Climate of the Baltic Sea Region

Physical Oceanography of the Baltic Sea and other regional seas

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Overview:

1. History of Baltic Sea research
2. Bottom topography
3. Water balance
4. Heat balance
5. Currents
6. Sea level
7. Temperature, salinity, density, and oxygen
8. Sea ice
9. Climate relevant processes (e.g. saltwater inflows, …)
10. Climate variability
11. Comparison with other seas

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.

References:

- The BACC Author Team (2008): Assessment of Climate Change for the Baltic Sea Basin. Series: Regional Climate Studies. Springer, Berlin, 474 pp.
- BACC II Author Team (2015). Second Assessment of Climate Change for the Baltic Sea Basin. Series: Regional Climate Studies. Springer, Berlin, 506 pp.

Links:

www.ipcc.ch

www.baltic.earth

1. History of Baltic Sea research

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

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1. totally ice covered Baltic, e.g. 1323, 1333, 1349, 1399, 1690

Carta Marina (1539)

map of Scandinavia from Olaus Magnus (1490-1557)

James Ford Bell Library, University of Minnesota

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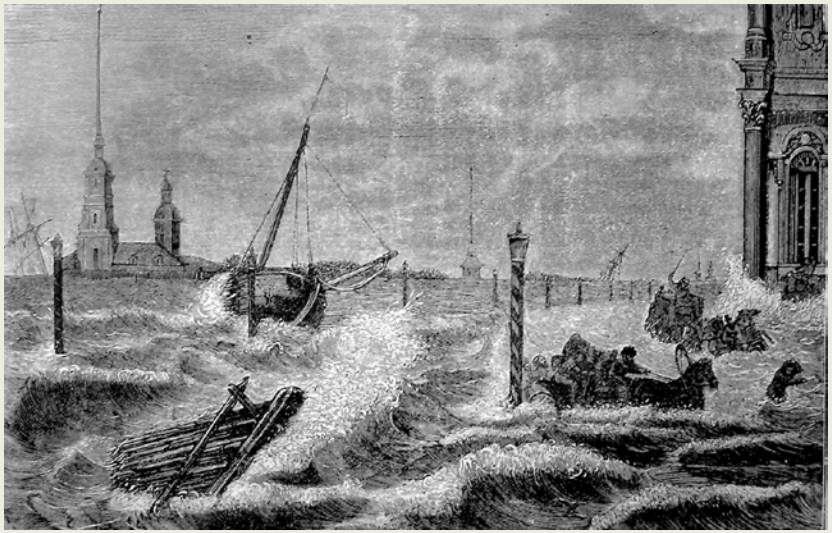
St. Petersburg

Example of an catastrophic flood:

November 1824, 4,21 m above normal
ca. 570 dead

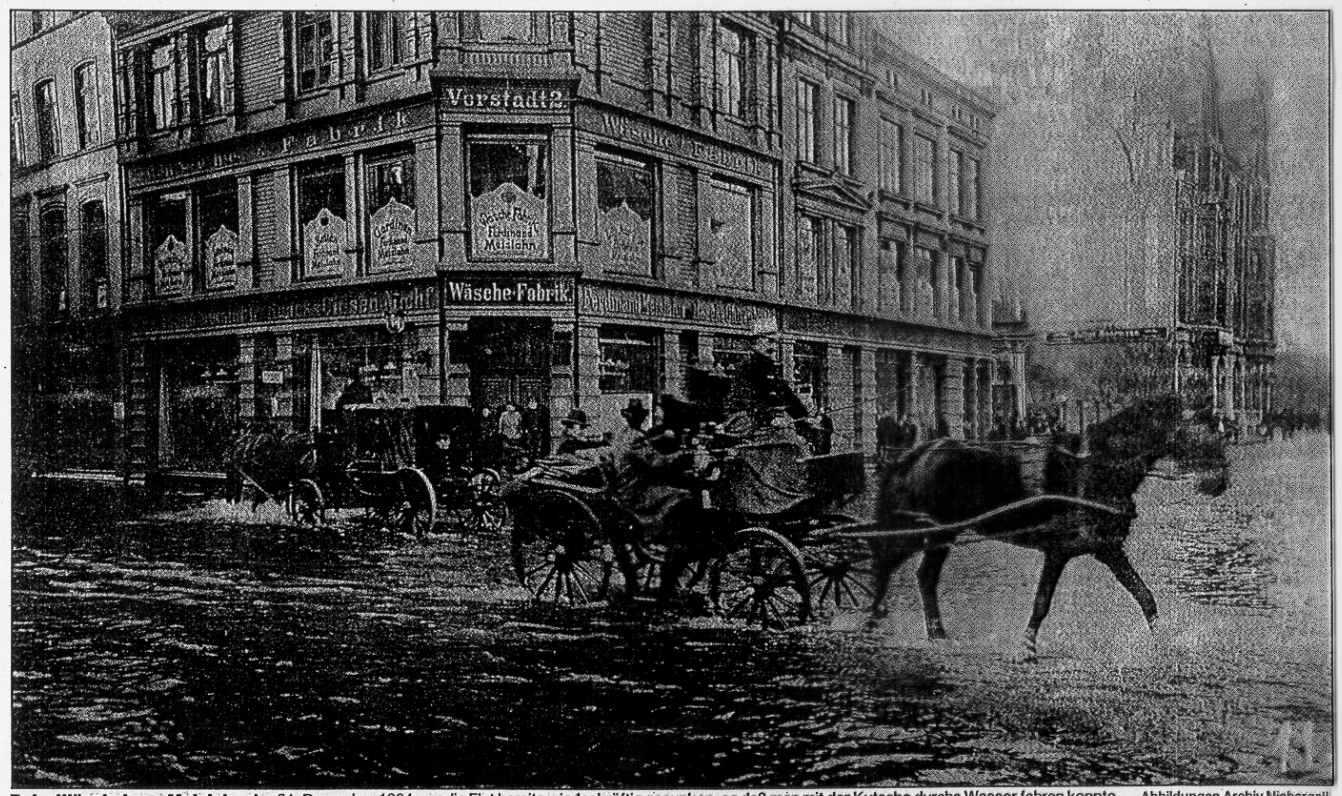


Highest sea level in Kiel 1904

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.



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

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-

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 Inseln in die Ostsee strömt. Bei

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4. Andreas Celsius (Prof in Uppsala) noticed 1724 land rise in the Bothnian Sea (but gave wrong explanation)

1. History of Baltic Sea research

- old universities with oceanographic research: St. Petersburg, Helsingfors (Helsinki), Uppsala, Königsberg (Kaliningad), Kiel, Copenhagen, Göteborg, (Kraków)

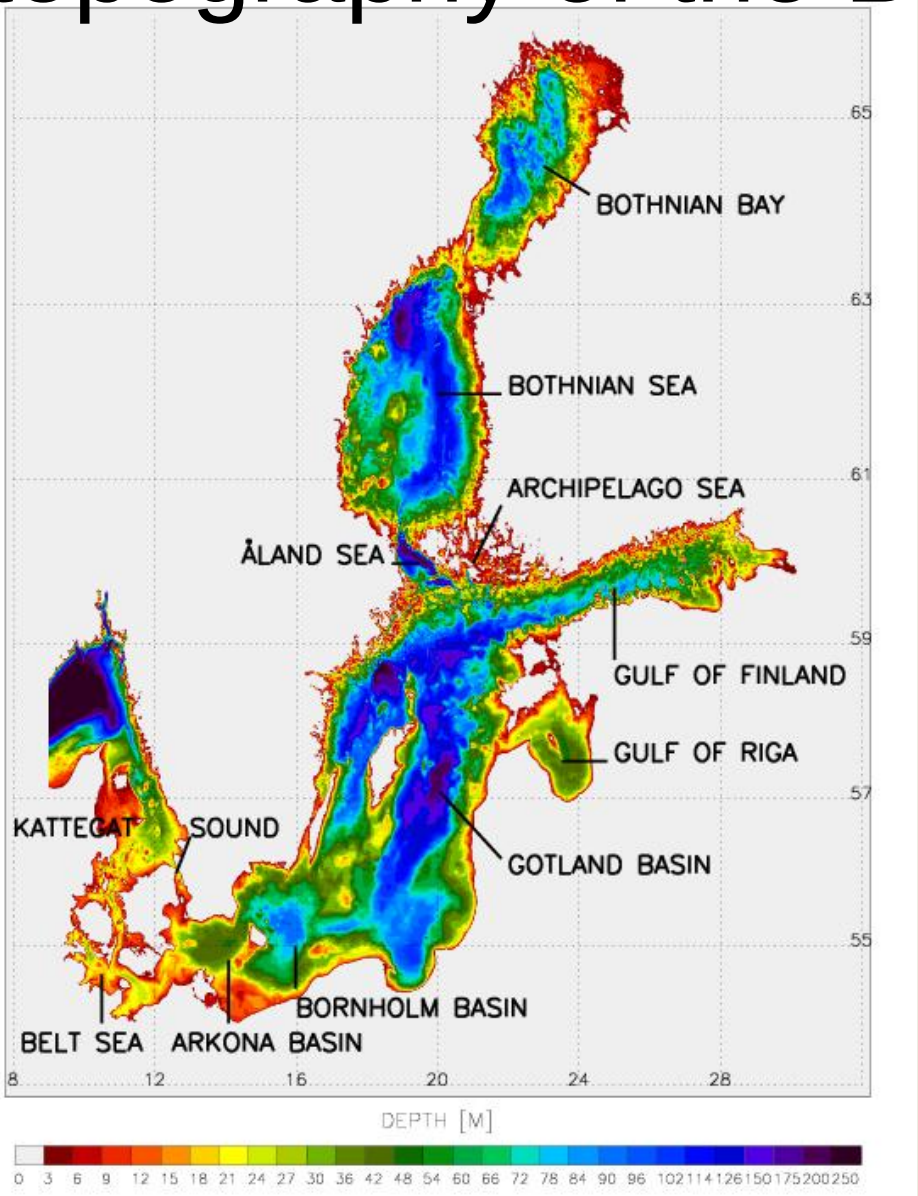
Important dates of Baltic Sea research

- 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)

Important dates of Baltic Sea research

- 1937: foundation of the Institute of Marine Research in Kiel
- 1957: first Conference of the Baltic Oceanographers (CBO) in Helsinki

2. Bottom topography of the Baltic Sea



3. Water balance of the Baltic Sea

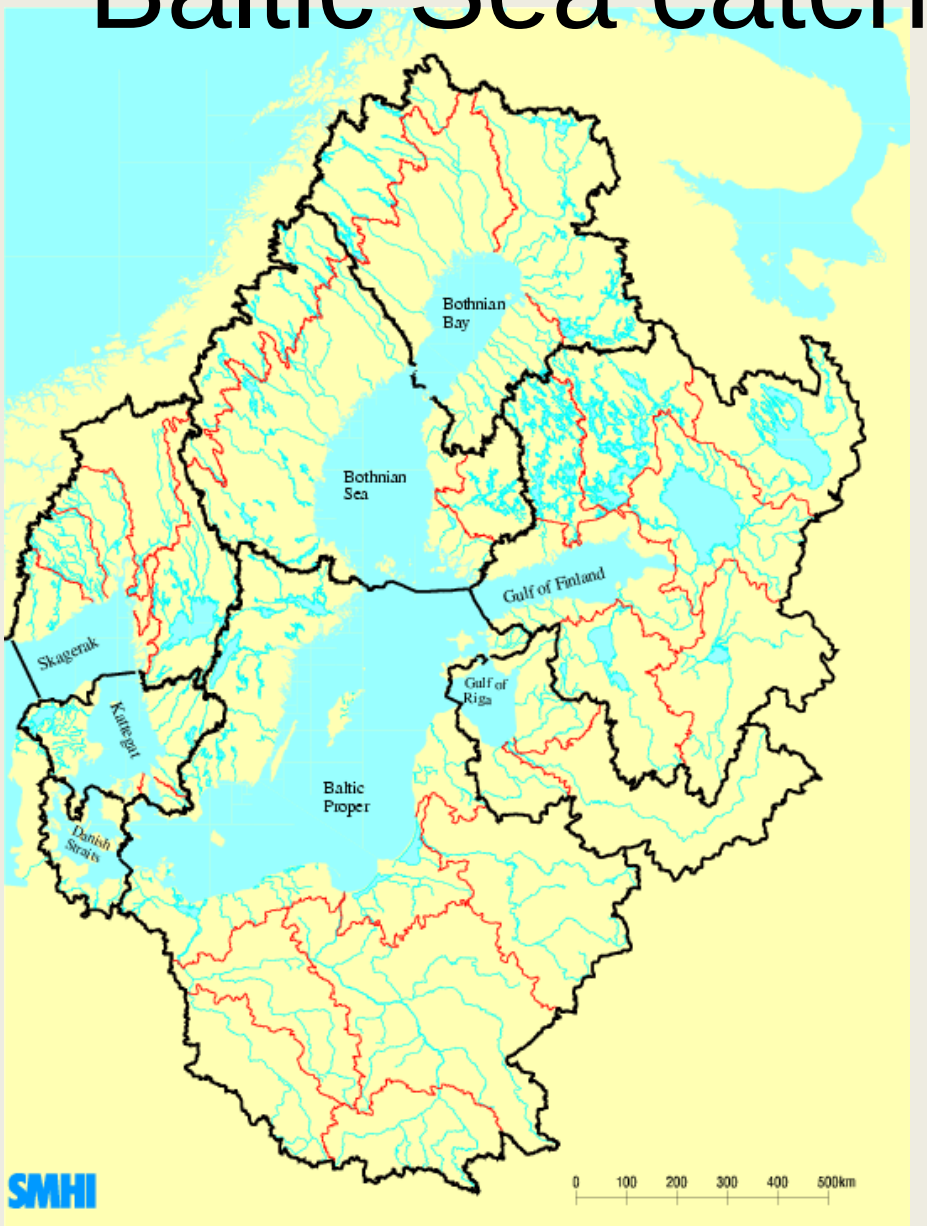
$$Q = Q_F + P - E = Q_{out} - Q_{in}$$

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

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

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

Baltic Sea catchment area

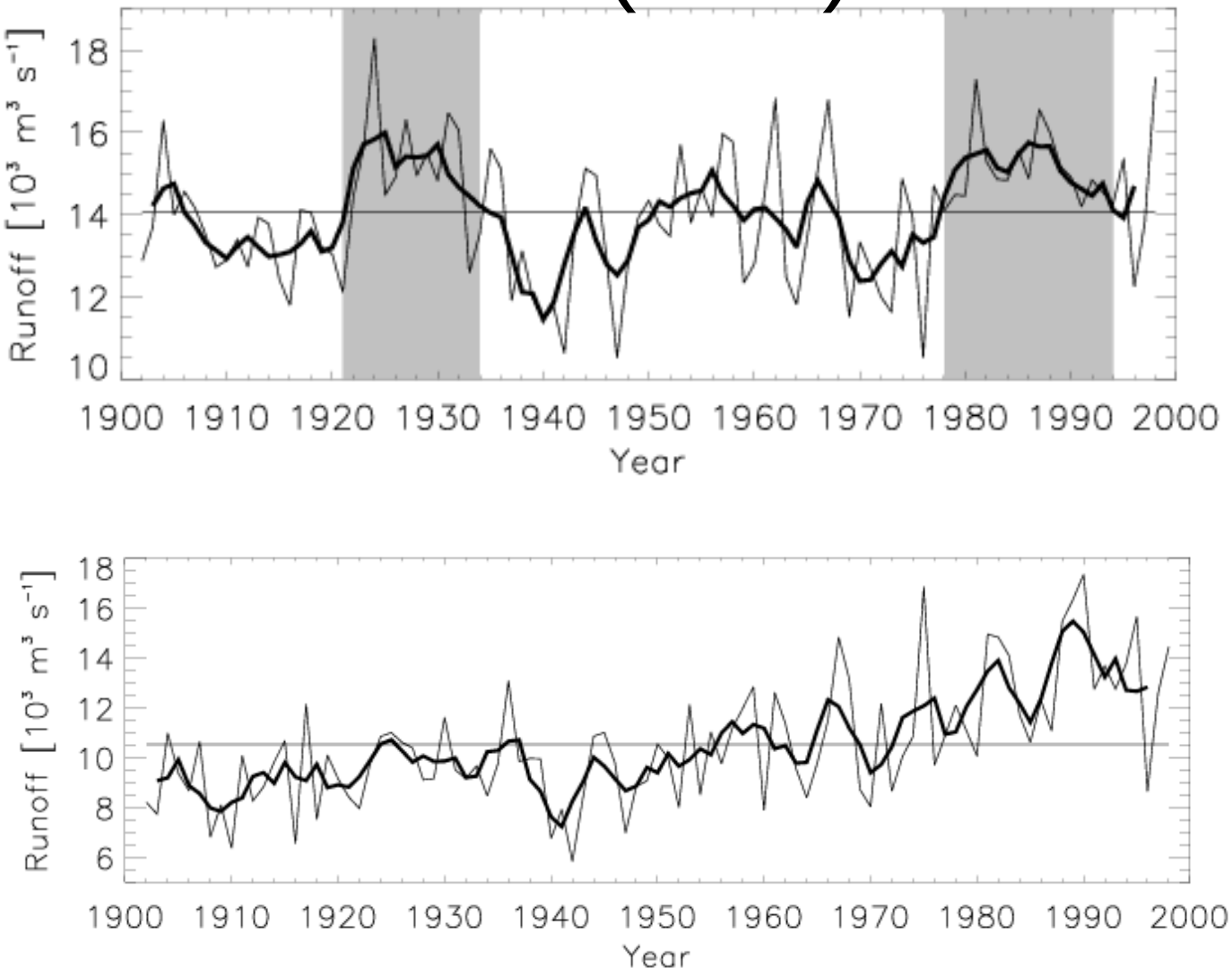


with Kattegat (without Skagerrak):
1 729 000 km^2 =
4 times Baltic Sea surface

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

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

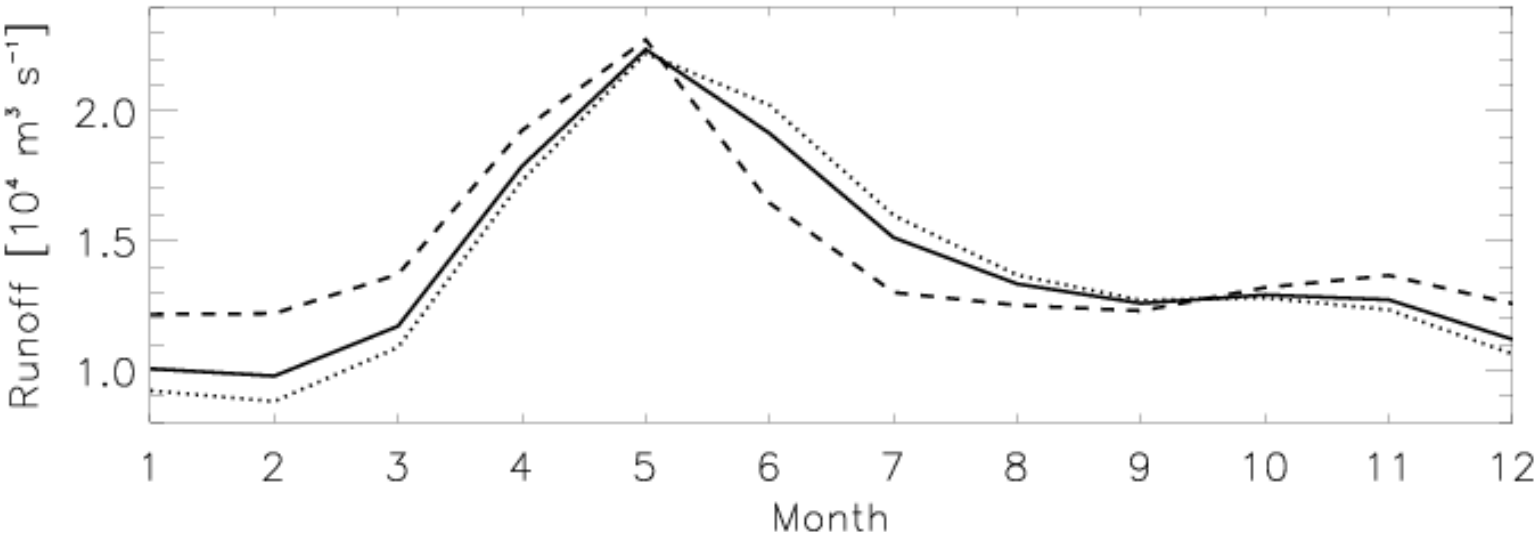
Annual and winter (JFM) mean runoff



(Meier and Kauker, 2003a)

(thick line: 4-year running mean runoff)

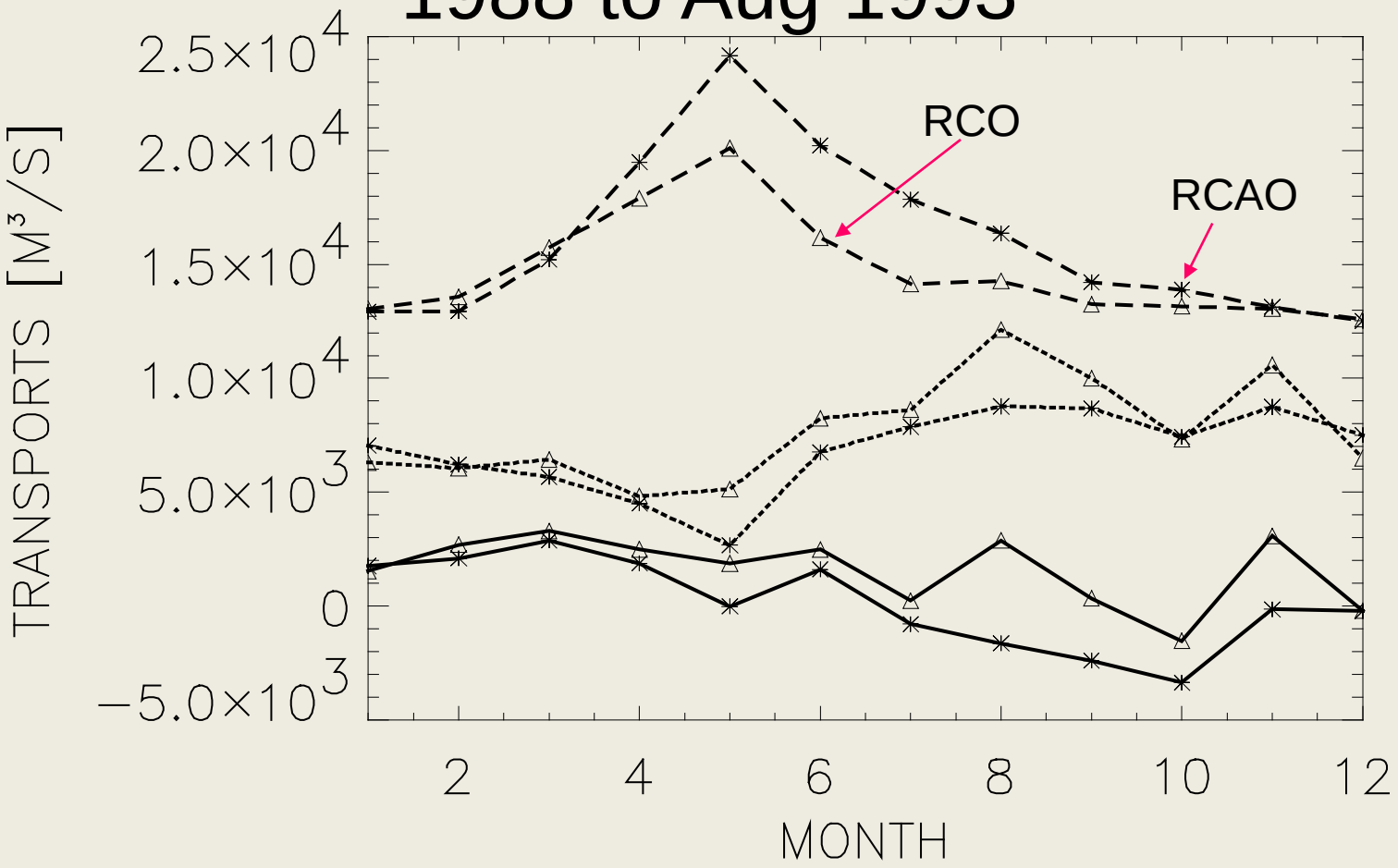
Monthly mean runoff to the Baltic without Kattegat



(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



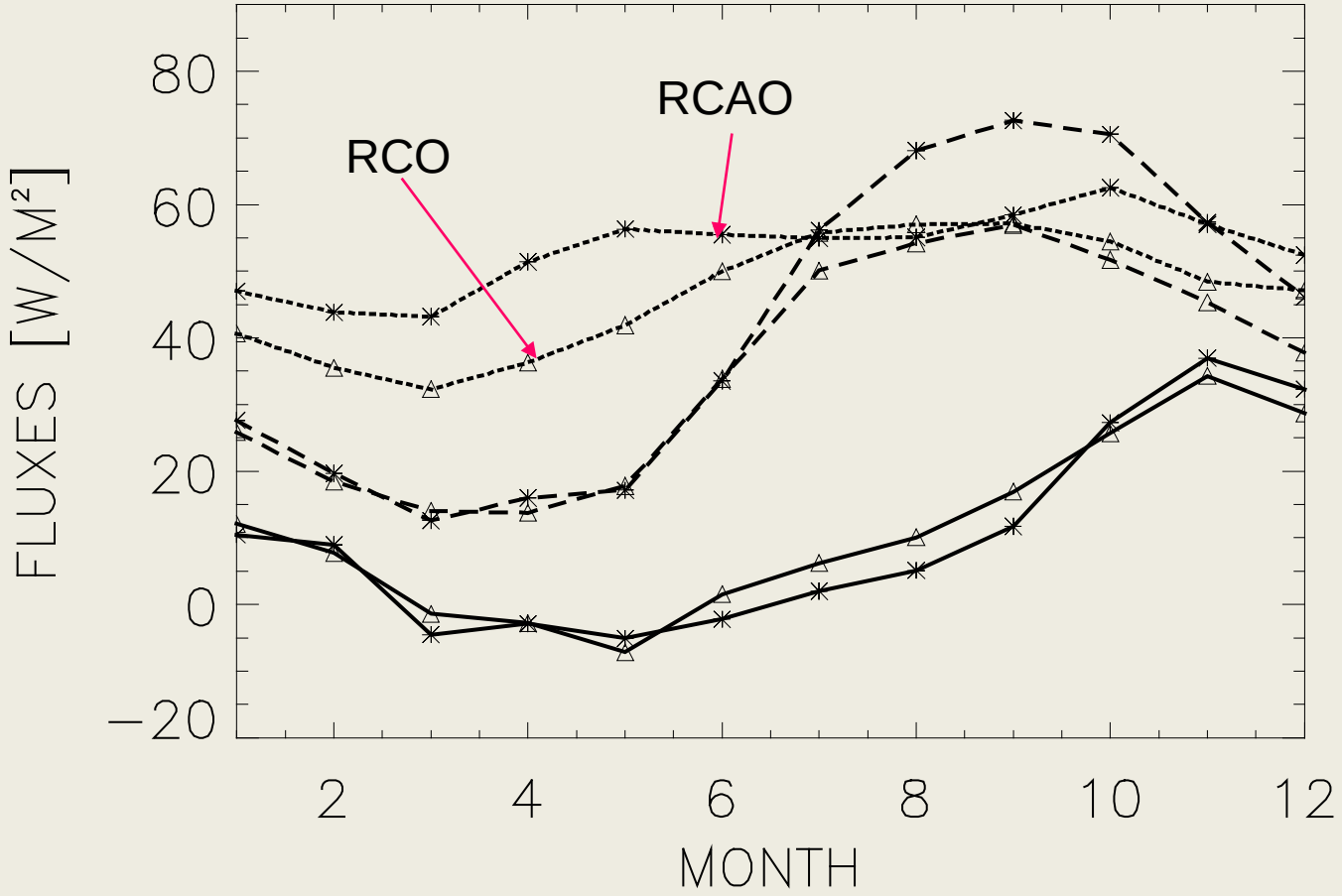
4. Heat balance

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

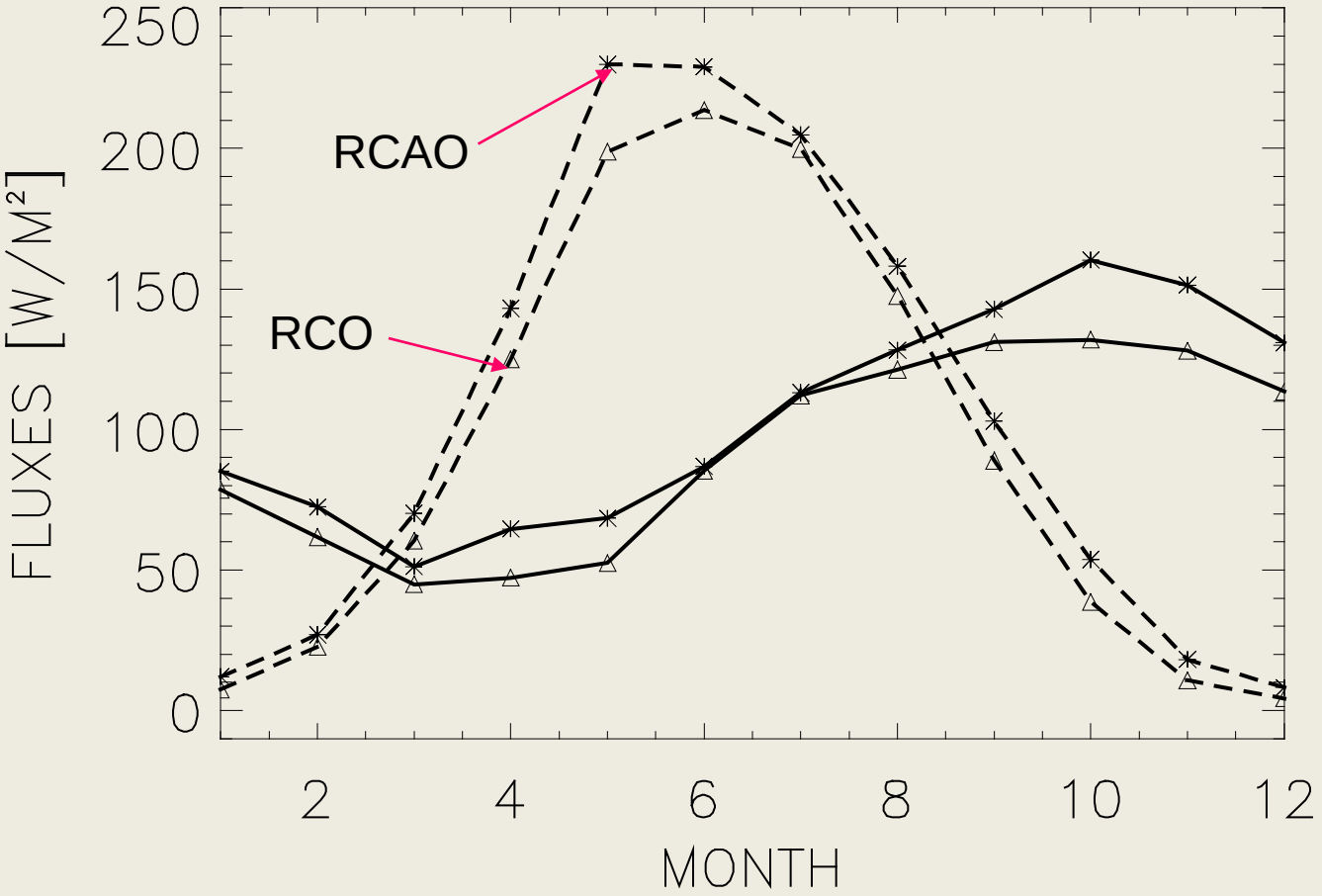
$Q_{SW} = 90\ \mathrm{Wm}^{-2}$	short - wave radiation
$Q_{LW} = -45\mathrm{Wm}^{-2}$	long - wave radiation
$Q_S = -12\mathrm{Wm}^{-2}$	sensible heat flux
$Q_L = -32\mathrm{Wm}^{-2}$	latent heat flux
$Q_a = 1\mathrm{Wm}^{-2}$	net atmospheric heat flux

Exercise: What are bulk formulae?

