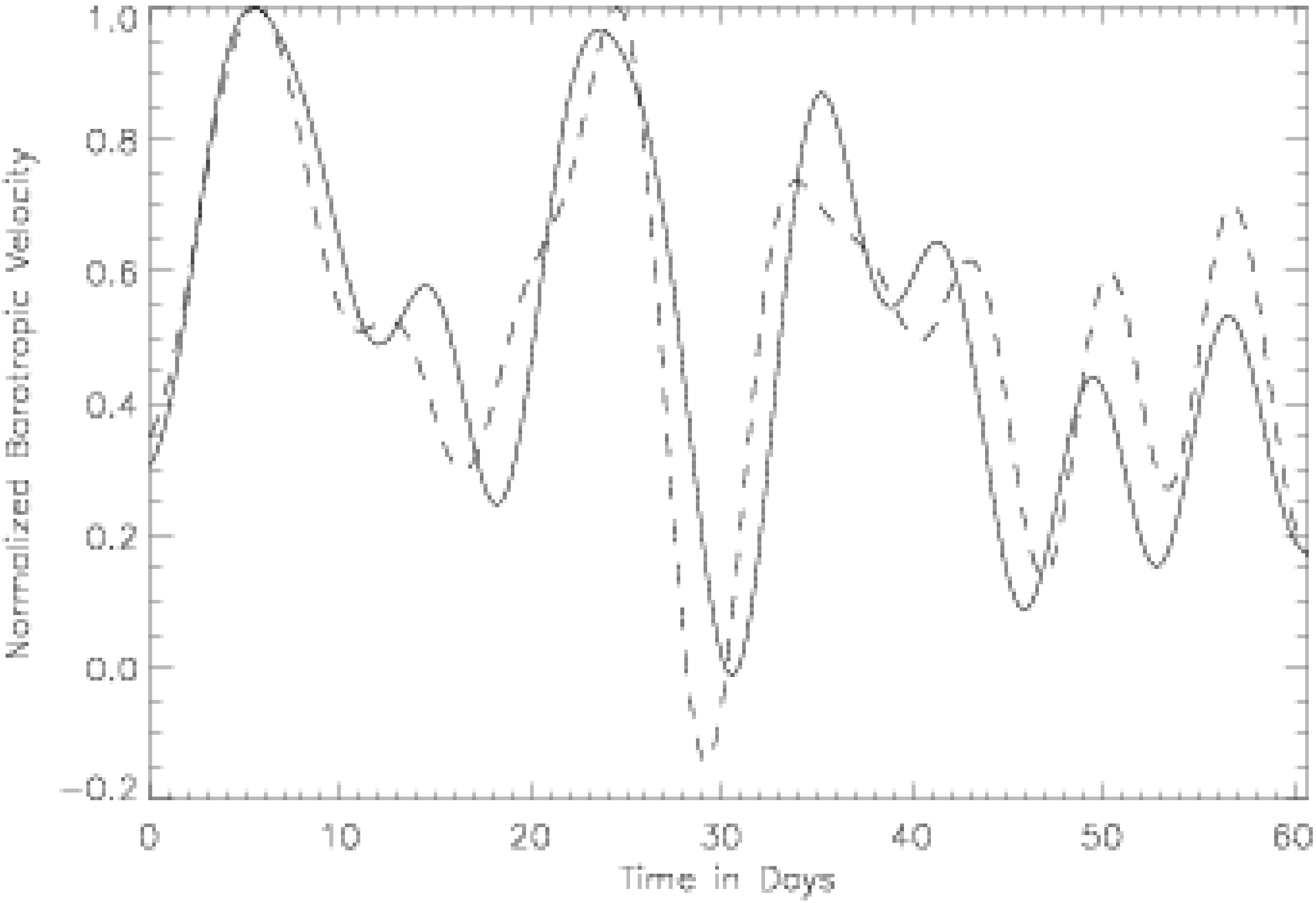
Juvenile freshwater height (in cm) calculated from the tracer marking all rivers



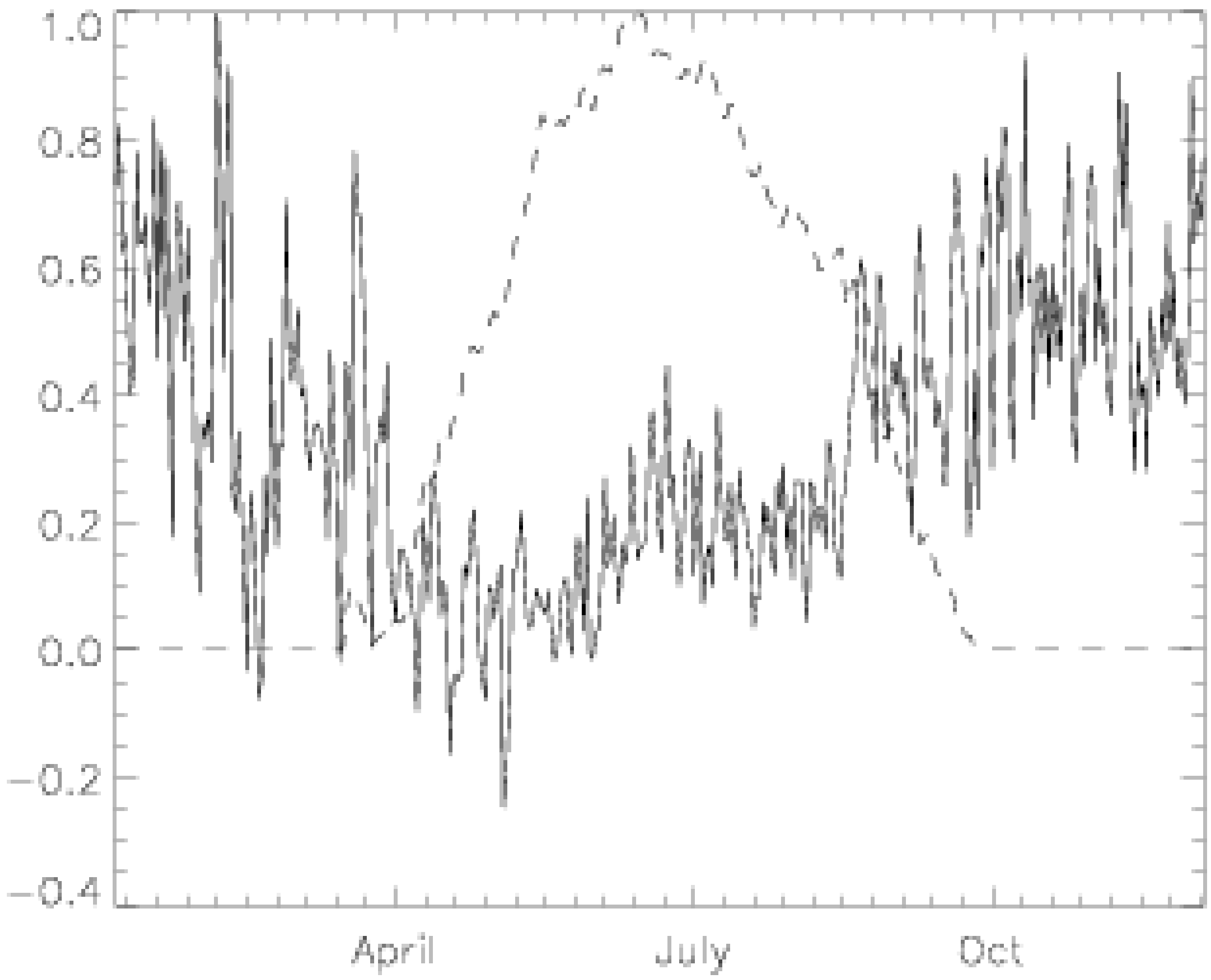
Hovmöller diagrams for the spreading of the tracer marking juvenile freshwater



Normalized barotropic flows at the entrances of the Baltic (solid) and Bothnian Sea (dashed)



Normalized mean meridional wind and juvenile freshwater height at 58 N



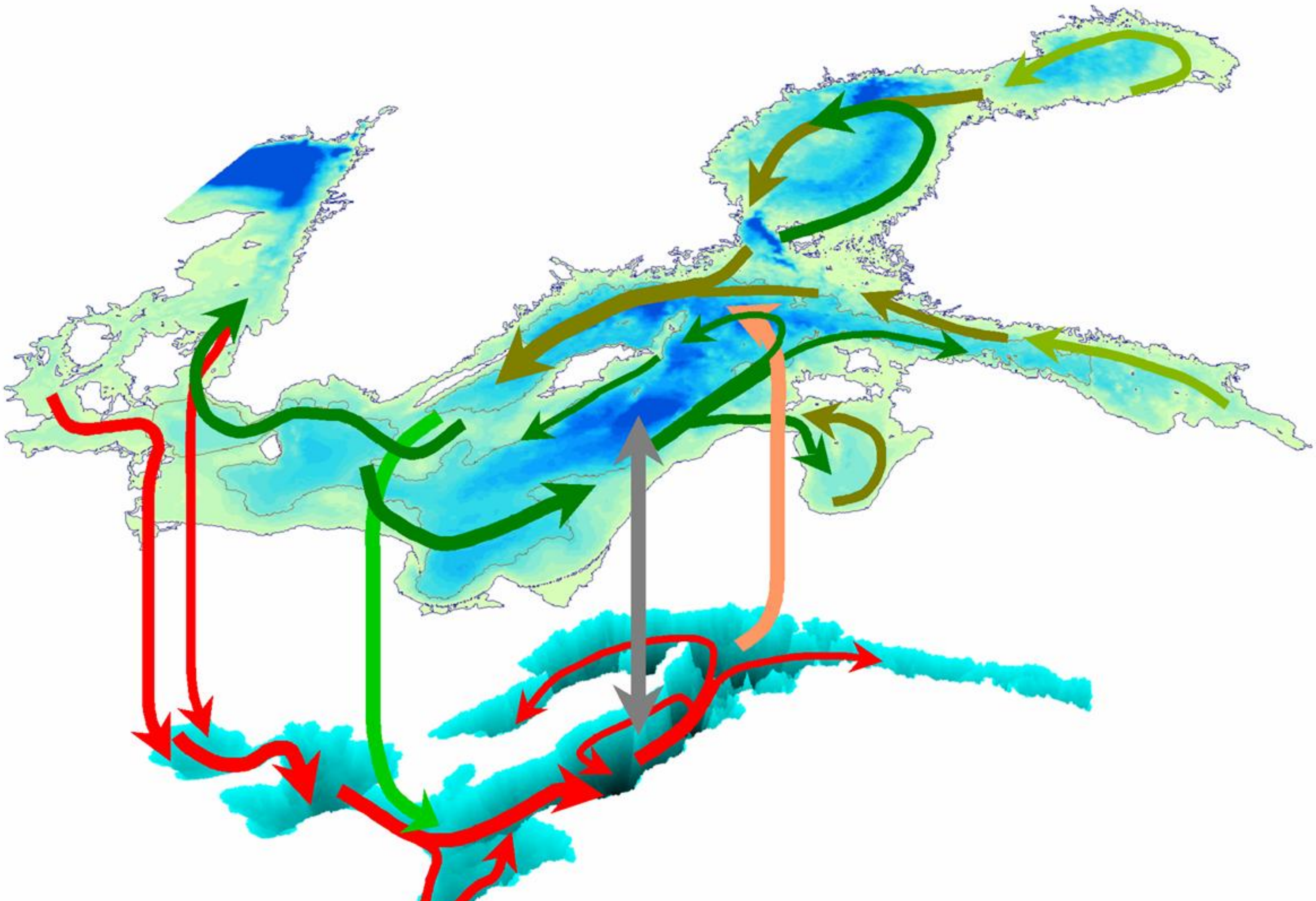
Conclusions I

1. Fresh water is flushed out of the Baltic during early spring when the zonal wind (with maximum during winter) decreases.
2. The interannual variability of the freshwater outflow is mainly explained by NAO.
3. Juvenile fresh water does not reach the Danish straits.
4. Juvenile freshwater in the Baltic proper is transported by barotropic flows.
5. Upwelling explains juvenile freshwater signals at the Swedish coasts (the analysis excludes the spreading by Kelvin waves).
6. During summer juvenile freshwater is advected south with the mean circulation.

16. On the Baltic conveyor belt

(Meier 2007)

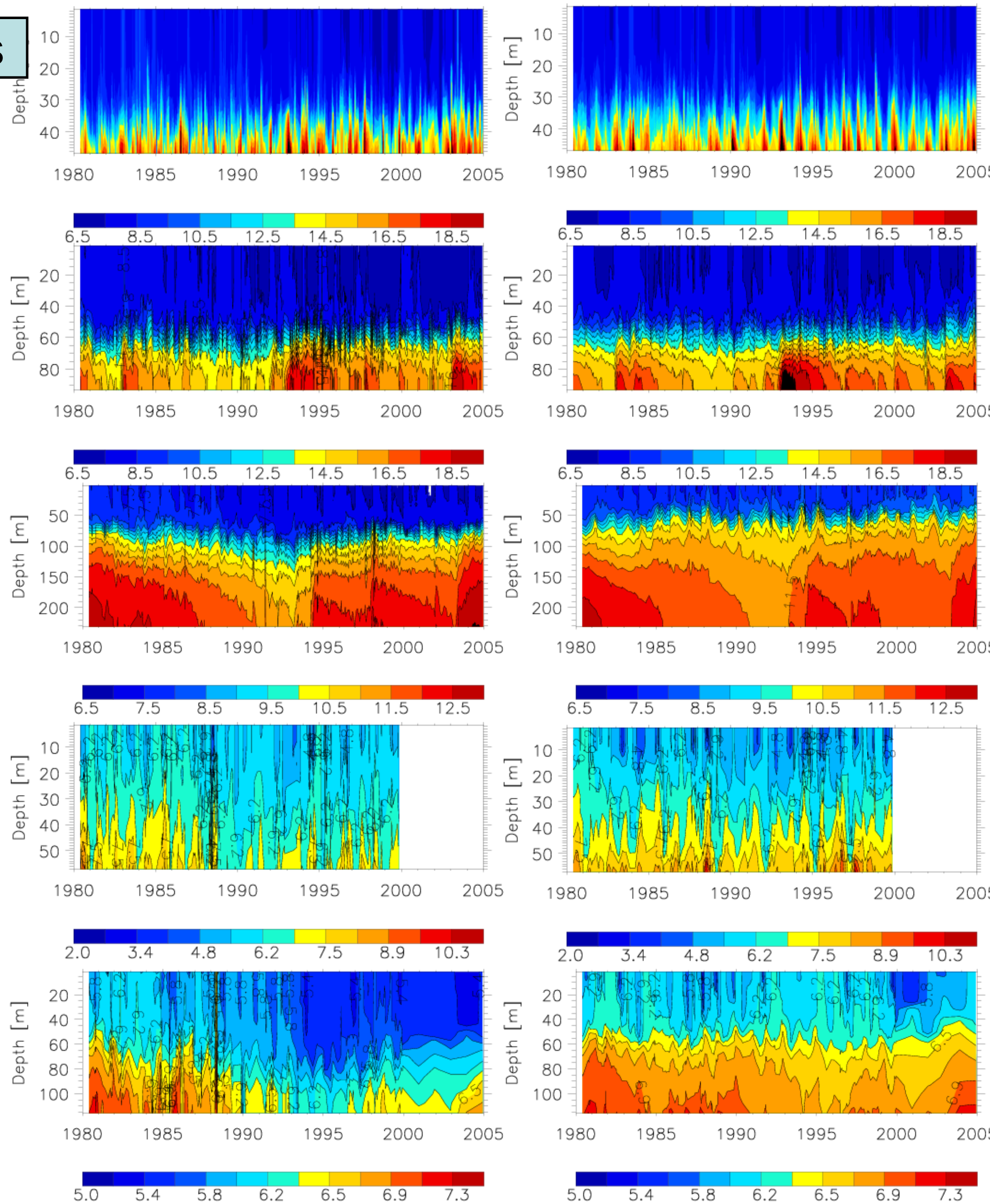
Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2007)



Salinity as function of time and depth

observations

model results



Arkona Basin (BY2)

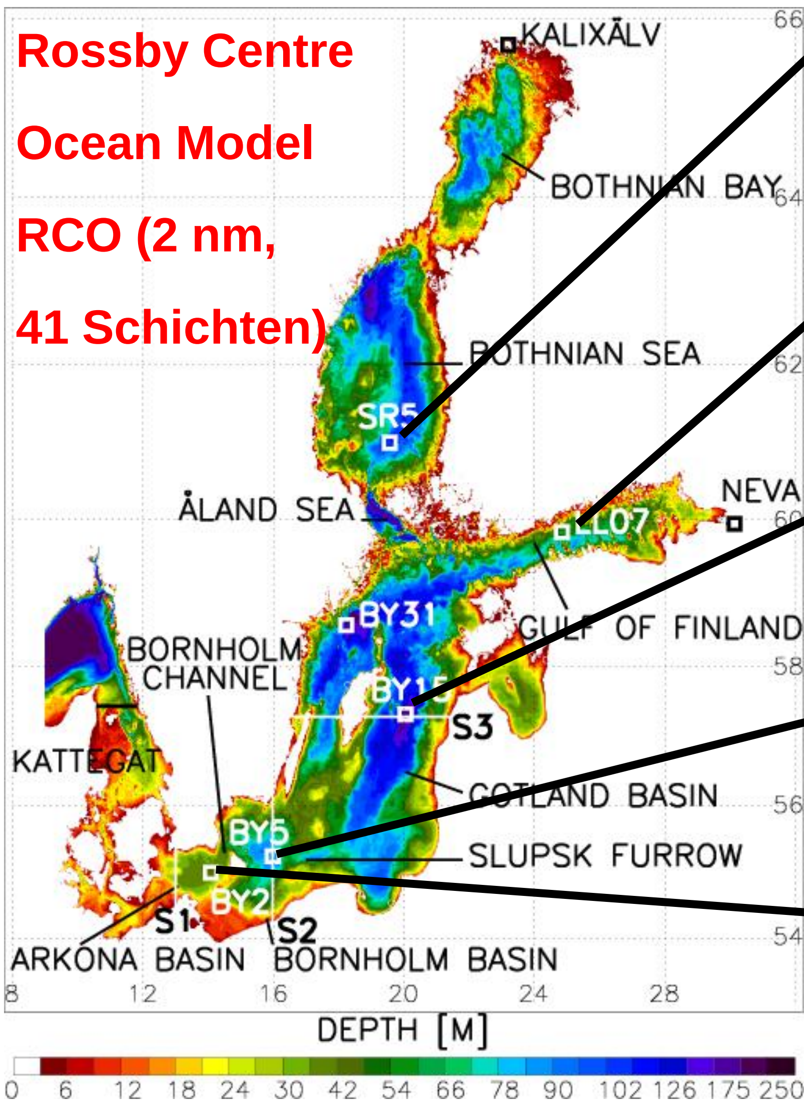
Bornholm Basin (BY5)

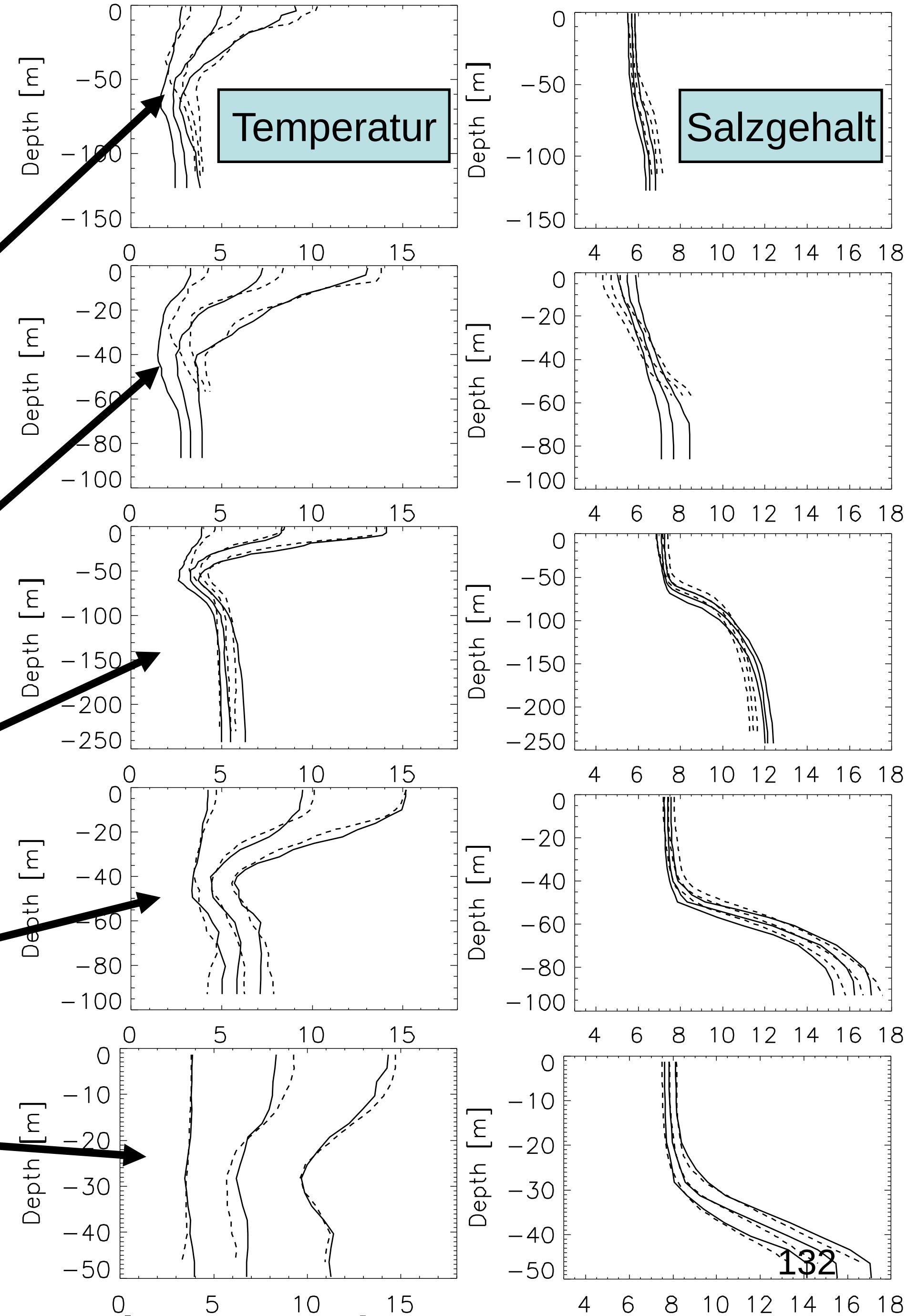
Gotland Basin (BY15)

Gulf of Finland (LL07)

Bothnian Sea (SR5)

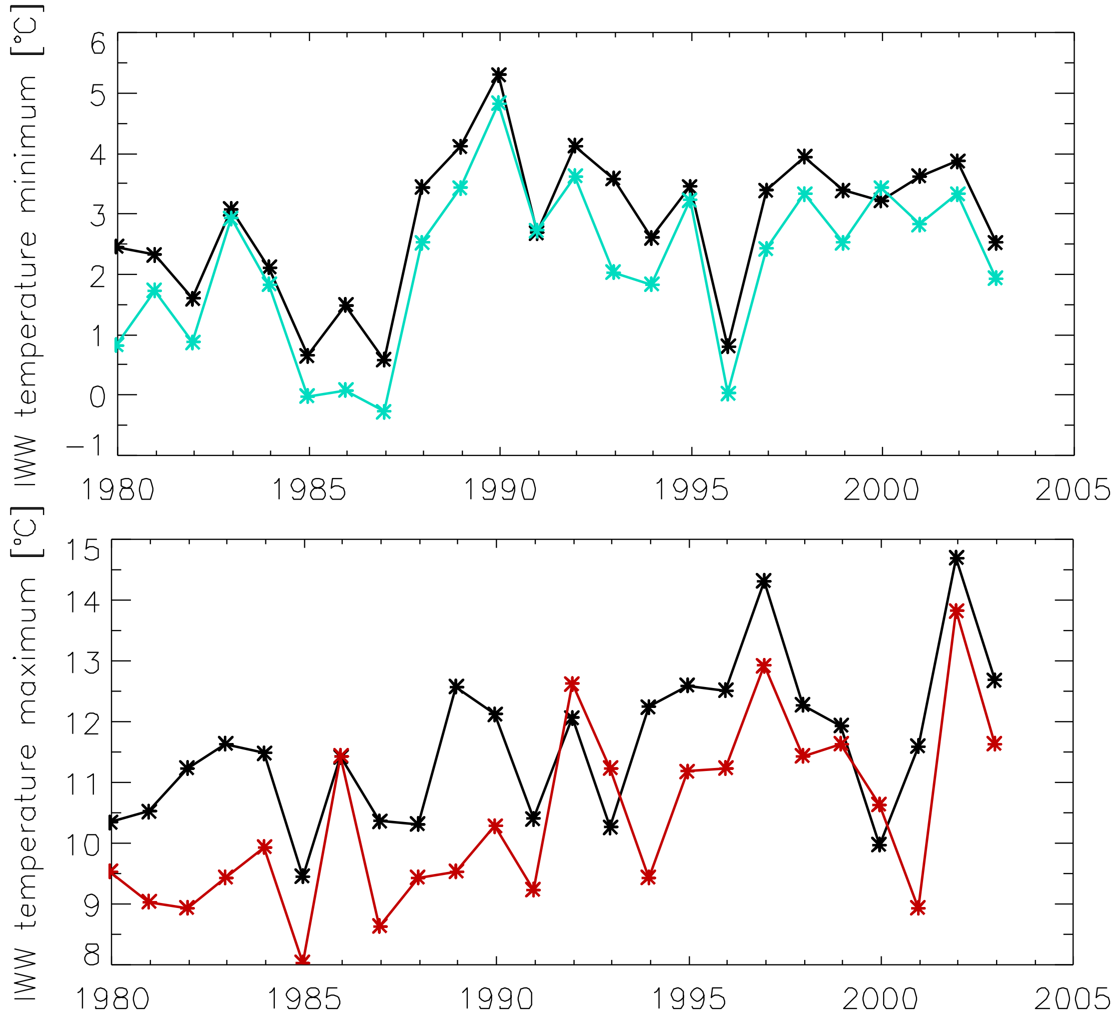
Median, 1. und 3. Quartile 1980-2004:
Beobachtungen (durchgezogen),
Modellergebnisse (gestrichelt)





(Meier et al. 2003, 2009)

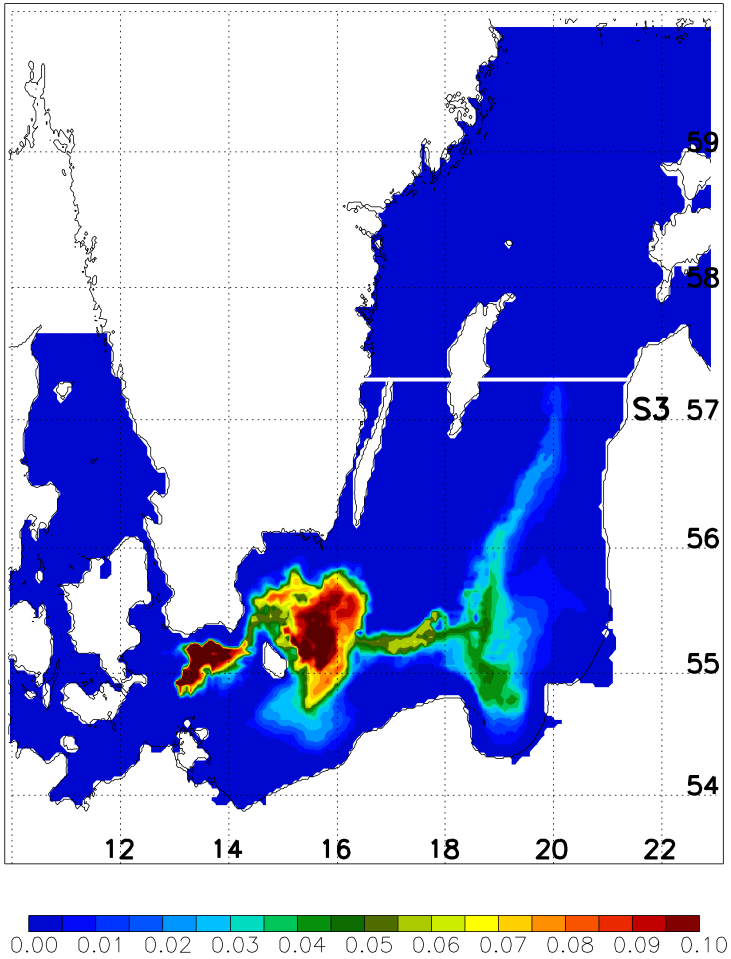
Annual temperature minimum (upper panel) and maximum (lower panel) in the intermediate winter water (IWW) at Bornholm Deep



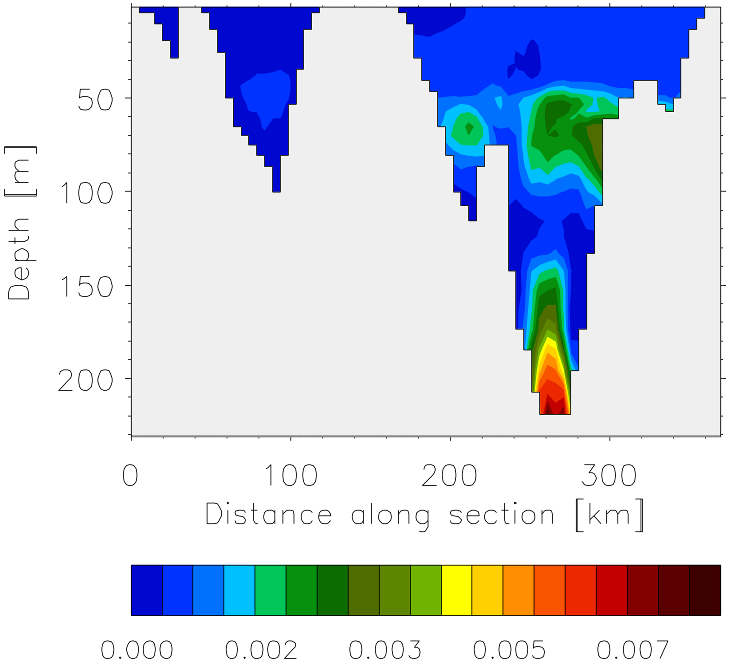
Model results (black lines)

Observations (blue/red) from Mohrholz et al. (2006)

Tracer marking inflowing saltwater > 17 psu

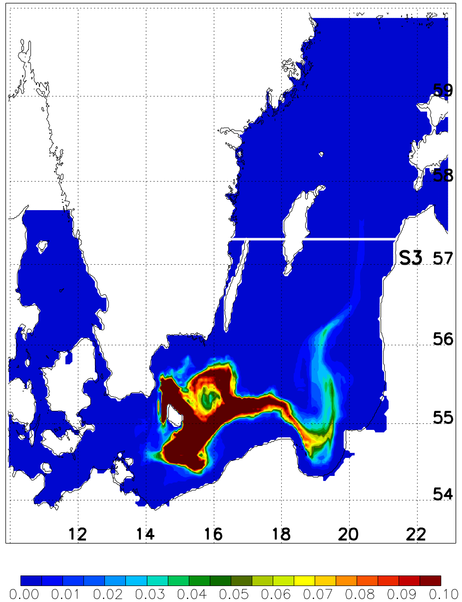


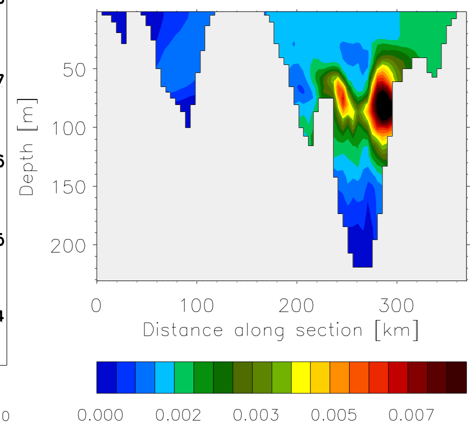
May 2003



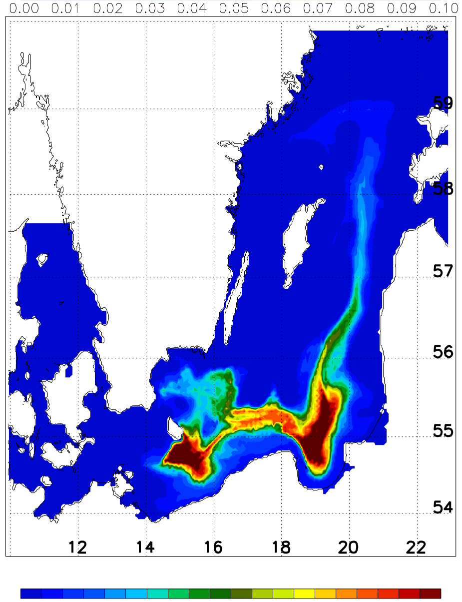
Tracer marking IWW in the BB halocline: 8.95 < S < 14.3 psu, T > 11ºC, at the surface 9 psu

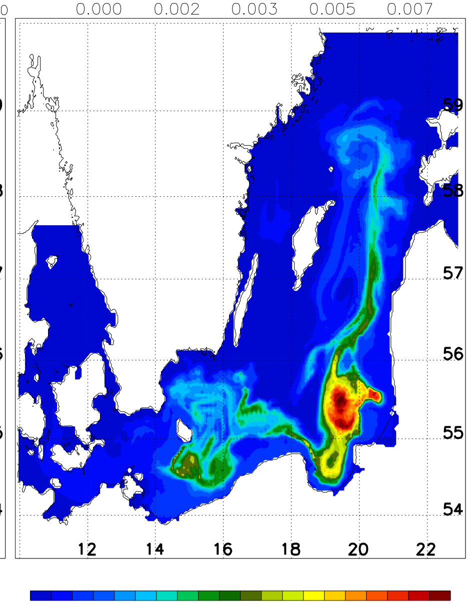
Nov 2002





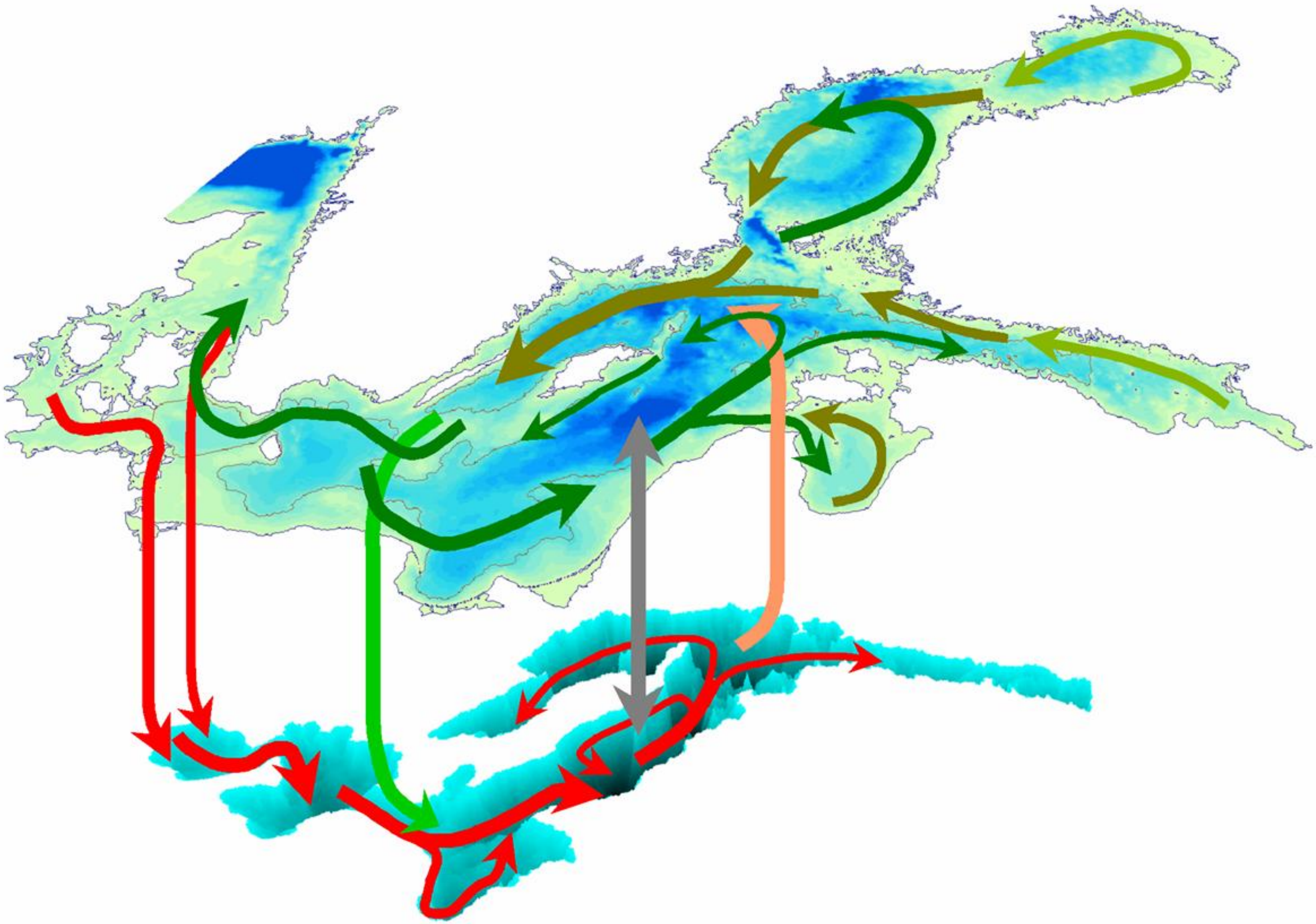
Jan 2003



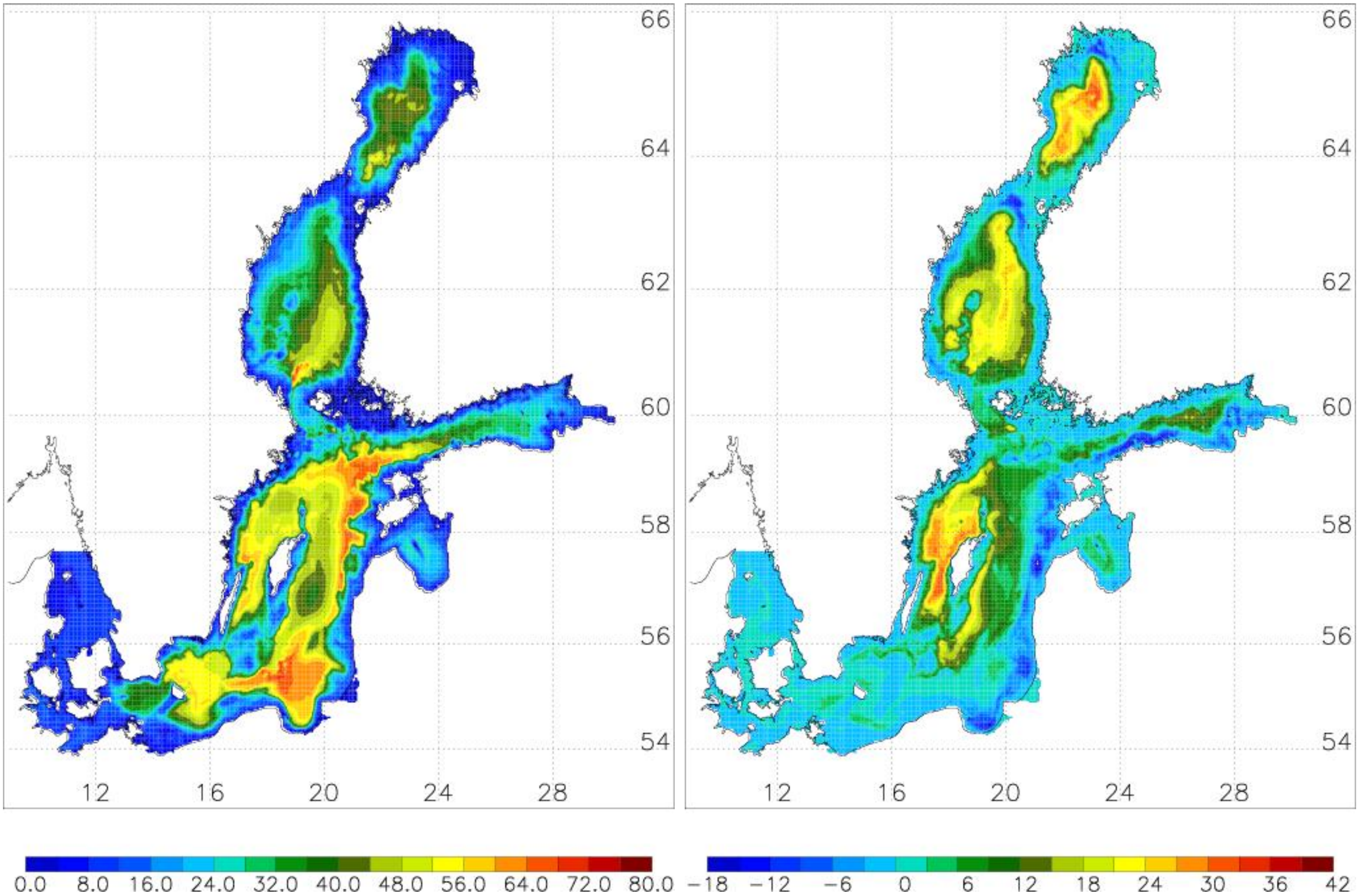


Mar 2003

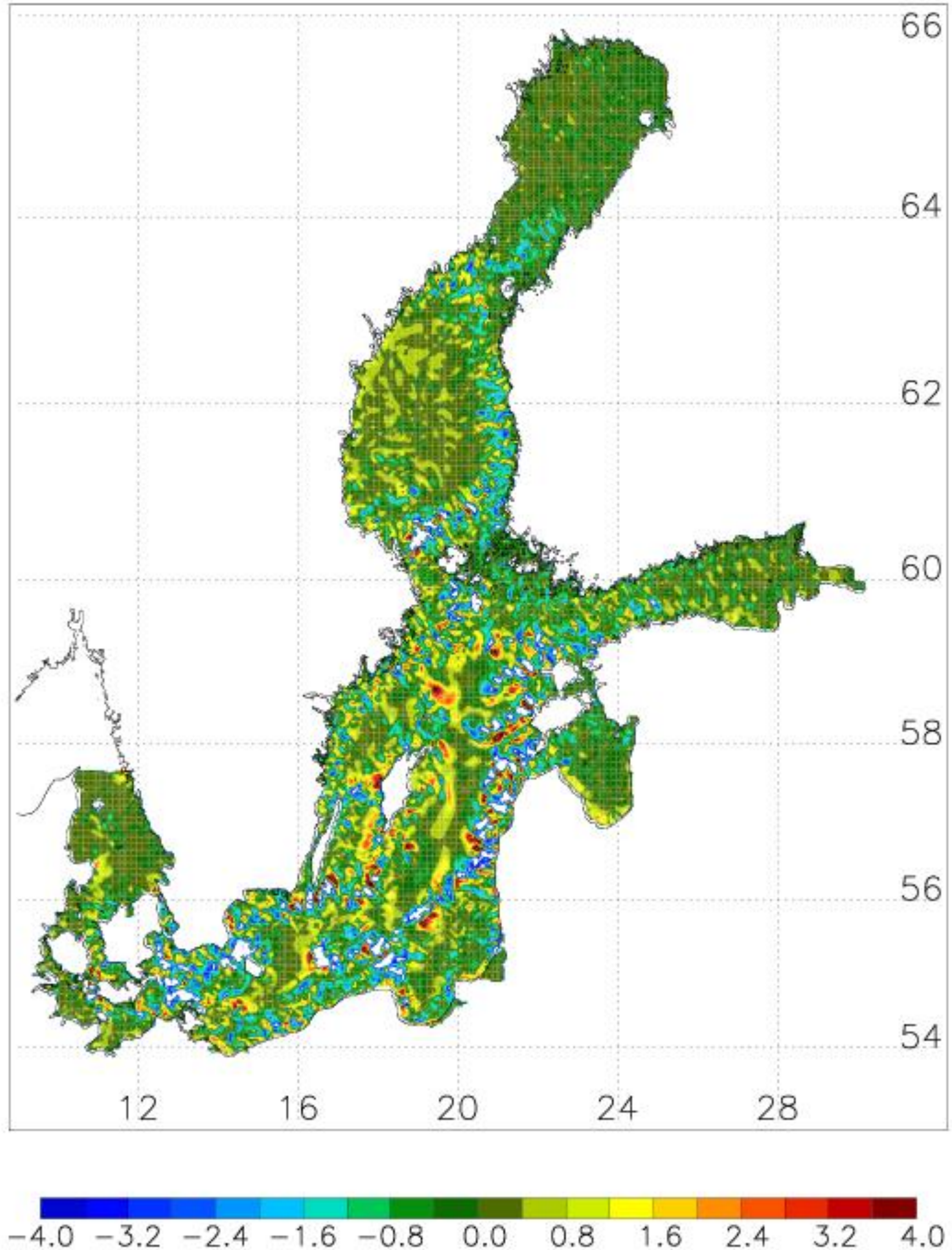
Schematic view of the large-scale circulation in the Baltic Sea (Elken and Matthäus, 2007)



Halocline depth for 1981-2004: annual mean (left) and difference between spring and autumn (right)



24-year mean vertical mass flux across the halocline of the tracer marking inflowing saltwater > 17 psu



Time scales

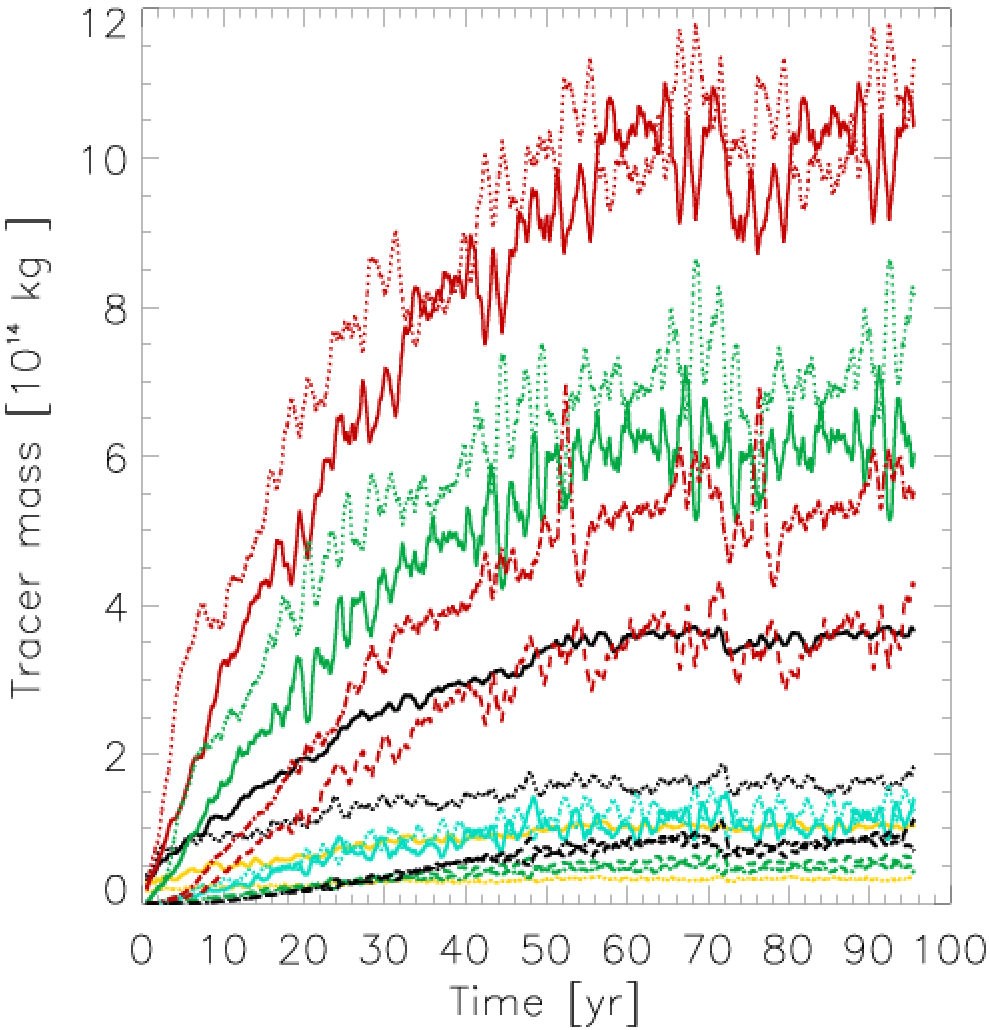
(Bolin and Rodhe, 1973; Björckström, 1978)