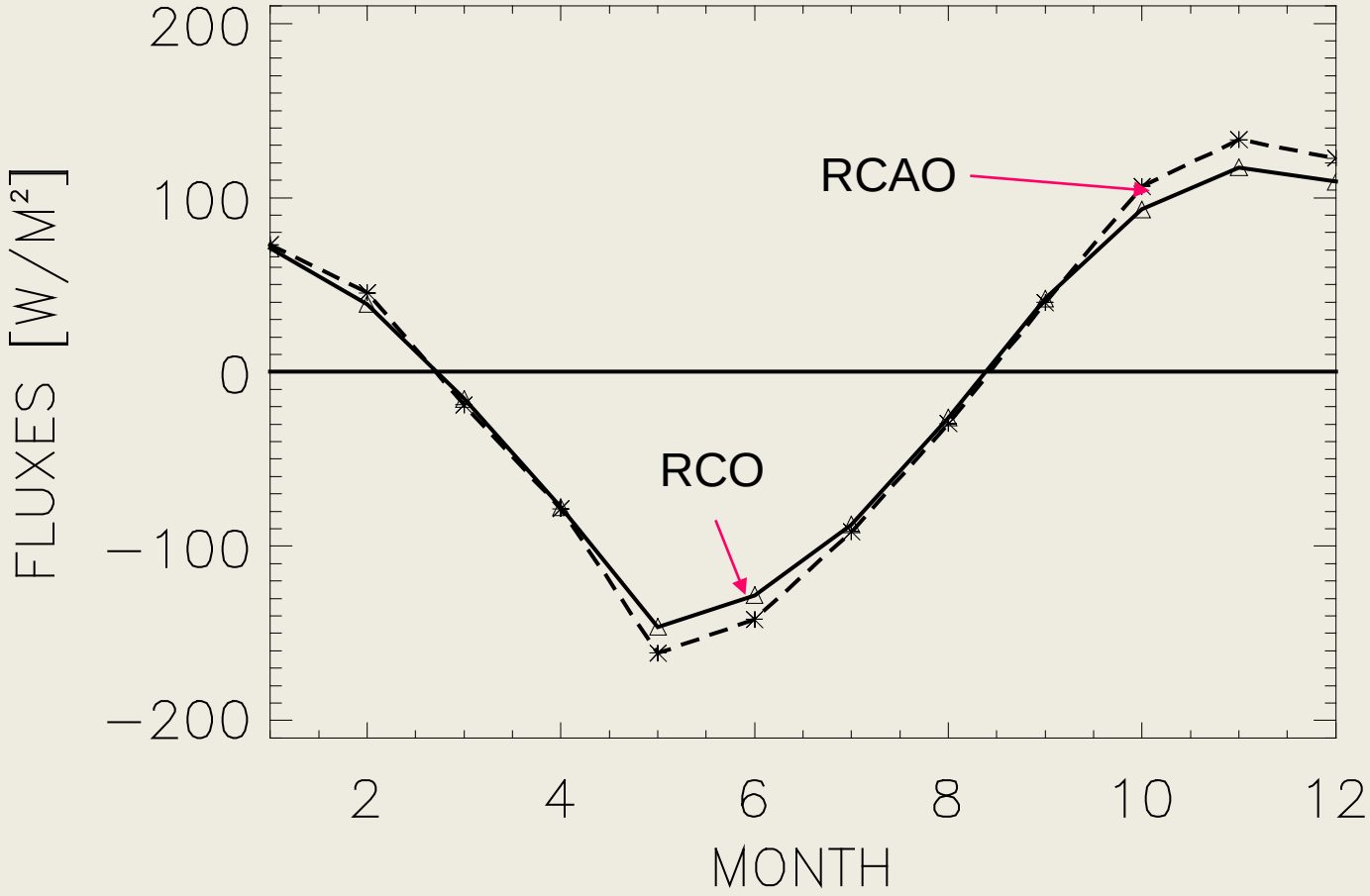
Monthly mean sensible (solid) and latent (dashed) heat flux, and long-wave radiation (dotted)



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



Monthly mean total heat flux



5. Currents

- only permanent current: Baltic current

10-year mean stream function of the vertical integrated flow

Lehmann and Hinrichsen (2000)

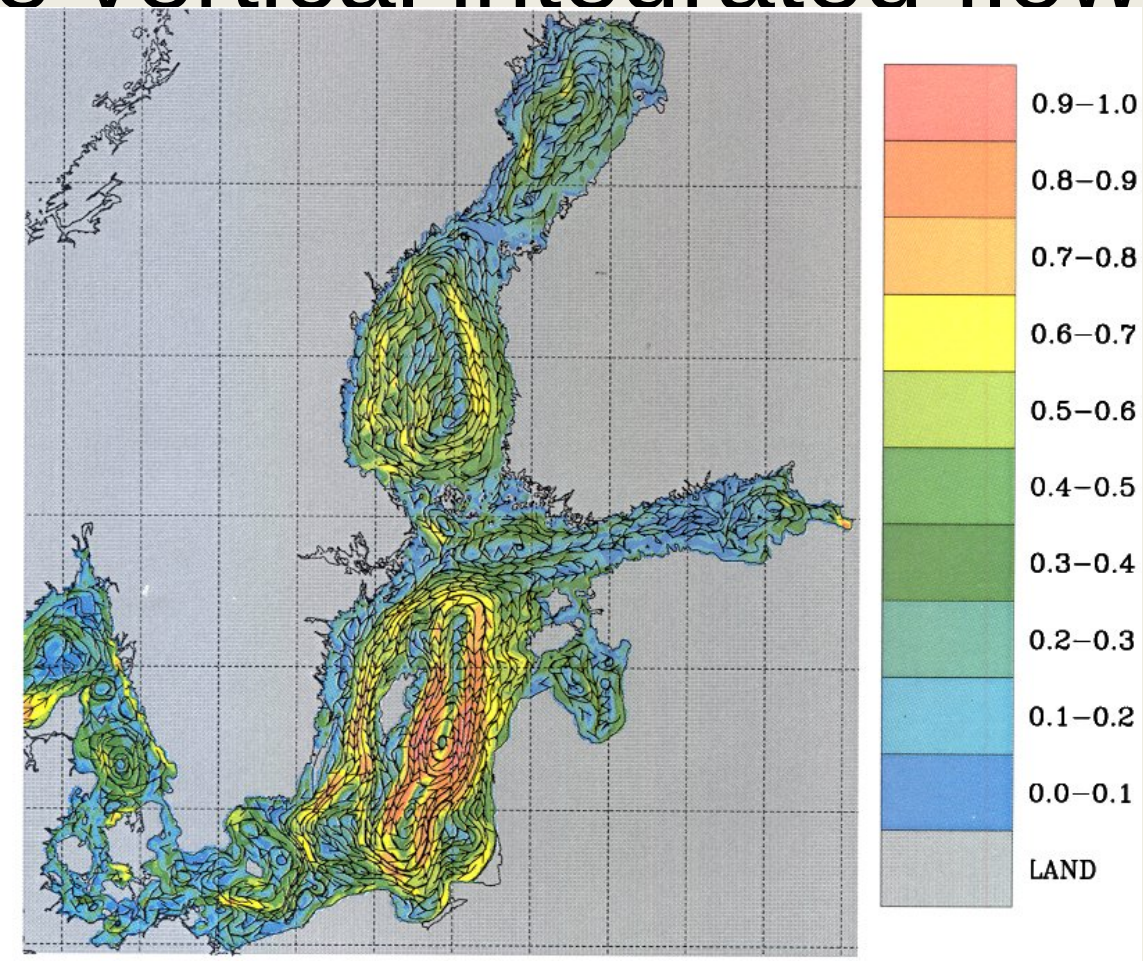
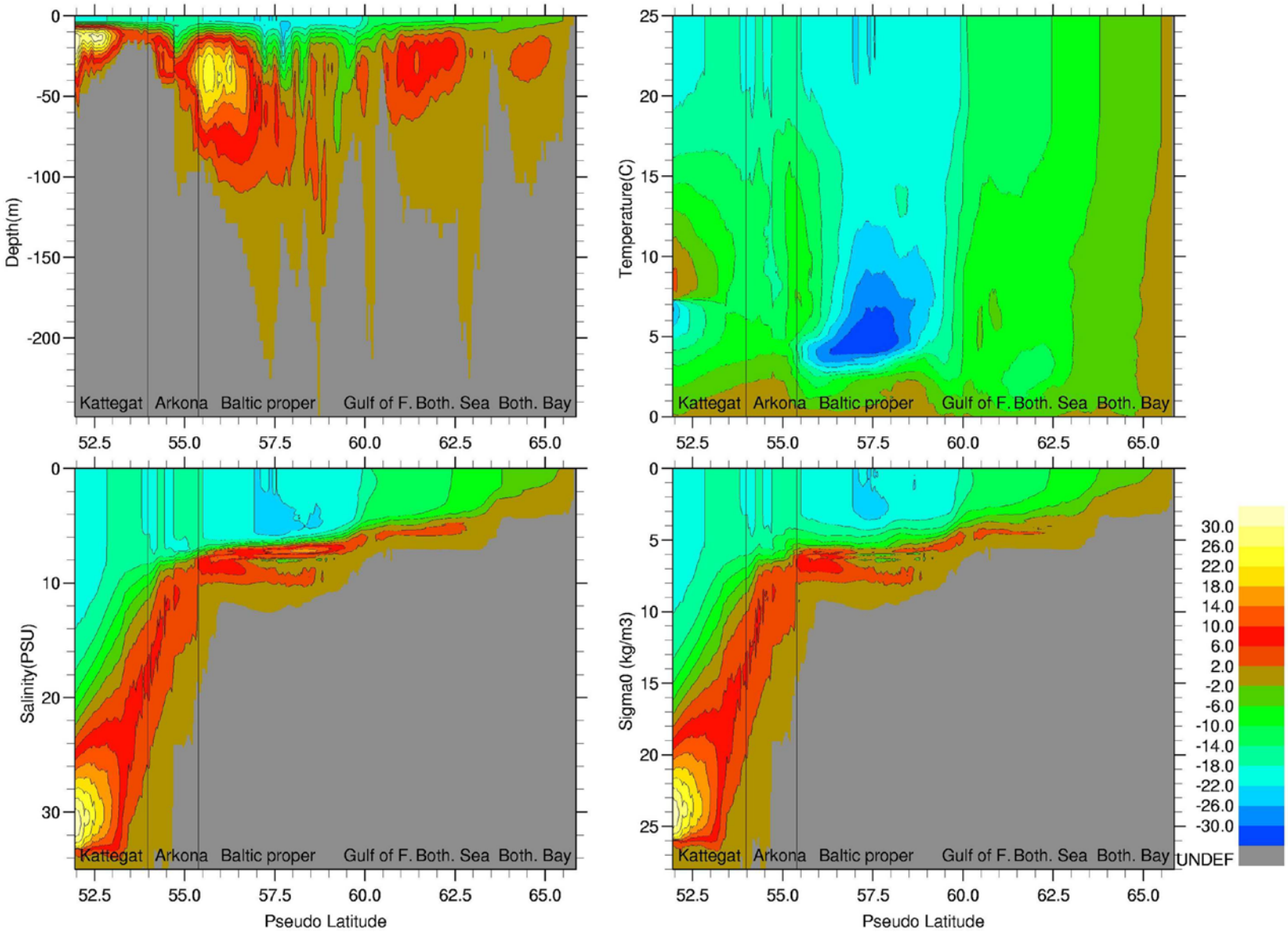


Figure 2: Streamlines representation of the 10-years average of the barotropic circulation underlayed with the stability of the barotropic flow. Colour bar represents stability values 0-1.



Overturning stream function

Döös et al. (2004)

Satellite image of SST

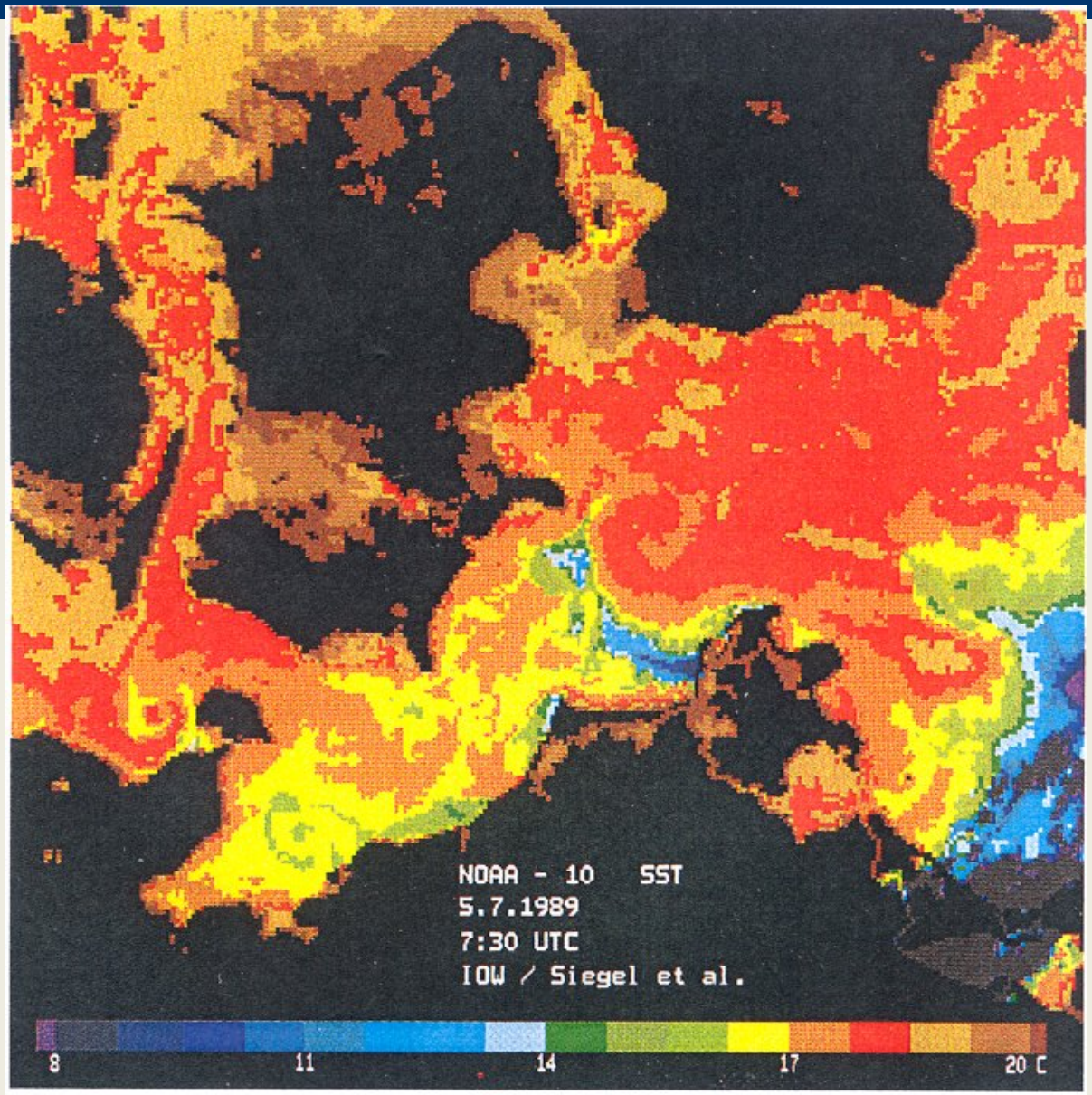


Abb. 25. Satellitenaufnahme der Wasseroberflächentemperatur in der westlichen Ostsee

Satellite image of chlorophyll

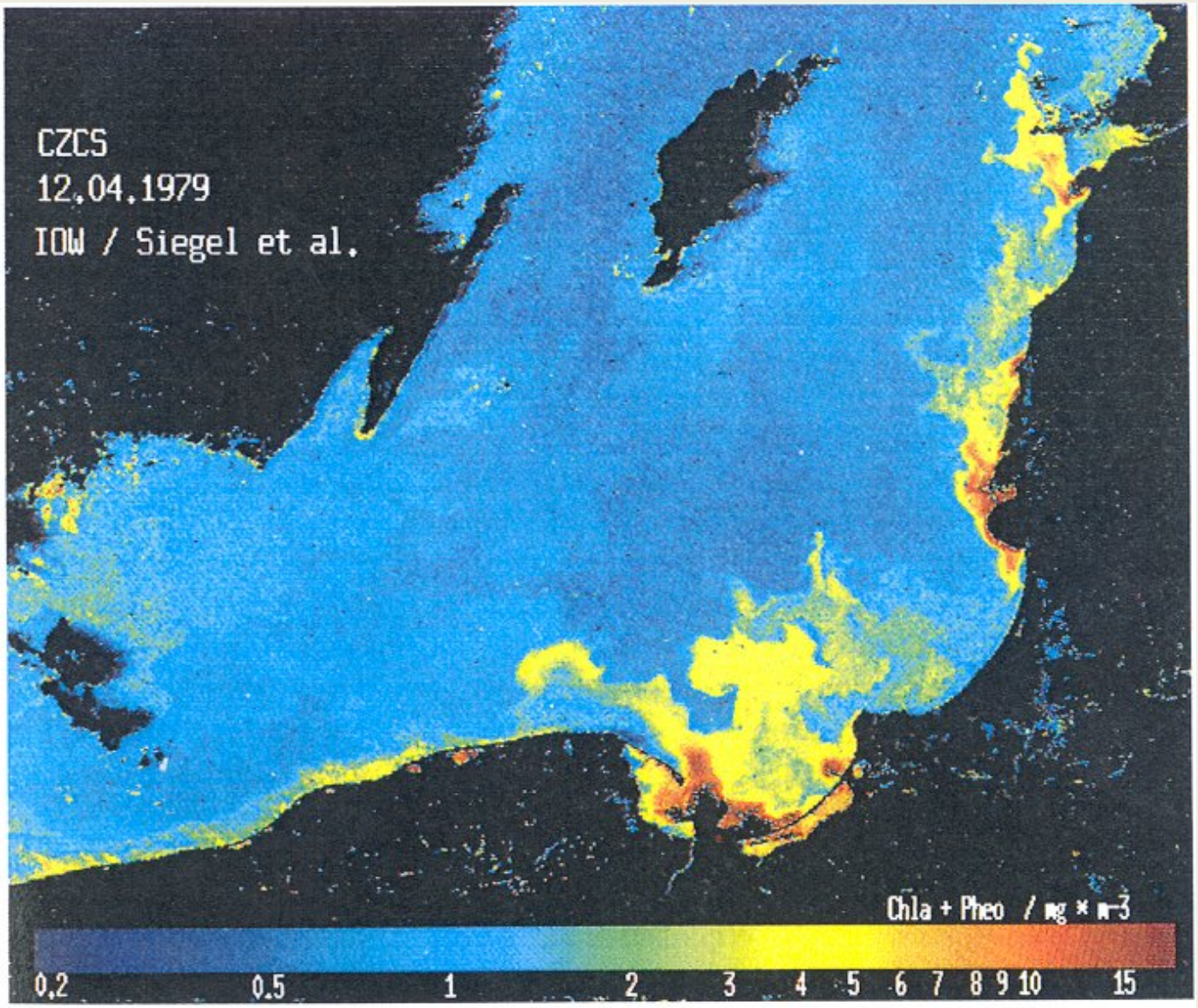


Abb. 26. Satellitenaufnahme der Chlorophyll-Verteilung in der eigentlichen Ostsee

6. Sea level

- tides:

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

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

Semi-diurnal tides

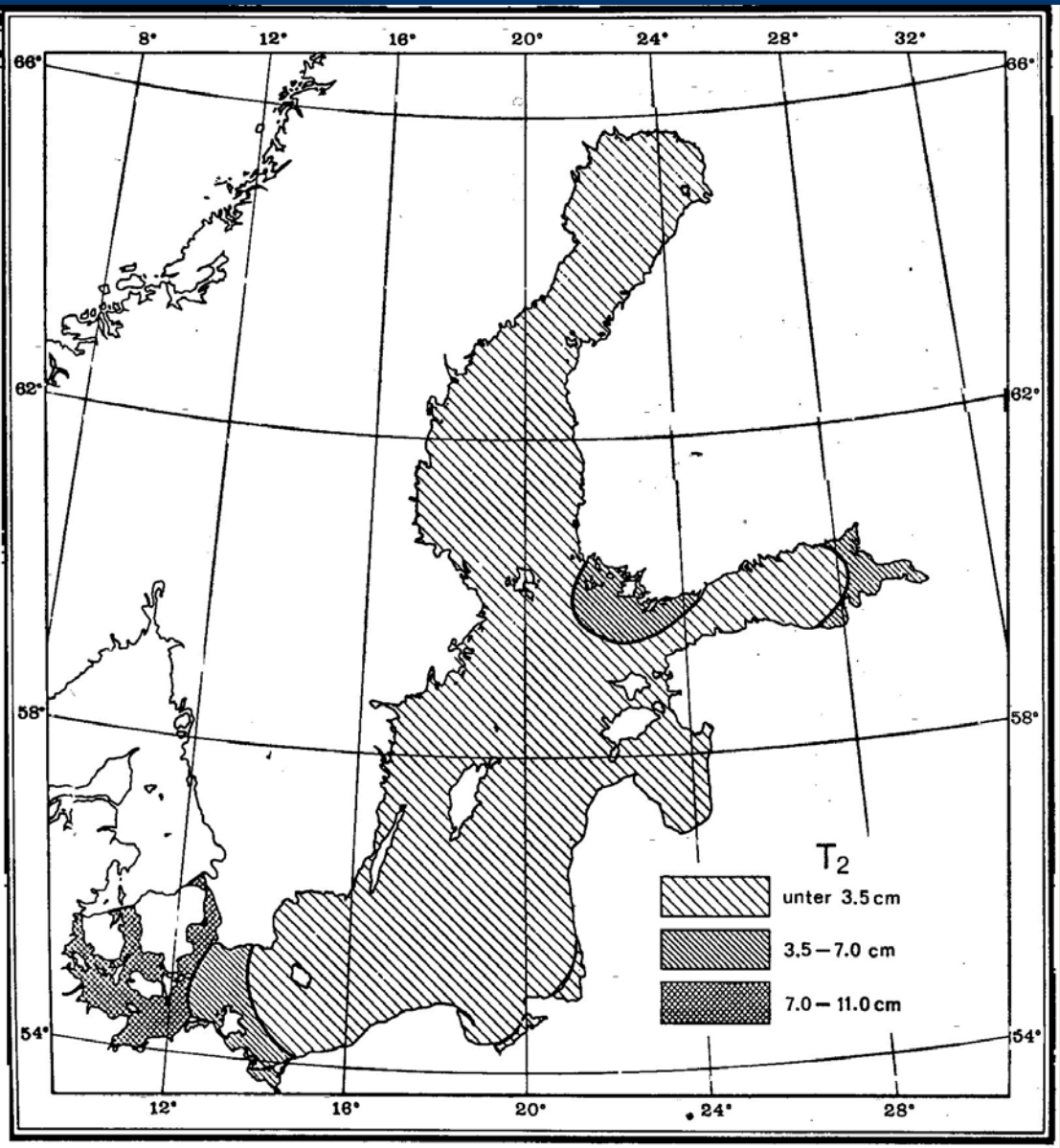


Abb. 2. Geographische Verteilung des Springtidenhubs T_2 der halbtägigen Gezeiten

Diurnal tides

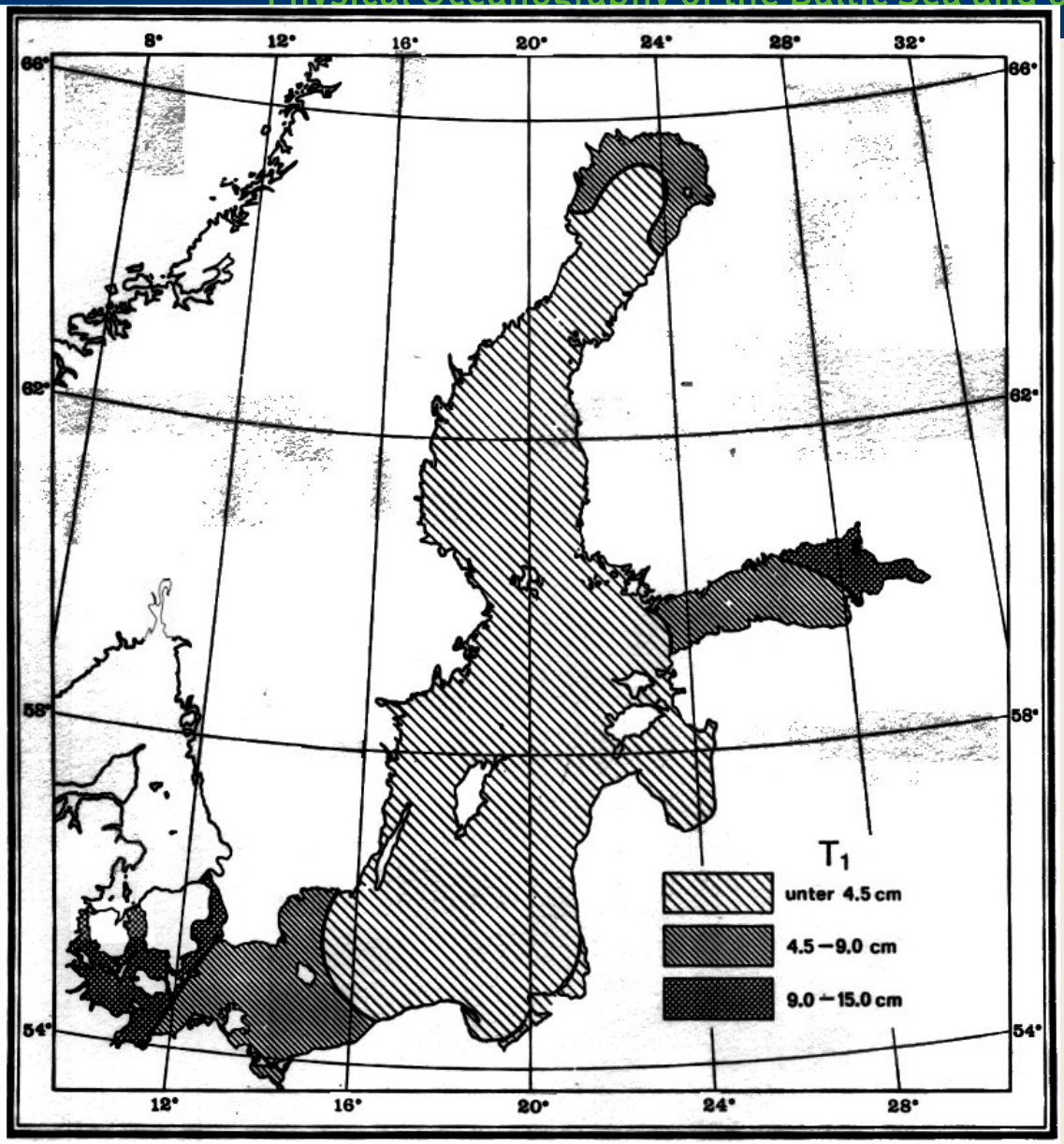


Abb. 3. Geographische Verteilung des Springtidenhubs T_1 der eintägigen Gezeiten

Ratio between diurnal and semi-diurnal tides

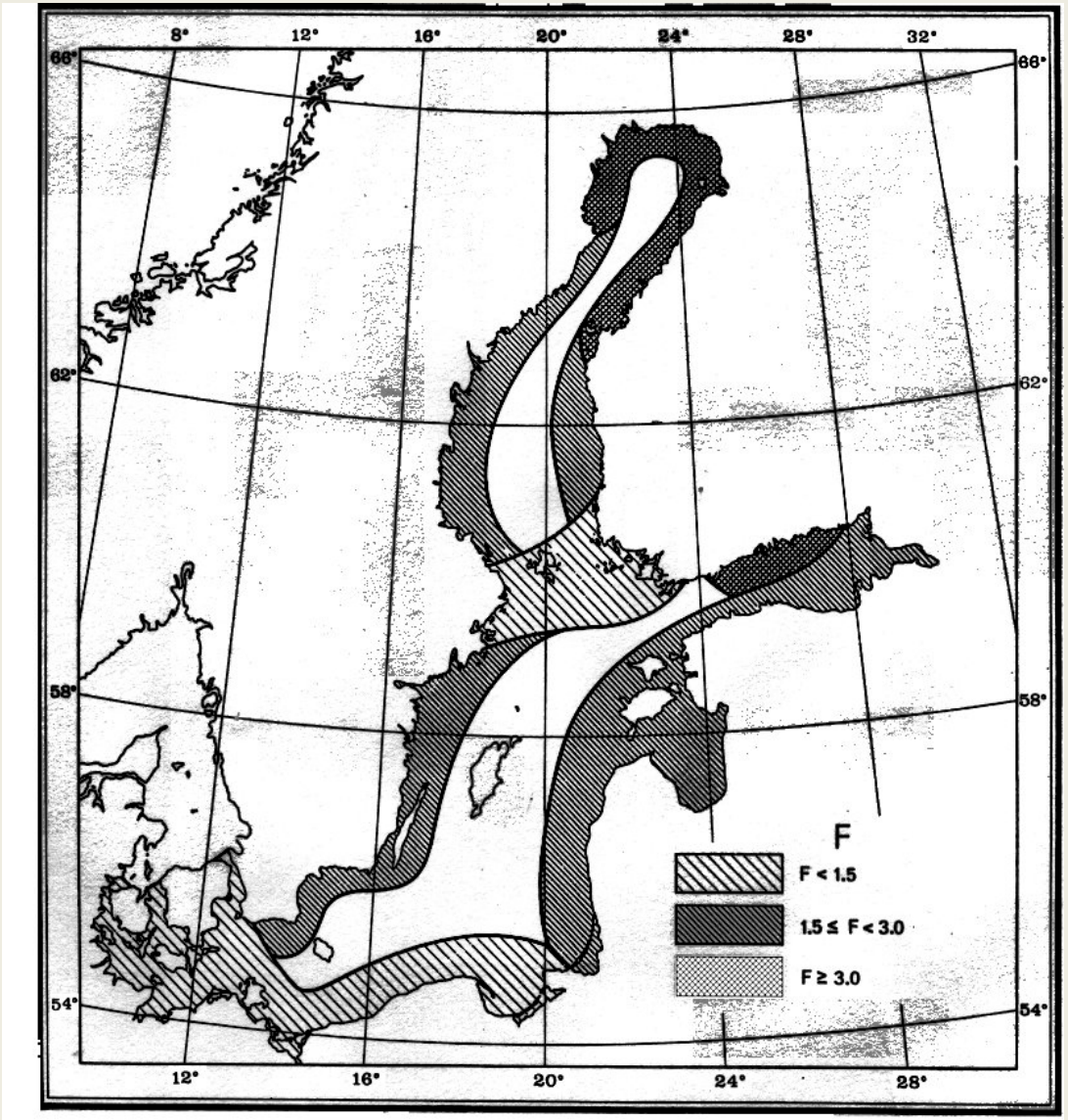
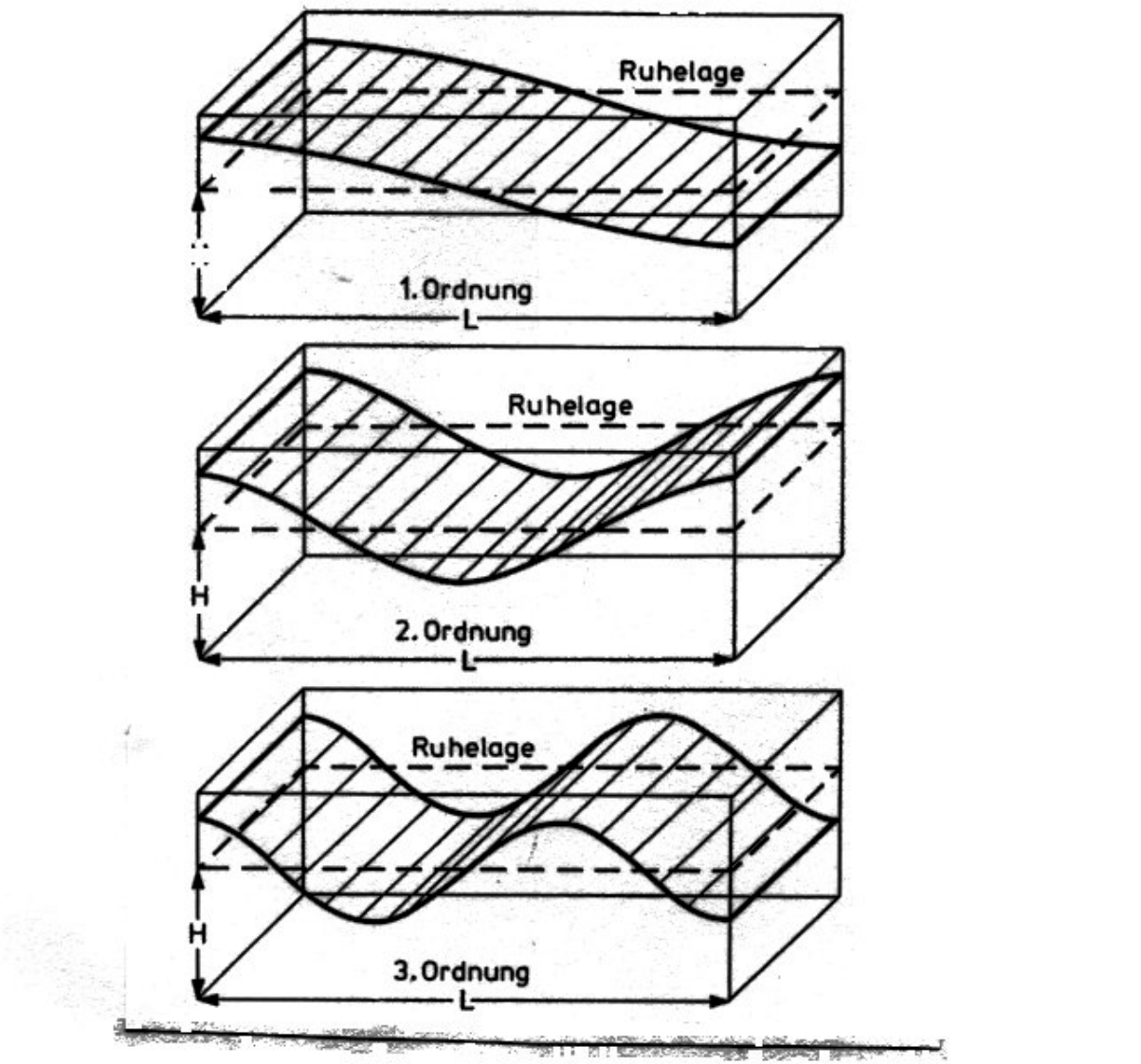