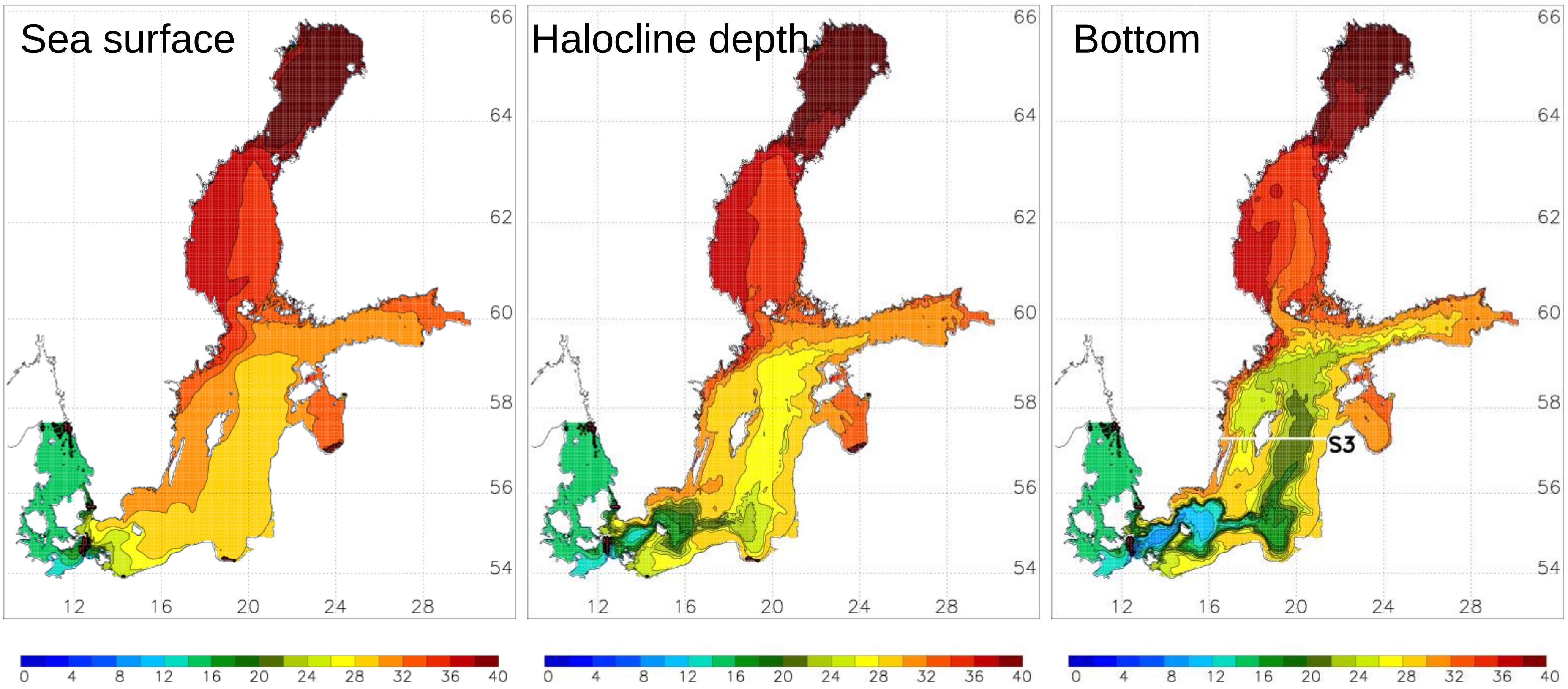
- Turn-over time t_0= volume / volumeflow
- Average age of particles in the reservoir at any one time a:

$$\frac{\partial a}{\partial t} + \nabla \cdot (\vec{v} a - K \cdot \nabla a) = 1$$

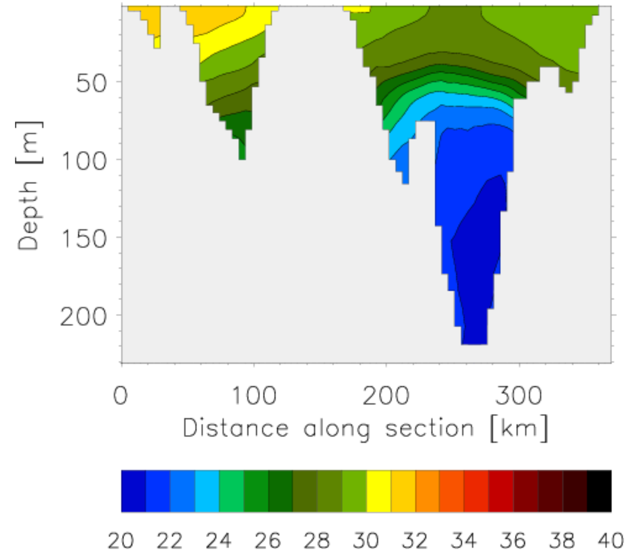
- Average transit time of particles leaving the reservoir t_t= the expected life time for newly incorporated particles = residence time
- In steady-state: $t_t = t_0$ and $a = t_0/2 + \sigma_t^2/2t_0$, σ_t^2 = variance of the transit-time distribution

Tracer masses marking inflowing water from Darss and Drogden sills

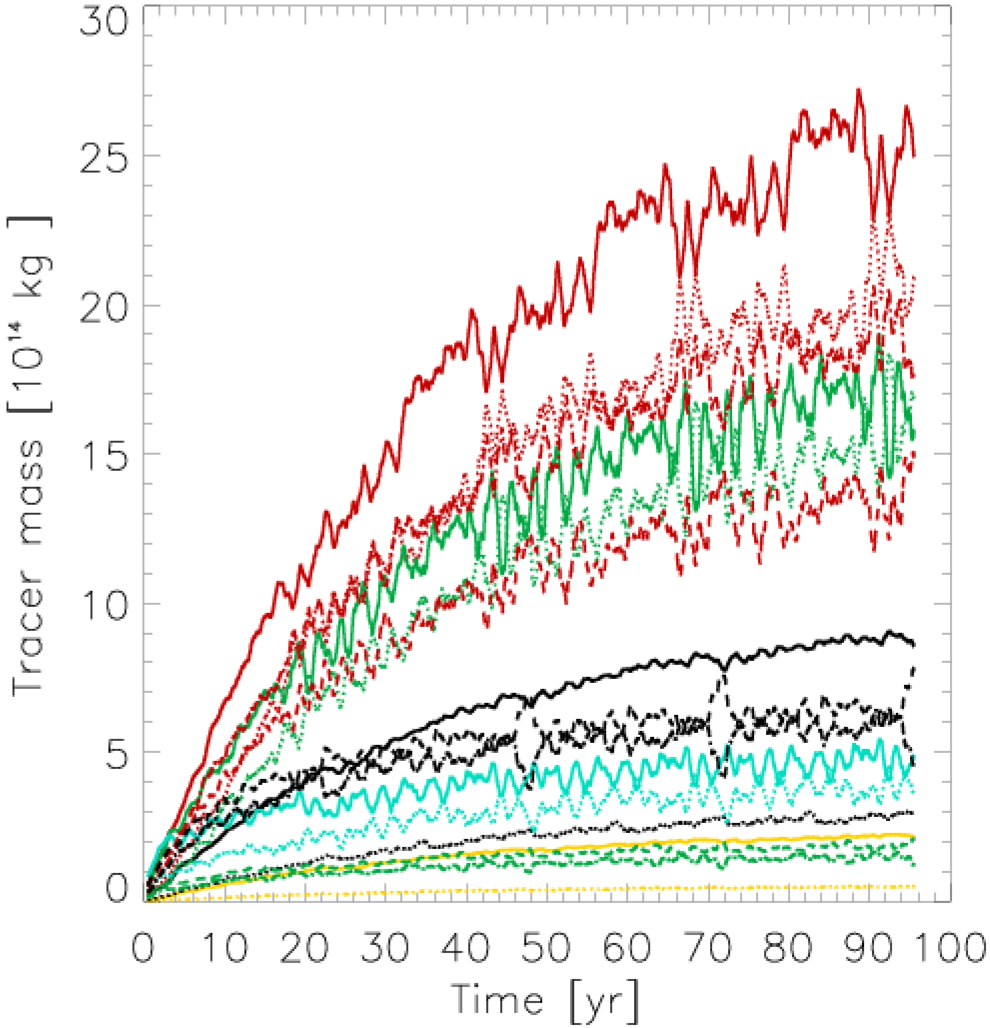


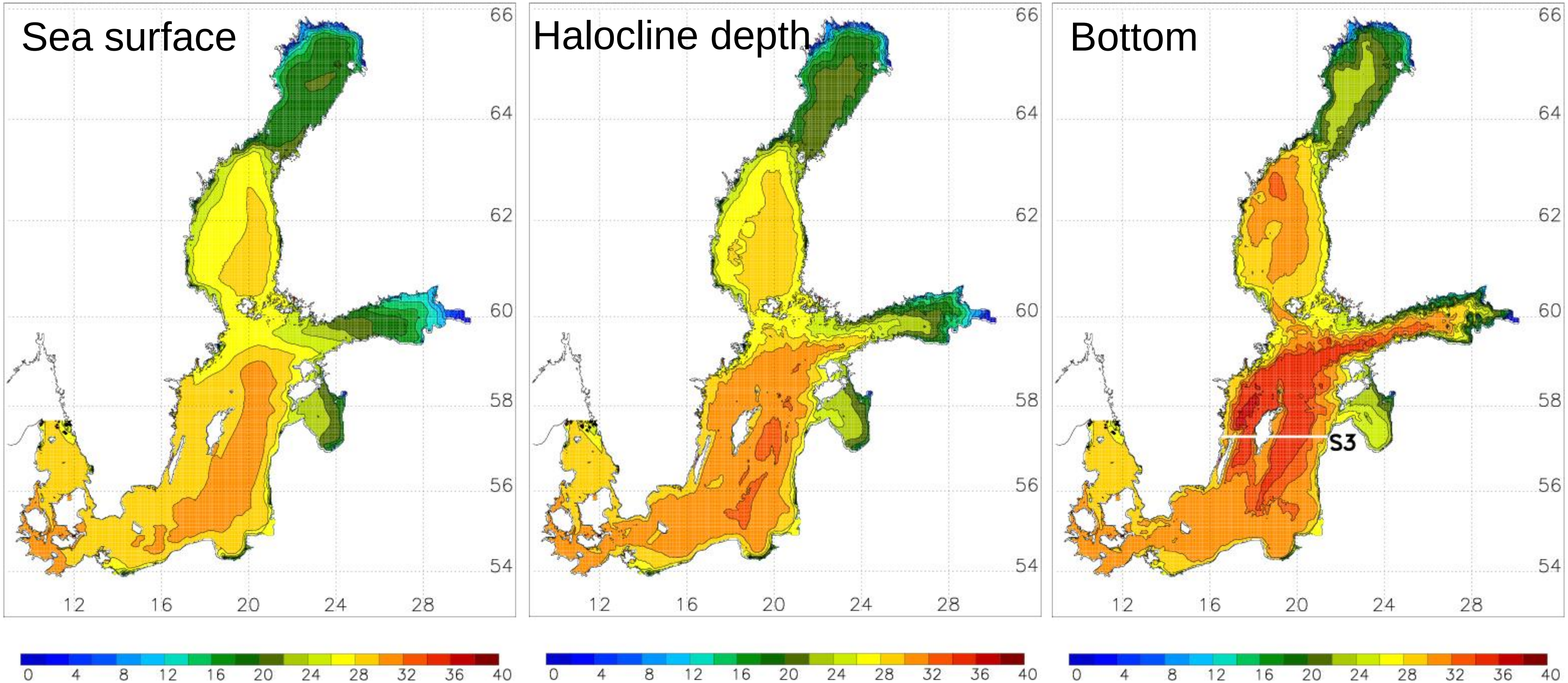


Mean age of the tracer marking inflow water

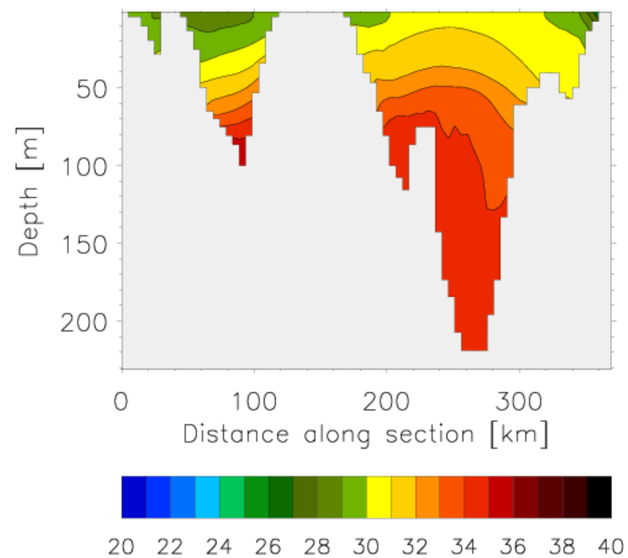


Tracer masses marking riverine freshwater





Mean age of the tracer marking riverine freshwater



Conclusions II

- The calculation of ages of inflowing water from Kattegat or of riverine freshwater in steady-state requires at least 100-year simulations because maximum ages are larger than 40 years.
- The downward flux across the halocline caused by entrainment of the surface water into the deep water flow can only be balanced by the upward advective and diffusive fluxes.

17. Causes of climate variability: Ventilation of the Baltic Sea deepwater during 1903-1998

Model experiments 1903-1998

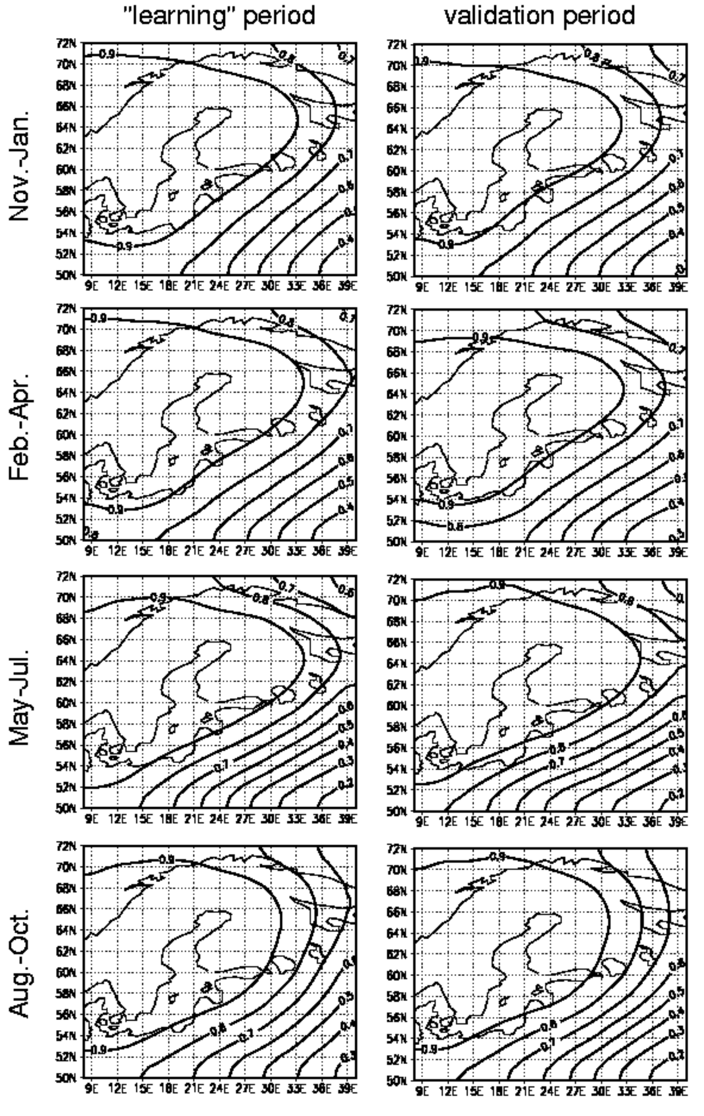
- Rossby Centre coupled ice-ocean model RCO (2 nm, 41 levels)
- observed runoff and sea level in Kattegat
- reconstructed atmospheric forcing using a statistical model
- initial conditions from profile data from November 1902

Reconstructed atmospheric forcing

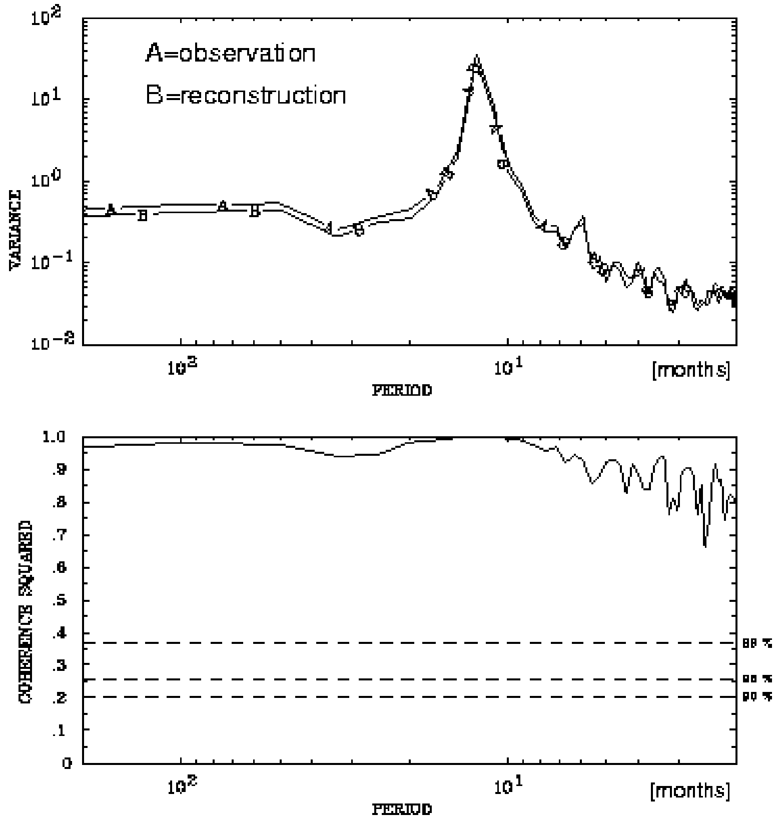
(Kauker and Meier, 2002; 2003)

- redundancy modes from gridded 1 1 observations 1980-1998 (`learning period')
- 1970-1979 validation
- predictor variables: 100-years of SLP at 18 locations, air temperature and precipitation (CRU)
- predictands: daily SLP, monthly air temperature, dew-point temperature, precipitation and cloud cover

Explained variances SLP

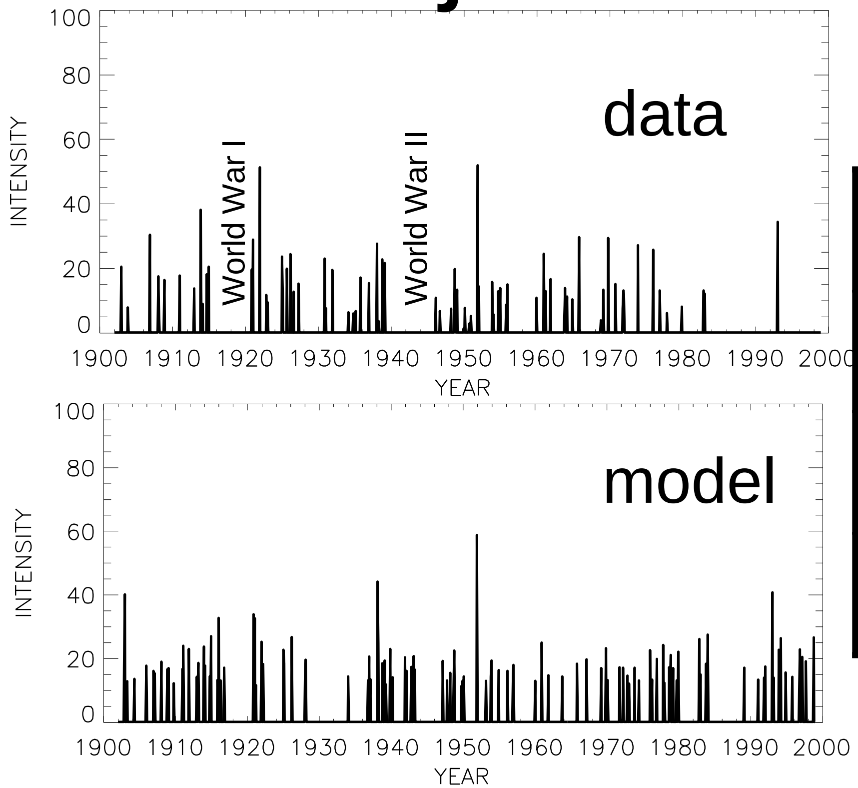


SAT Stockholm



The cross-spectra of the reconstructed and observed monthly air temperature at Stockholm. Shown is the variance (observation=A, reconstruction=B) (upper panel) and the squared coherency (lower panel) on monthly to decadal time scales. The significance level are estimated with a Bartlett procedure with a chunk length of 100 months.

Major Baltic inflows



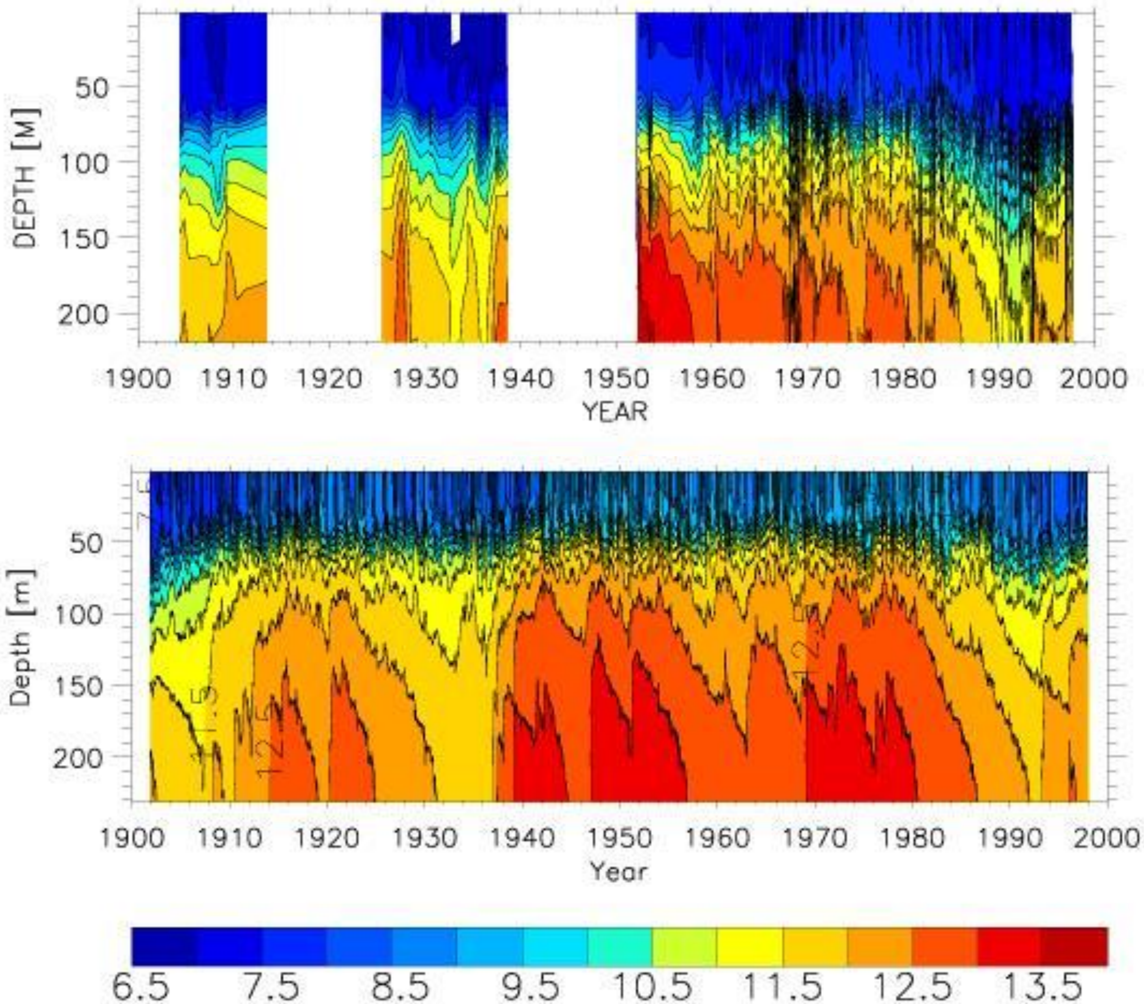
	data	model
No.	82	115
V_{17} [km^3]	81.1	86.6
M_{17} [10^{12}kg]	1.55	1.87

Major Baltic inflows during the period 1902-1998 as characterized by an intensity index based on the amount of salt (in kg) transported across the sills in water bodies with salinities S≥17 psu divided by 10^{11} kg: (a) observations according to Matthäus and Franck (1992), Fischer and Matthäus (1996), supplemented and updated, (b) model.

Salinity Gotland Deep

Data

Model

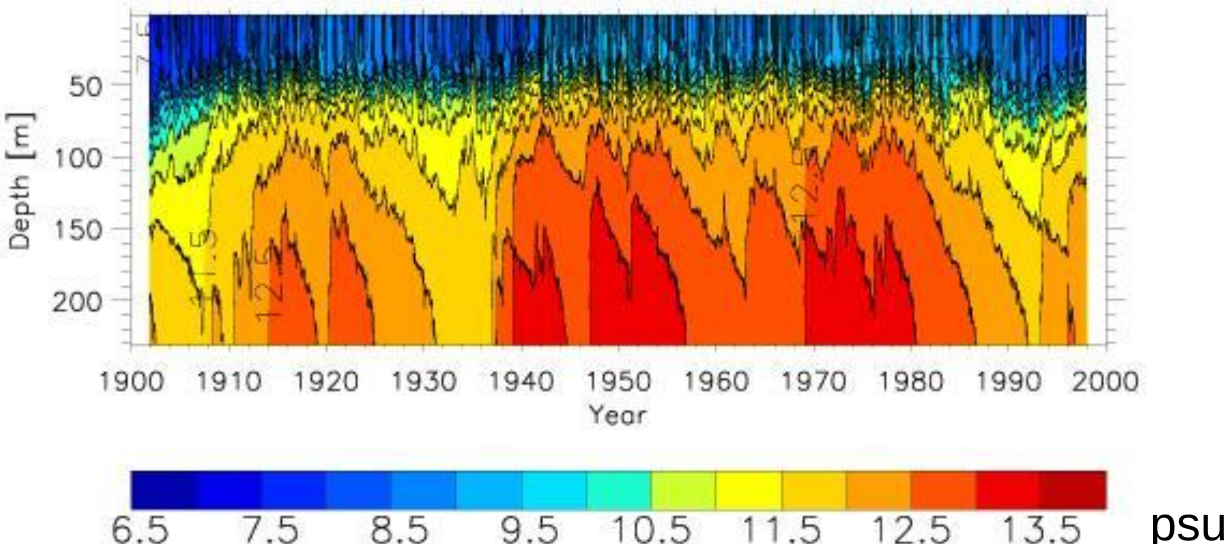


psu

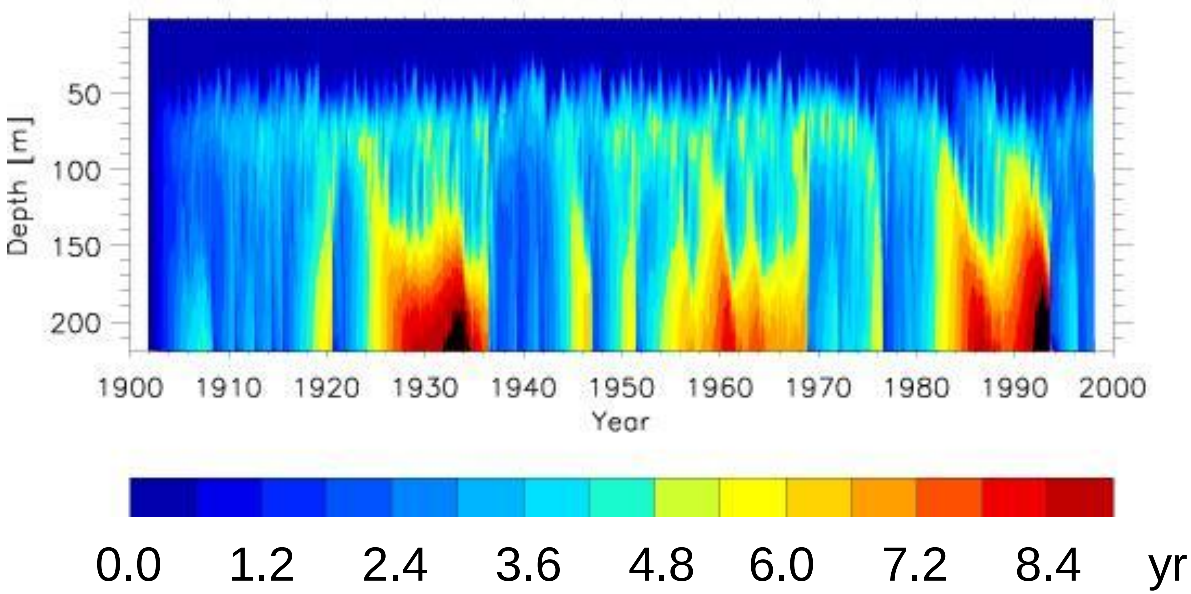
(Meier, 2005)

Stagnation periods

Salinity



Age

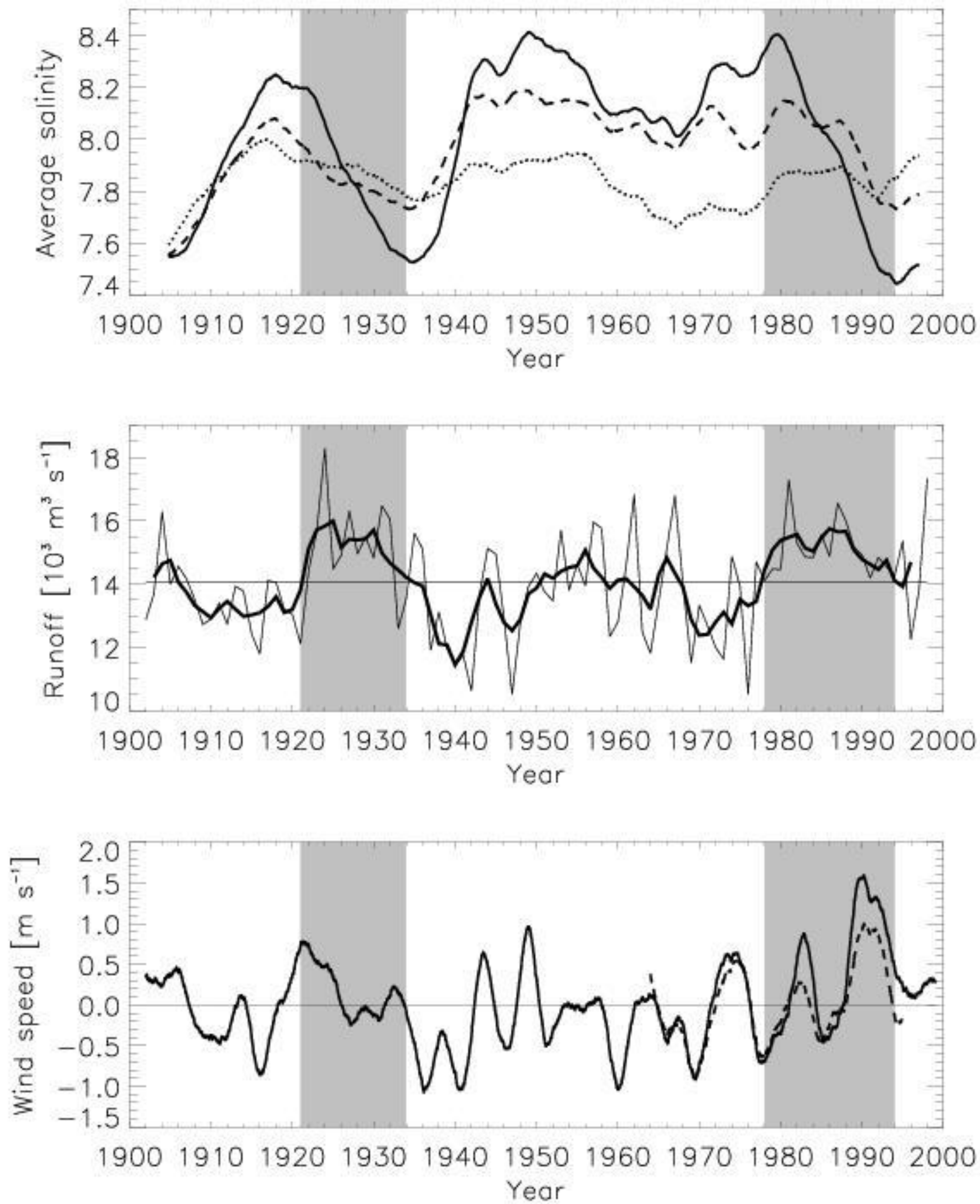


(Meier, 2005)

Salinity

Runoff

Wind

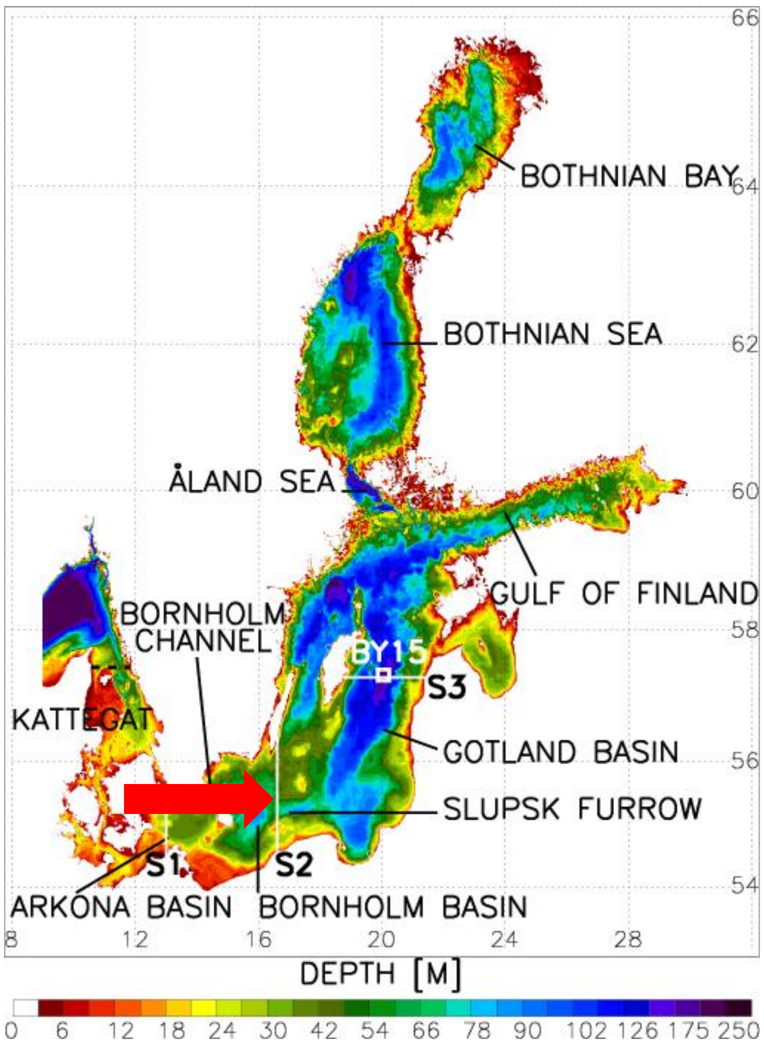


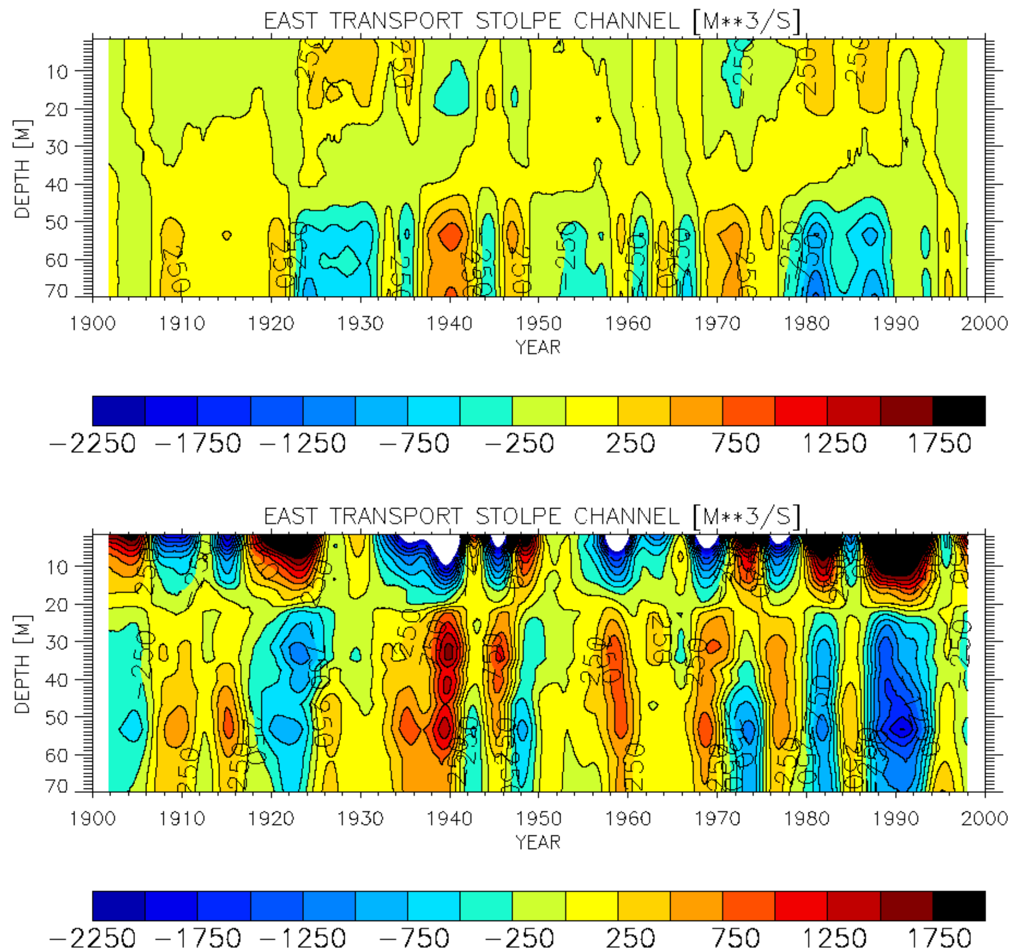
— 4-yr running mean

Stagnation periods are shaded

(Meier and Kauker, 2003a)

Laufendes 4-Jahresmittel der horizontal-integrierten Volumentransportanomalie [m³/s]





(Meier & Kauker 2003a)

Conclusions III

1. decadal variability is realistically simulated using RCO, e.g. inflows, stagnation phases
2. mean salinity amounts to 7.4 psu, variations of about 1 psu, no trend
3. half of the decadal variability of salinity is explained by accumulated freshwater inflow variations (Meier and Kauker, 2003a)
4. another significant part is caused by the low-frequency variability of the wind (Meier and Kauker, 2003a)
5. remainder might be caused by the high-frequency wind anomaly, i.e. specific atmospheric conditions causing major saltwater inflows (Lass and Matthäus, 1996)
6. no impact of river regulation, sea ice (air temperature), sea level in Kattegat on decadal time scale

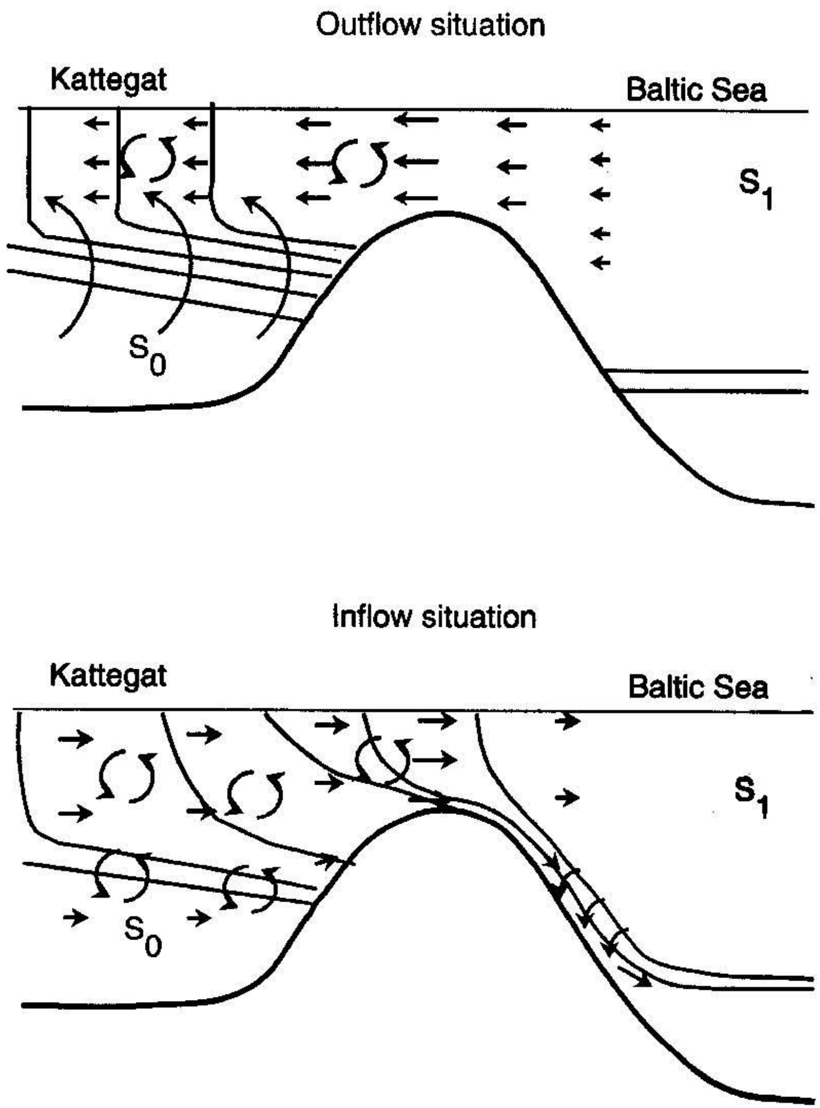
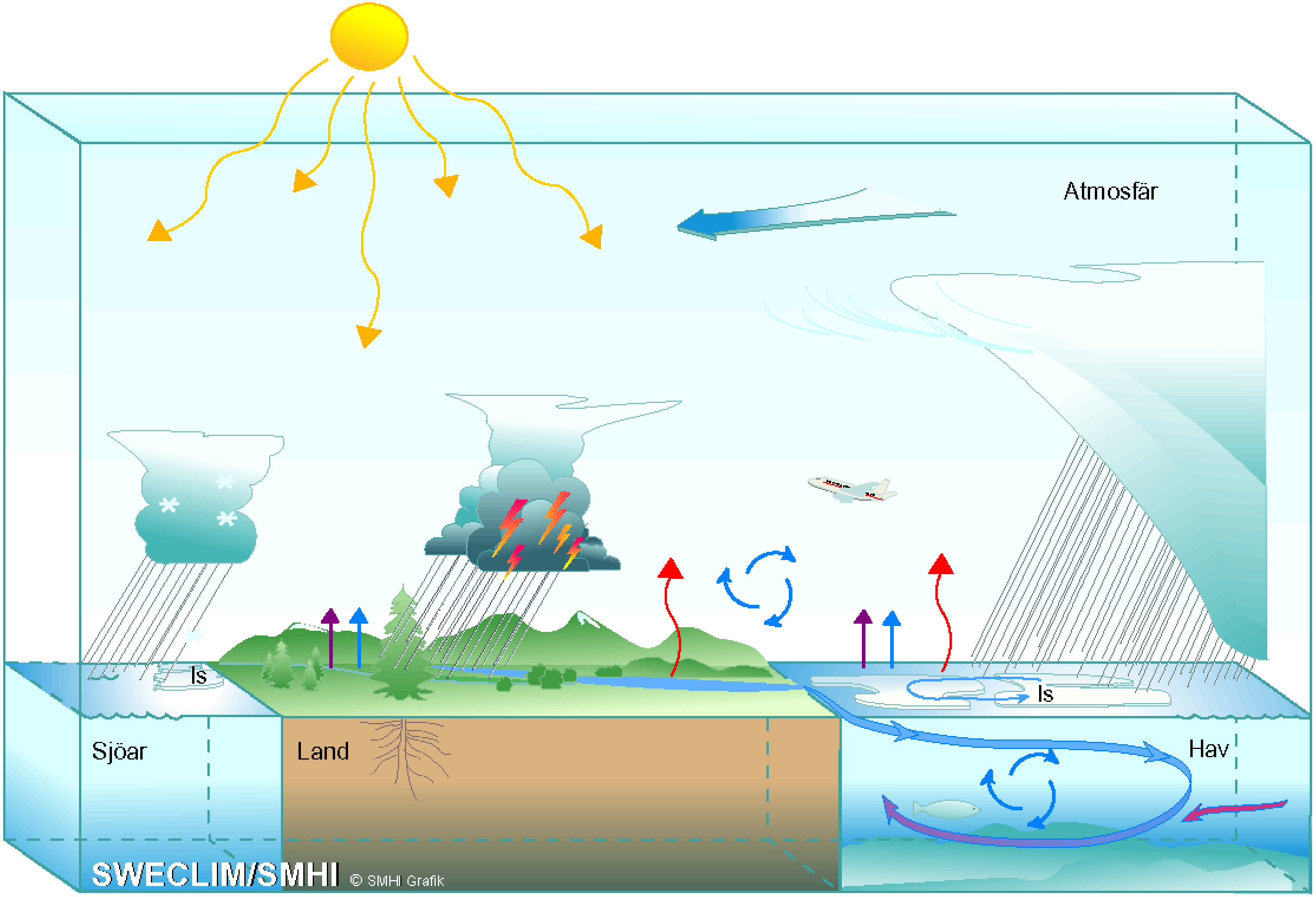


Fig. 4. Sketch illustrating the flow, mixing, and salinity stratification in the Danish Straits during outflow from (upper panel) and inflow to (lower panel) the Baltic Sea.