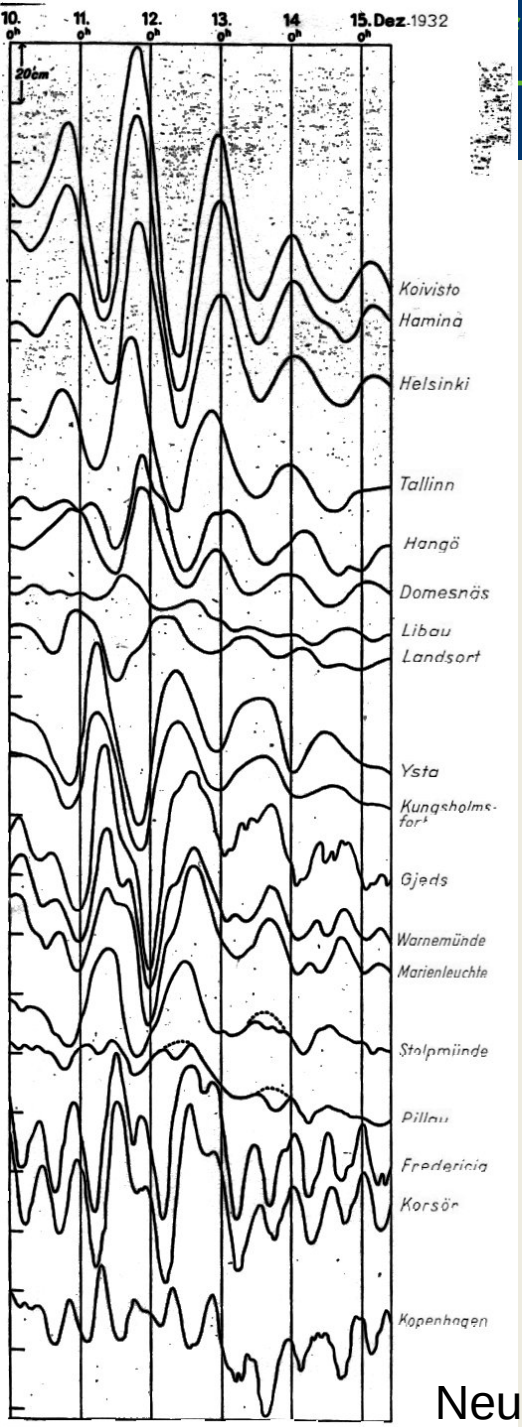
Abb. 4. Geographische Verteilung der Formzahl F

0<F<0.25: semi-diurnal tide

3<F: diurnal tide

Schematic of seiches





Neumann (1941)

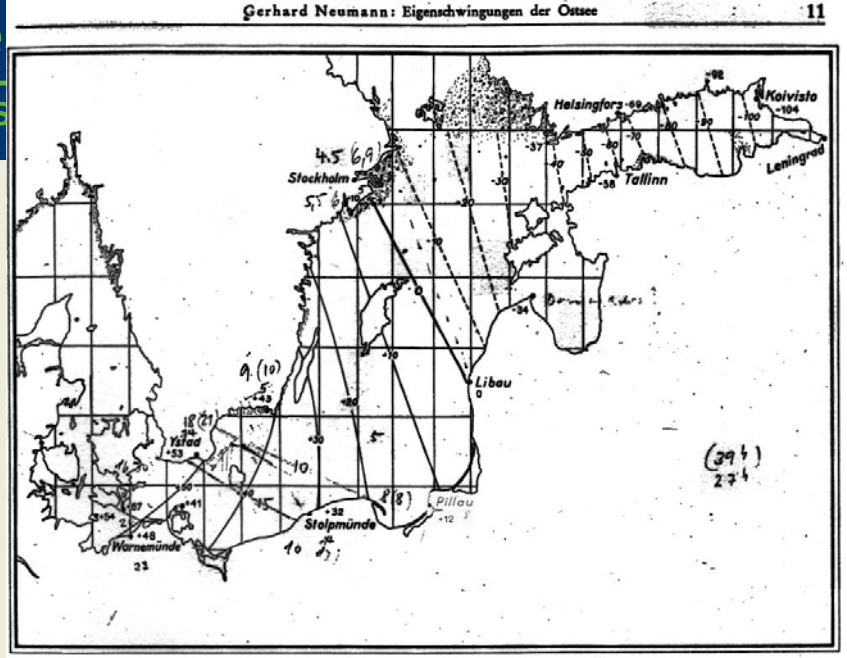


Abb. 4: Linien gleicher Hubhöhe für die Schwingung vom 11. bis 12. Dezember 1932. Die gestrichelten Linien geben den Senkungsbetrag des Wasserspiegels zwischen dem Maximum im Finnischen Meerbusen am 11. Dezember und dem Minimum am 12. Dezember an, die ausgezogenen Linien den Hebungsbetrag zwischen dem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

12 Aus dem Archiv der Deutschen Seewarte und des Marineobservatoriums, 61. Band, Nr. 4

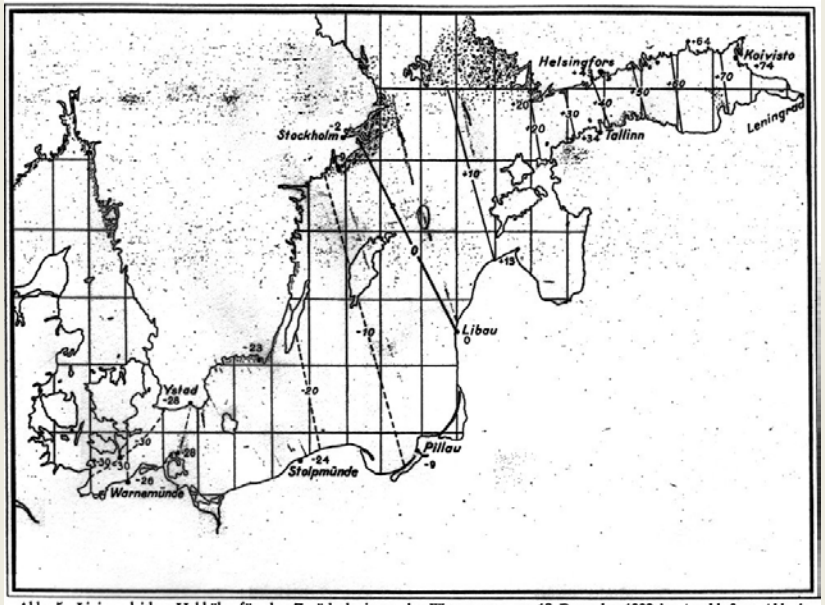
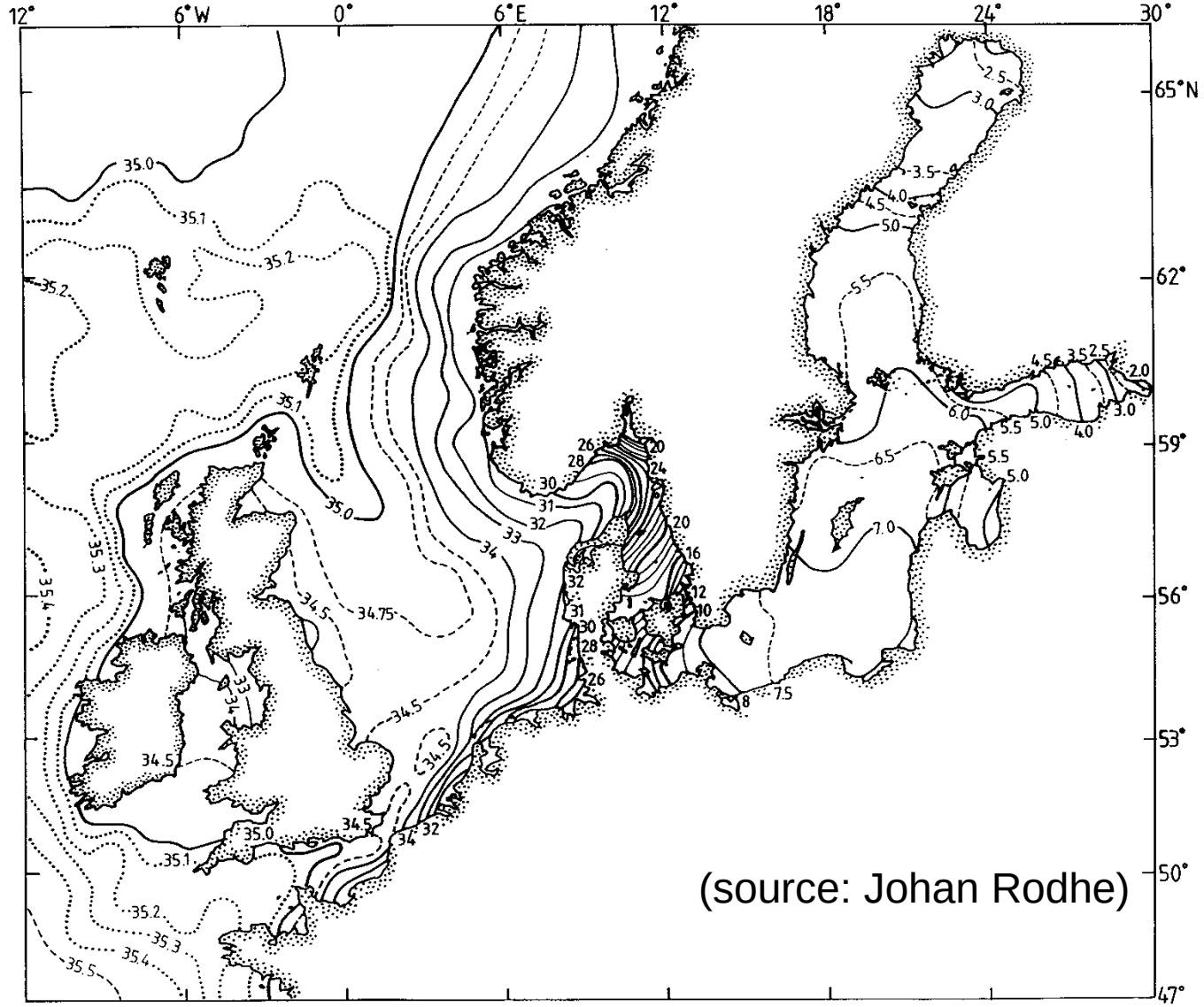


Abb. 5: Linien gleicher Hubhöhe für das Zurückschwingen der Wassermasse am 12. Dezember 1932 im Anschluß an Abb. 4. Die gestrichelten Linien geben den Senkungsbetrag, die ausgezogenen Linien den Hebungsbetrag des Wasserspiegels an. Die Zahlen bedeuten cm.

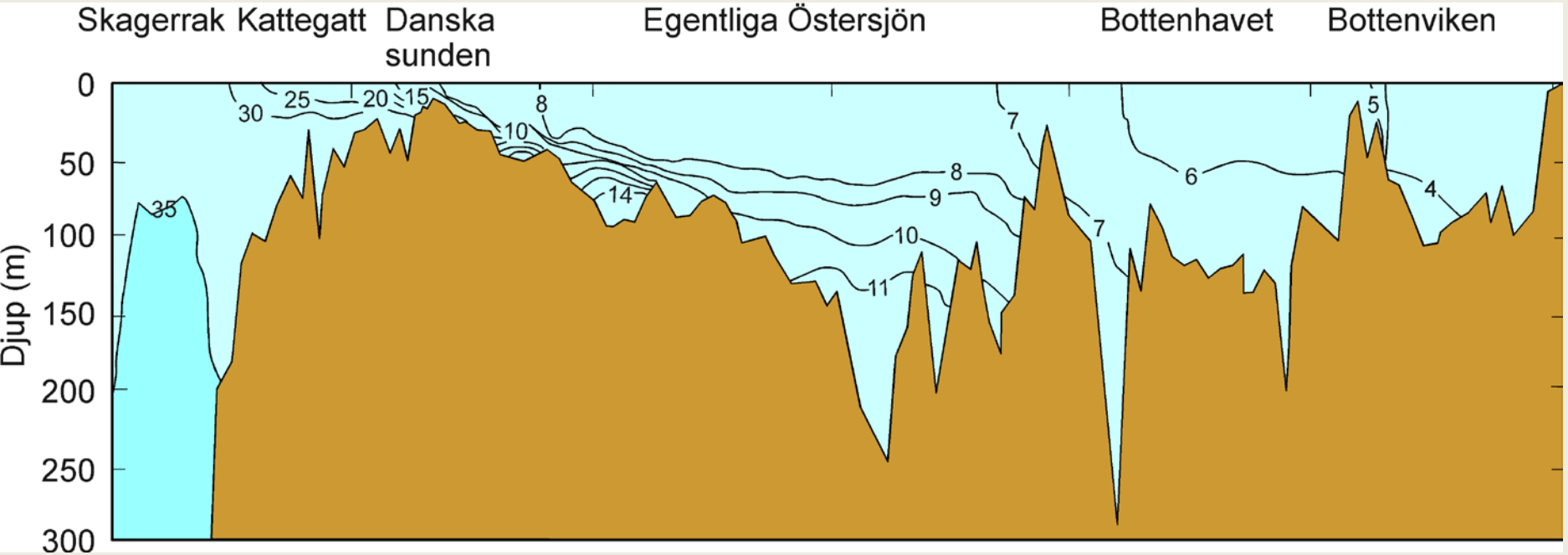
7. Temperature, salinity, density, and oxygen

Sea surface salinity

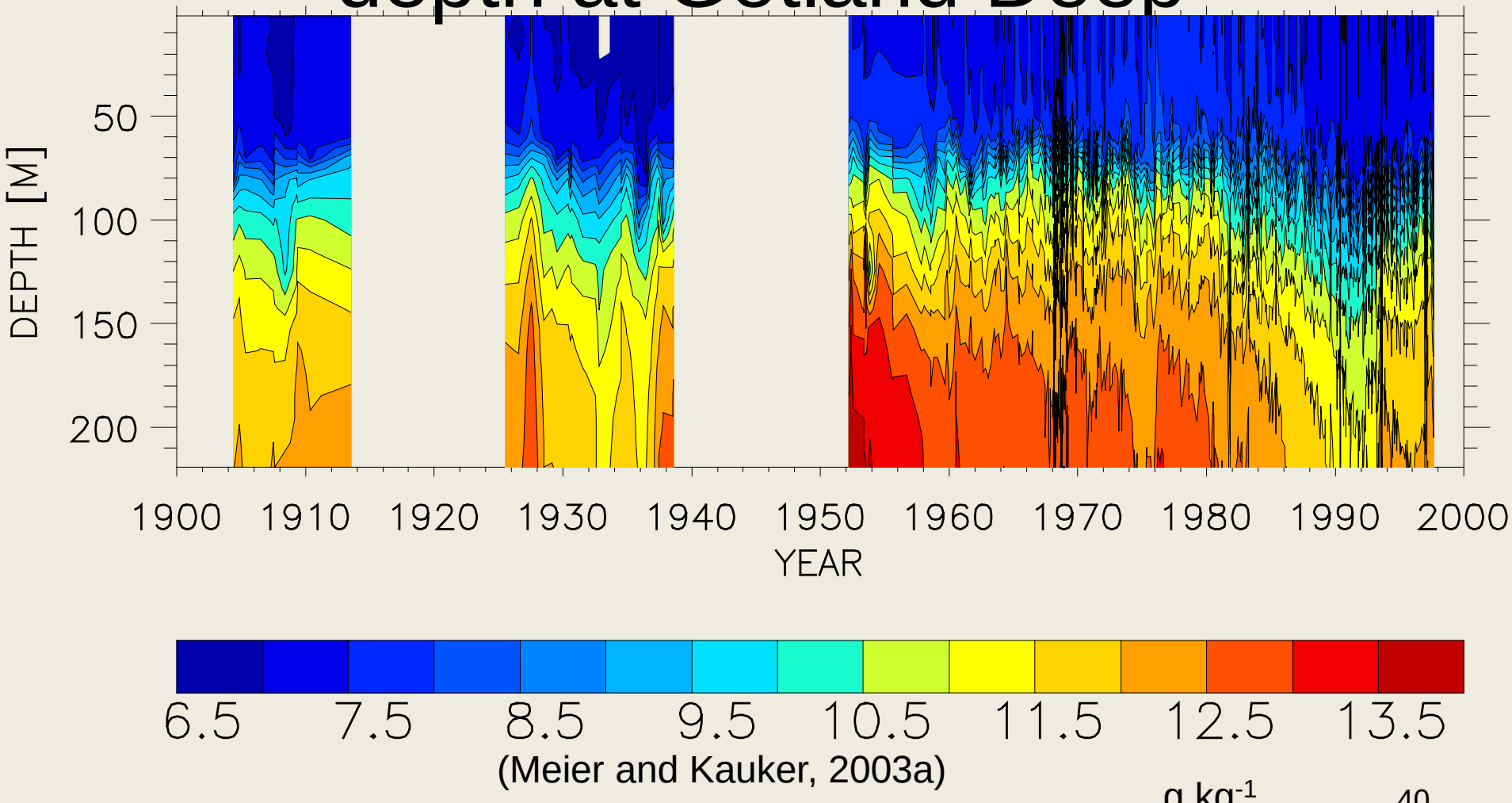


(source: Johan Rodhe)

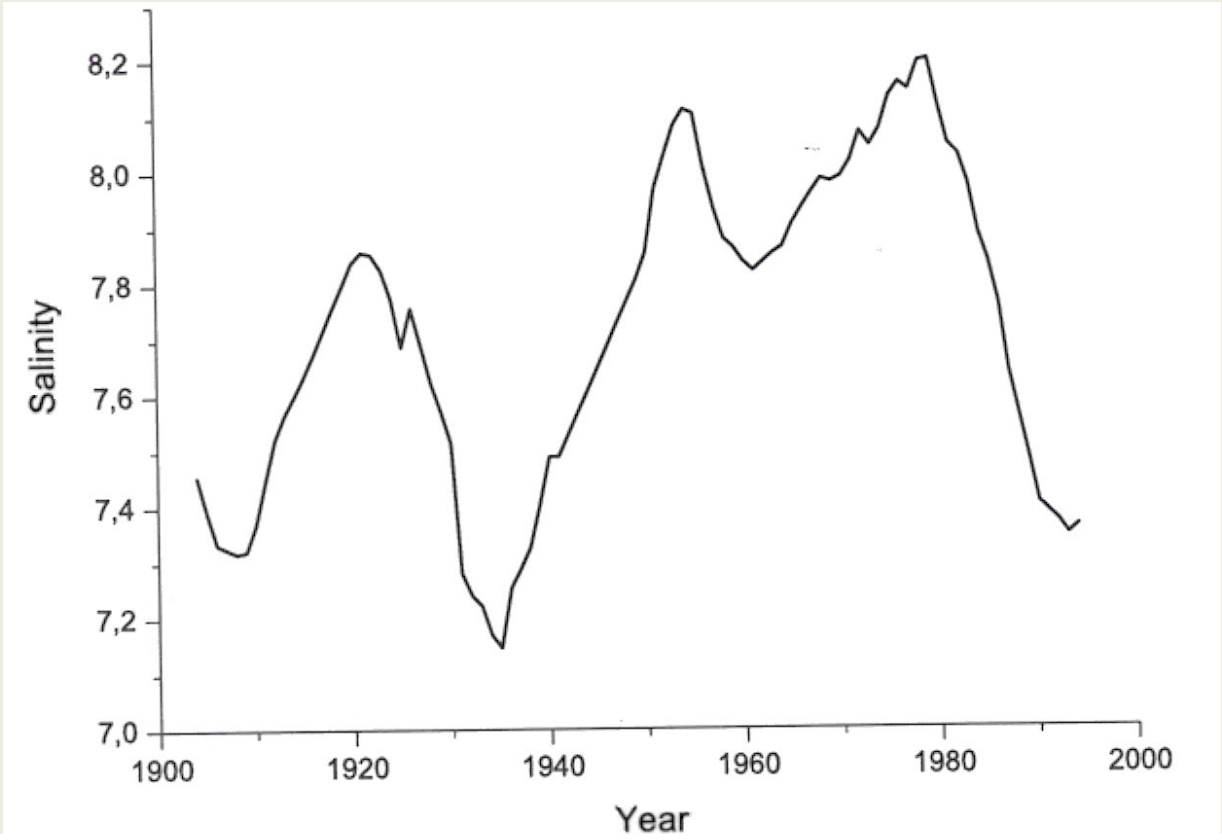
Cross section of salinity



Salinity as function of time and depth at Gotland Deep

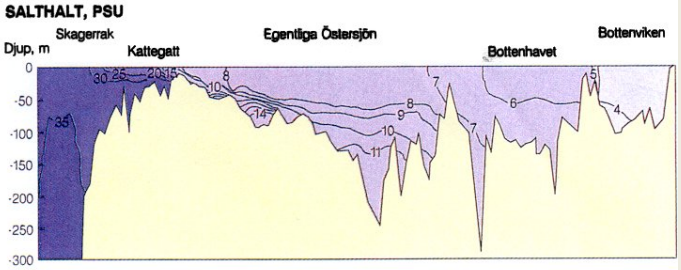


Average salinity of the Baltic Sea



Winsor et al. (2001)

Cross section of temperature



Salthaltens fördelningen längs en sektion från Skagerrak till Bottenviken 1988.

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

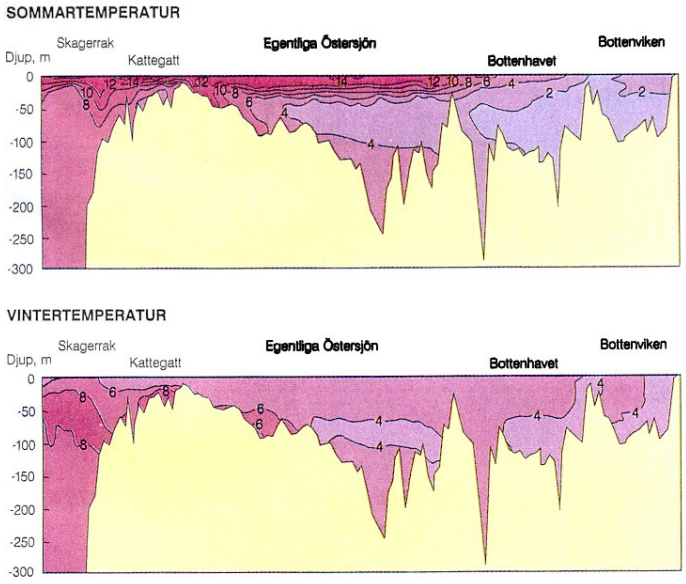


Fig. 3.11. Temperaturfördelningen i ett vertikalsnitt från Skagerrak till Bottenviken[30].

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

b) Vinterförhållanden med nästan homogen temperatur i vattenpelaren.

Temperature, salinity, density profiles in the Baltic proper

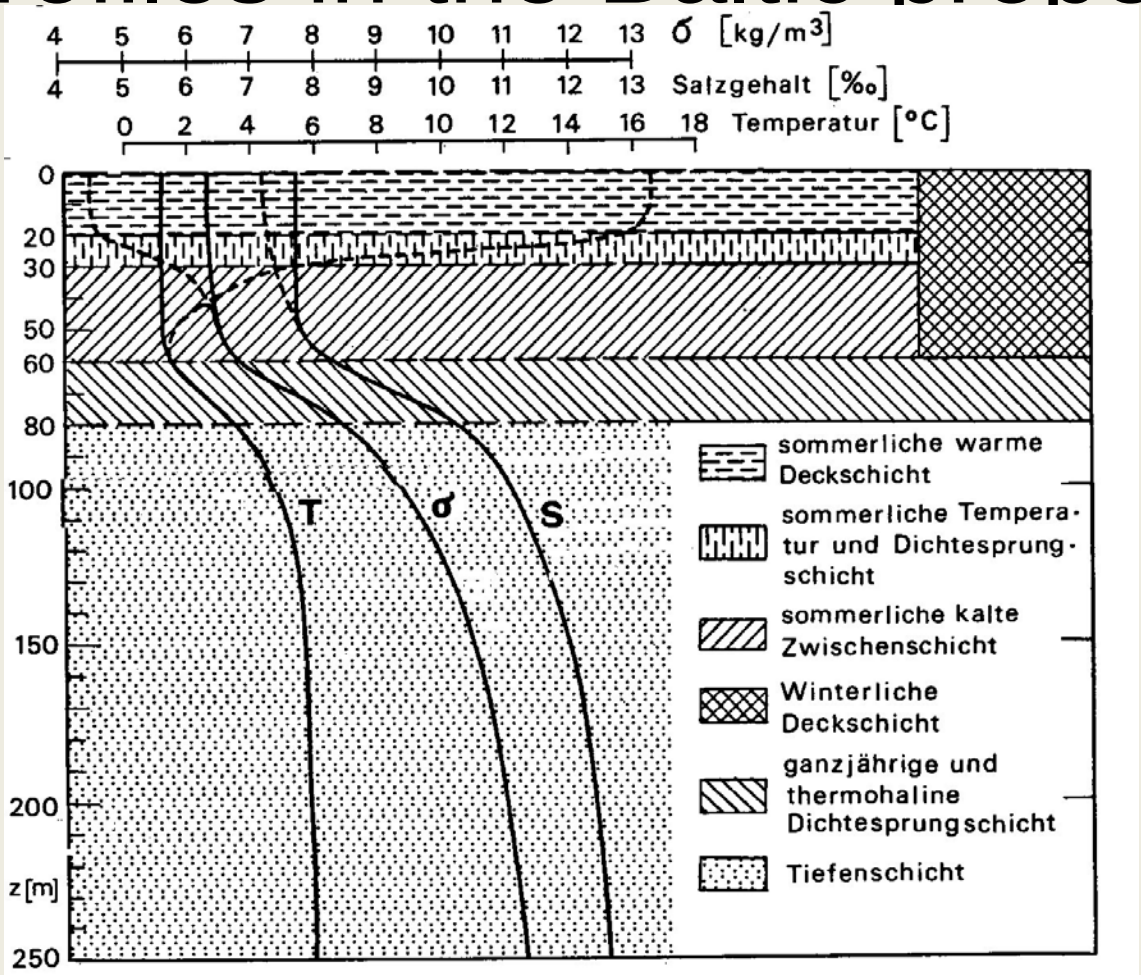
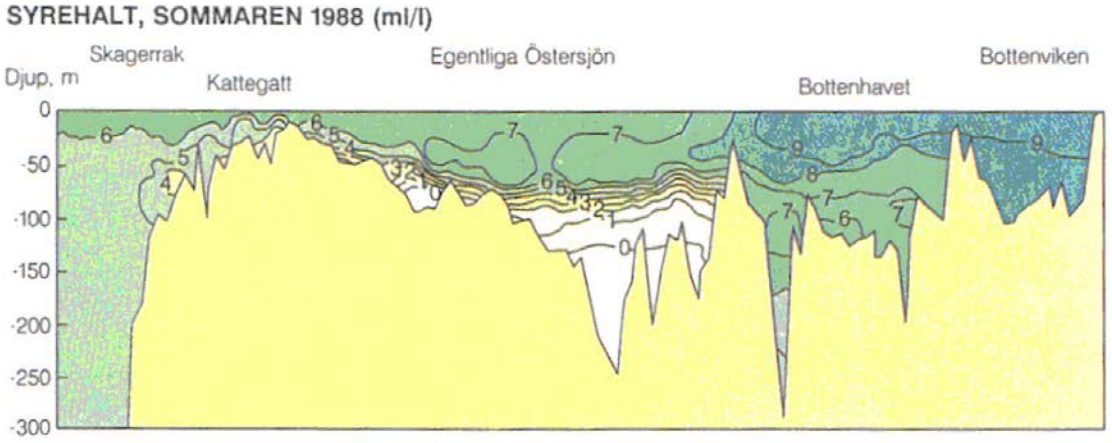


Abb. 32. Typische thermohaline Schichtungsstruktur in der zentralen Ostsee im Winter (ausgezogen) und im Sommer (teilweise gerissen)

Cross section of oxygen



a) Sommarförhållanden

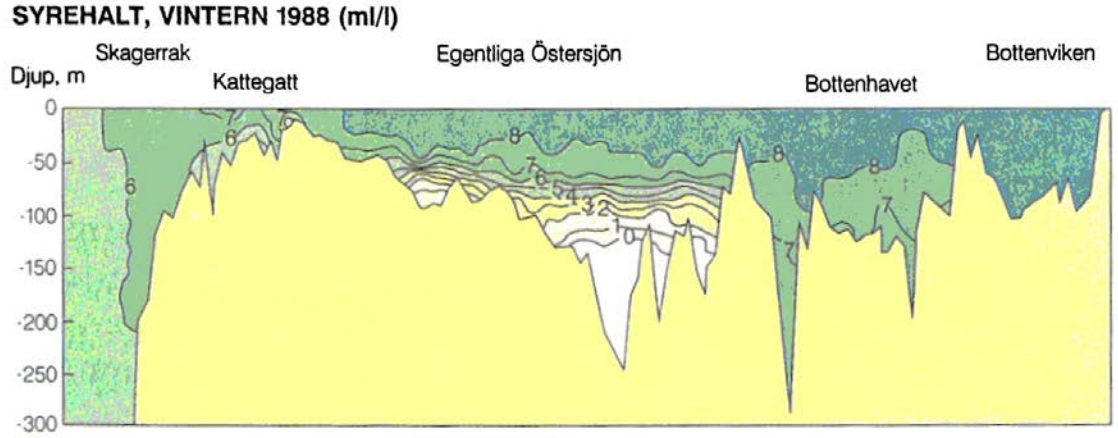


Fig. 7.1 *Syrgaskoncentrationen i ml/l under sommar- och vinterförhållanden i ett längdsnitt från Skagerrak till Bottenviken*[30]

8. Baltic sea ice

(Courtesy of Seppo Keränen)

Probability of ice occurrence 1931-1960

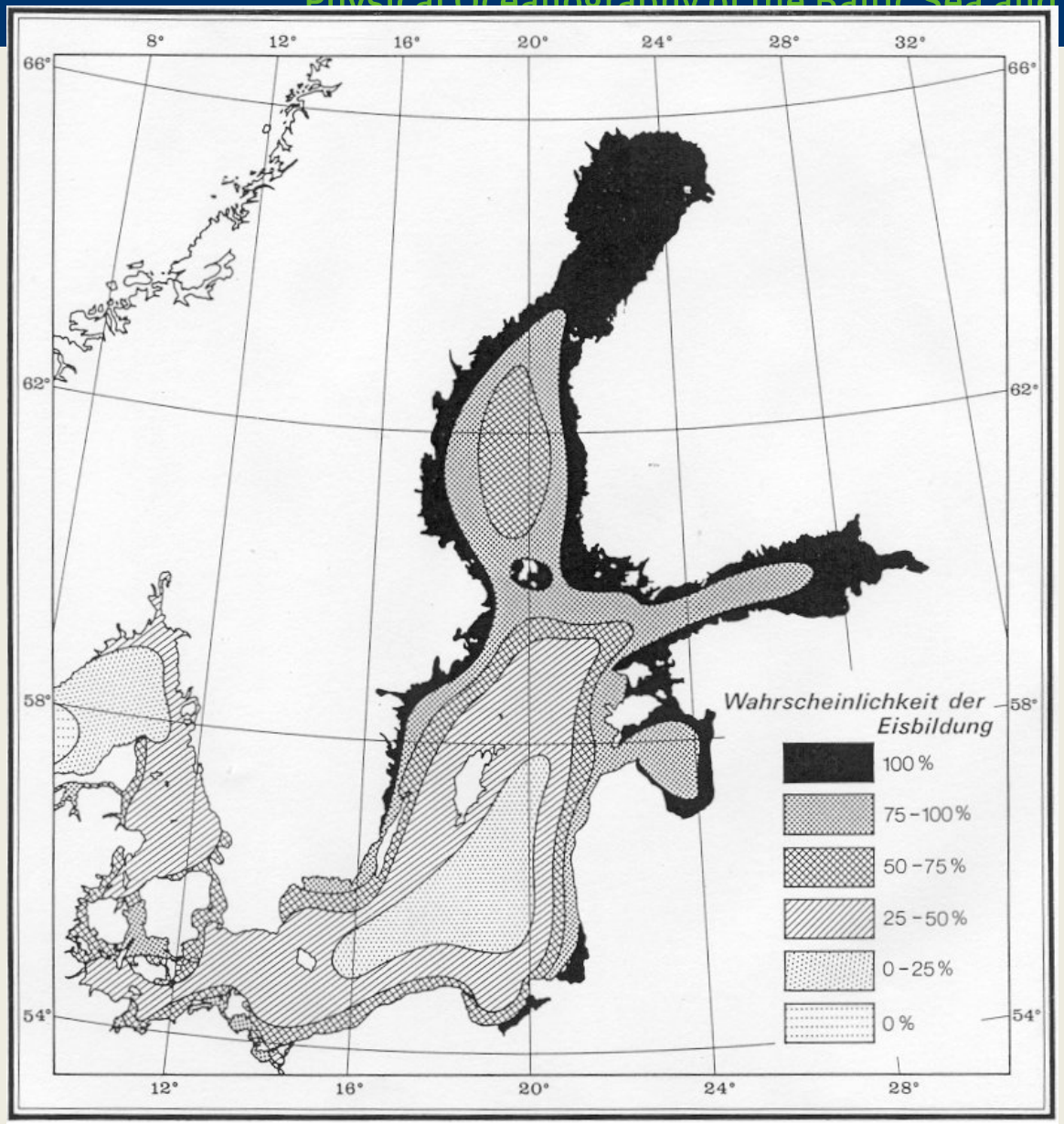
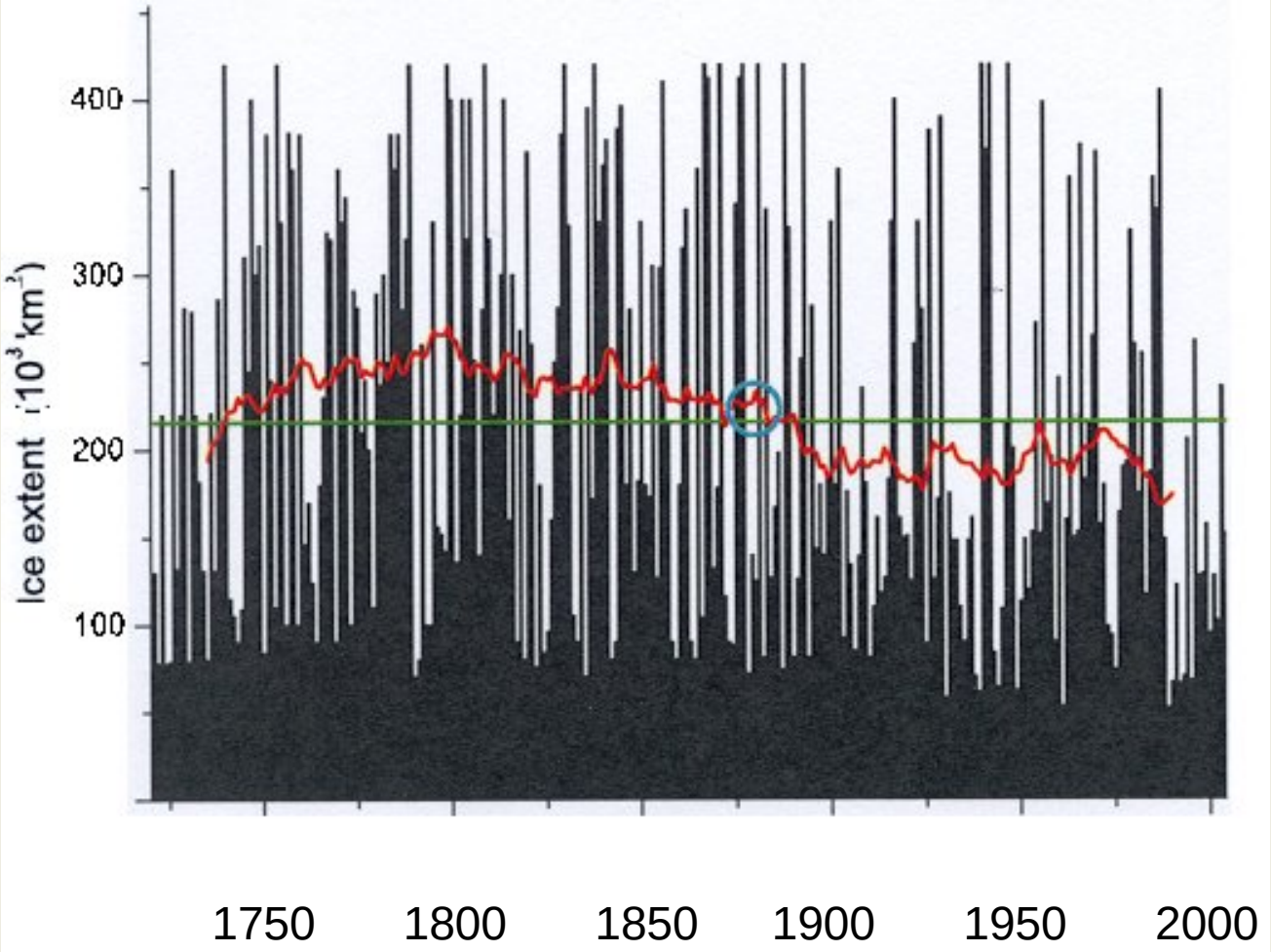


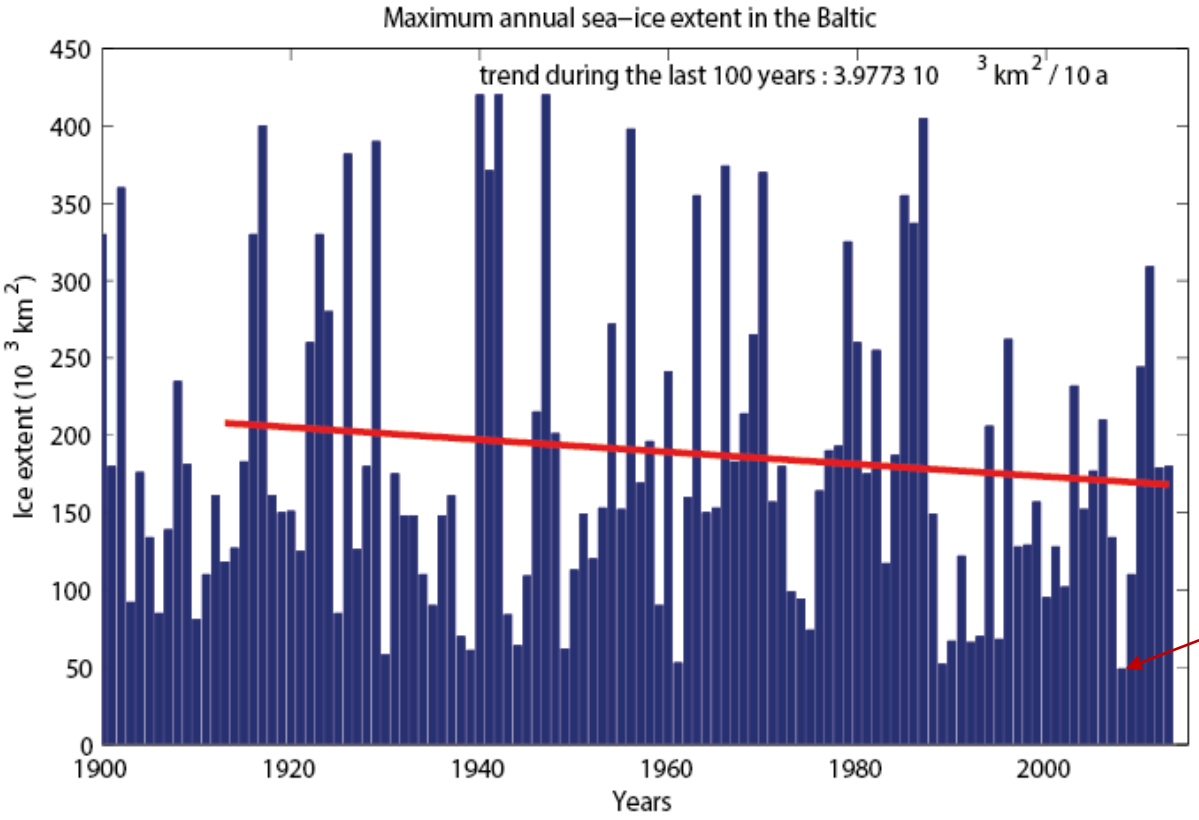
Abb. 1. Wahrscheinlichkeit der Eisbildung, berechnet für den Zeitraum 1931-1960 (nach PALOSUO, 1966).

Maximum ice extent



Omstedt and Chen (2001)

Sea ice cover

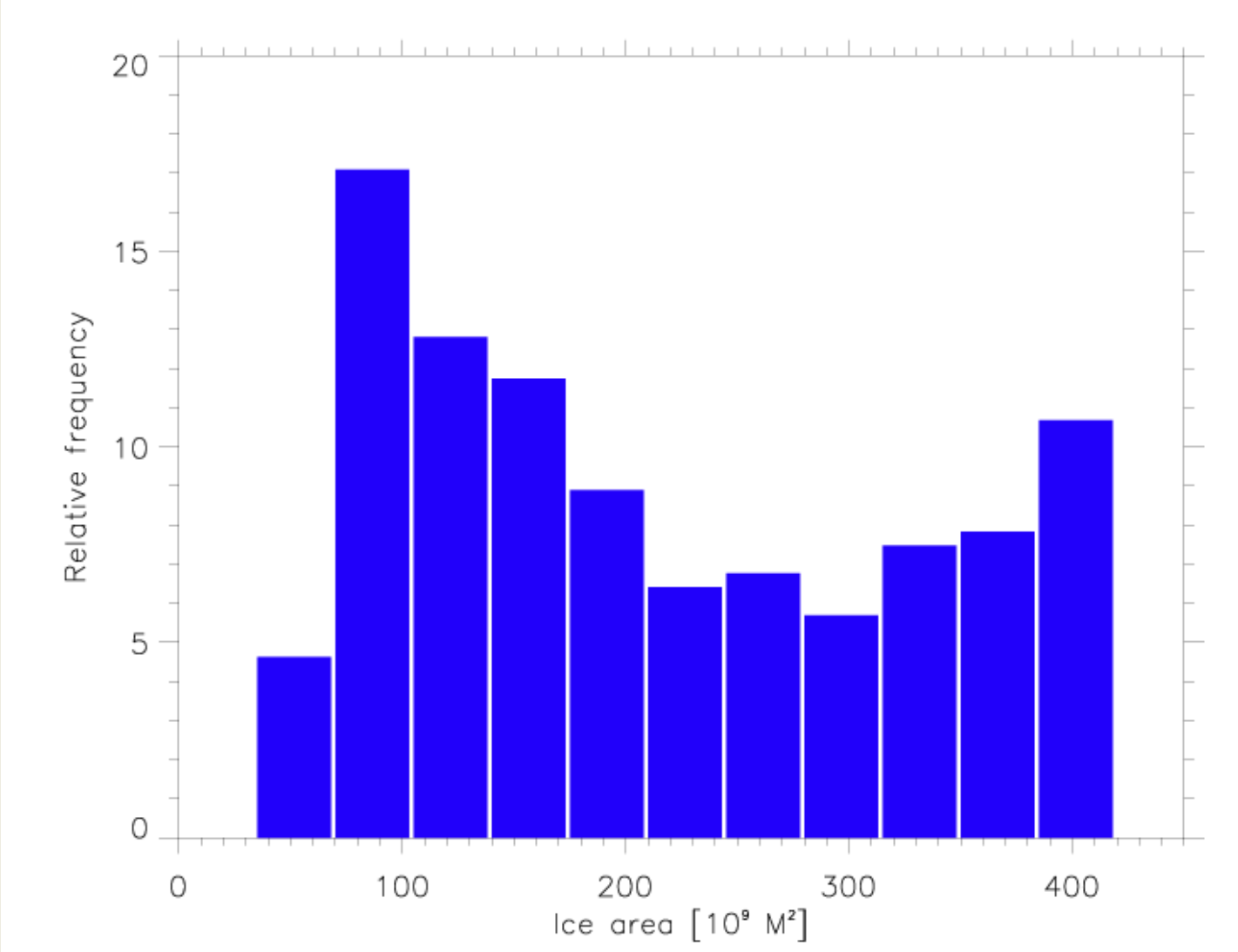


→ **Frequency of mild ice winters has increased**

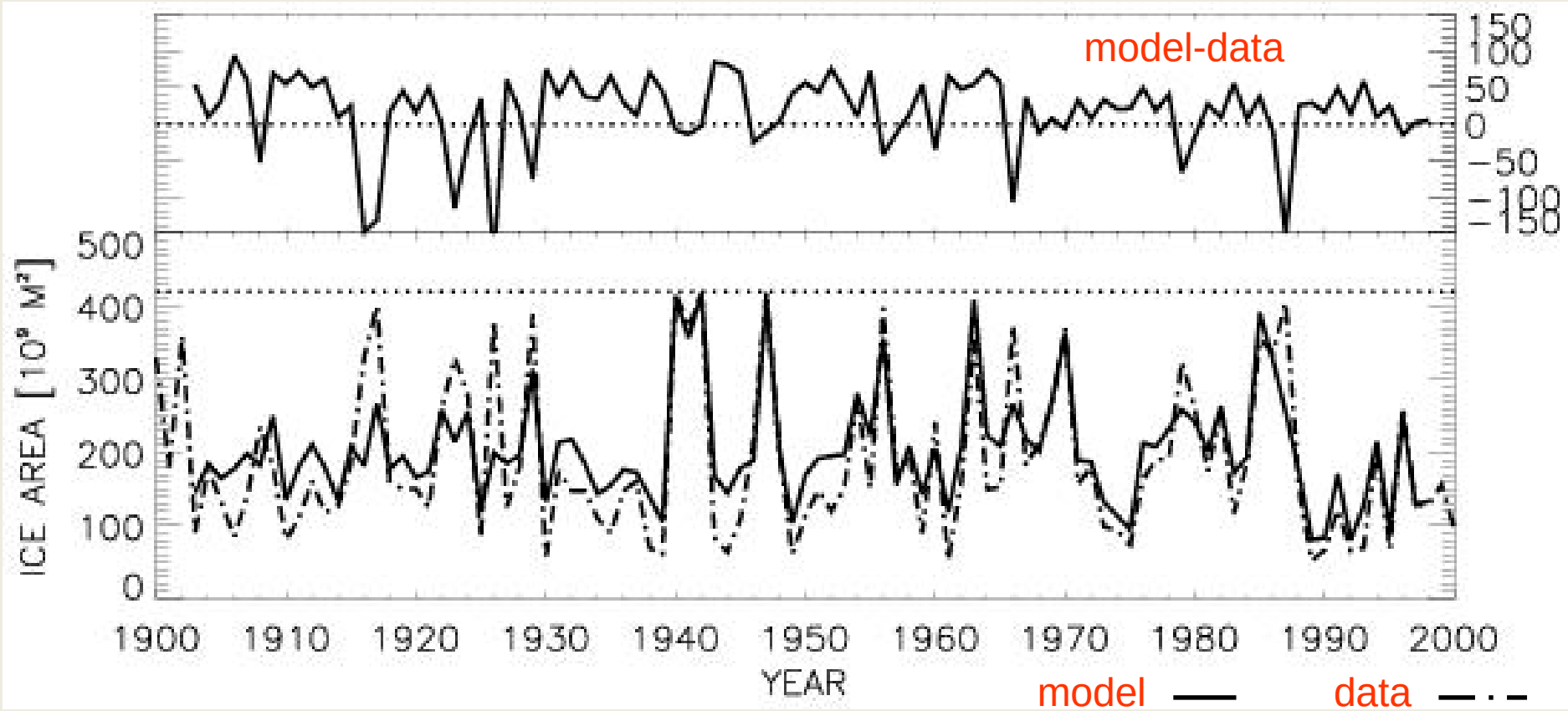
Winter 2007/2008 lowest ever recorded ice cover

Fig. 8.3 The maximum extent of sea-ice cover in the Baltic Sea, 1900–2012. The red line shows a long-term declining trend of ~2% per decade

Relative frequency of maximum ice extent during 1720-2000



Annual maximum ice extent

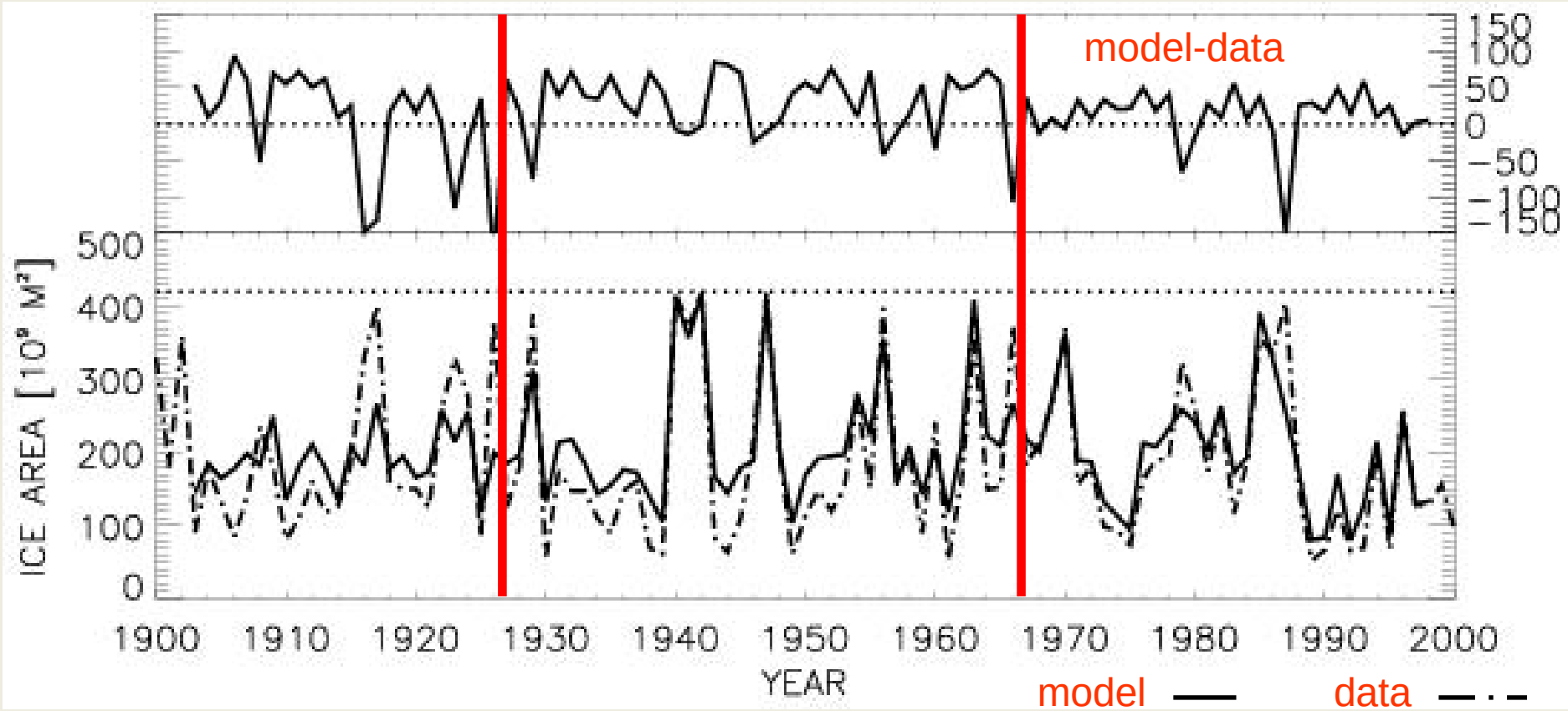


Period	ME	RMSE	R	VAR
1903-98	16.8	55.2	0.87	0.71
1903-26	3.9	73.9	0.66	0.37
1927-66	29.1	52.8	0.94	0.79
1967-98	11.1	39.5	0.93	0.83

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

Annual maximum ice extent



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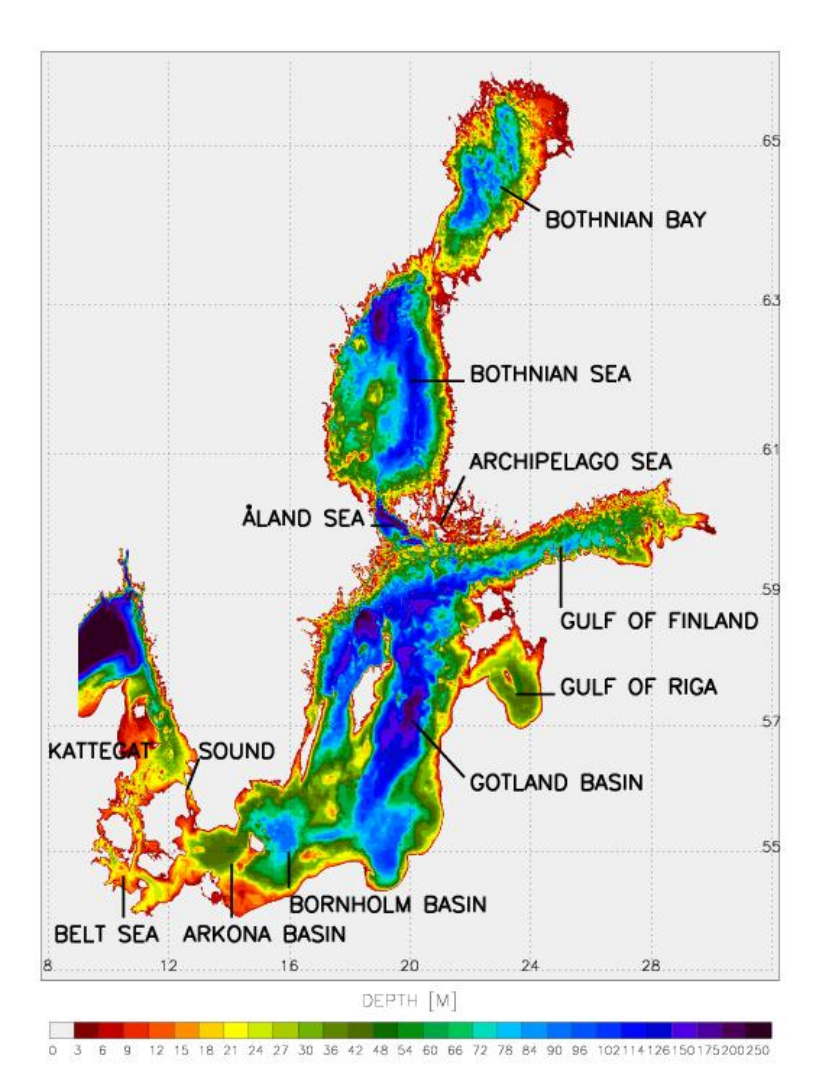
1927-66	29.1	52.8	0.94	0.79
1967-98	11.1	39.5	0.93	0.83

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

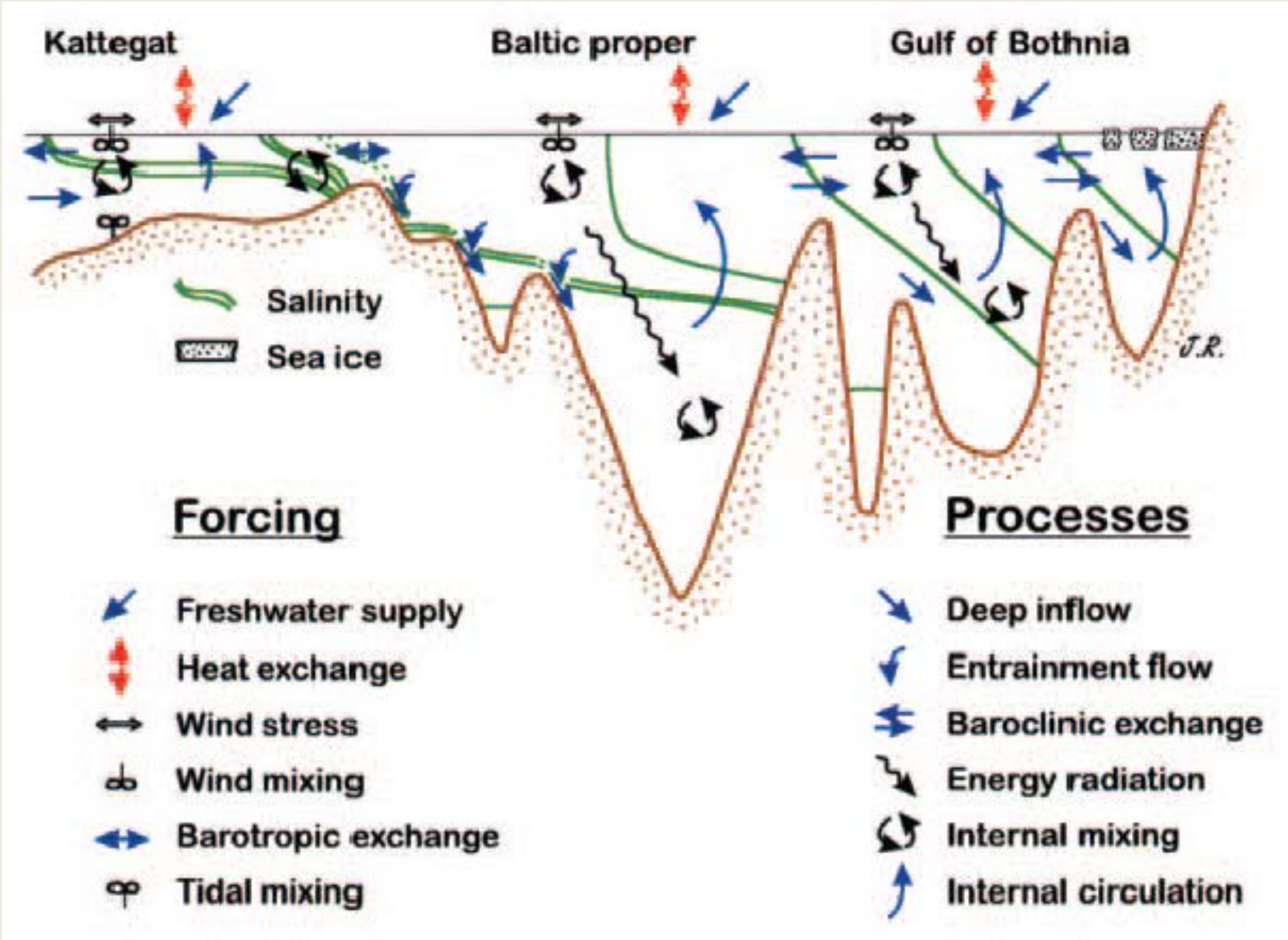
VAR=explained variance

9. Climate relevant processes

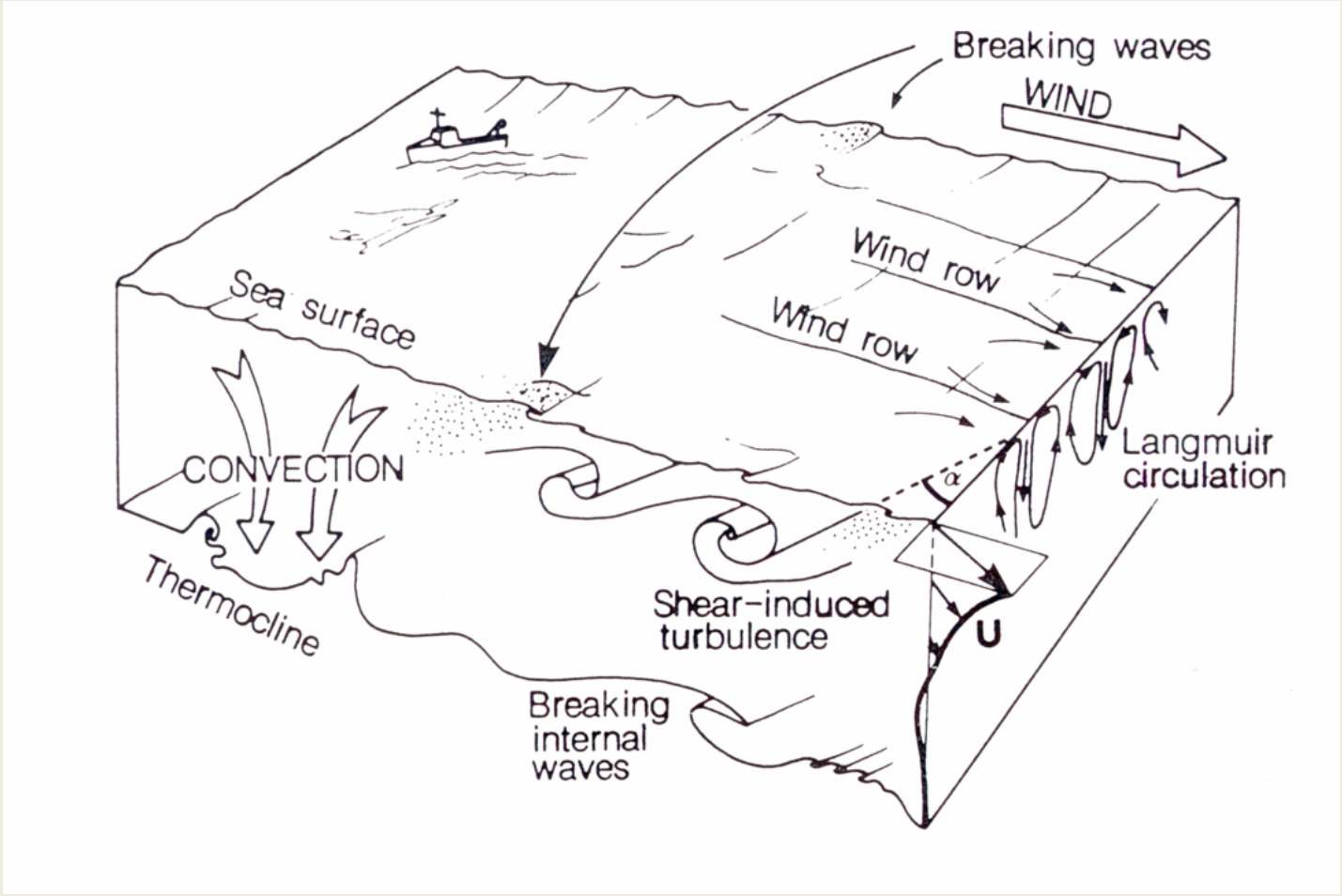
The circulation of the Baltic Sea is determined by :



- the interactions between atmosphere-ice-ocean
- the water exchange through the Danish straits,
- the bottom topography, (mean depth 52 m, max depth 459 m)
- the river runoff.