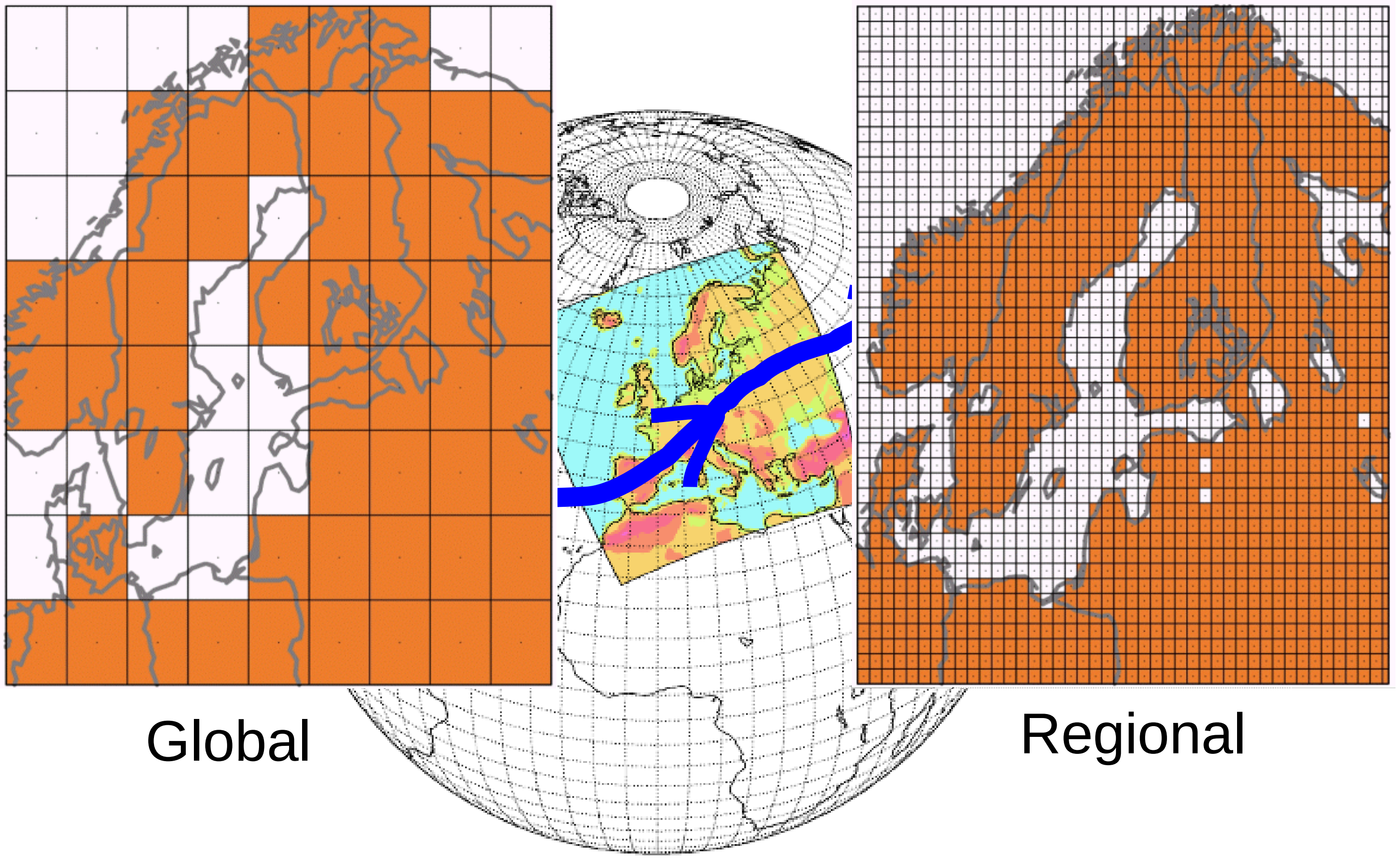
(Rodhe & Winsor 2002)

18. Scenarios of temperature, salinity, and sea ice

Atmosphere-ice-ocean-land surface system

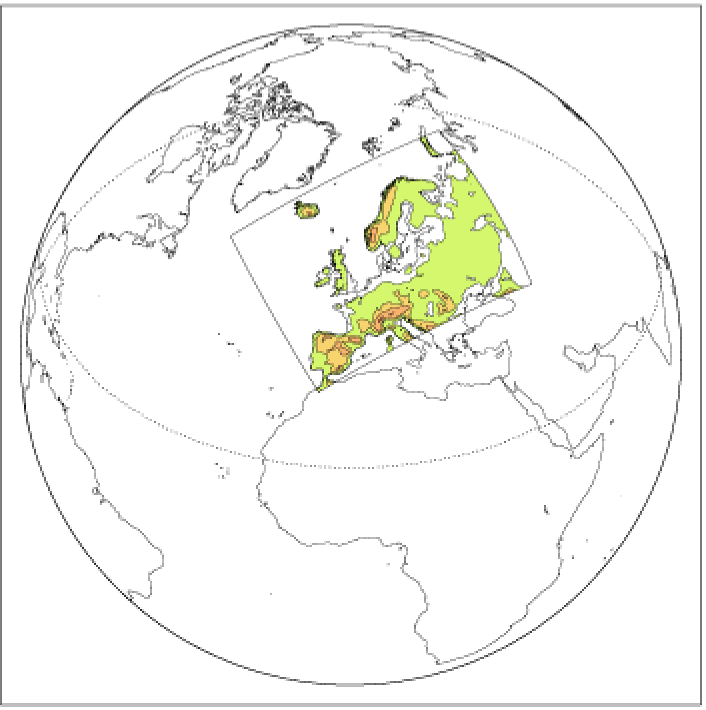


Regional climate modeling at the Rossby Centre

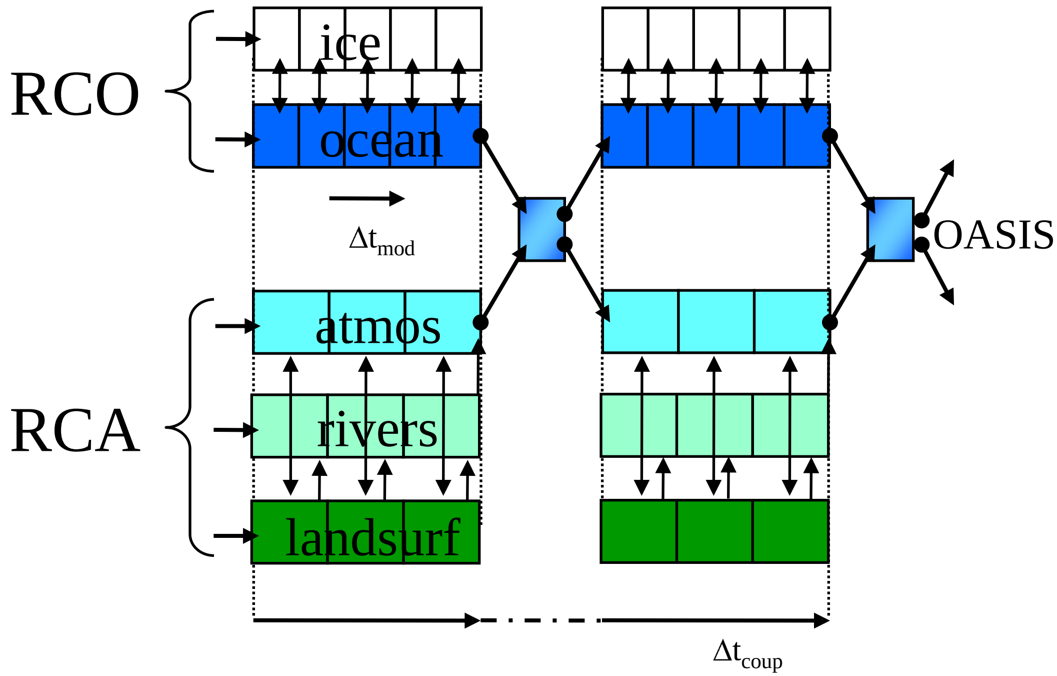


The **coupled** system RCAO

RCA: 44 km, 30 min
RCO: 11 km, 10 min
Coupling timestep: 3 h



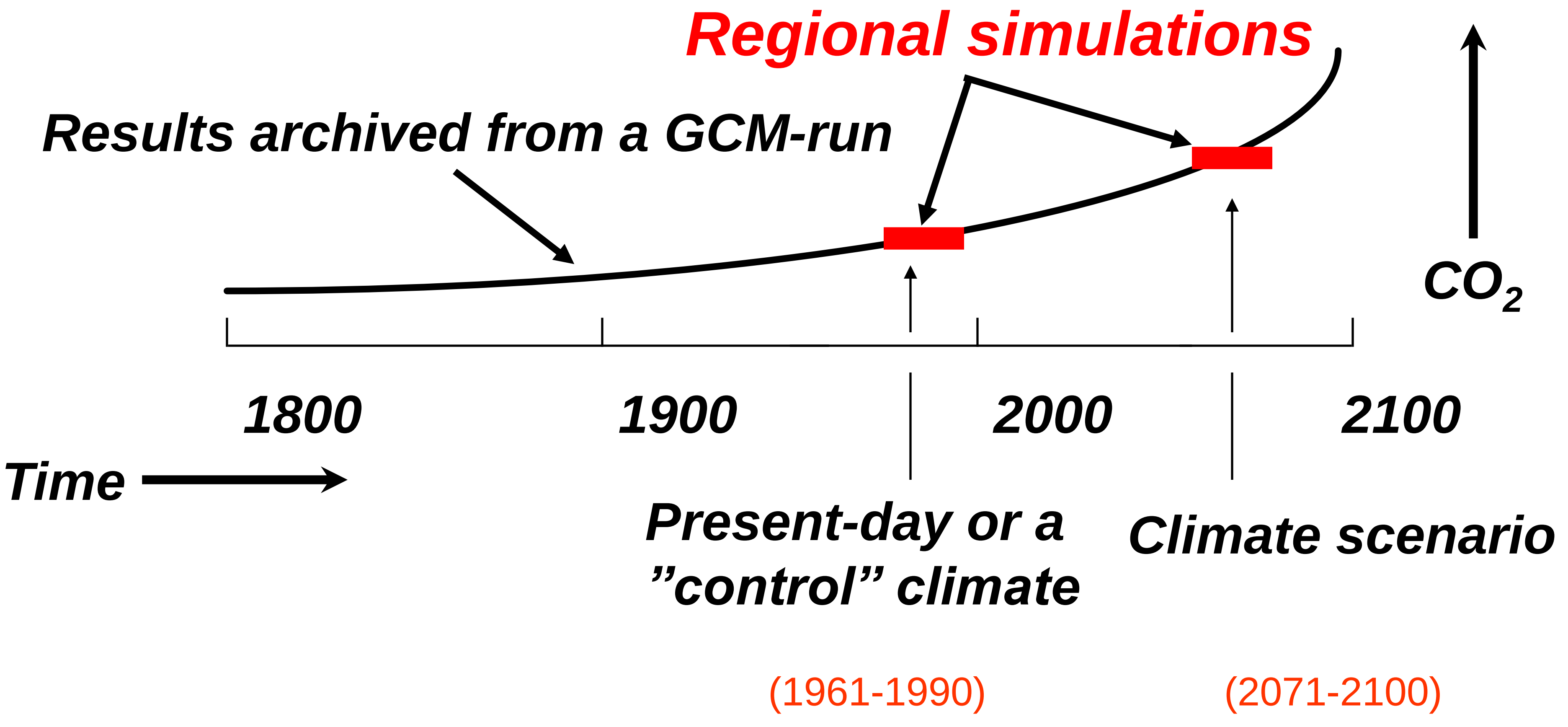
Model domain, covering most of Europe and parts of the North Atlantic Ocean and Nordic Seas. Only the Baltic Sea is interactively coupled.



The coupling scheme of RCAO. Atmosphere and ocean/ice run in parallel.

(Döscher et al., 2002)

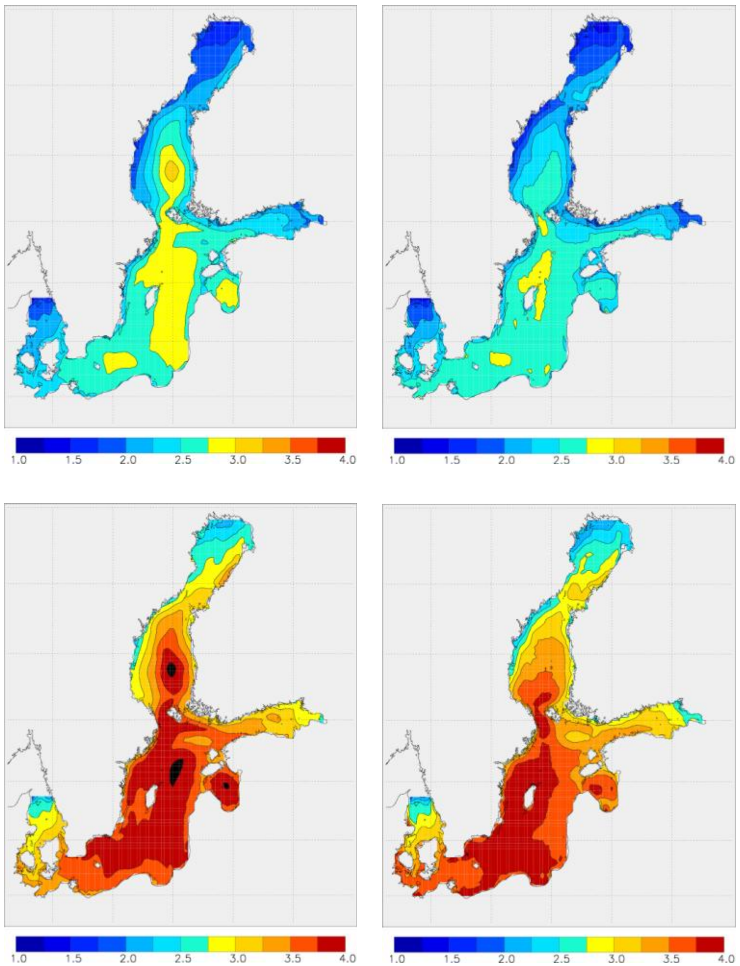
Regionalization is done for "time-slices" from GCMs



Δ-change scenarios using RCO versus RCAO time slice experiments:

B2

A2



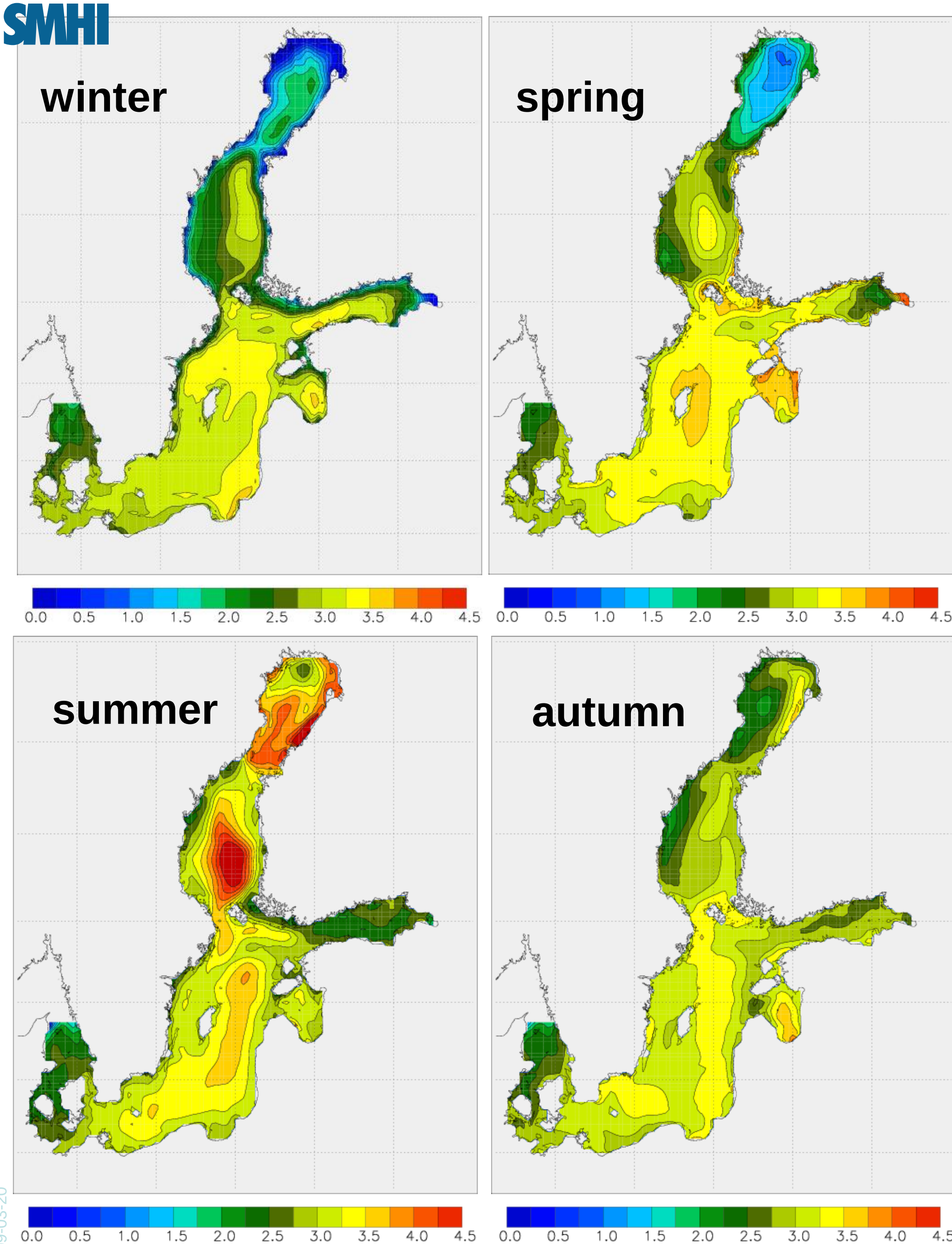
RCO RCAO

Annual mean SST change of the ensemble average in uncoupled (left) and coupled (right) scenarios

	RCO	RCAO
H/B2	+2.1	+1.9
E/B2	+2.8	+2.9
H/A2	+3.2	+3.0
E/A2	+3.7	+3.8
average	+3.0	+2.9

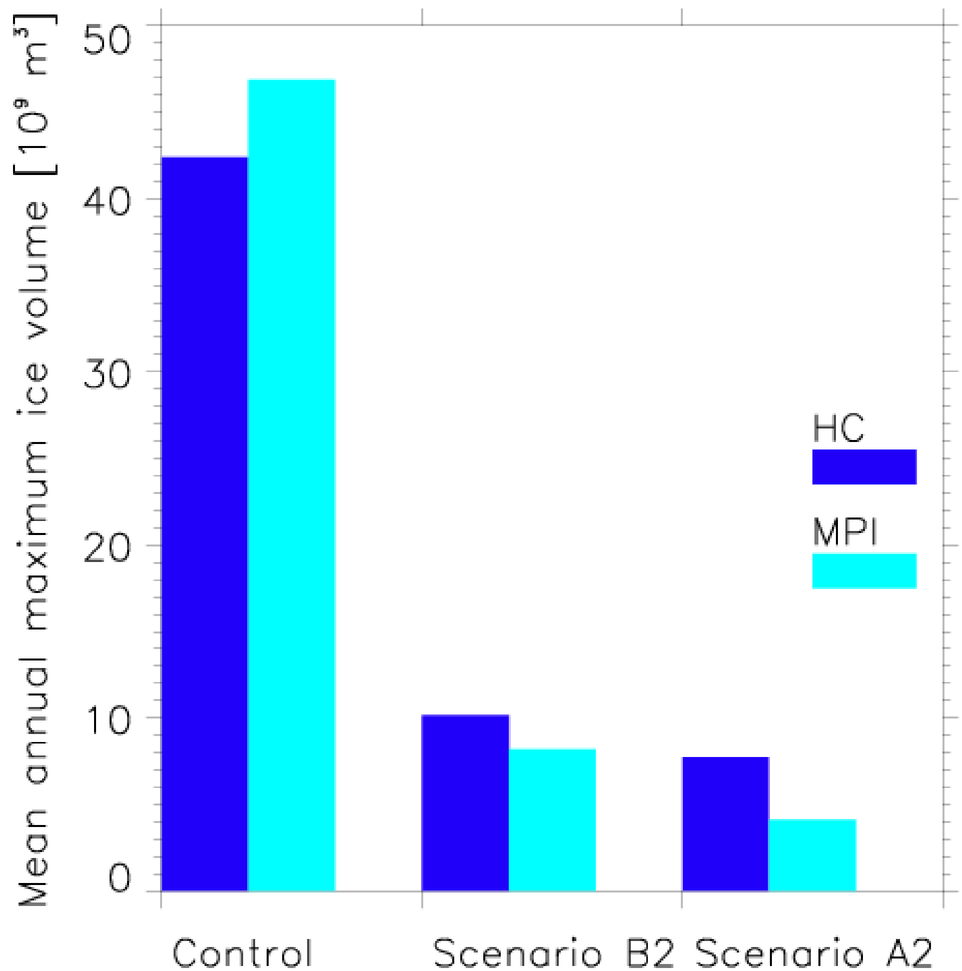
(Meier, 2005b)

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



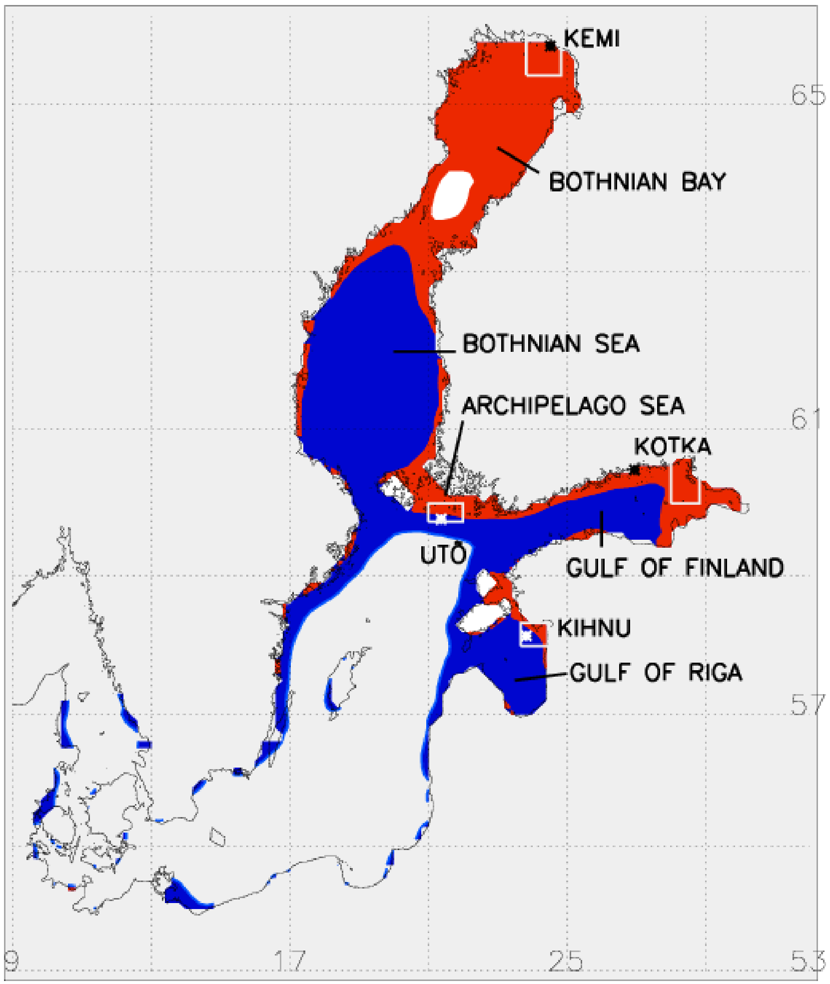
Seasonal mean SST differences between the ensemble average scenario and simulated present climate (in °C): DJF (upper left), MAM (upper right), JJA (lower left), and SON (lower right) (Meier, 2006).

Mean annual maximum ice volume in control and scenario experiments



(Meier et al., 2004c)

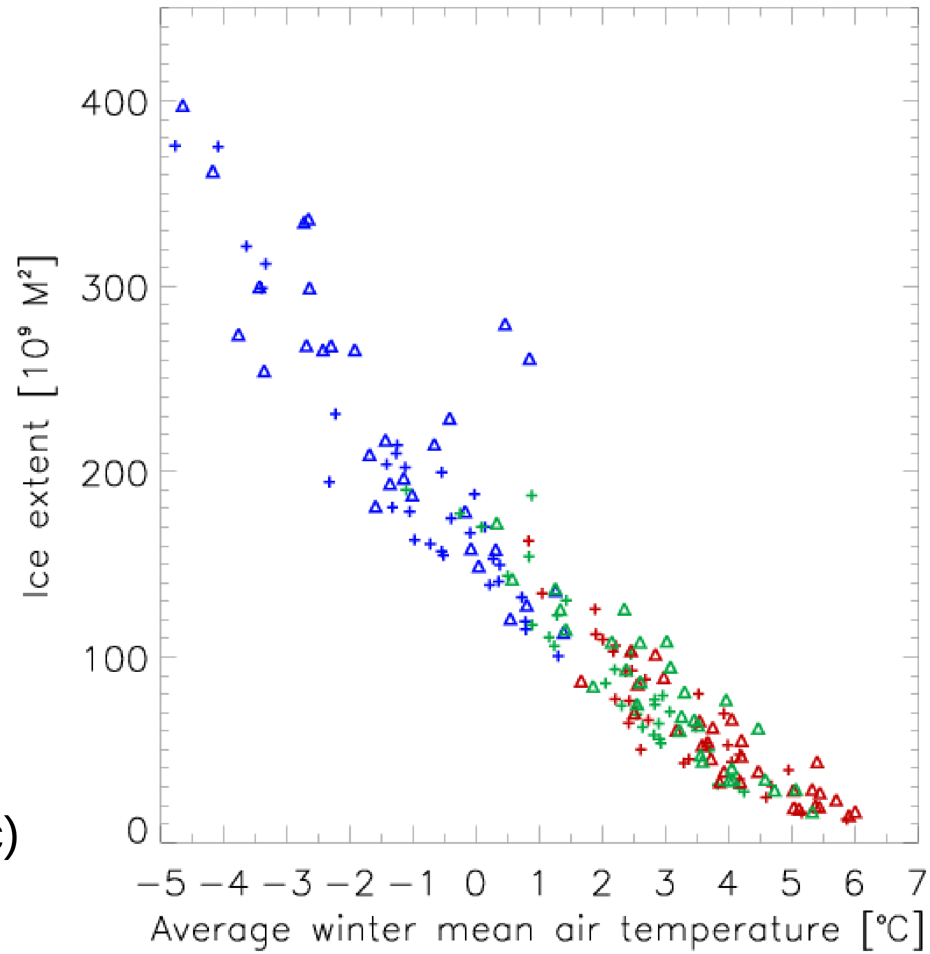
Mean maximum ice cover in control (blue) and scenario (red)



Mean maximum ice extent change: - 60-70%

(Meier et al., 2004c)