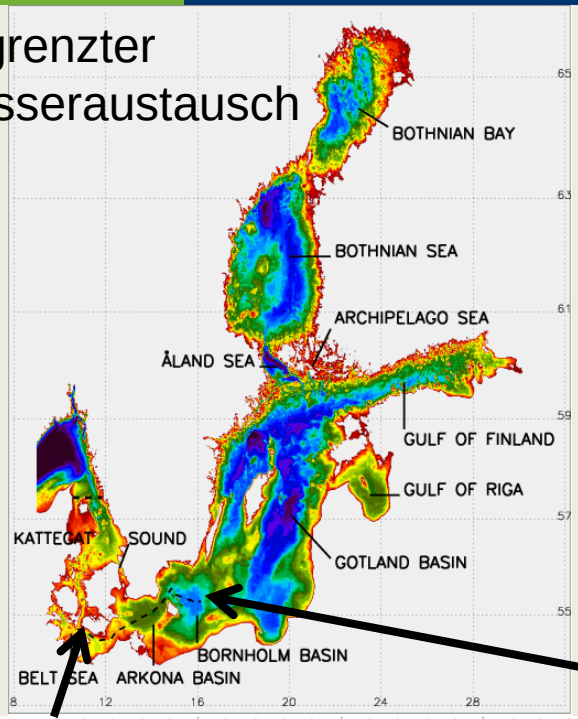

Kattegat
Baltic proper
Gulf of Bothnia
Salinity
Sea ice
J.R.
Forcing
Freshwater supply
Heat exchange
Wind stress
Wind mixing
Barotropic exchange
Tidal mixing
Processes
Deep inflow
Entrainment flow
Baroclinic exchange
Energy radiation
Internal mixing
Internal circulation

Processes in the surface boundary layer

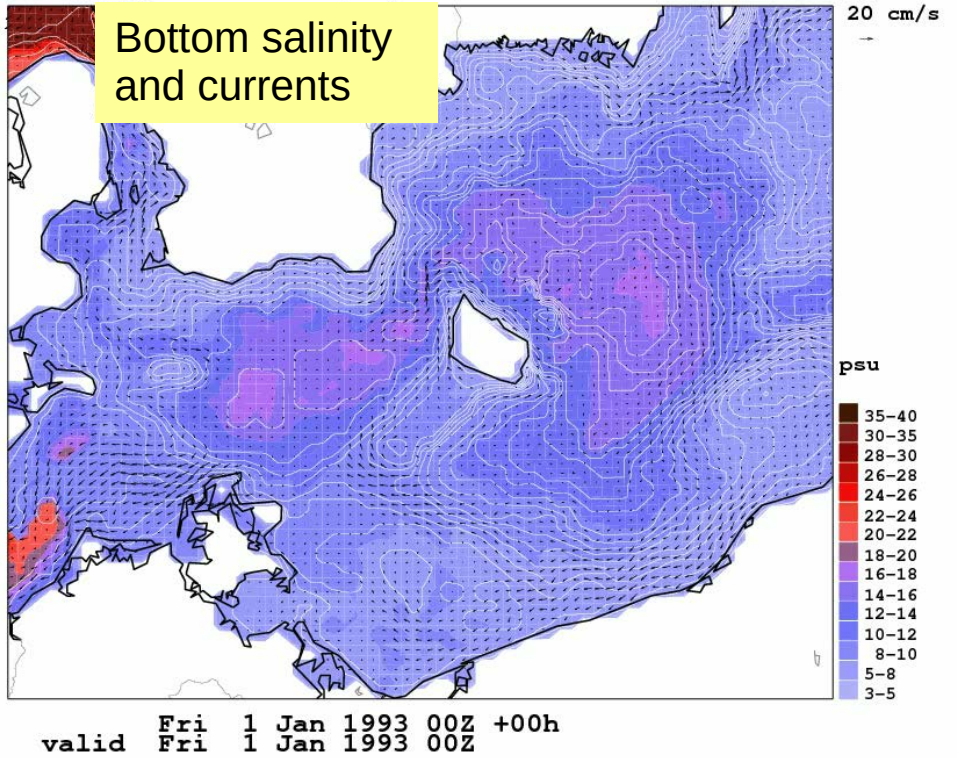


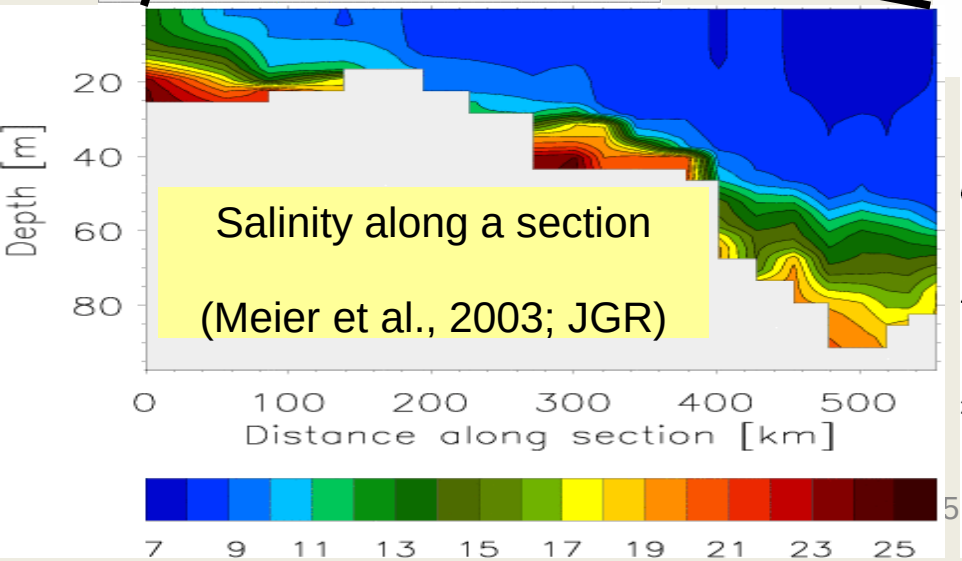
(Source: Thorpe, 1985)

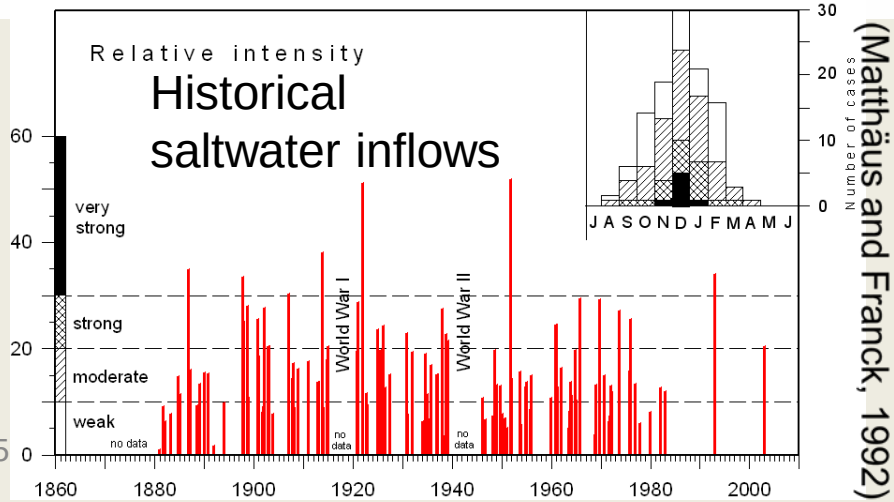
Begrenzter Wasseraustausch



Saltwater inflow January 1993

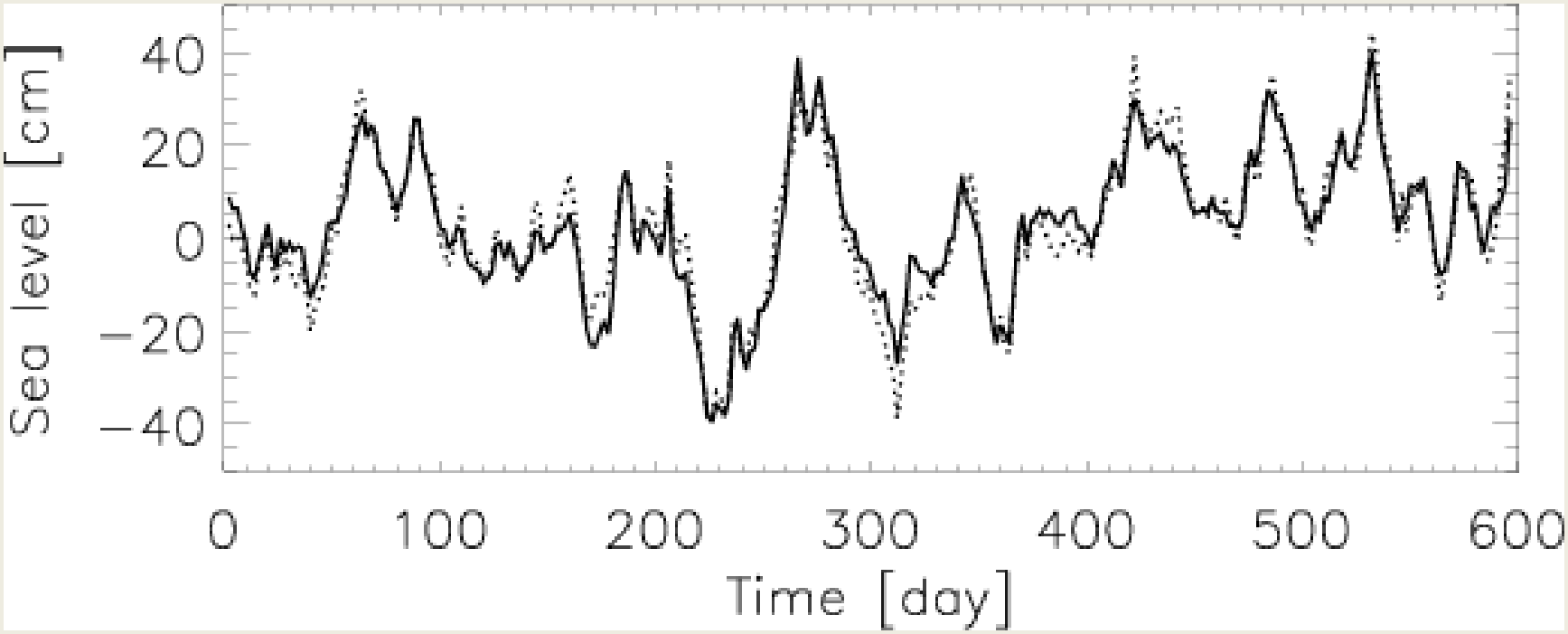






The major Baltic inflow in January 2003 and preconditioning by smaller inflows in summer/autumn 2002

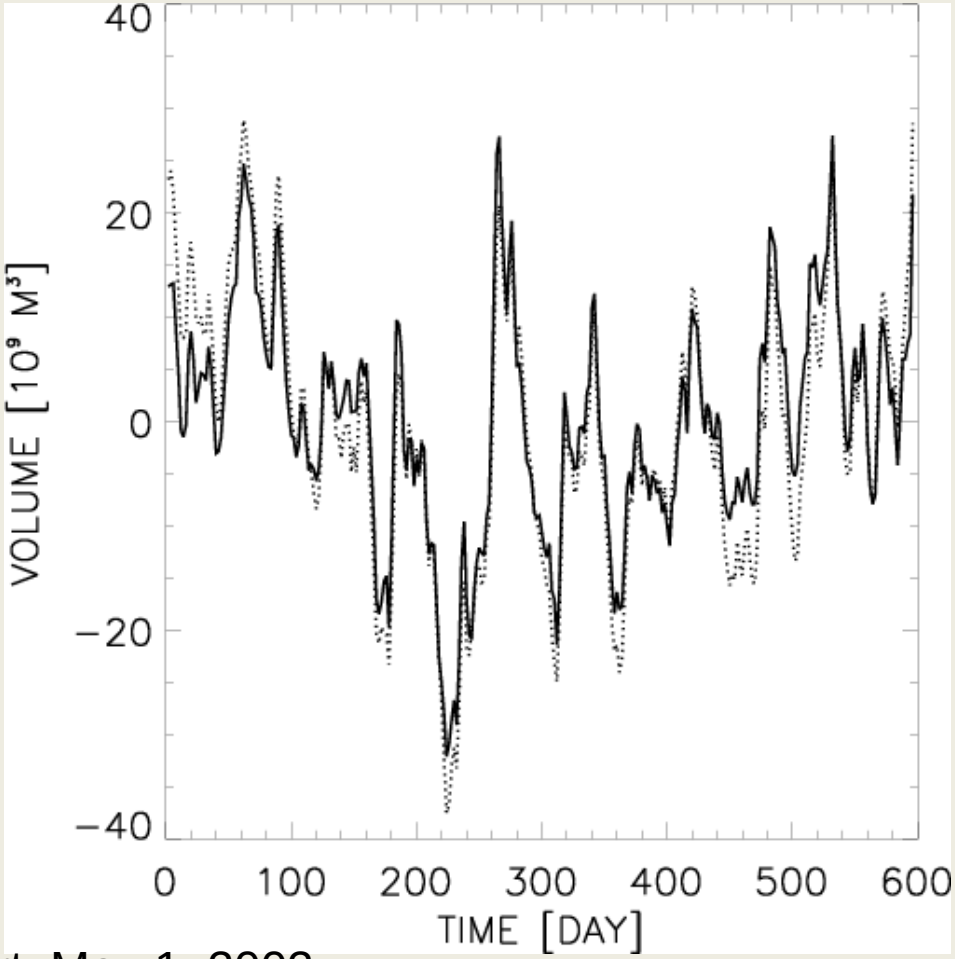
Sea level at Landsort: model (solid), observations (dotted)



Start: May 1, 2002

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

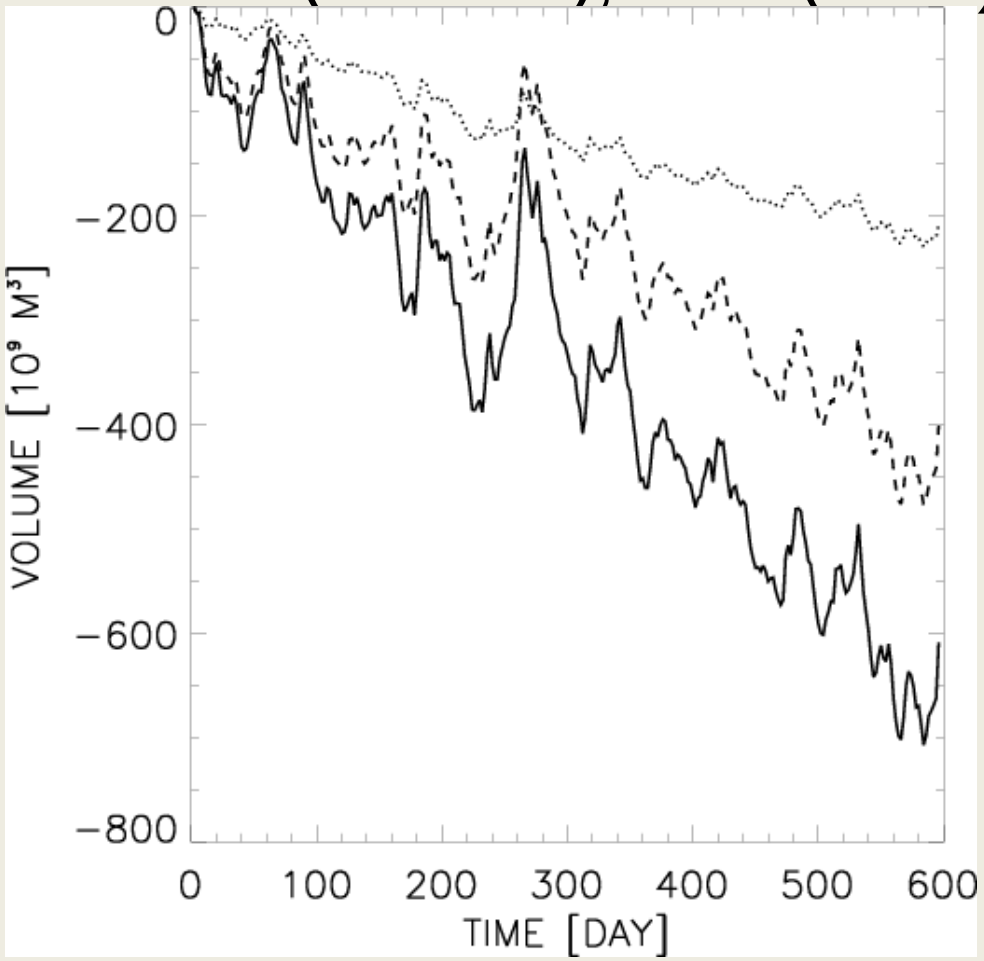
Detrended accumulated inflow through the Sound: RCO (solid), hydraulic model (dotted)



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

Start: May 1, 2002

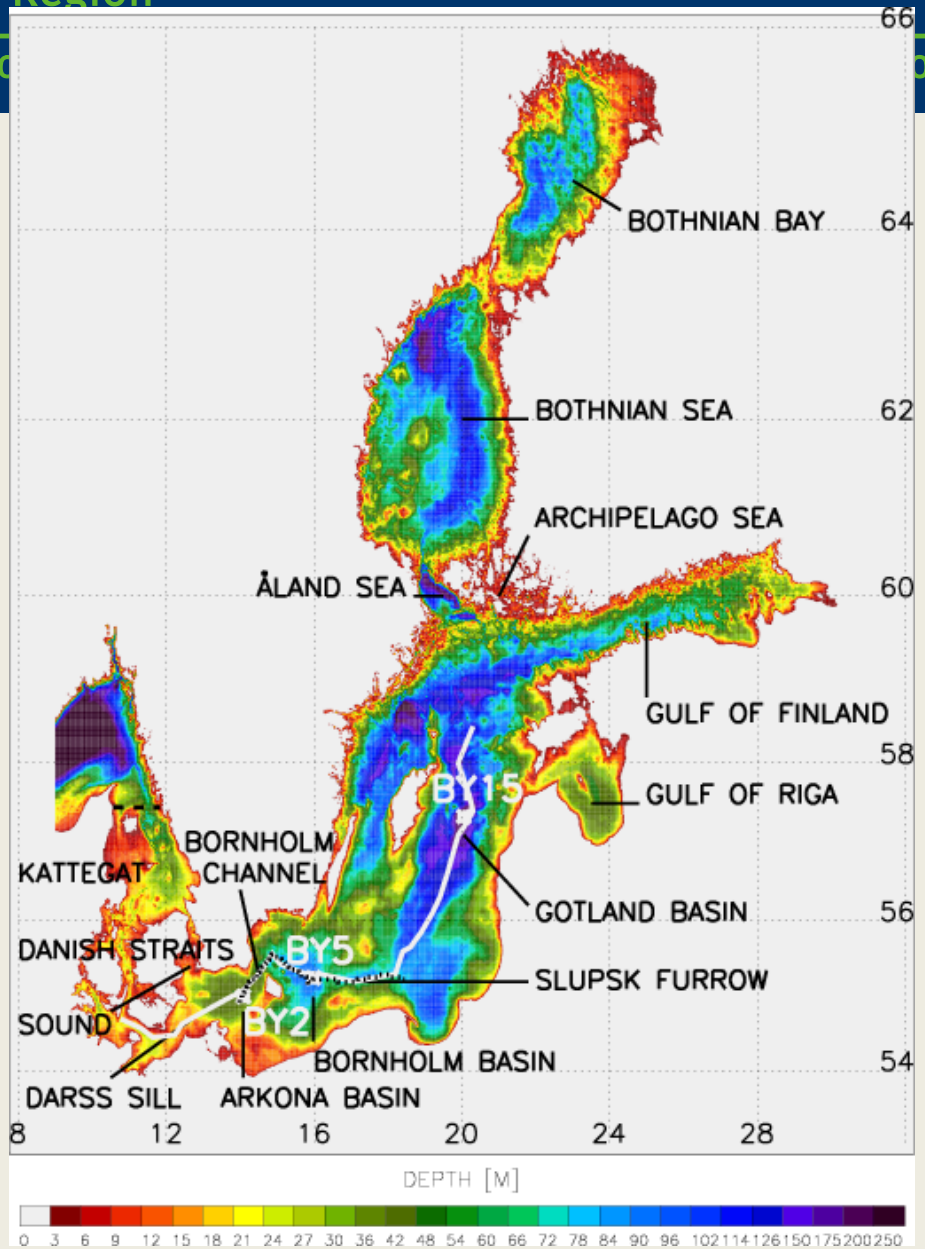
Accumulated inflow: Sound (dotted), Darss Sill (dashed), sum (solid)



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

Start: May 1, 2002

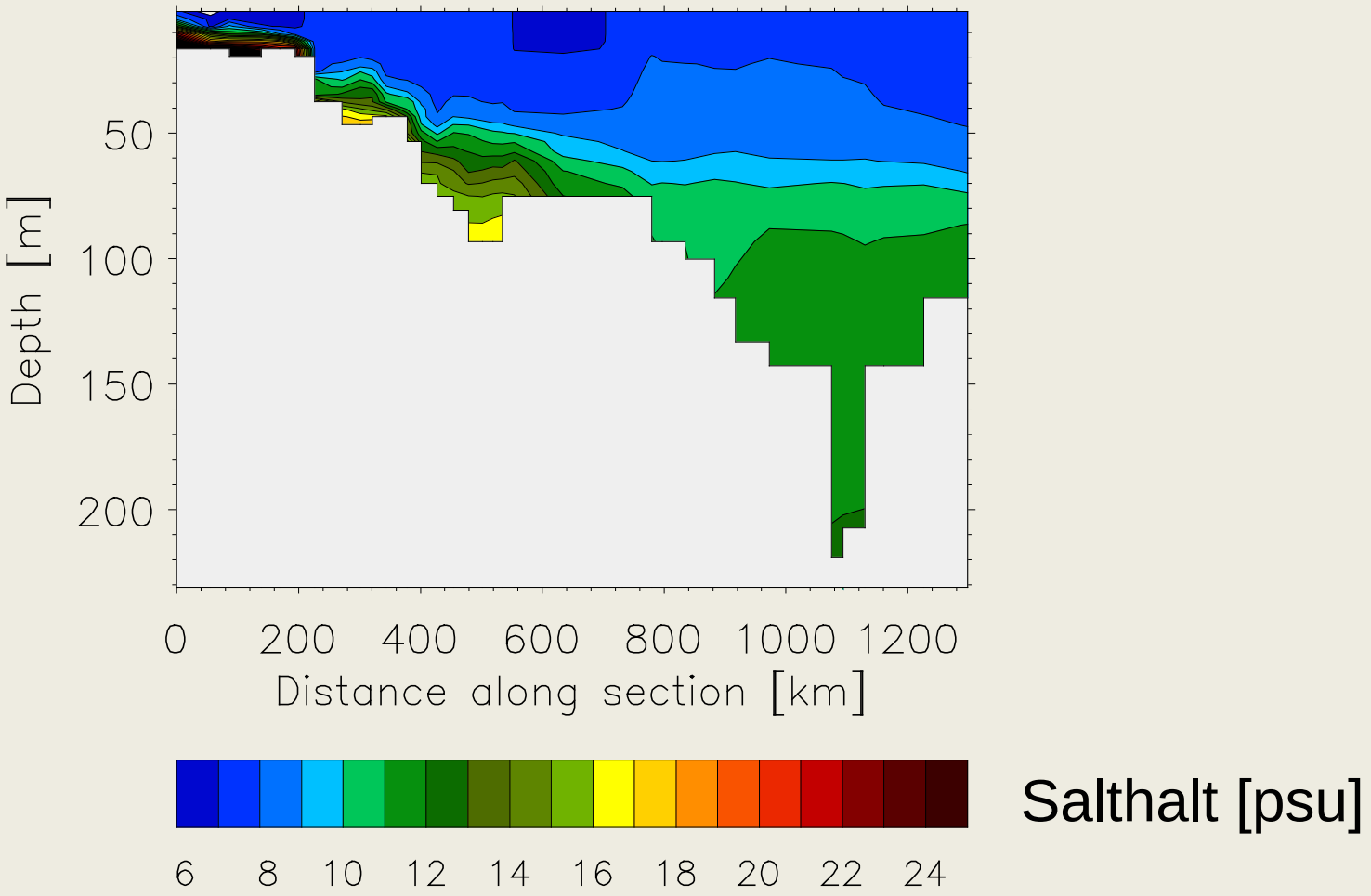
Regional model
RCO
1/30°



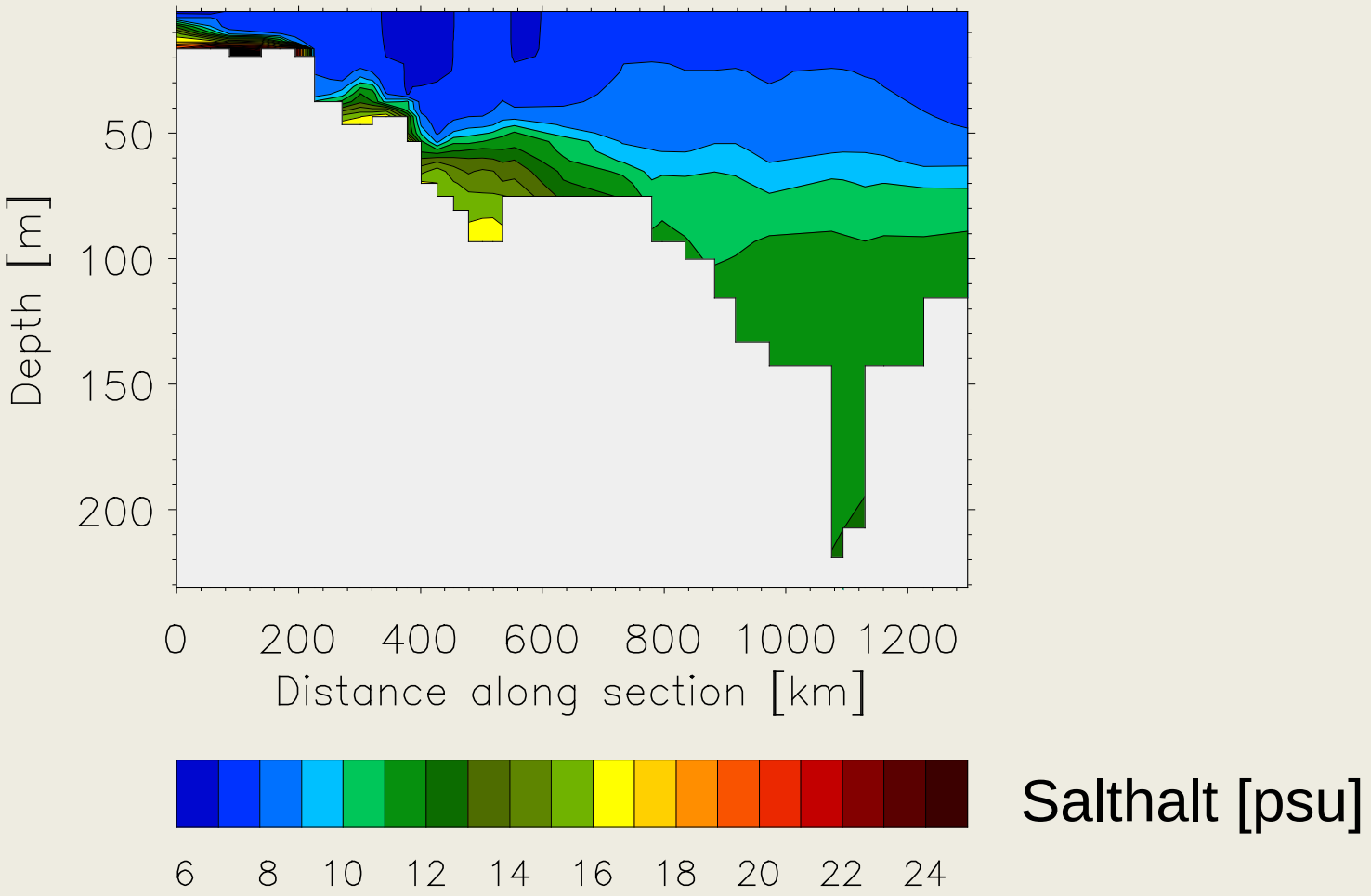
Baltic Sea topography

Depth [m]

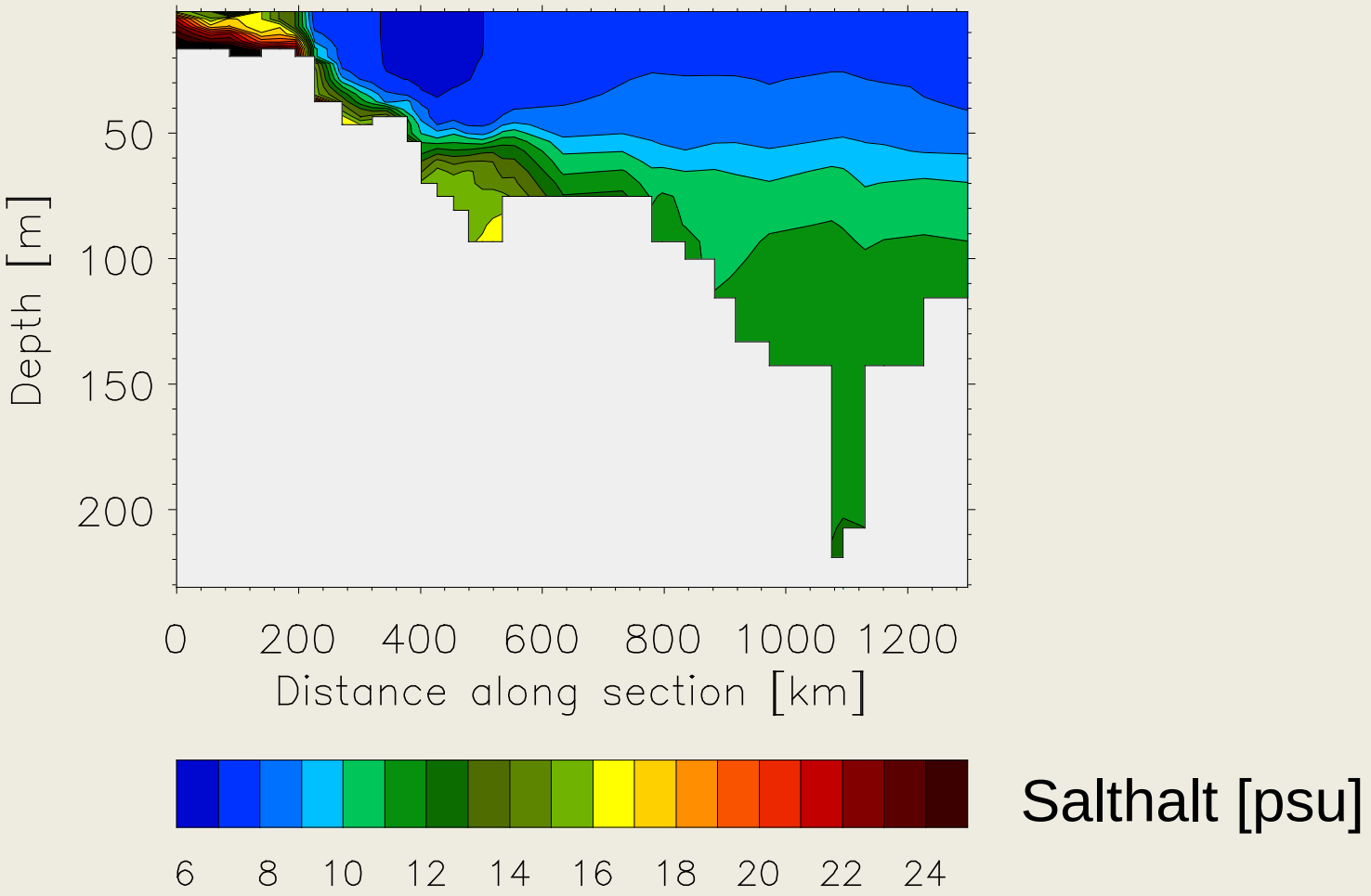
2 Oktober 2002



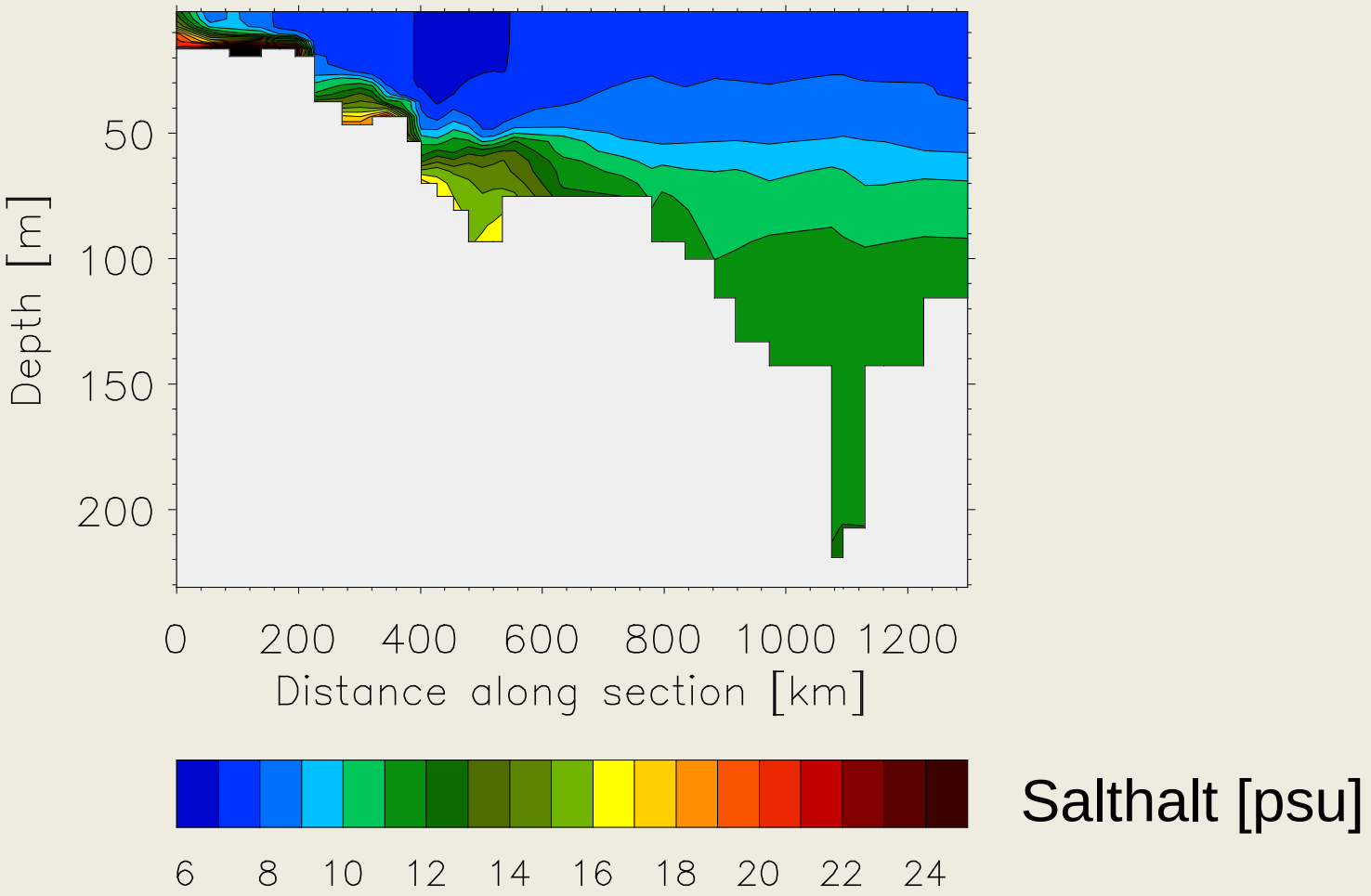
18 Oktober 2002



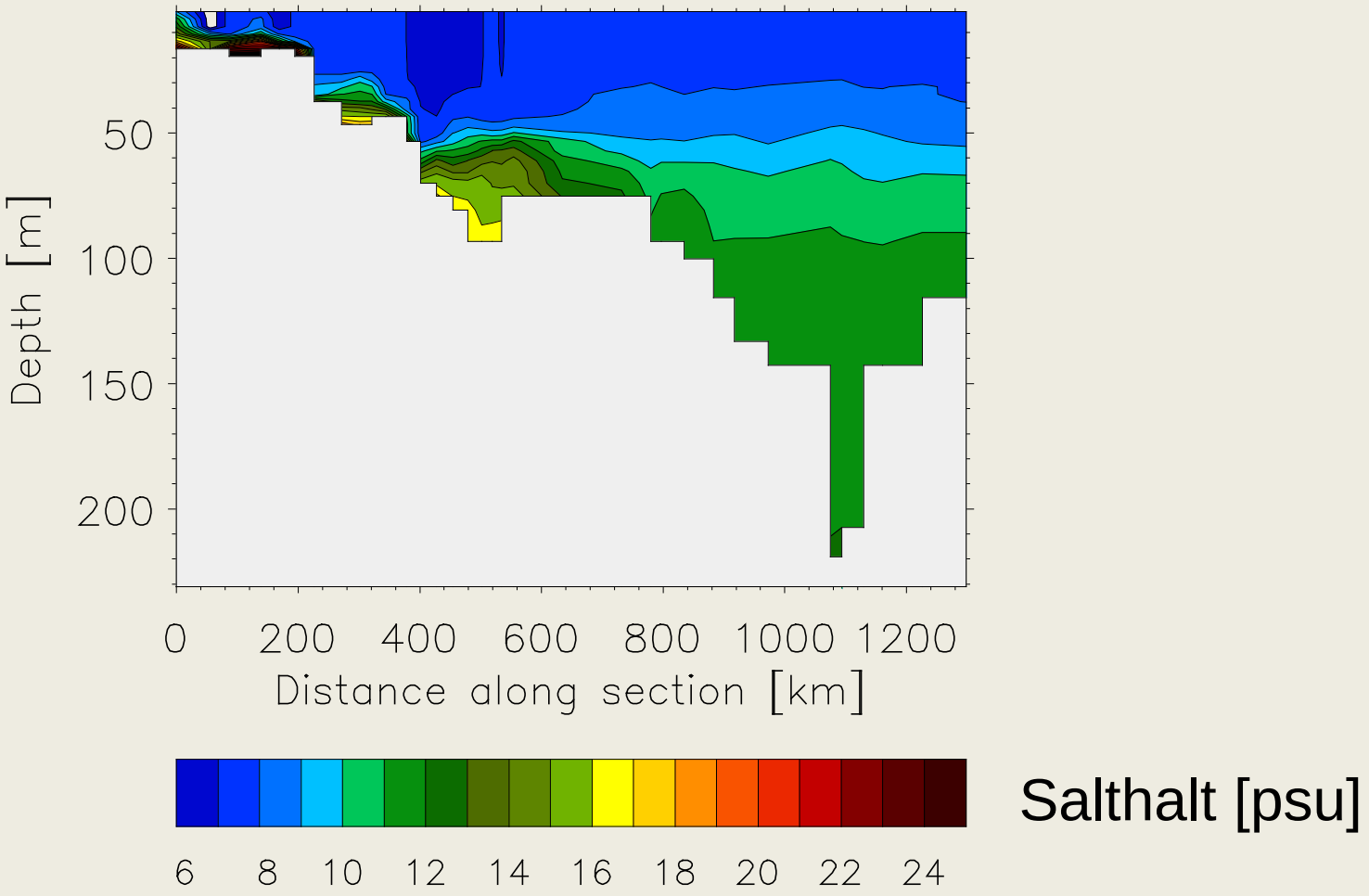
1 November 2002



15 November 2002



1 December 2002



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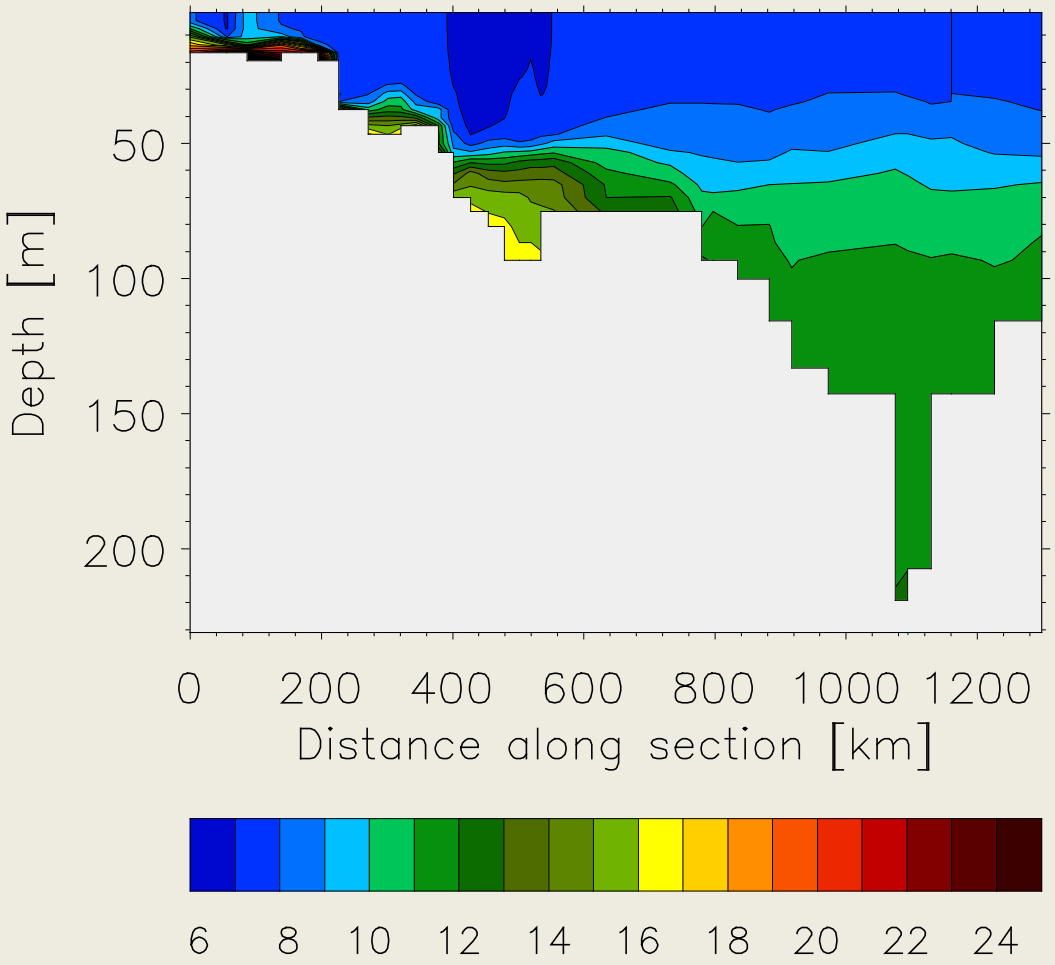

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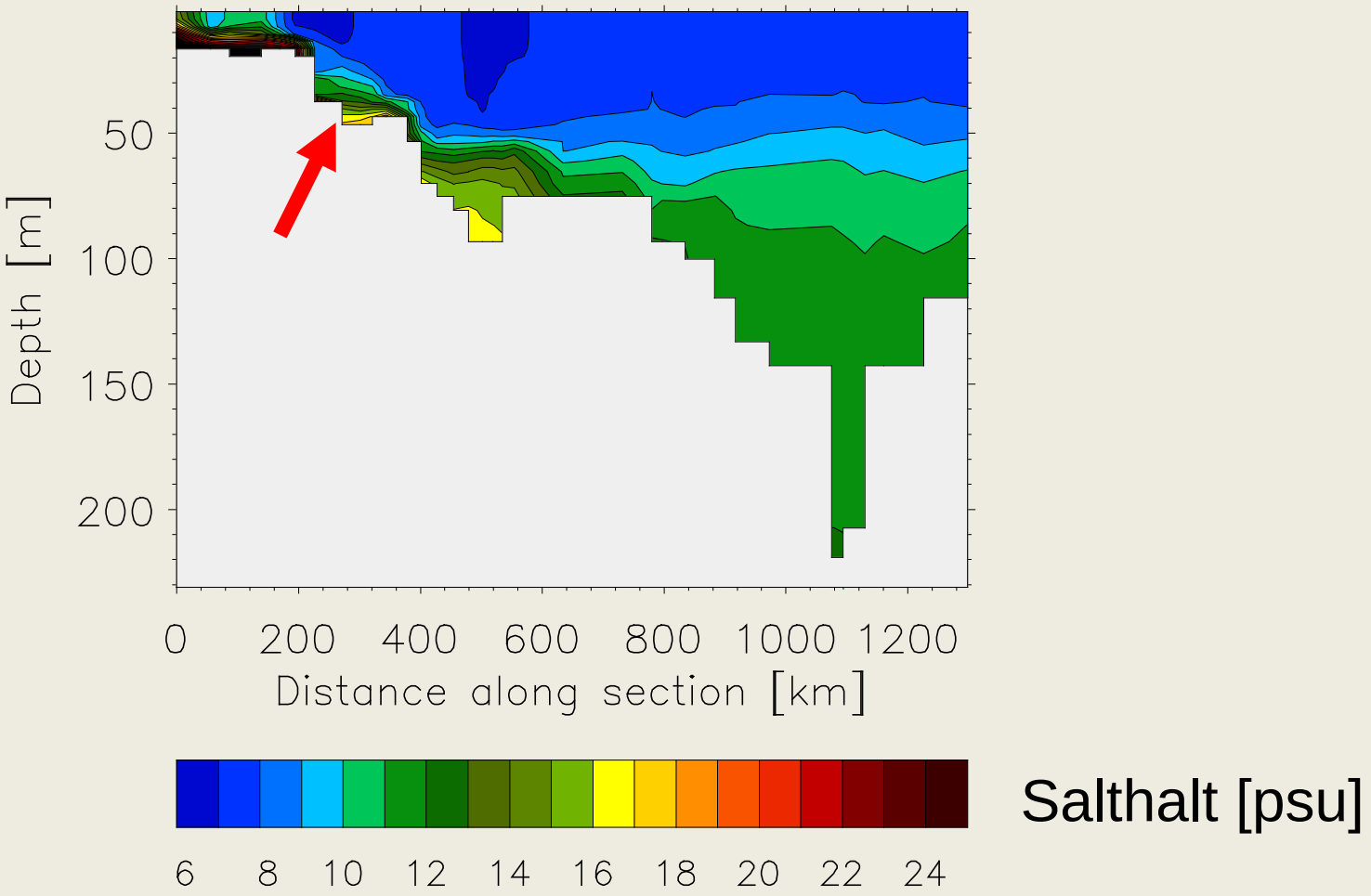
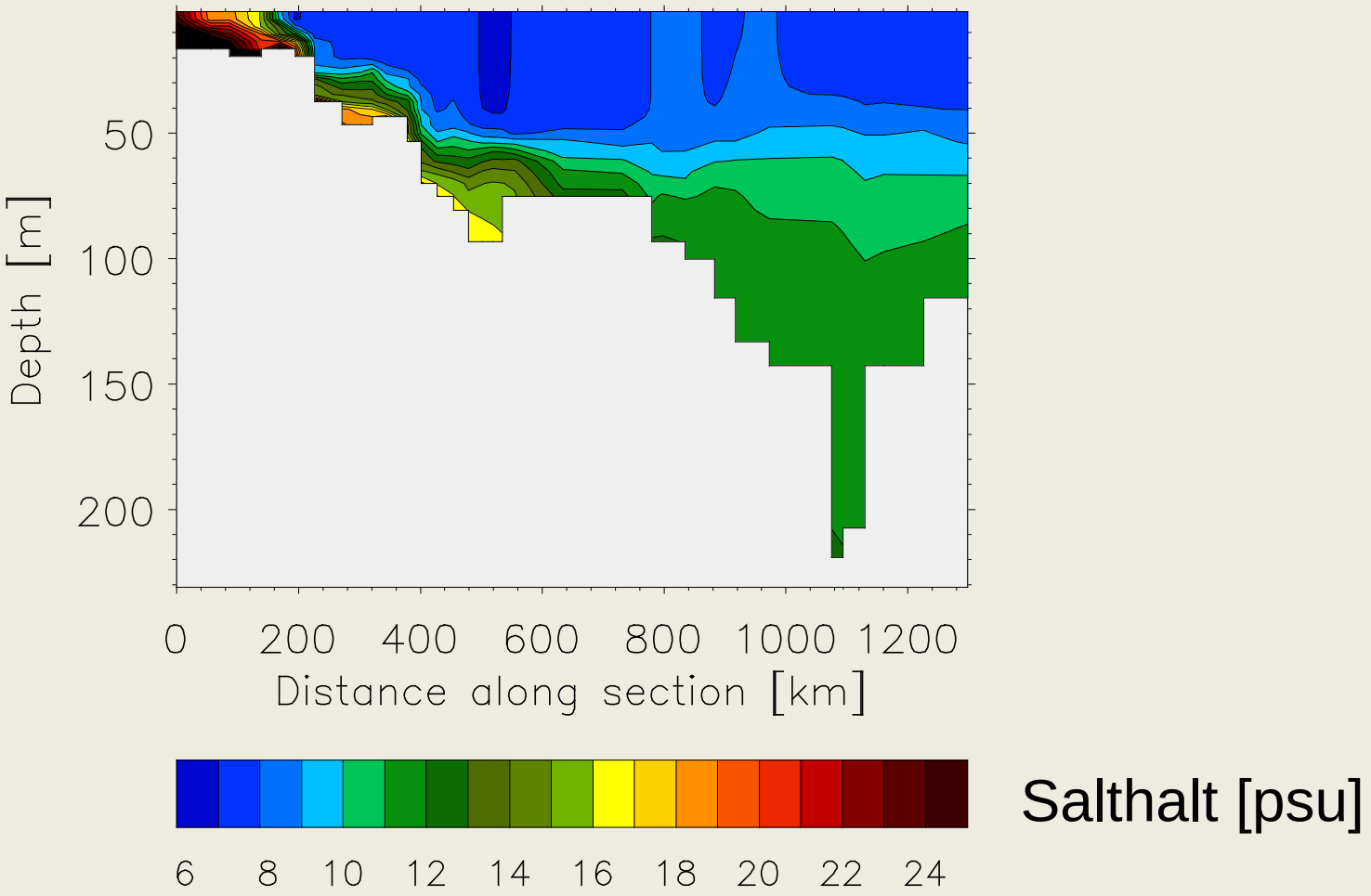
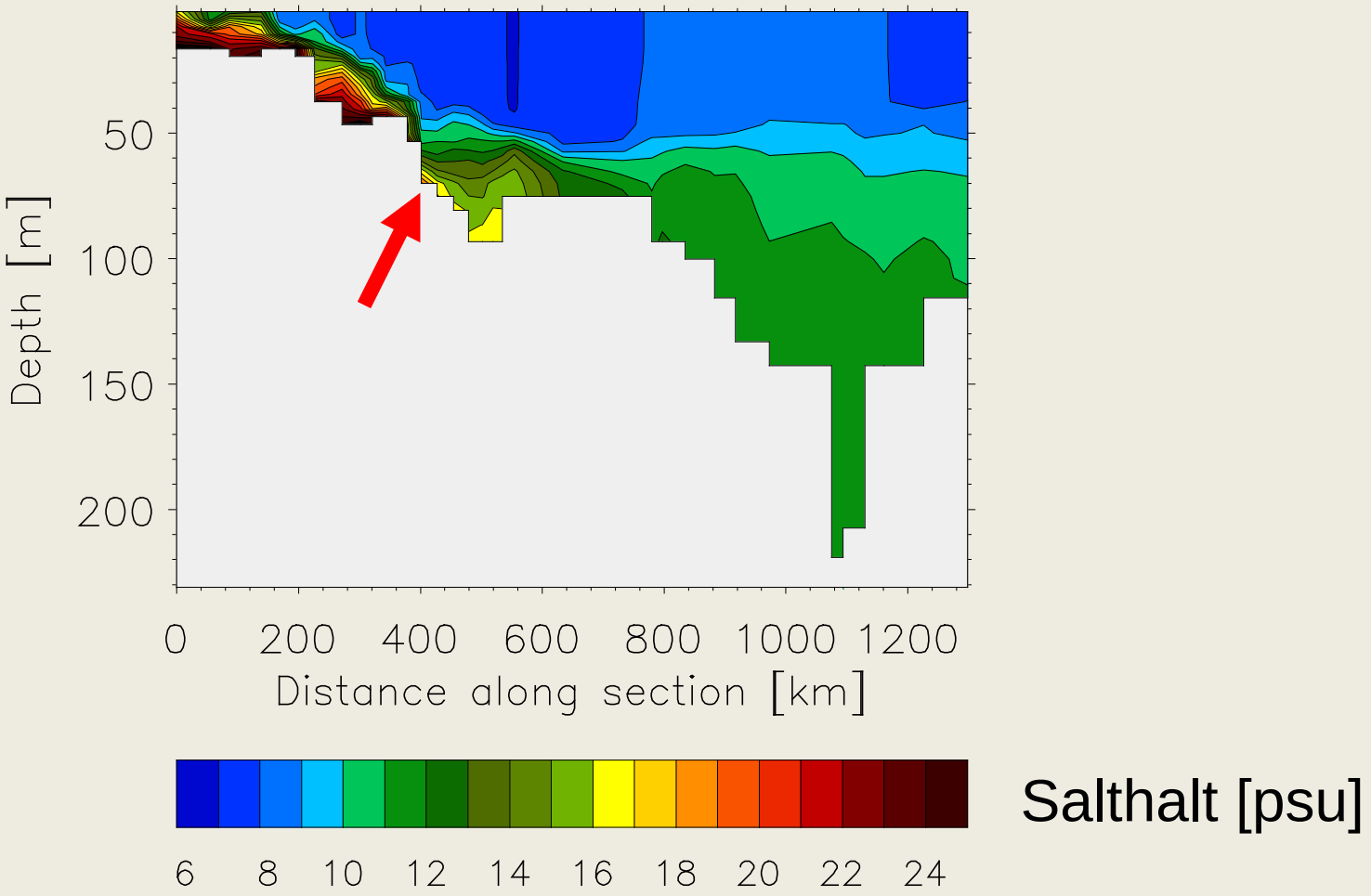