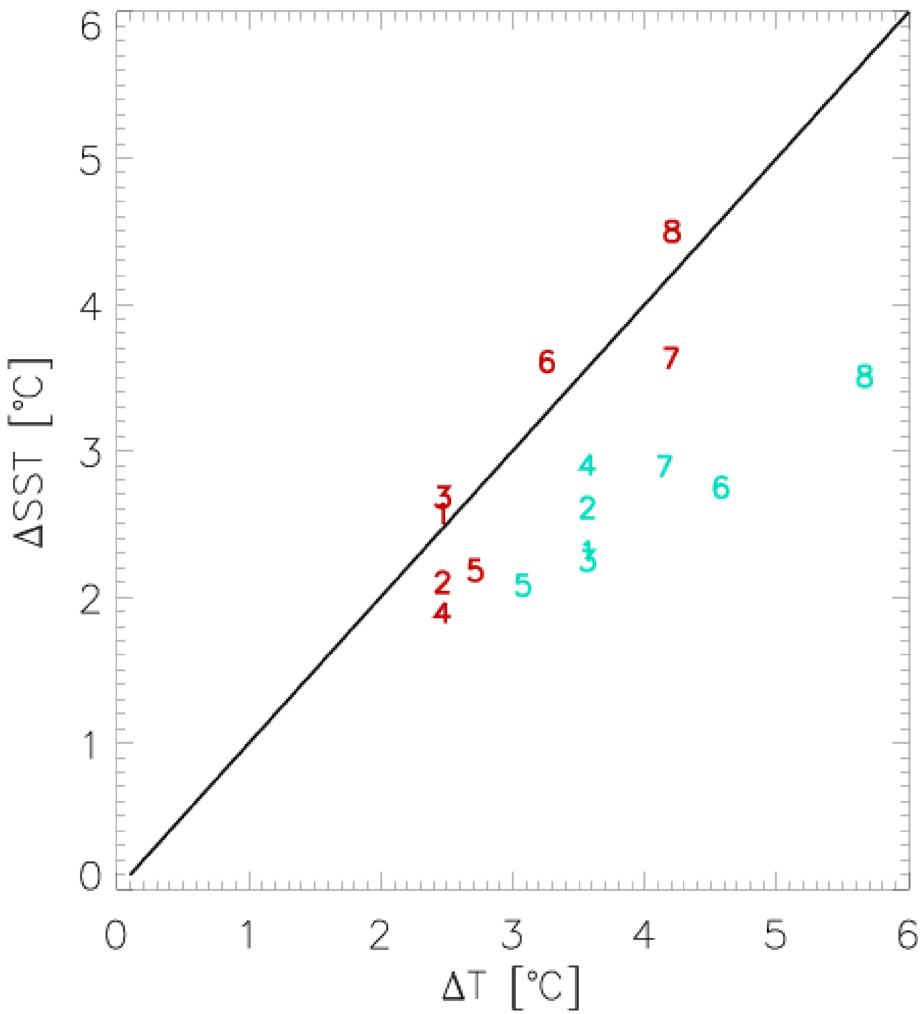
Scatterplot of annual maximum ice extent and winter mean (DJF) air temperature at Stockholm



(Meier et al., 2004c)

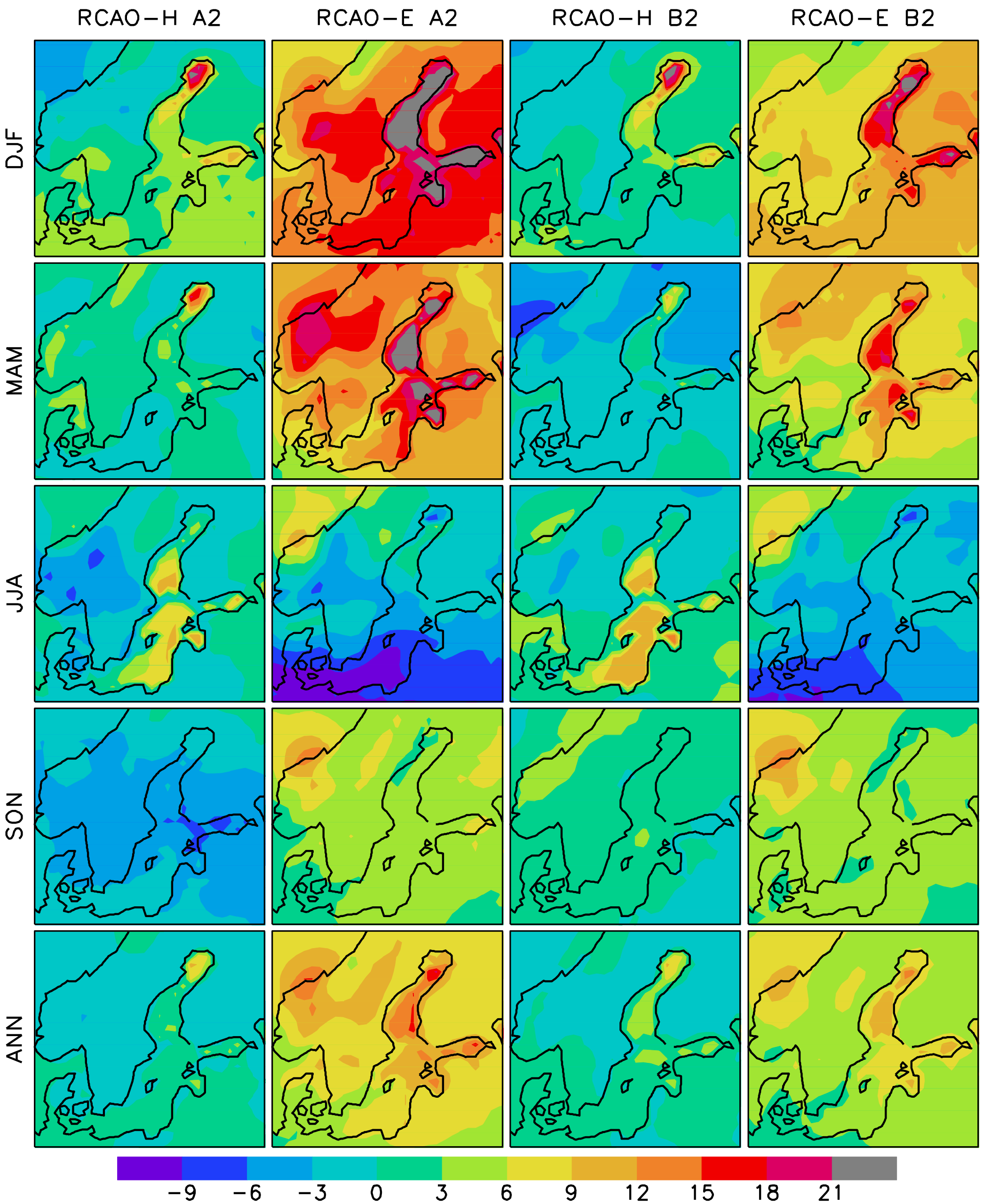
RCAO-H (plus signs), RCAO-E (triangles), control (blue), B2 (green), A2 (red)

SST changes versus air temperature changes for winter (blue) and summer (red)

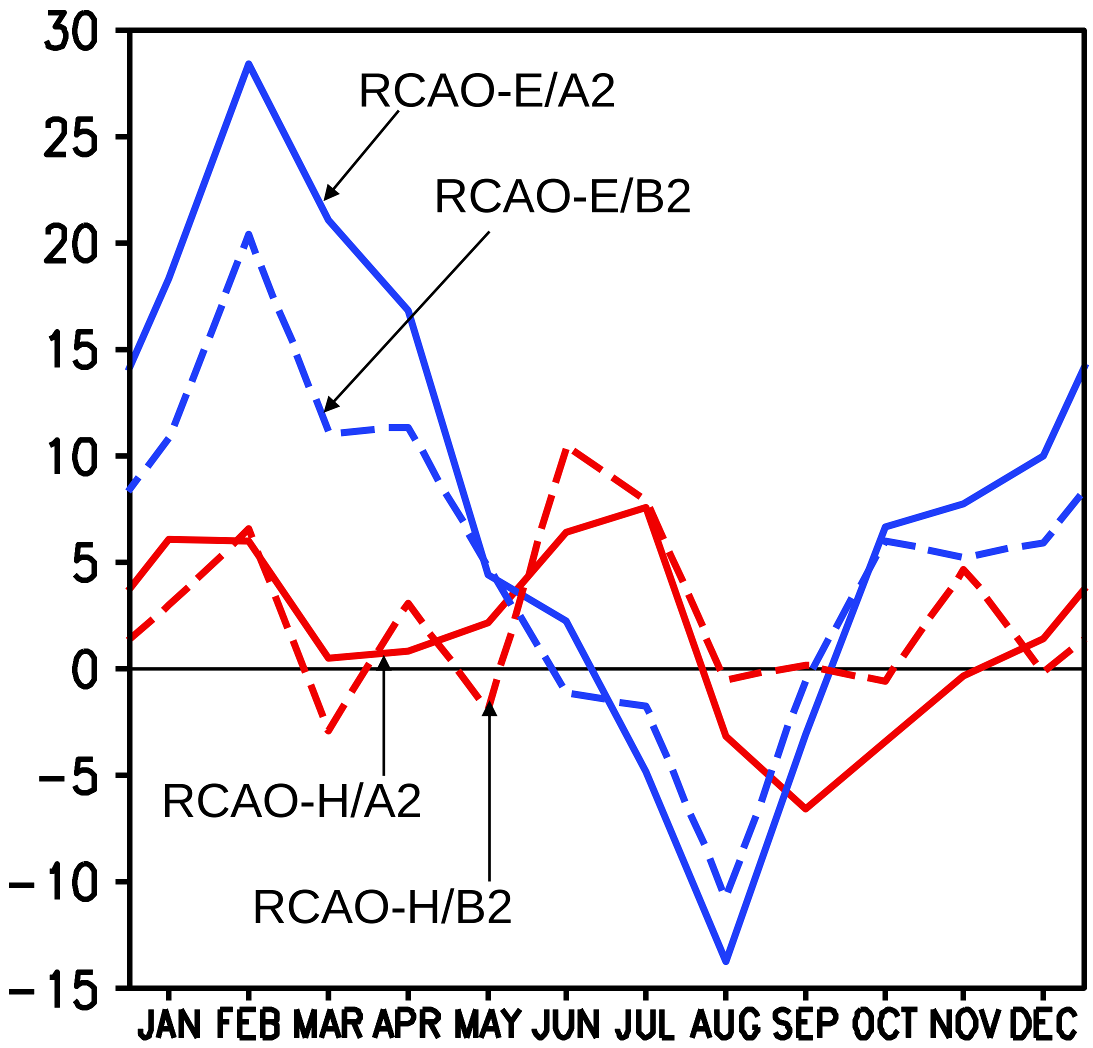


(Meier et al., 2004c)

Wind speed changes [%]

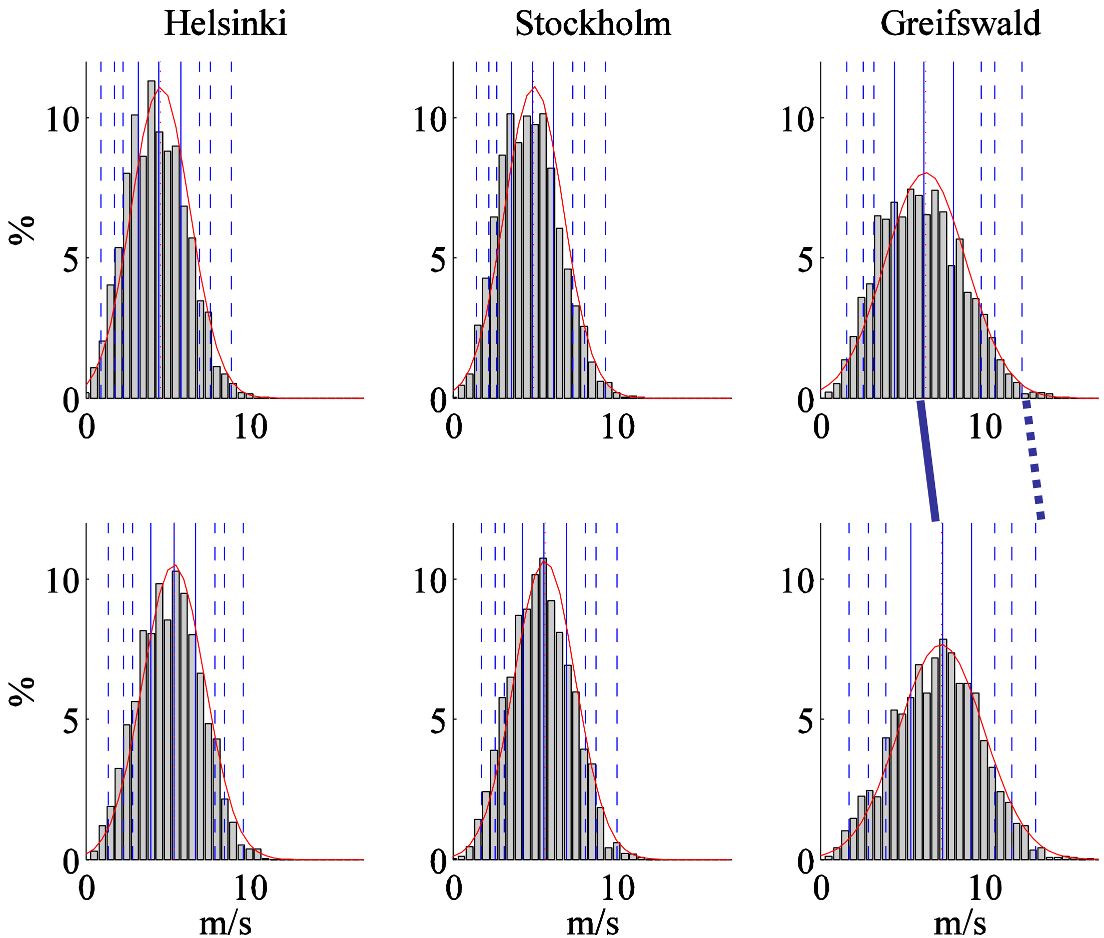


Relative wind changes



(Räisänen et al., 2004)

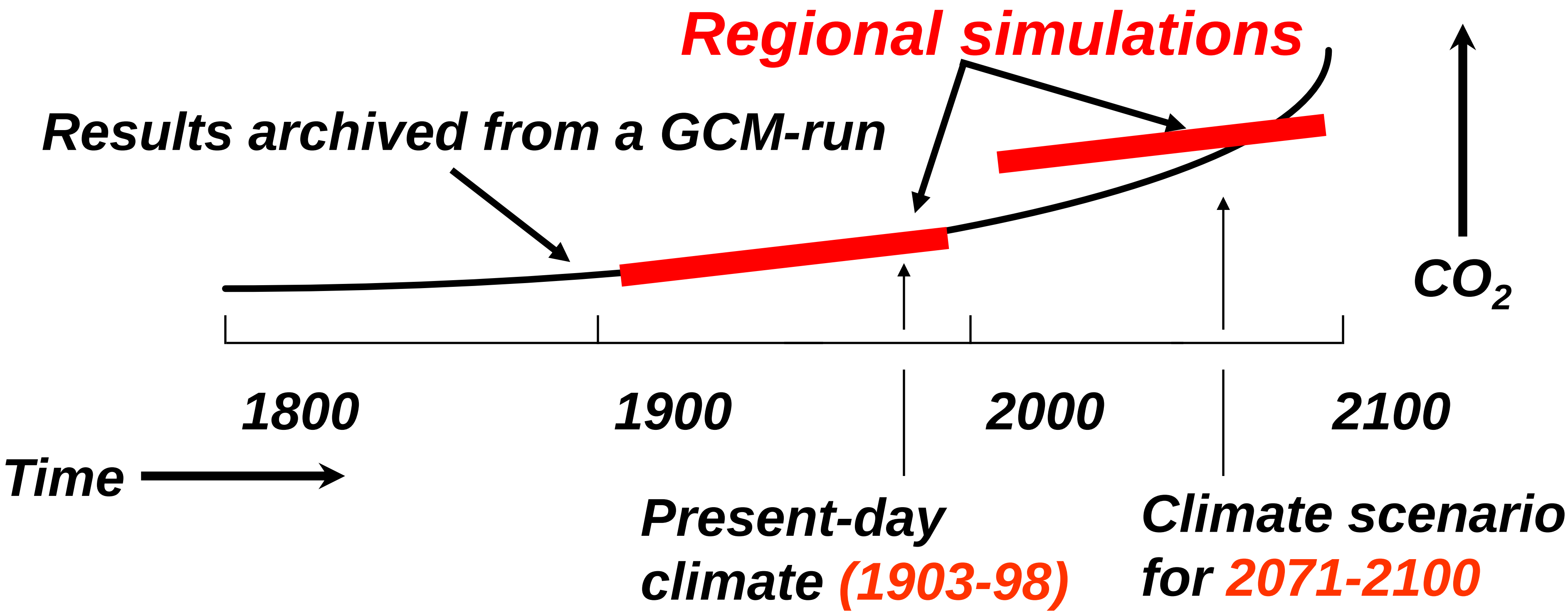
Winter time frequency histograms of wind speed



Control climate
RCAO-E/CTRL

Scenario climate
RCAO-E/A2

Δ-change scenarios based upon present climate



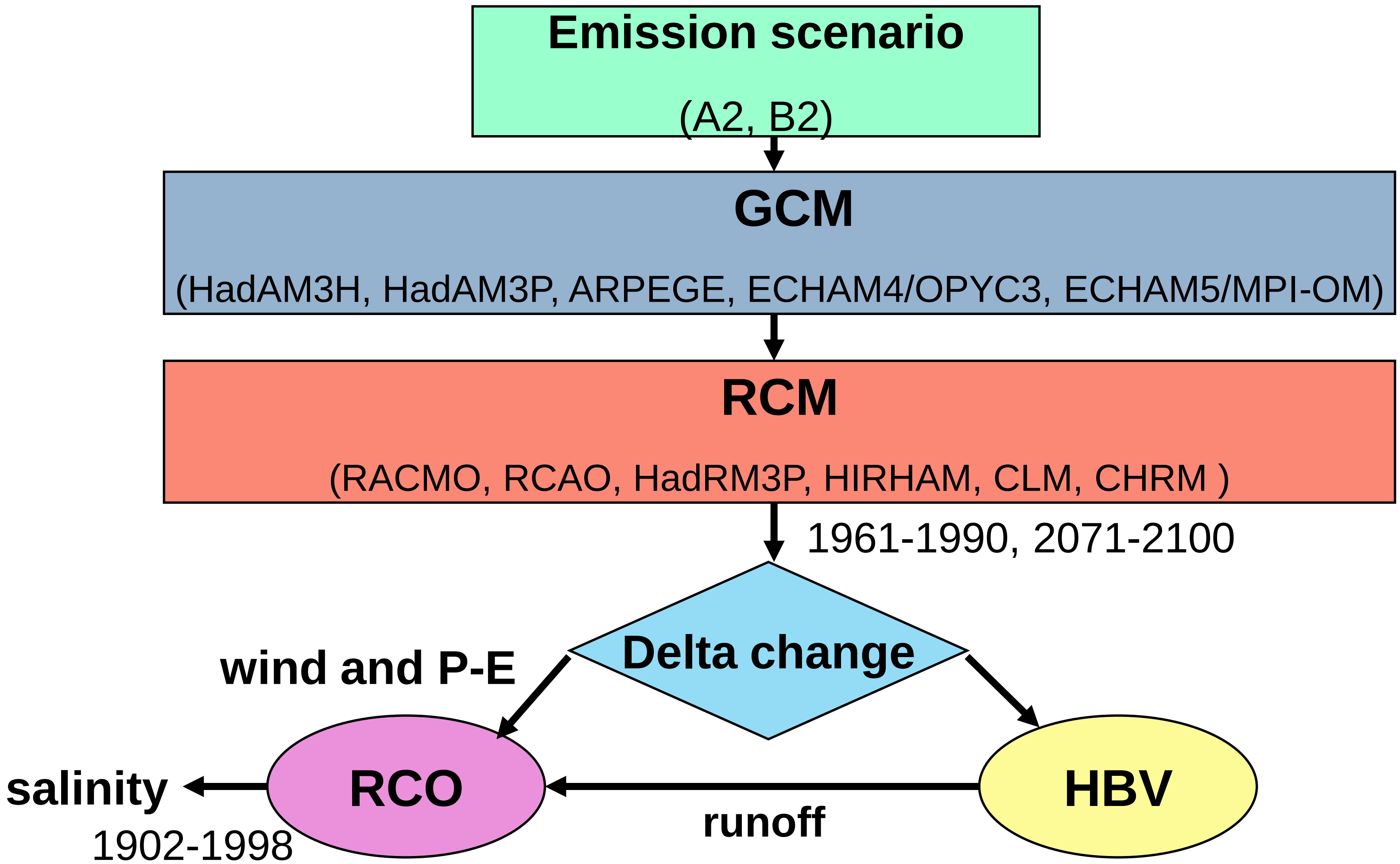
Δ-change: present variability plus monthly mean changes from RCAO

Time slice approach

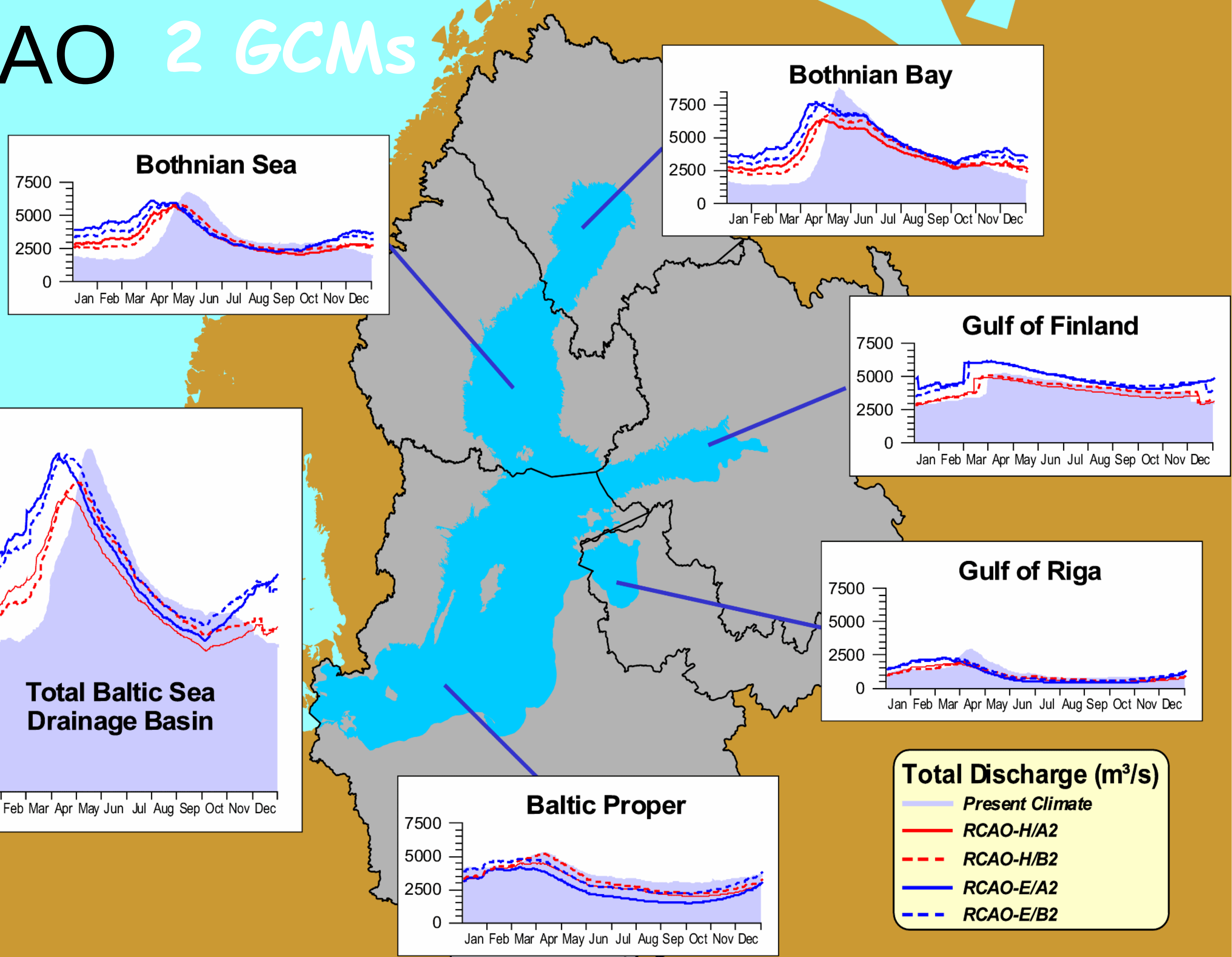
For the deep water response there is a spin-up problem due to the long time scales.