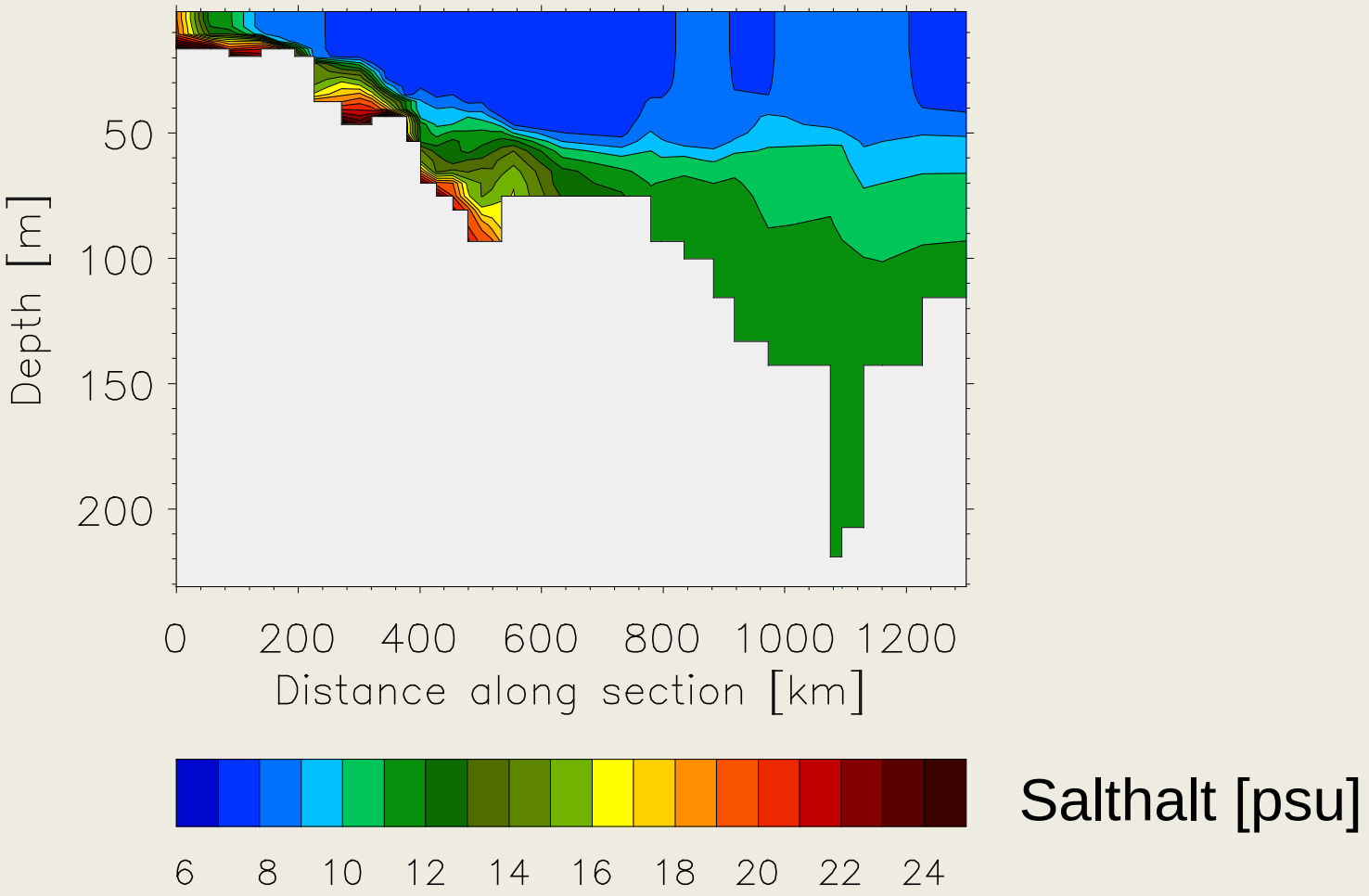
14 Januari 2003



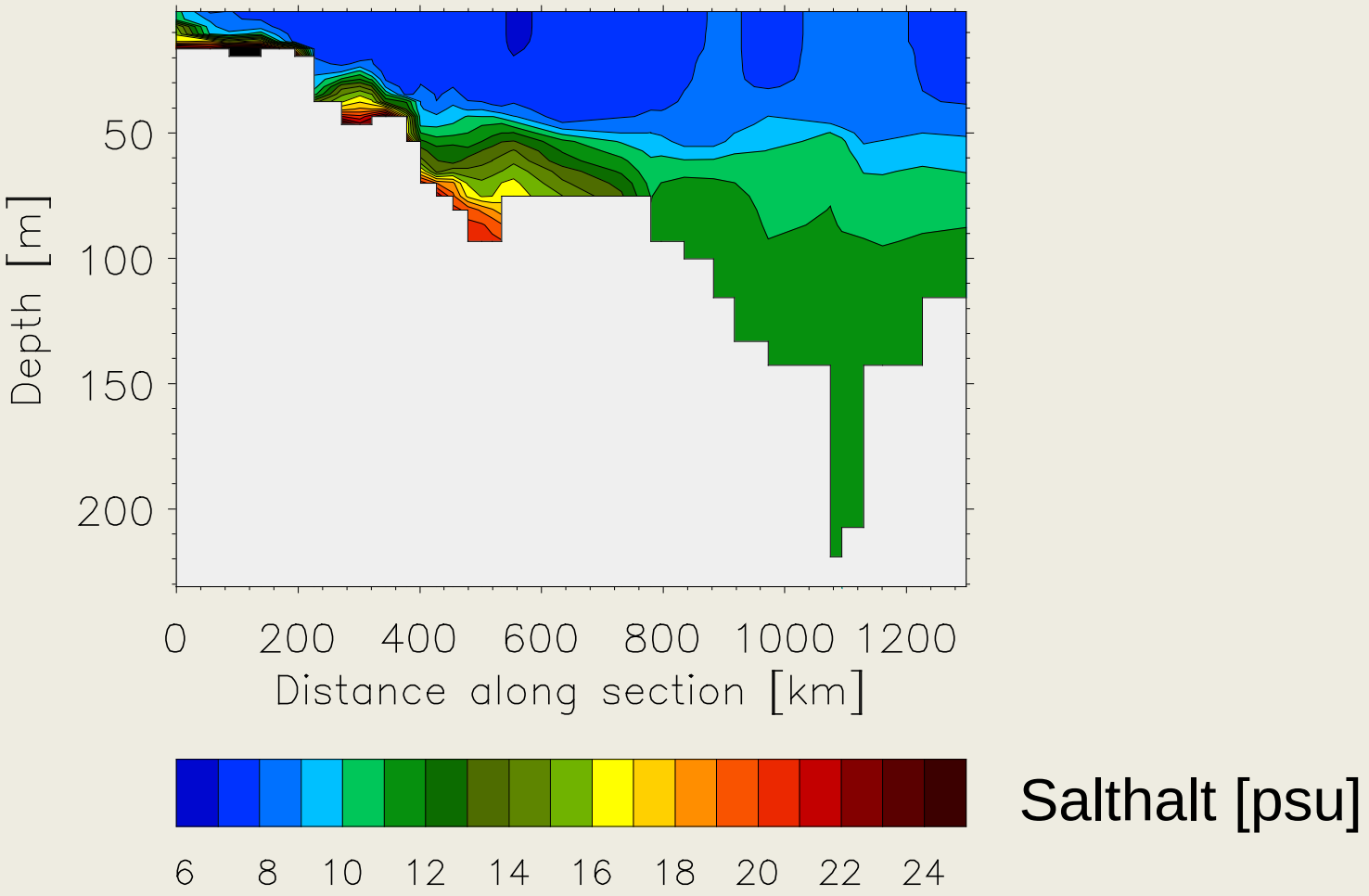
24 Januari 2003



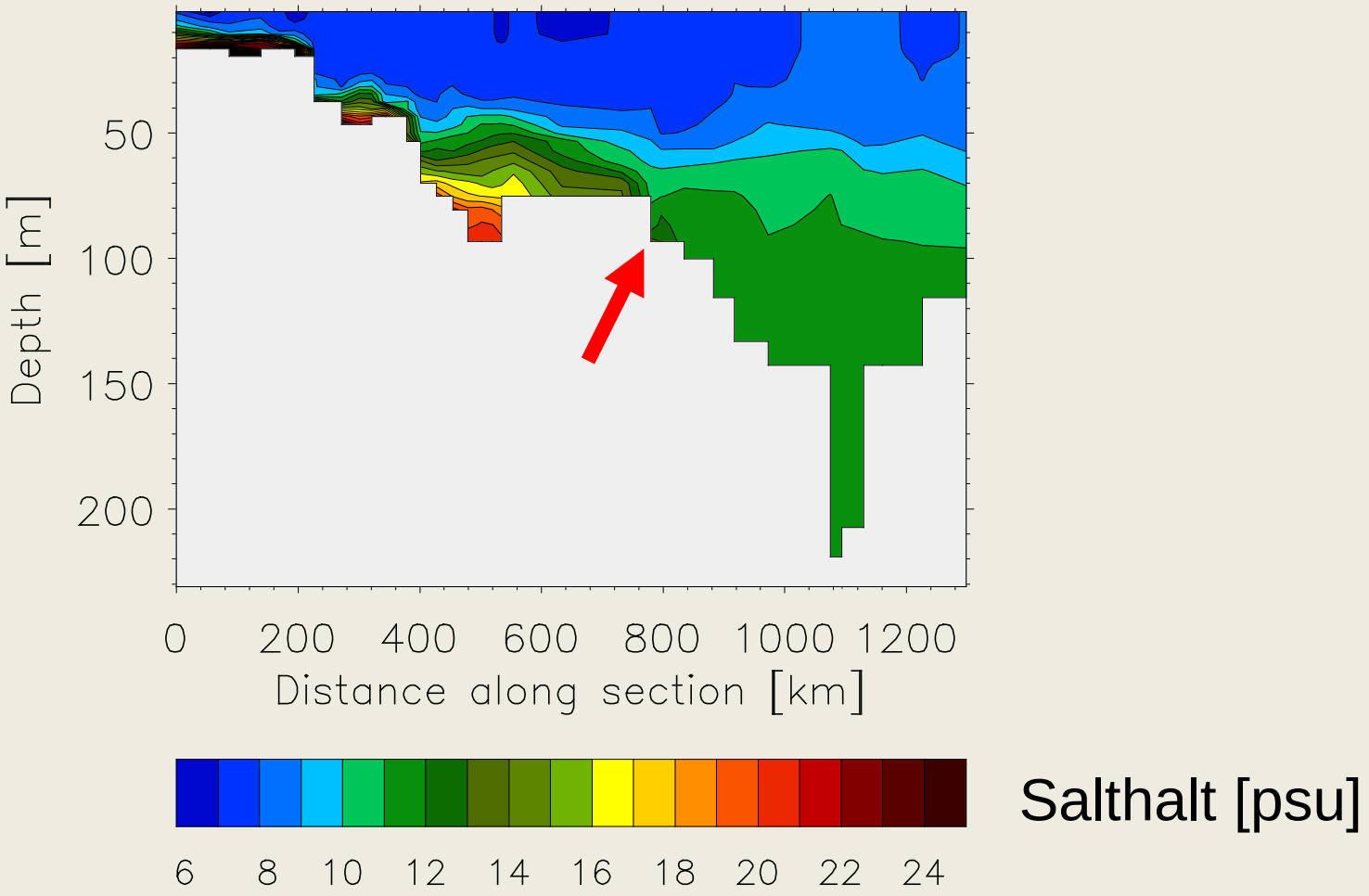
3 Februari 2003



13 Februari 2003



1 Mars 2003


Depth [m]
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Distance along section [km]
6
8
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16
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22
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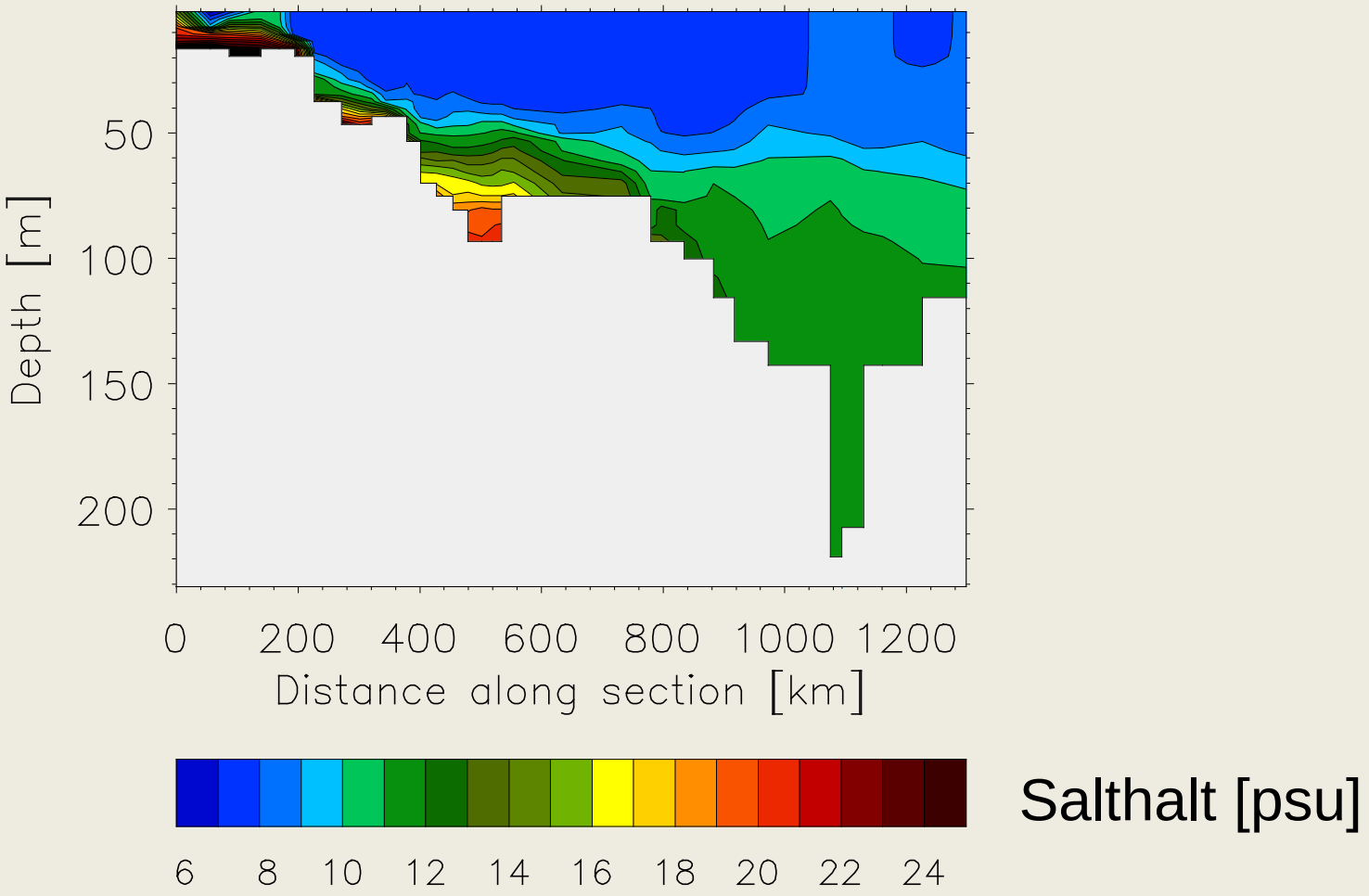
Salthalt [psu]

15 Mars 2003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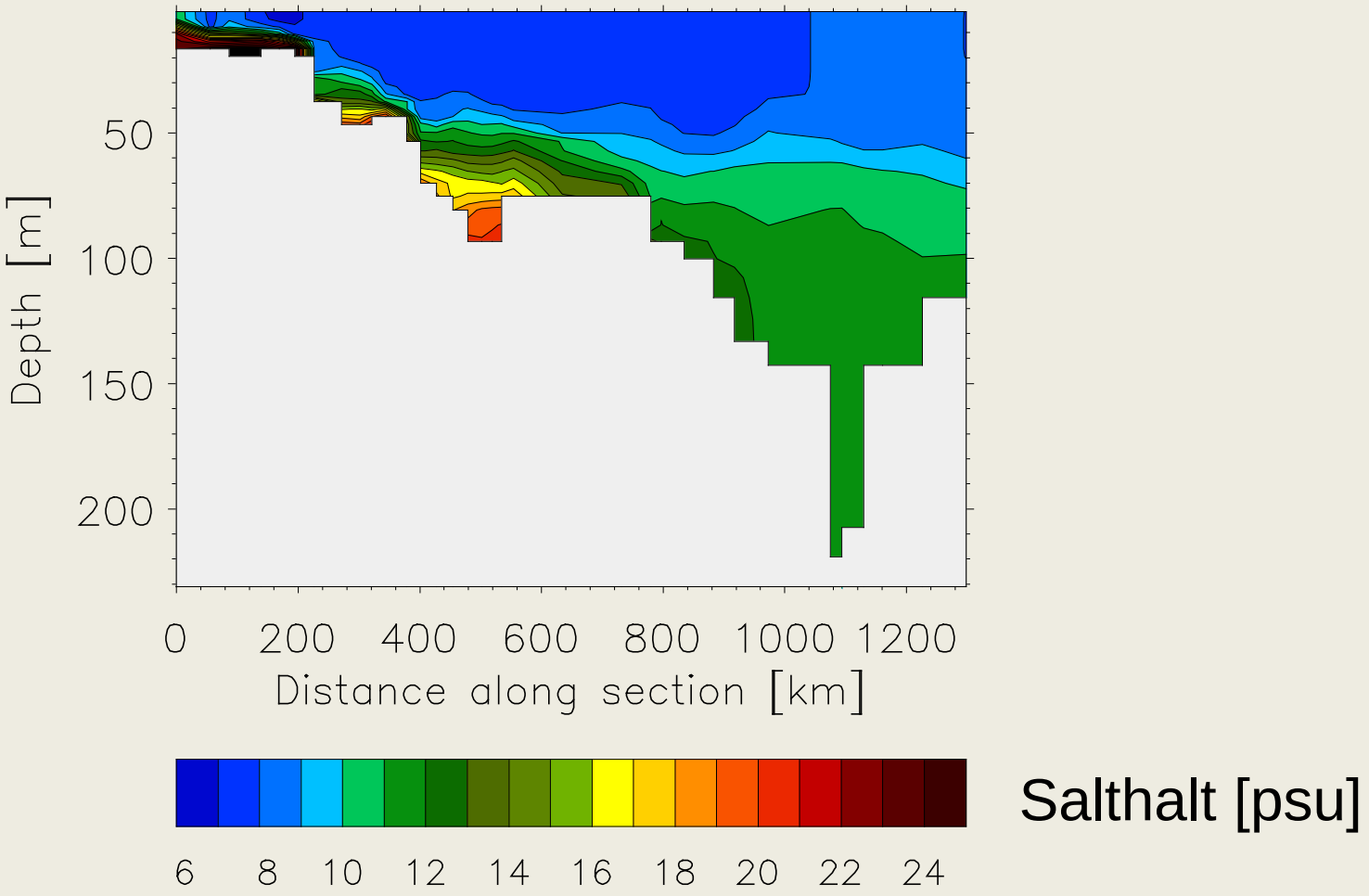
Salthalt [psu]

27 Mars 2003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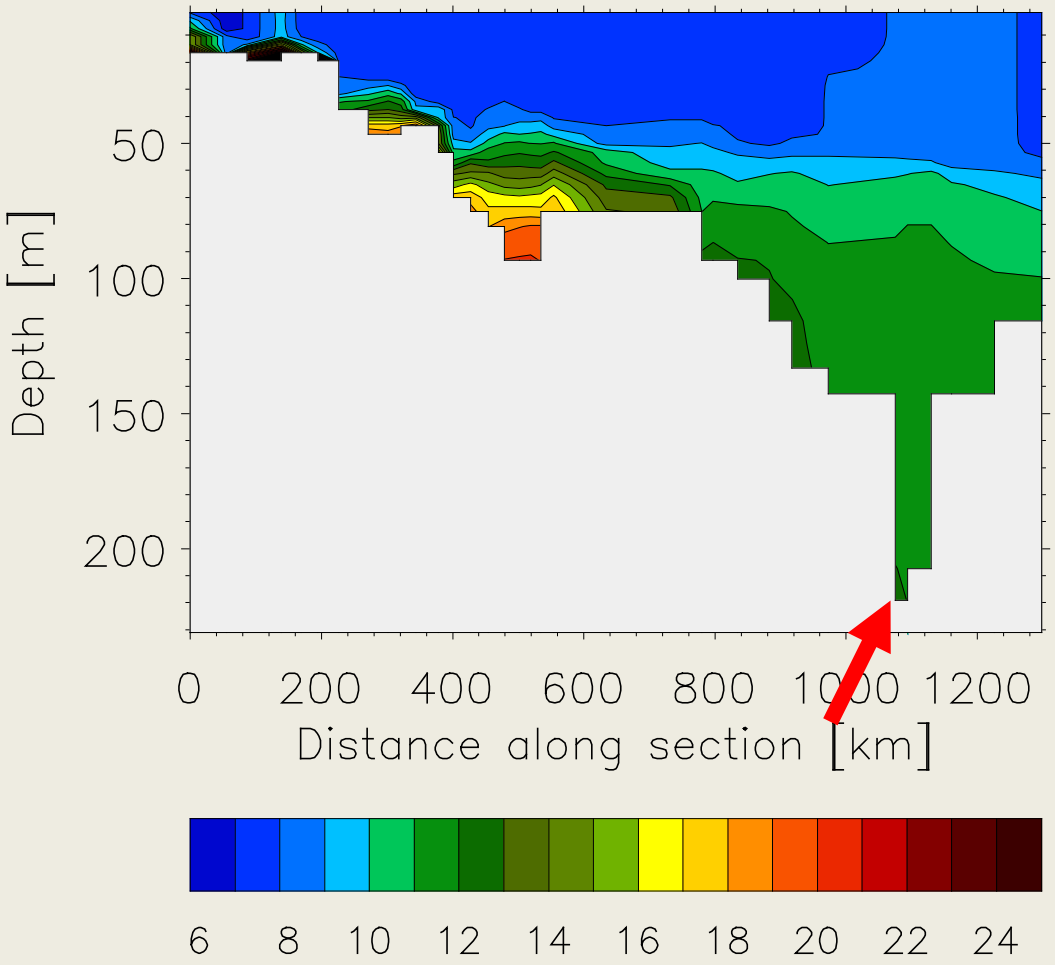
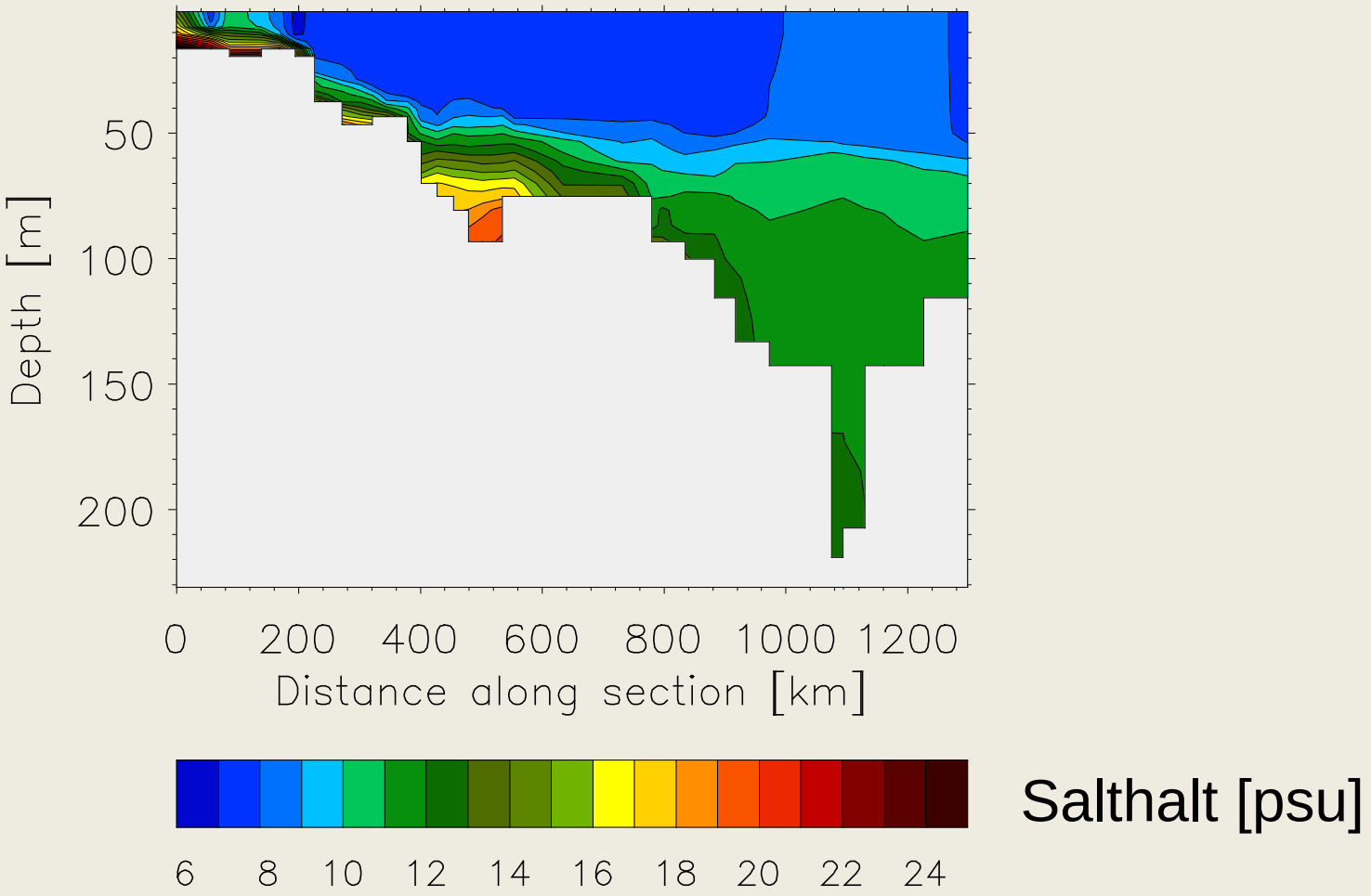
Salthalt [psu]

20 April 2003



6 Maj 2003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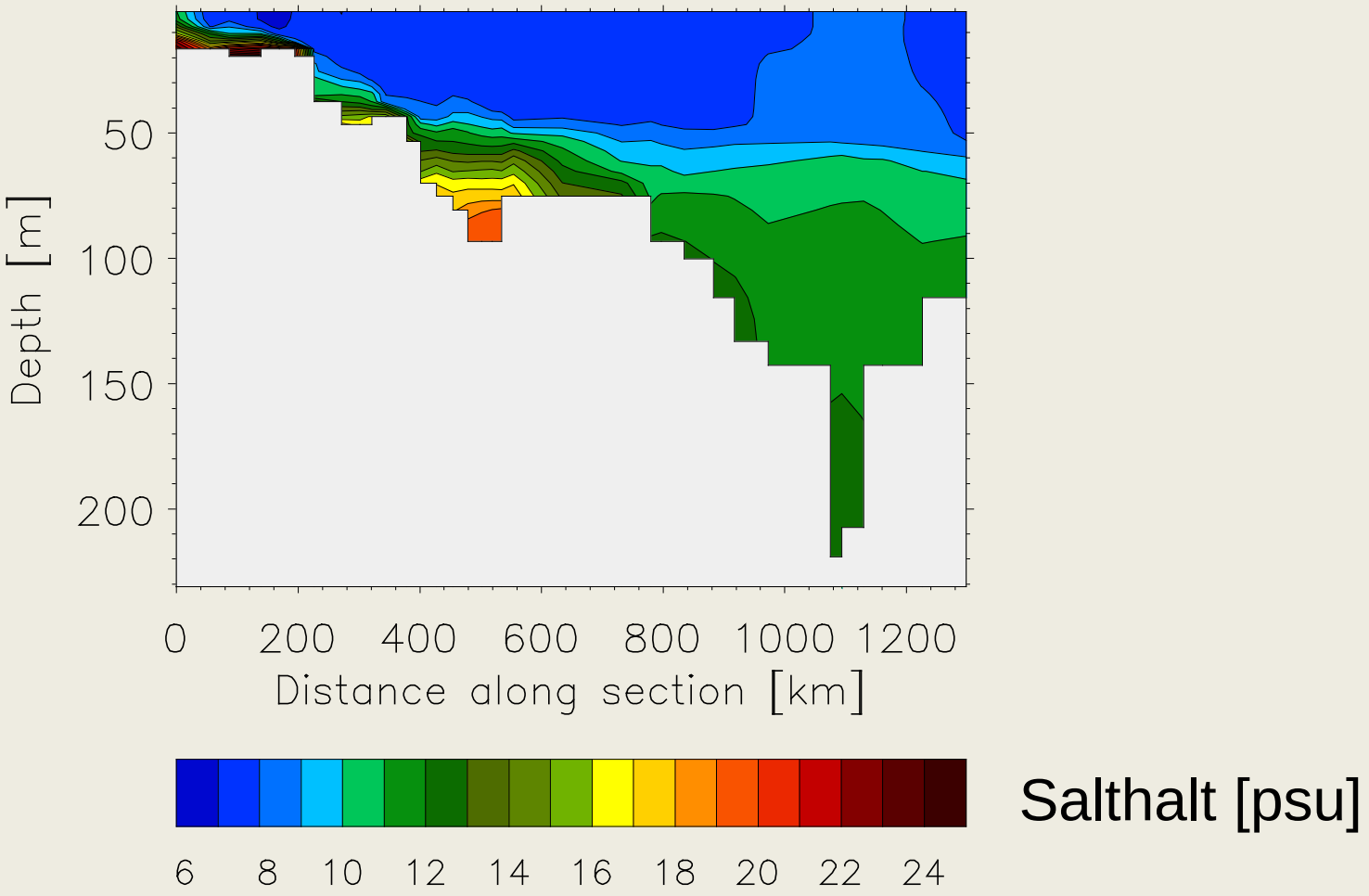
Salthalt [psu]

20 Maj 2003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Distance along section [km]
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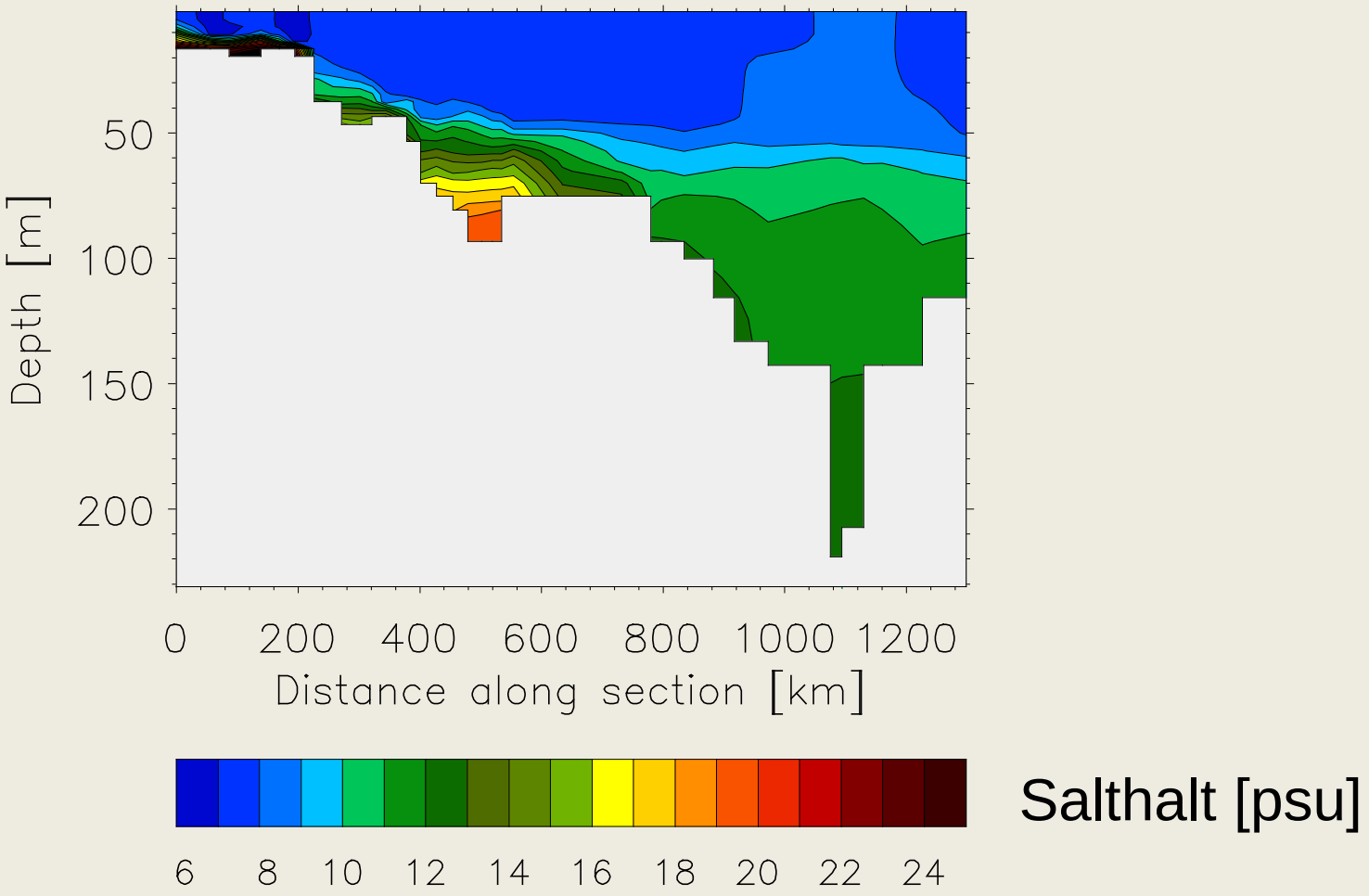
Salthalt [psu]

3 Juni 2003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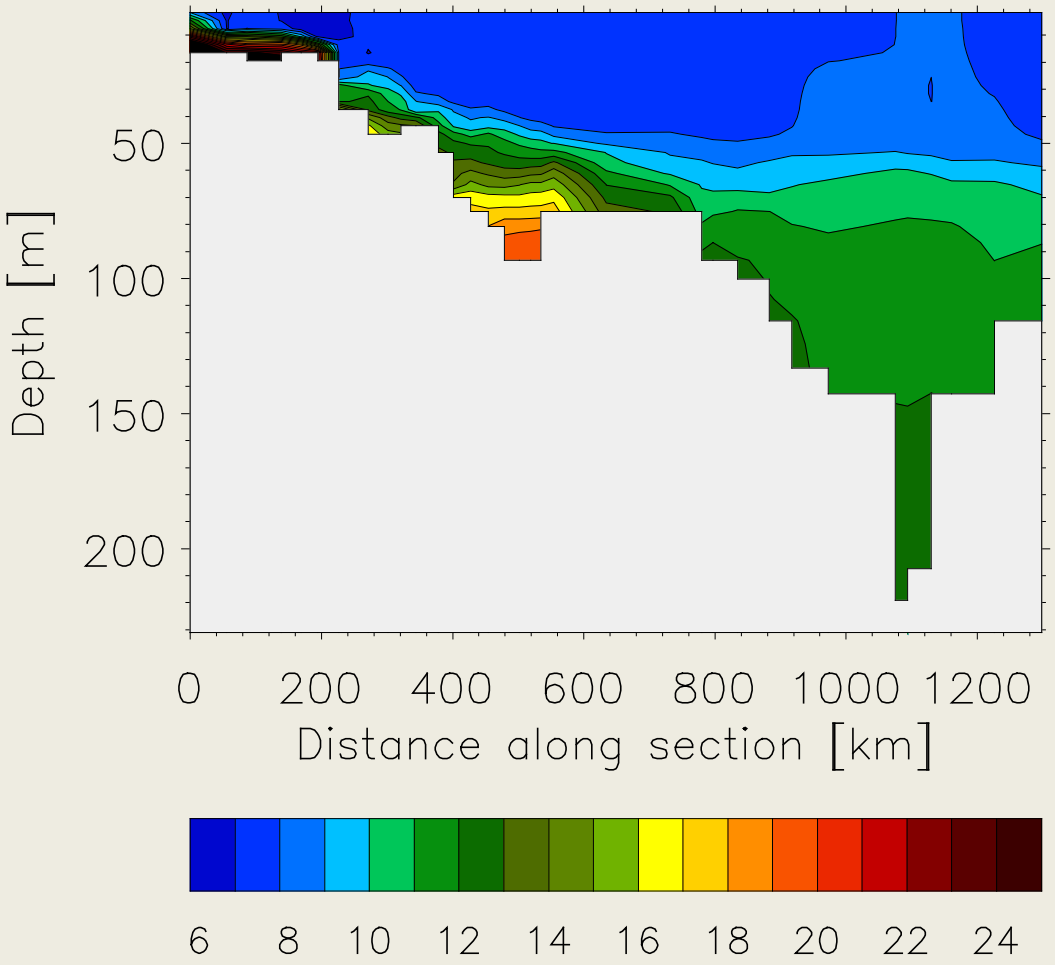
Salthalt [psu]

17 Juni 2003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Distance along section [km]
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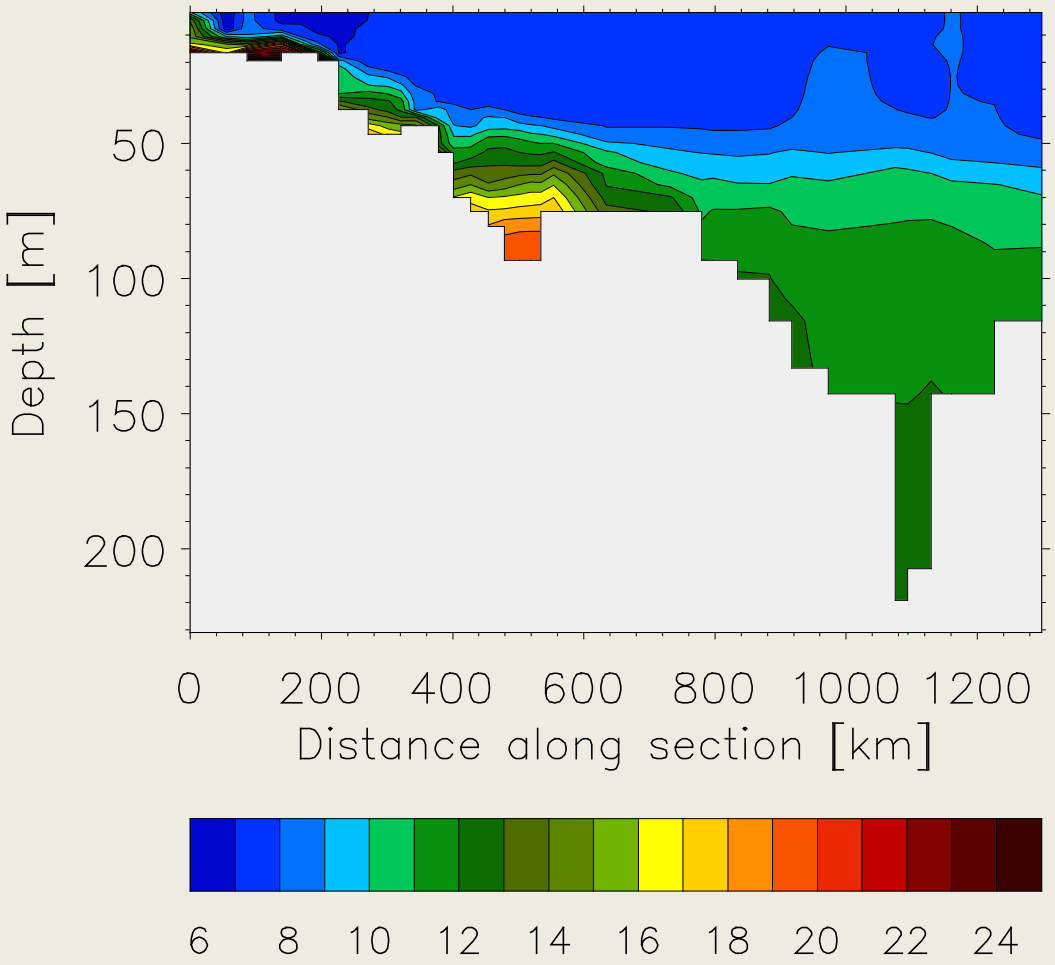
Salthalt [psu]