Solution: delta approach

Model hierachy

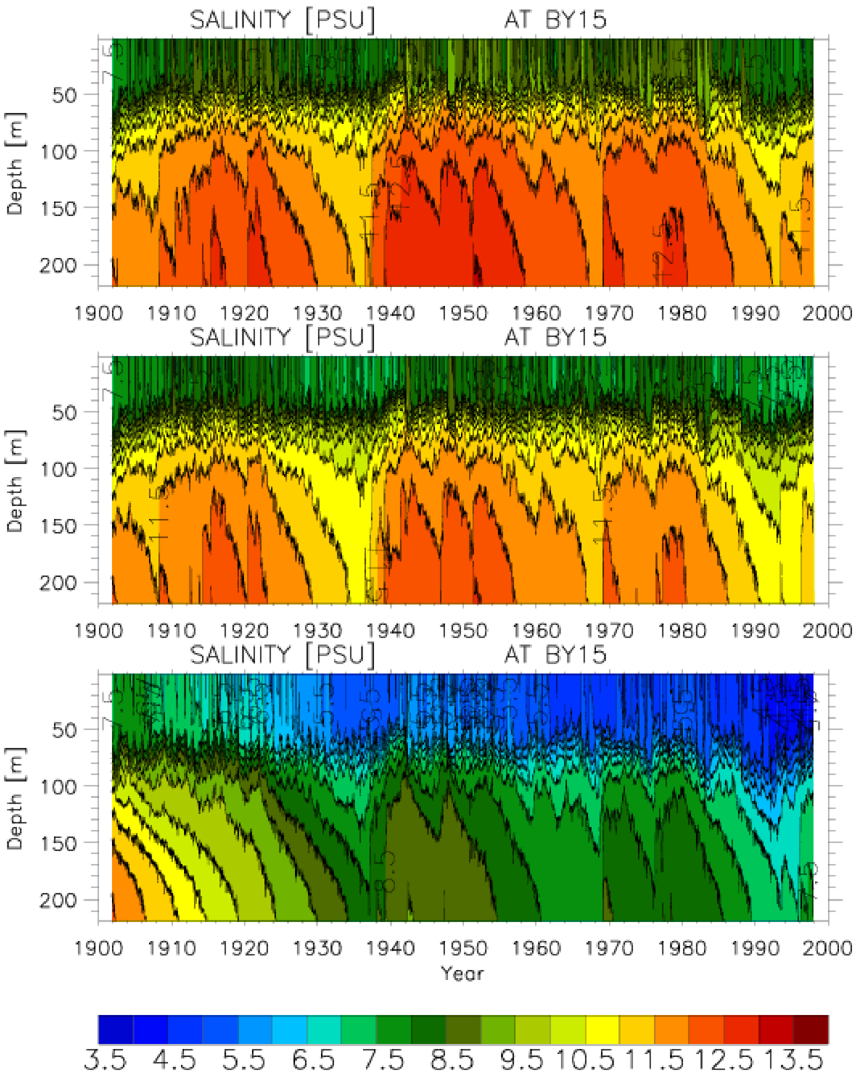


RCAO
A2
B2



Graham, 2004, *AMBIO*.

Salinity as function of depth and time at Gotland Deep



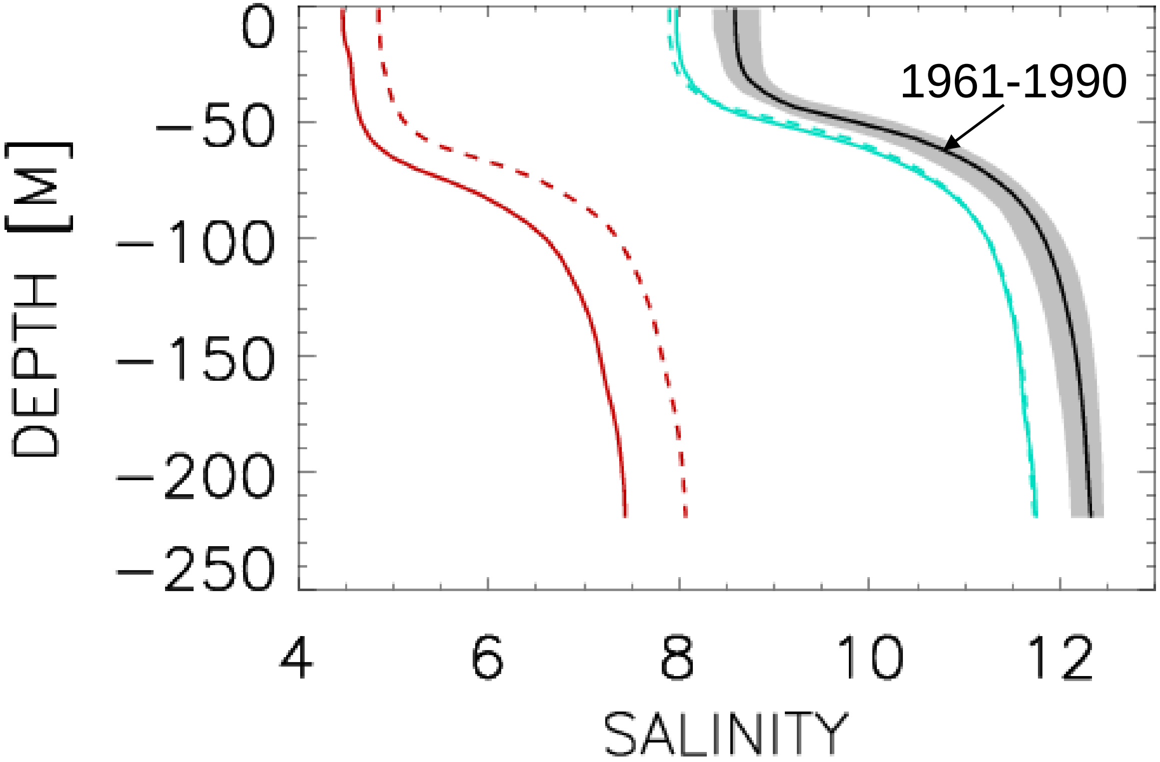
Hindcast
1902-1998

RCO-H/B2 (runoff change +3%)

RCO-E/B2 (runoff change +17%)

(Meier, 2005b)

Median salinity profiles for 1961-1990 and 2071-2100 at Gotland Deep



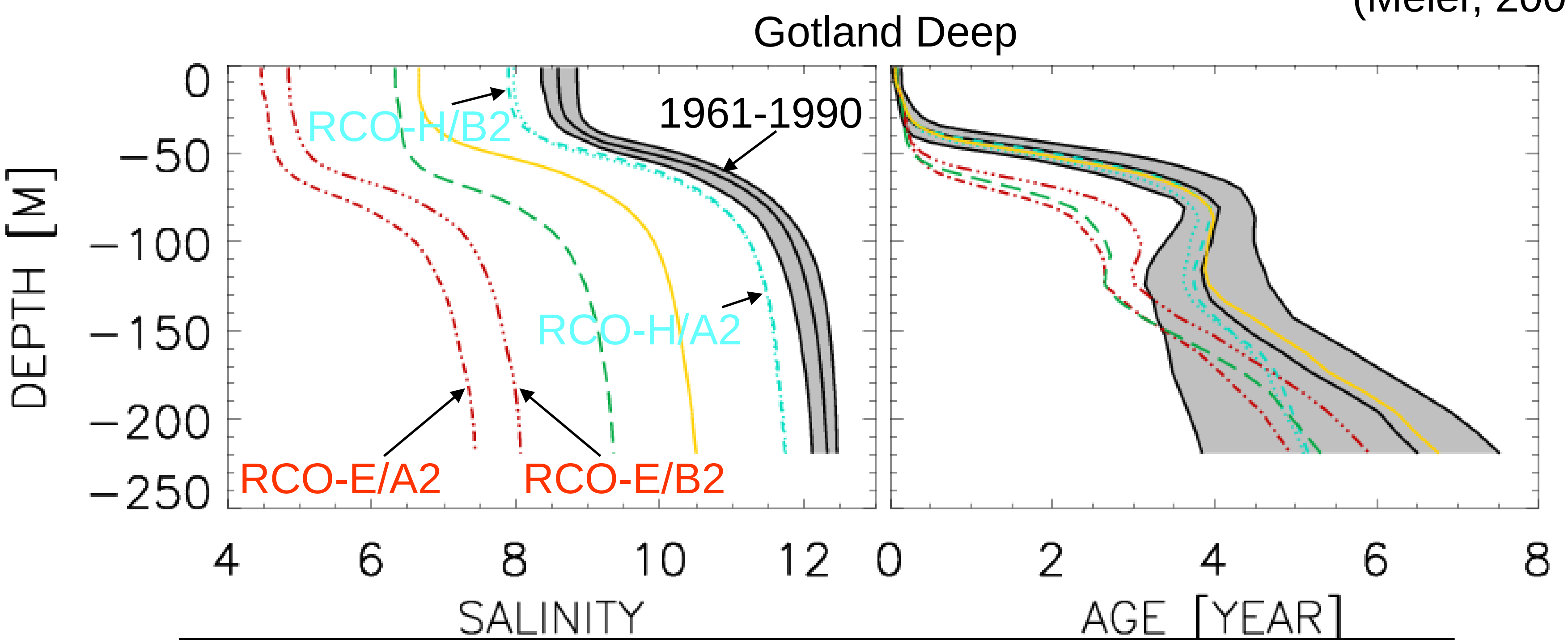
Present climate (median, 1. and 3. quartiles)

RCO-H/B2, A2 scenarios

RCO-E/B2, A2 scenarios

Median salinity and age profiles for 1961-1990 at Gotland Deep

(Meier, 2005b)

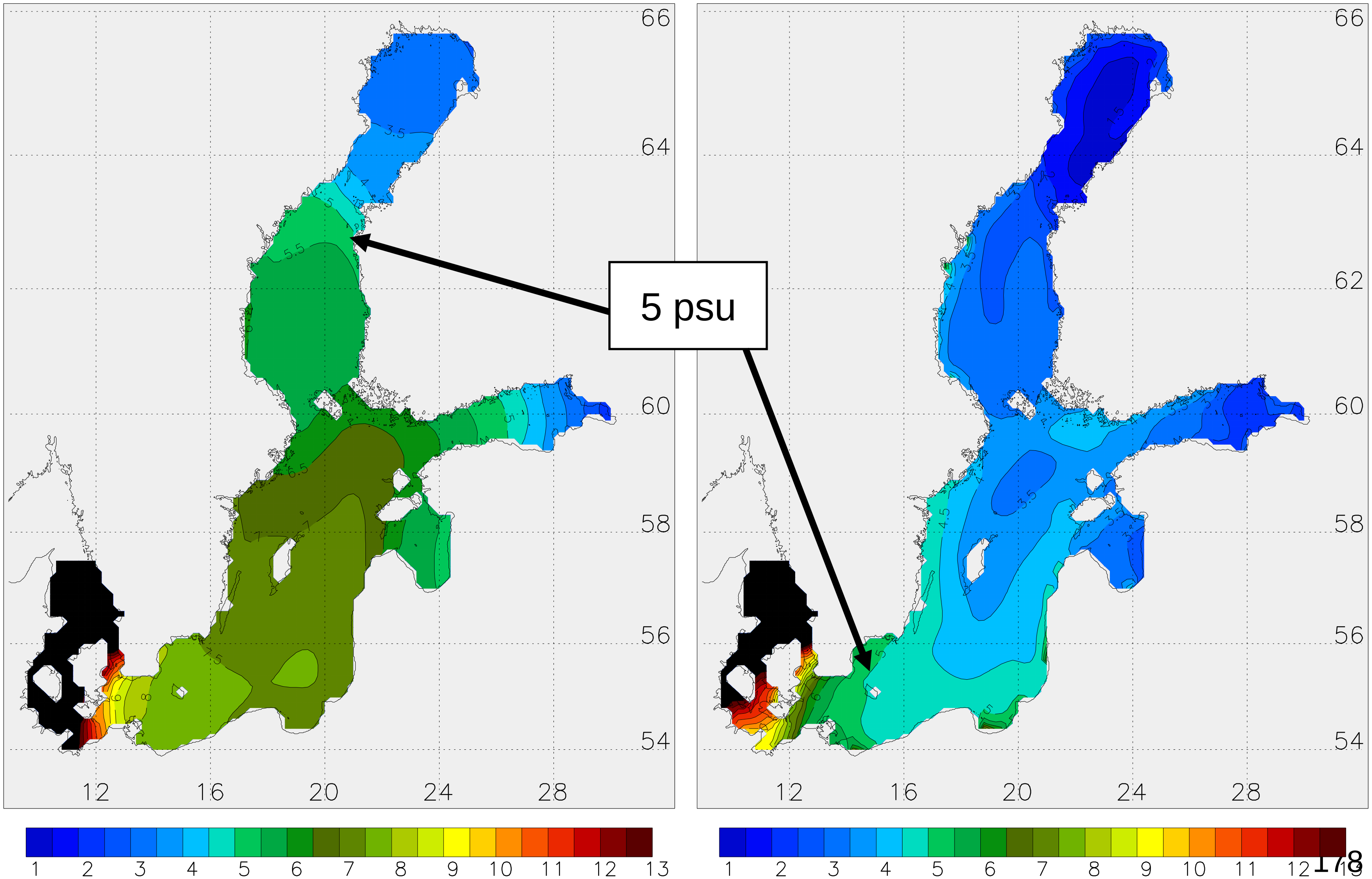


Present climate (median, 1. and 3. quartiles)
RCO-H/B2, A2 scenarios
RCO-E/B2, A2 scenarios
RCO-E/A2 but only freshwater inflow change
RCO-E/A2 but only wind and SLP changes

Sea surface salinity

Present climate

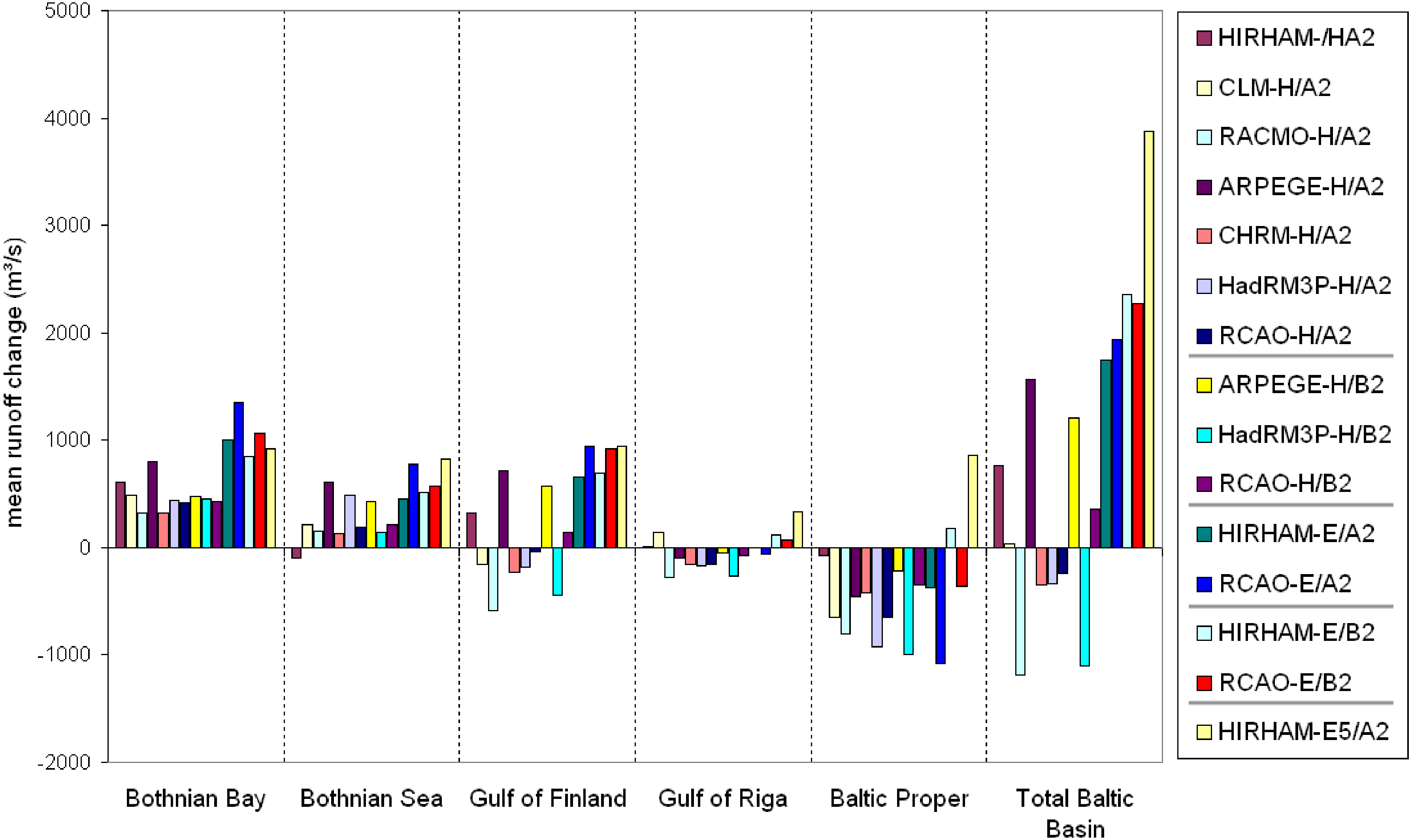
Projection with the largest change
RCAO-ECHAM4/A2



Meier et al. (2006)

Run	RCM	GCM	Scenario	SST and sea ice
1	HIRHAM	HadAM3H	A2	HCSST
2	CLM	HadAM3H	A2	HCSST
3	RACMO	HadAM3H	A2	HCSST/RCO
4	CHRM	HadAM3H	A2	HCSST
5	RCAO	HadAM3H	A2	RCO
6	RCAO	HadAM3H	B2	RCO
7	HadRM3H	HadAM3H	A2	HCSST
8	HadRM3P	HadAM3P	A2	HCSST
9	HadRM3P	HadAM3P	B2	HCSST
10	-	ARPEGE	A2	Obs/HadCM3
11	-	ARPEGE	B2	Obs/HadCM3
12	HIRHAM	ECHAM4	A2	OPYC3
13	HIRHAM	ECHAM4	B2	OPYC3
14	RCAO	ECHAM4	A2	RCO
15	RCAO	ECHAM4	B2	RCO
16	HIRHAM	ECHAM5	A2	HCSST

Mean Annual Change in Runoff



(Source: Phil Graham, SMHI)

Salinity at Gotland Deep

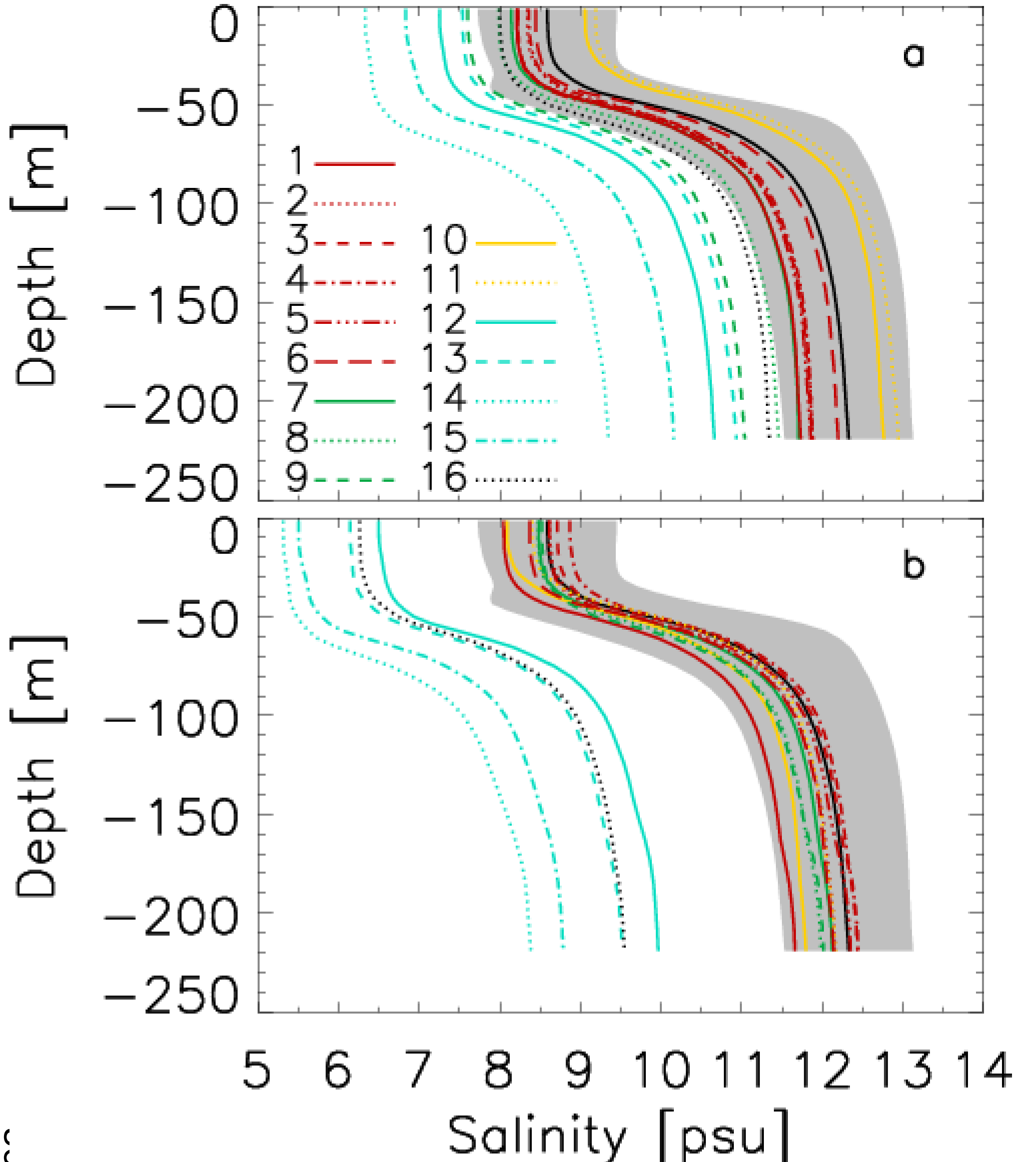


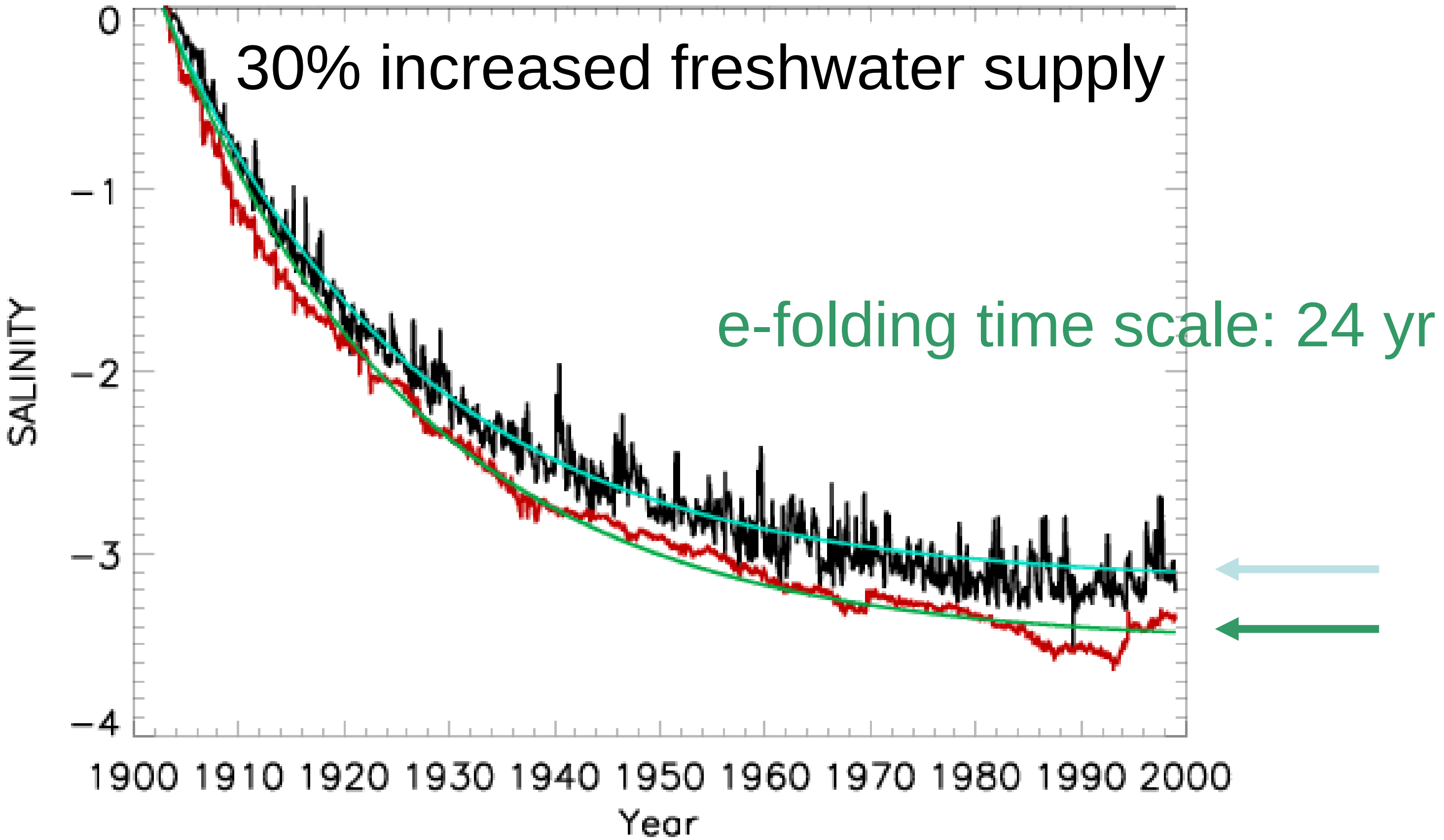
Figure 1. Median profiles of salinity at monitoring station BY15 for present climate 1961-1990 (black solid line, shaded areas indicate the +/- 2 standard deviation band calculated from two-daily values for 1903-1998) and in projections for 2071-2100 (colored lines). In (a) only effects from wind changes 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).

“Quasi” steady-state sensitivity experiments:

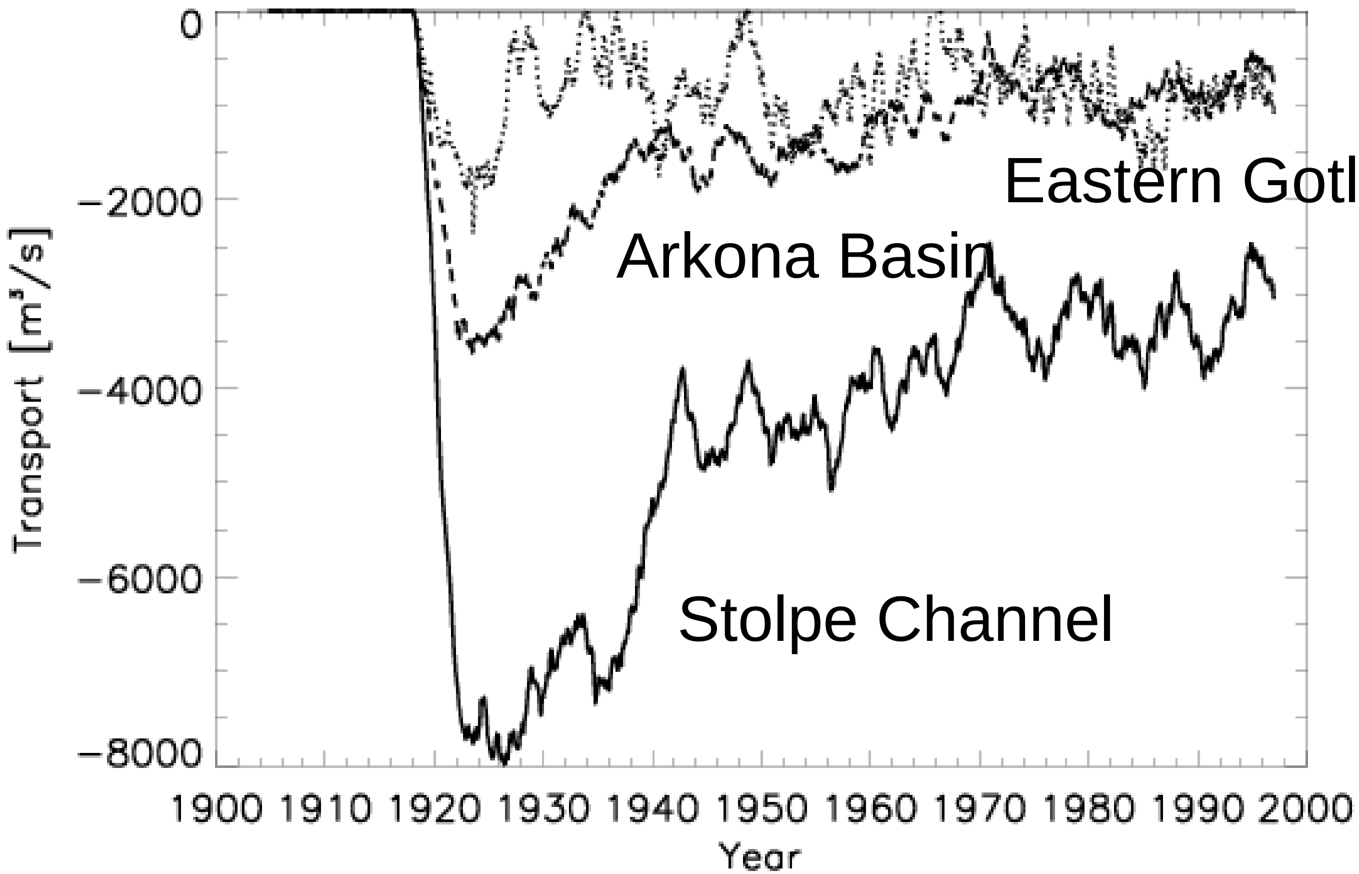
increased or reduced:

- freshwater inflow
- wind speed
- sea level in Kattegat

Anomaly of surface (black) and bottom (red) salinity at Gotland Deep



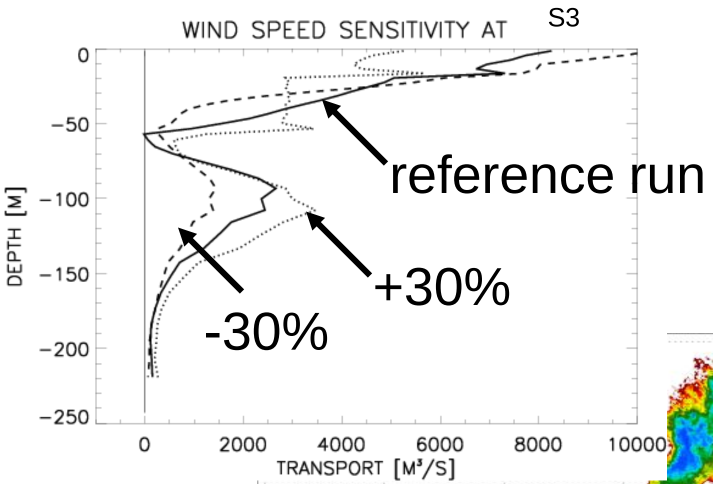
Volume flow anomaly into the deepwater

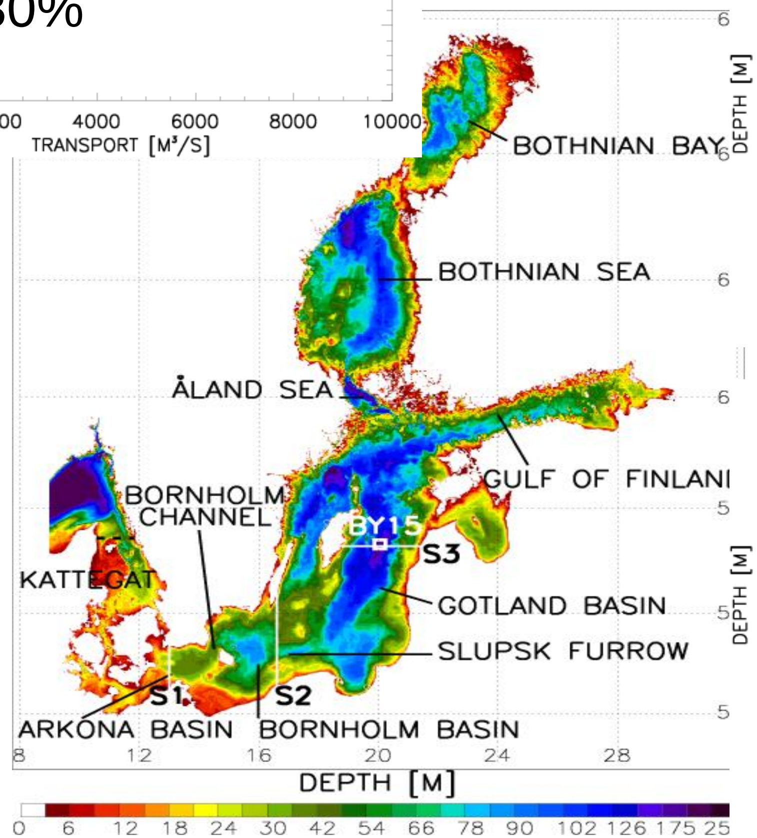


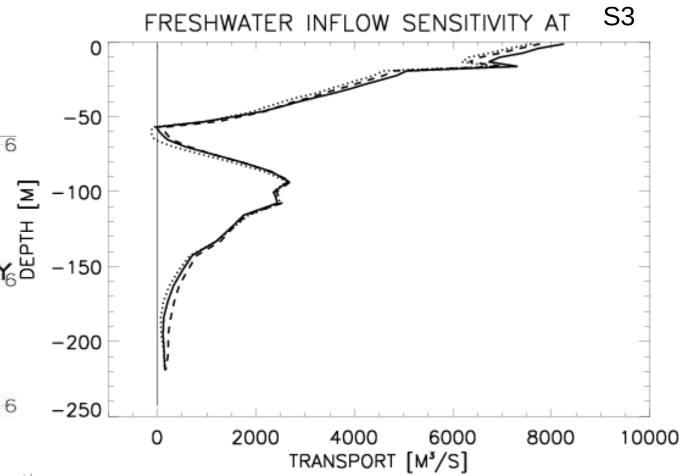
Note: similarities/differences to AMOC (Atlantic Meridional Overturning Circulation)

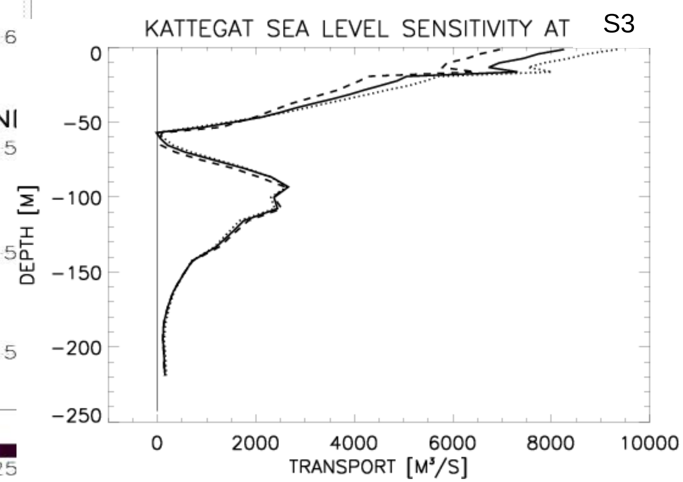
(Meier, 2005)

Horizontally integrated transports

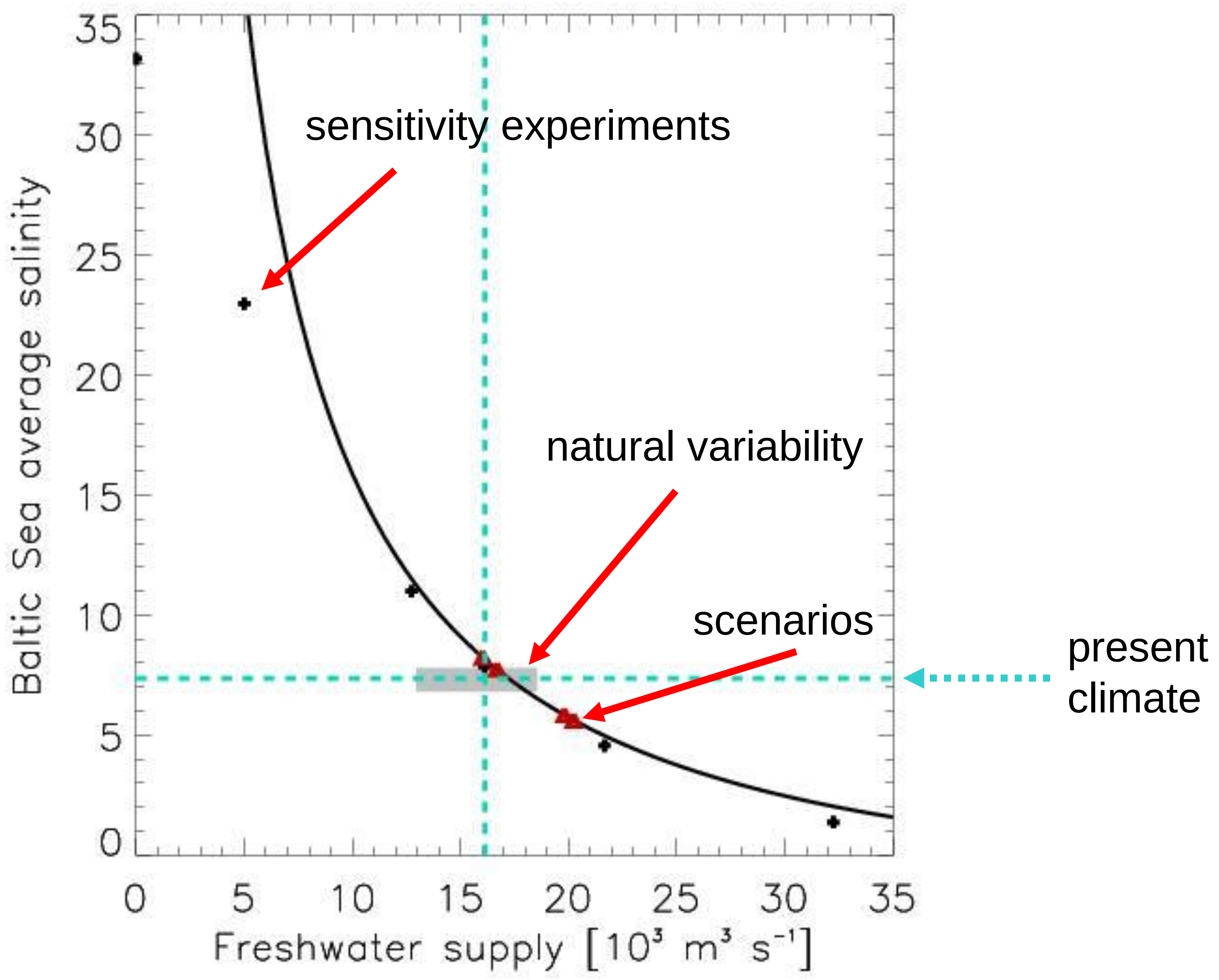






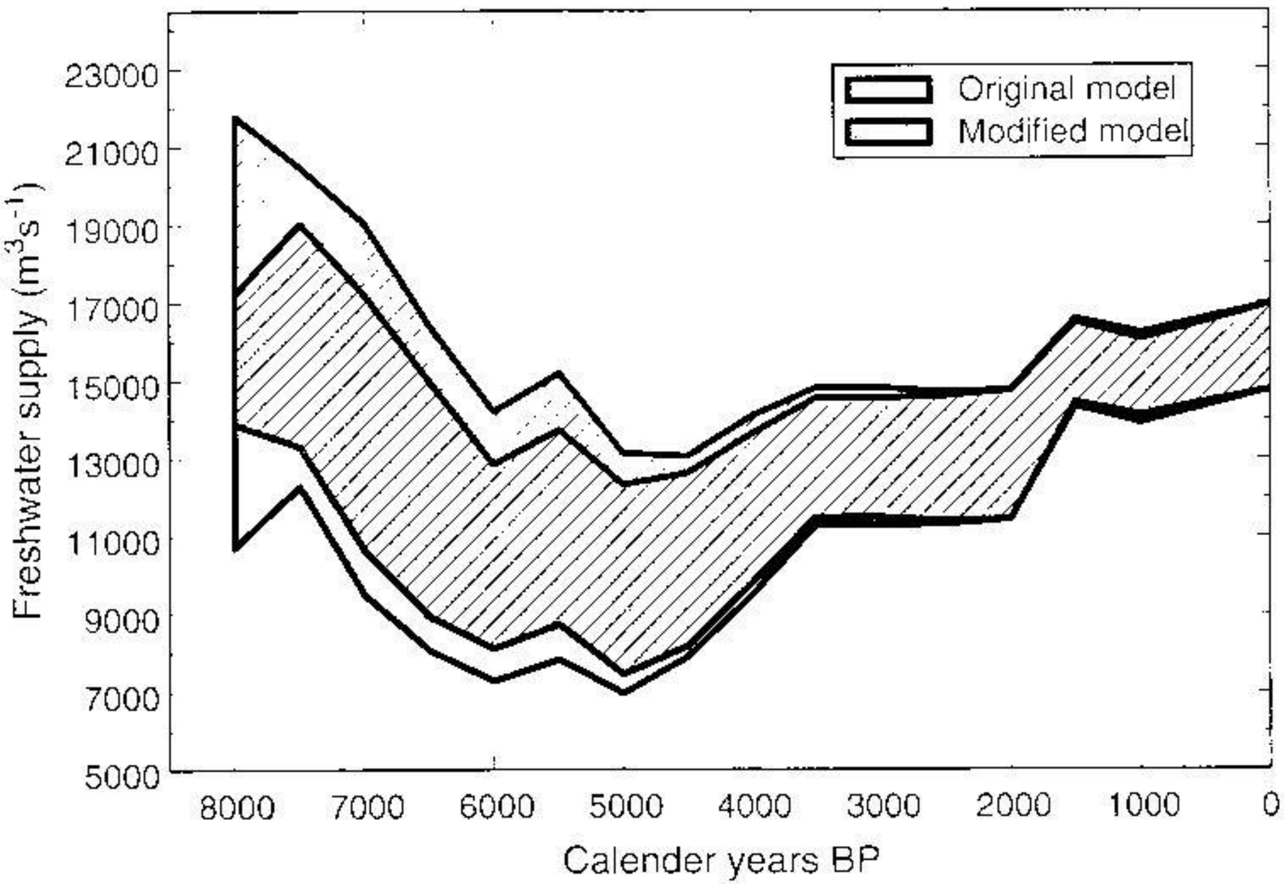


Sensitivity of salinity to the freshwater supply

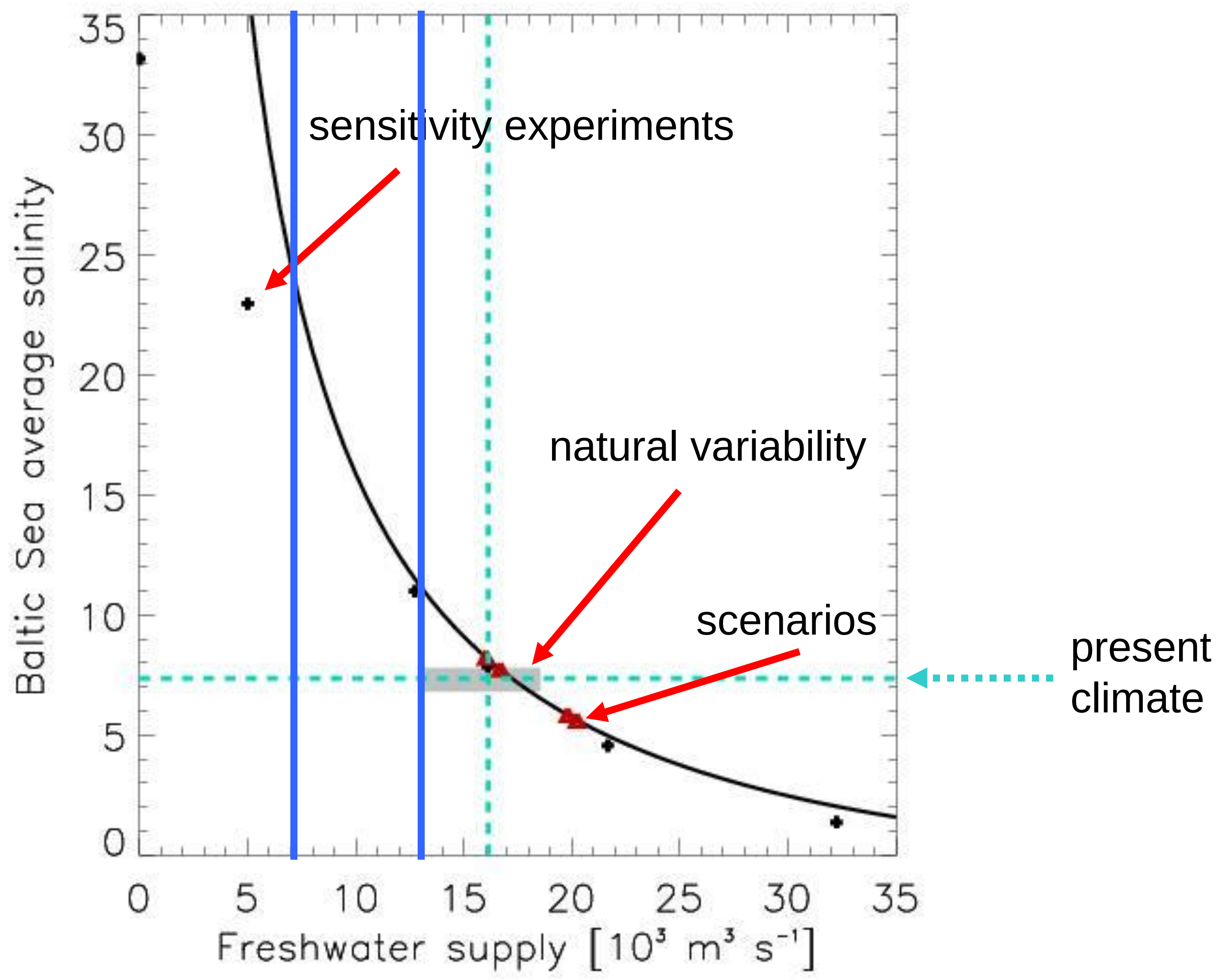


Variations in freshwater supply that is necessary to explain salinity variations derived from proxy data

(Gustafsson and Westman, 2002)

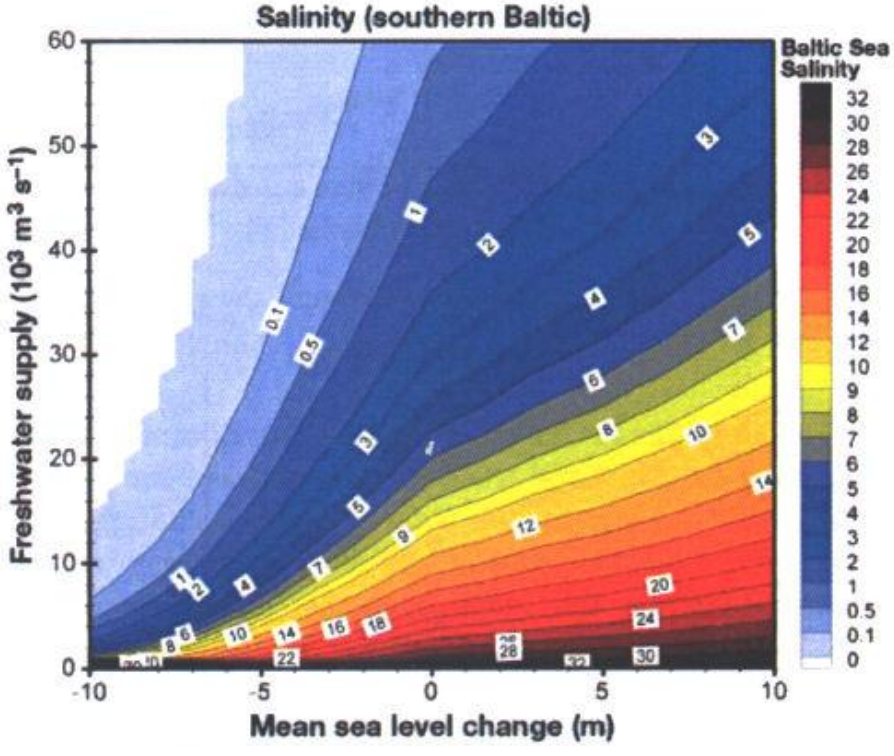


Sensitivity of salinity to the freshwater supply



Salinity in the southern Baltic proper as function of freshwater supply and mean sea level change

(Gustafsson, 2004)



Conclusions IIII

1. Changes (< 30%) of fresh- or saltwater inflow or low-frequency wind long compared to the internal response time may cause the Baltic Sea to drift into a new state with significantly changed salinity but with only slightly altered stability and deep water ventilation. The vertical overturning circulation is partially recovered. By contrast long-term changes of the high-frequency wind affect deep water ventilation significantly.

2. Although the presented salinity scenarios differ considerably (7-47%), a robust feature of future climate might be a lower salinity compared to present climate. Both projected precipitation and wind speed changes might be important.

Conclusions
(sections 16 to 18)

1. Past climate variability on daily to decadal timescale is well simulated, e.g. inflows, stagnation phases.
2. Half of the decadal variability of salinity is explained by accumulated freshwater inflow variations. Another significant part is caused by the low-frequency variability of the wind.
3. Changes of freshwater inflow and wind speed long compared to the internal response time may cause the Baltic Sea to drift into a new steady-state with significant lower salinity but with only slightly altered stability and deep water ventilation. The vertical overturning circulation is partially recovered.

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