1 Juli 2003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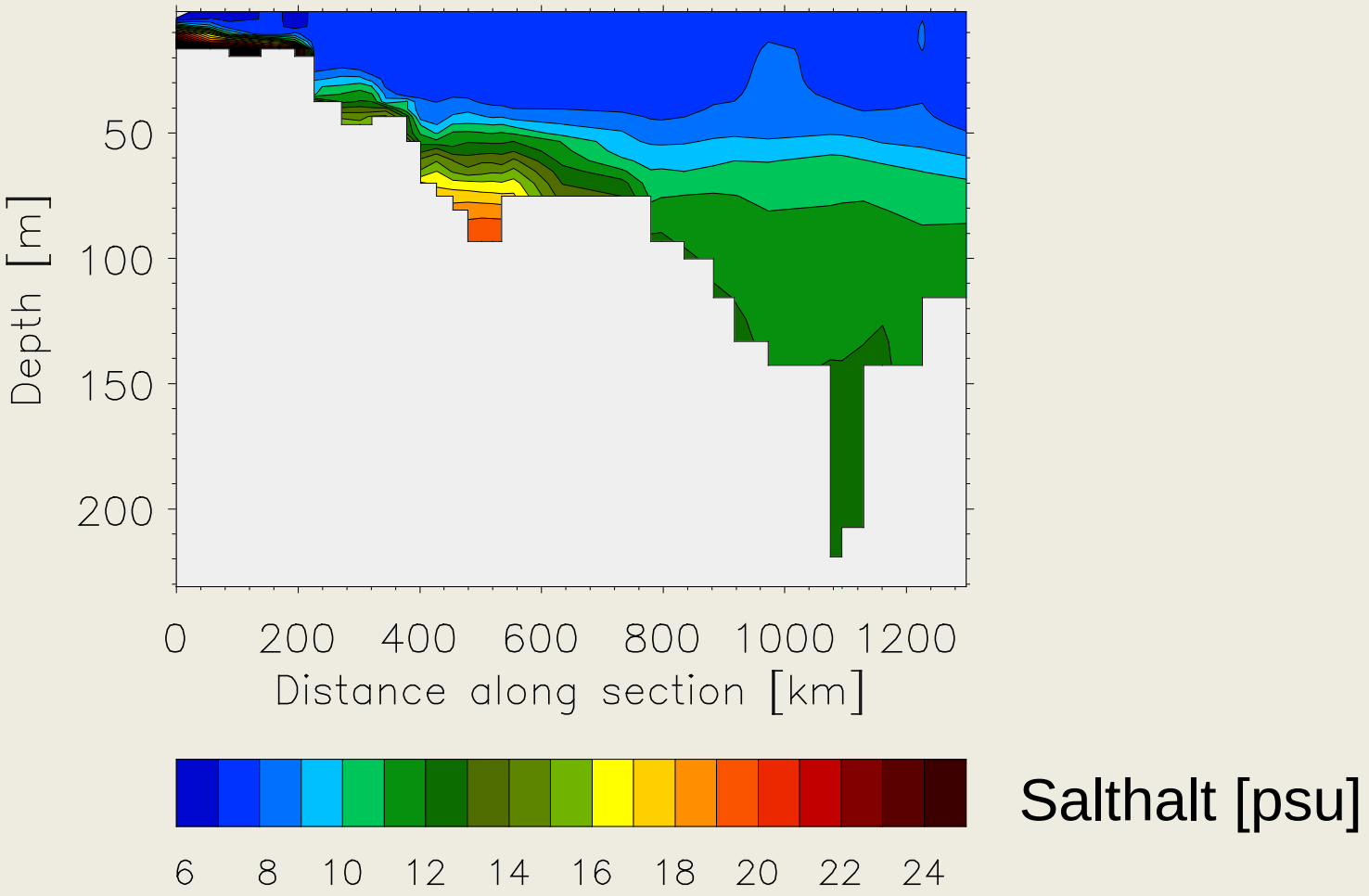
Salthalt [psu]

29 Juli 2003


Depth [m]
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Distance along section [km]
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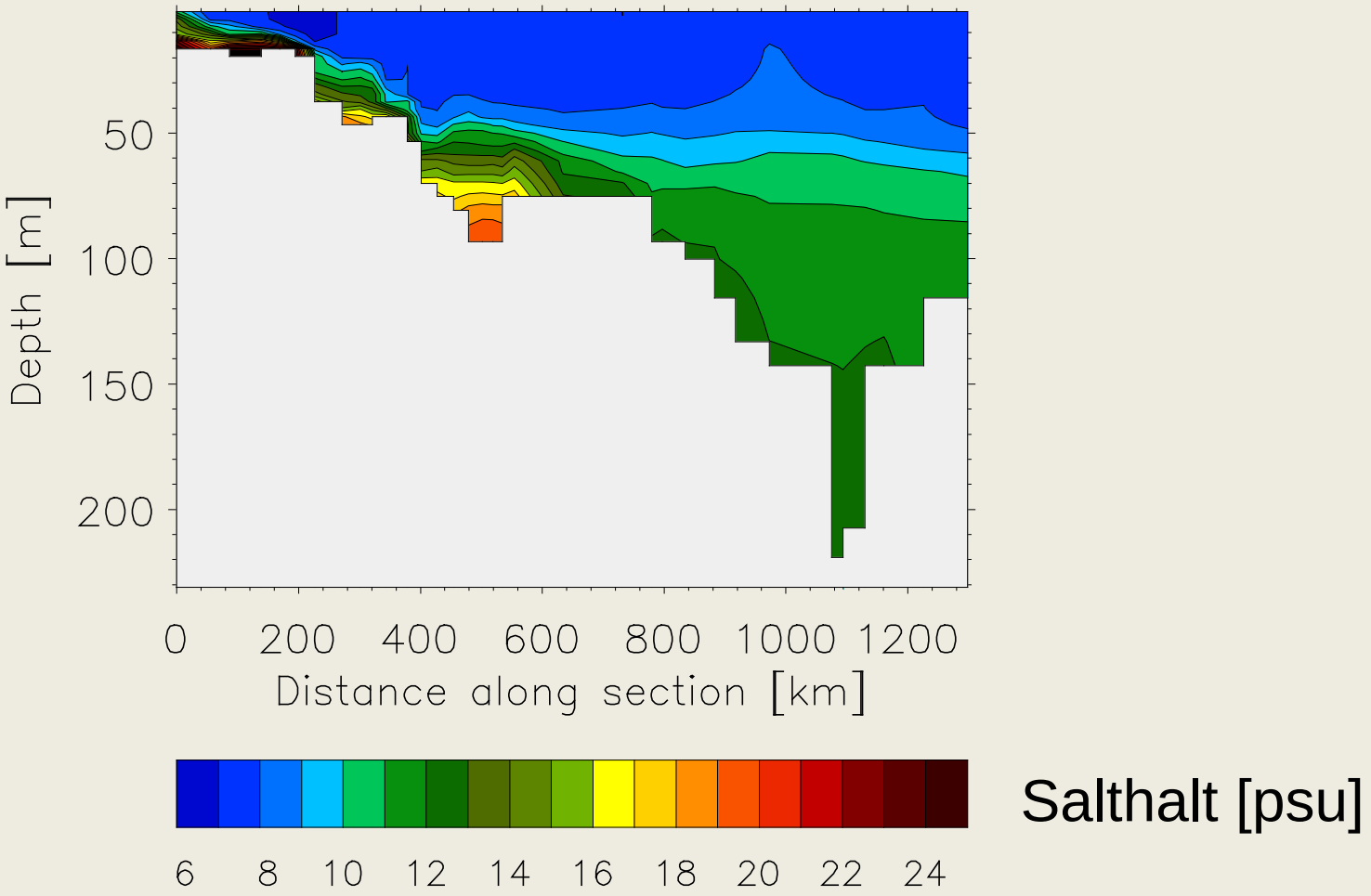
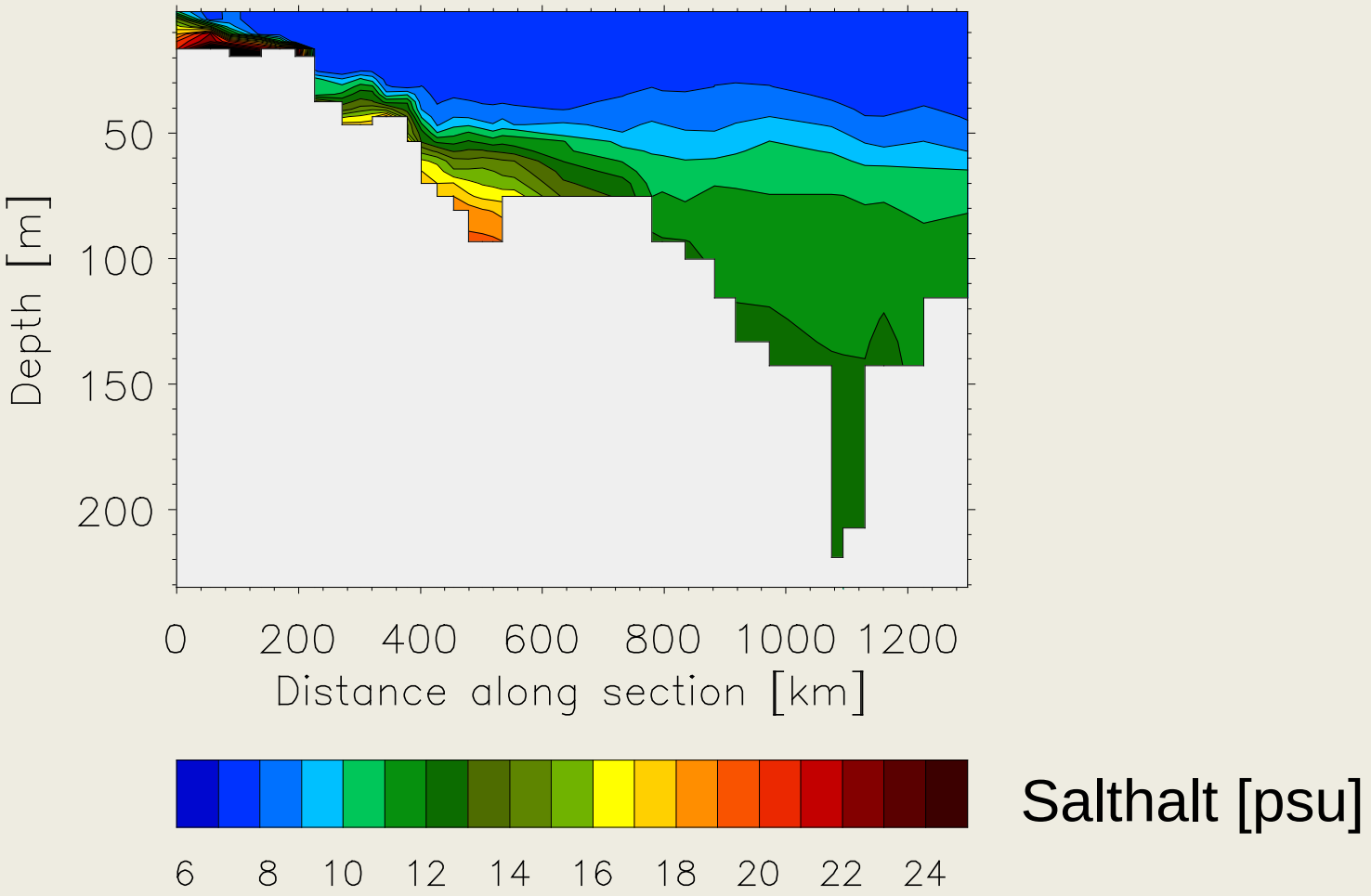
Salthalt [psu]

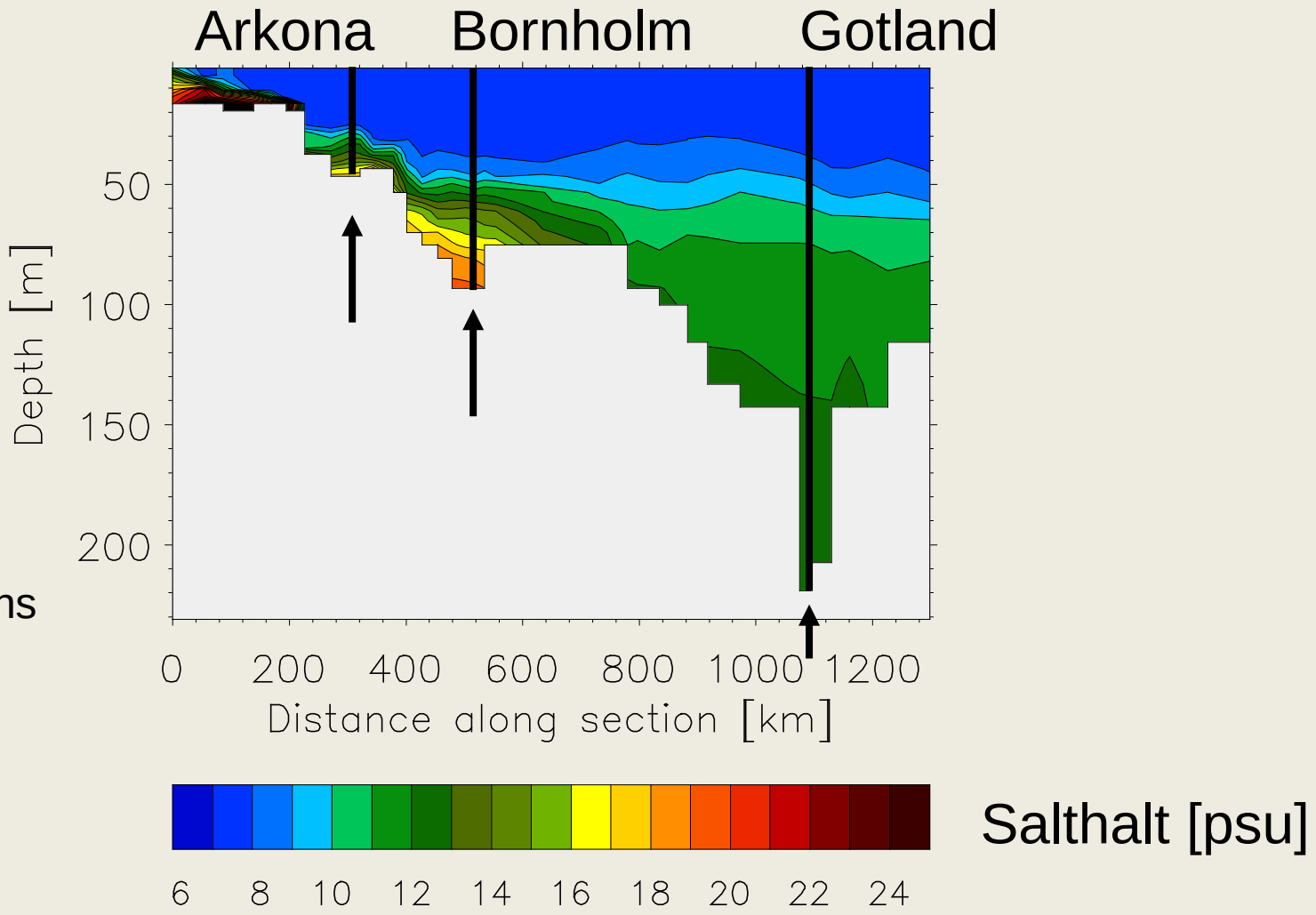
1 September 2003



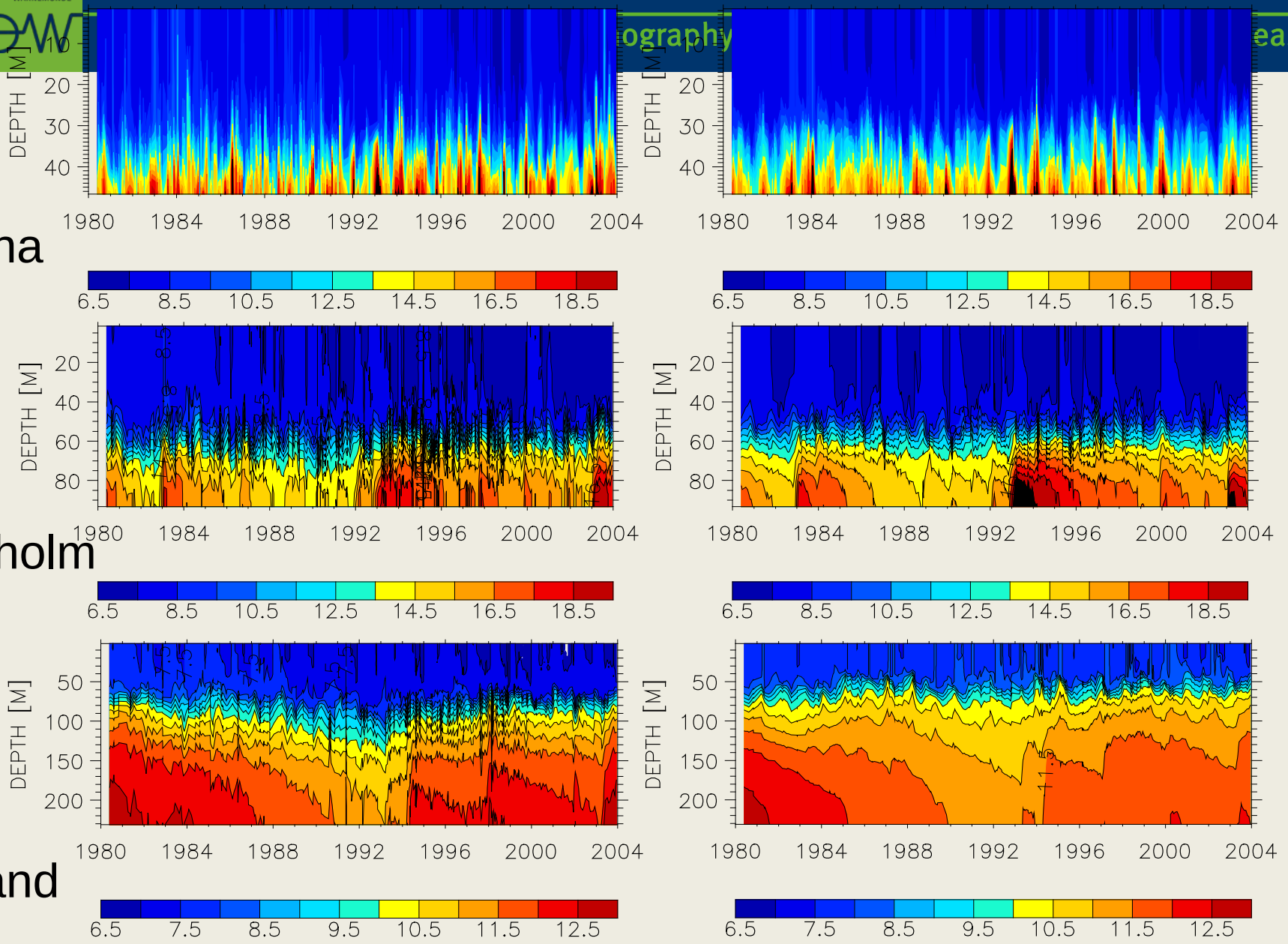
29 Oktober 2003

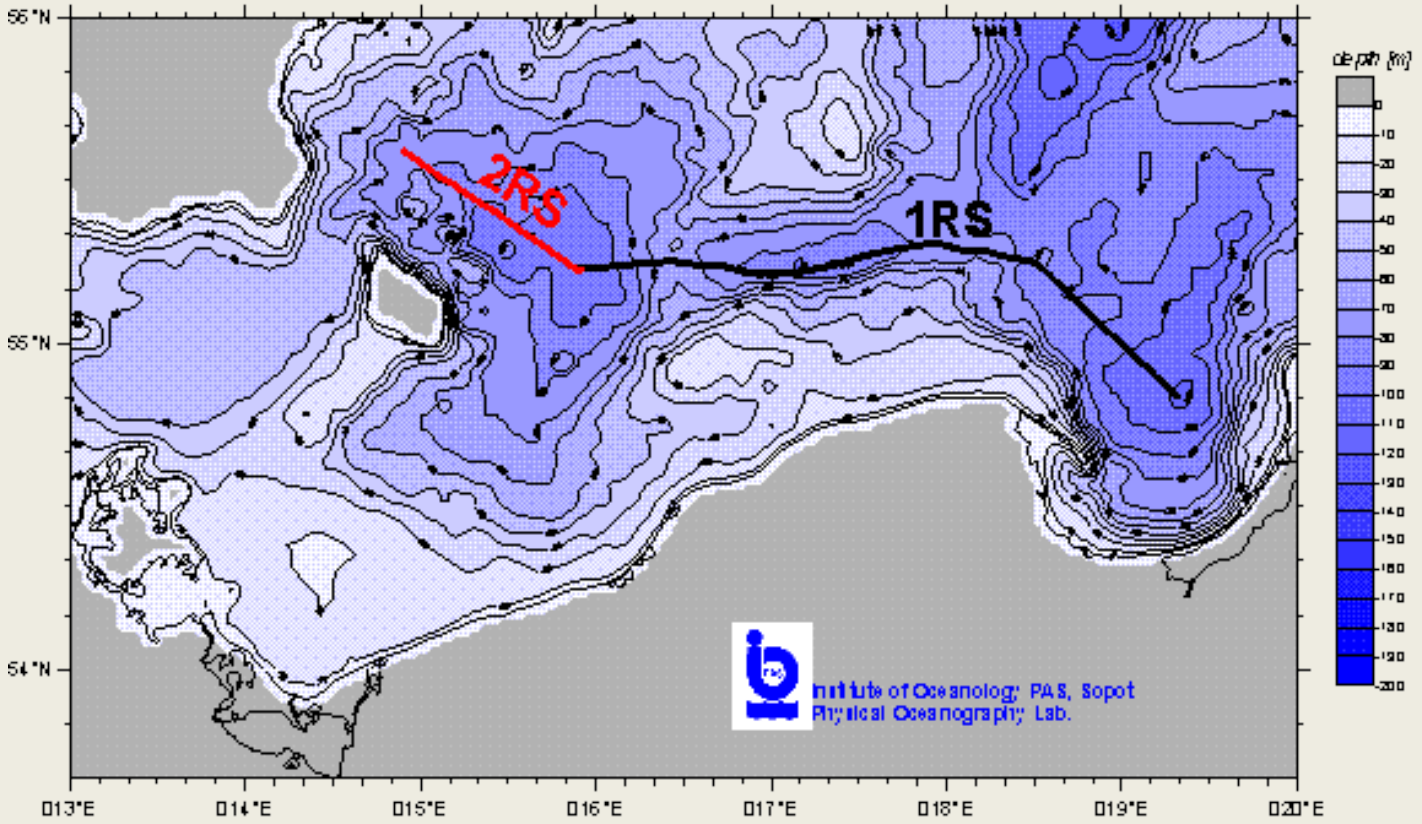


29 Oktober 2003



BY5: after 12 days,
BY15: after 3 months


ography
eas
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
6.5 7.5 8.5 9.5 10.5 11.5 12.5
observations
salinity [g kg-1]
model


56°N
55°N
54°N
13°E
14°E
15°E
16°E
17°E
18°E
19°E
20°E
2RS
1RS
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20
30
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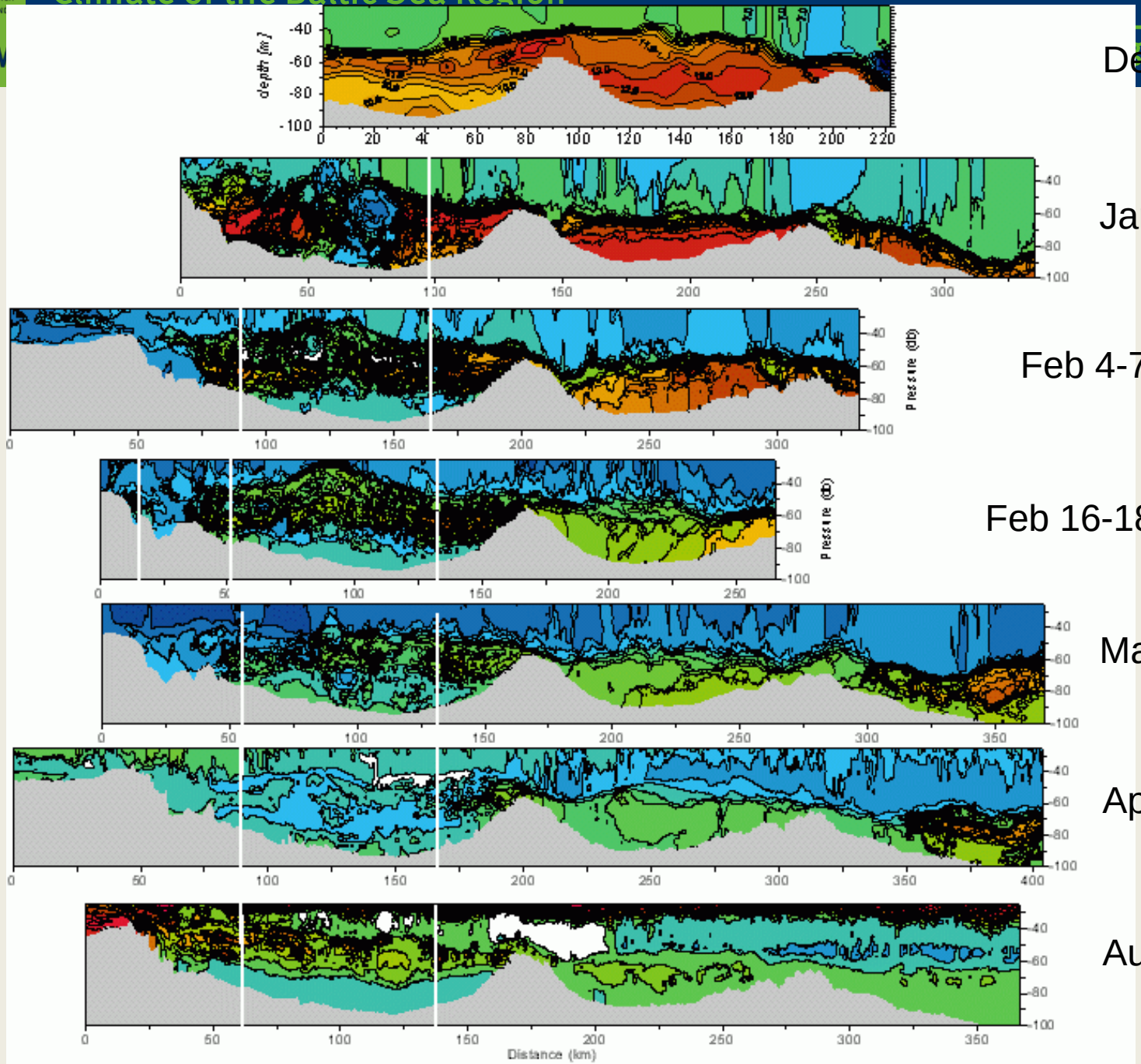
Institute of Oceanology PAS, Sopot
Physical Oceanography Lab.



Dec 2002

Jan 2003

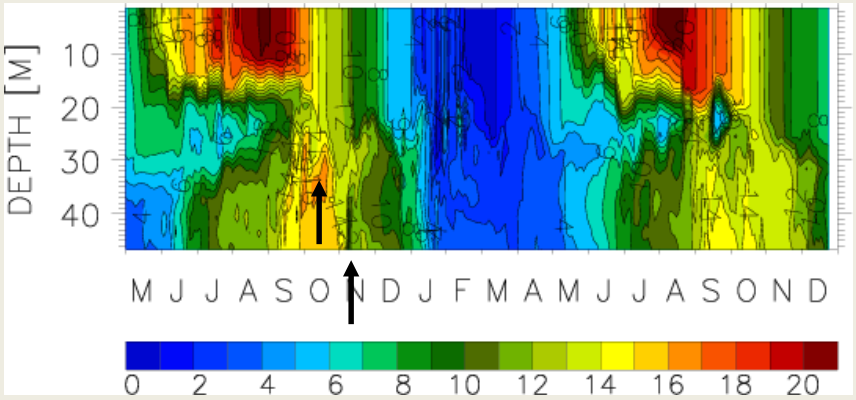
Feb 4-7, 2003

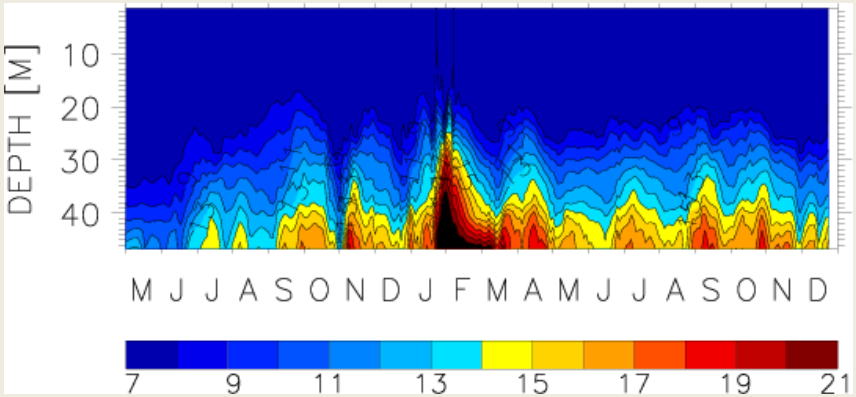
Feb 16-18, 2003

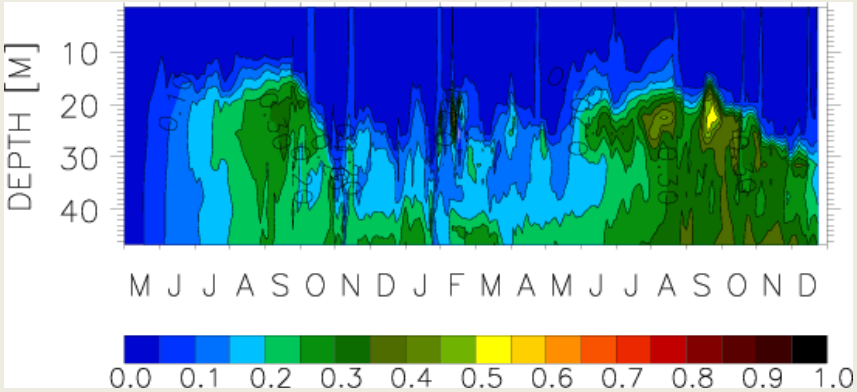
Mar 2003

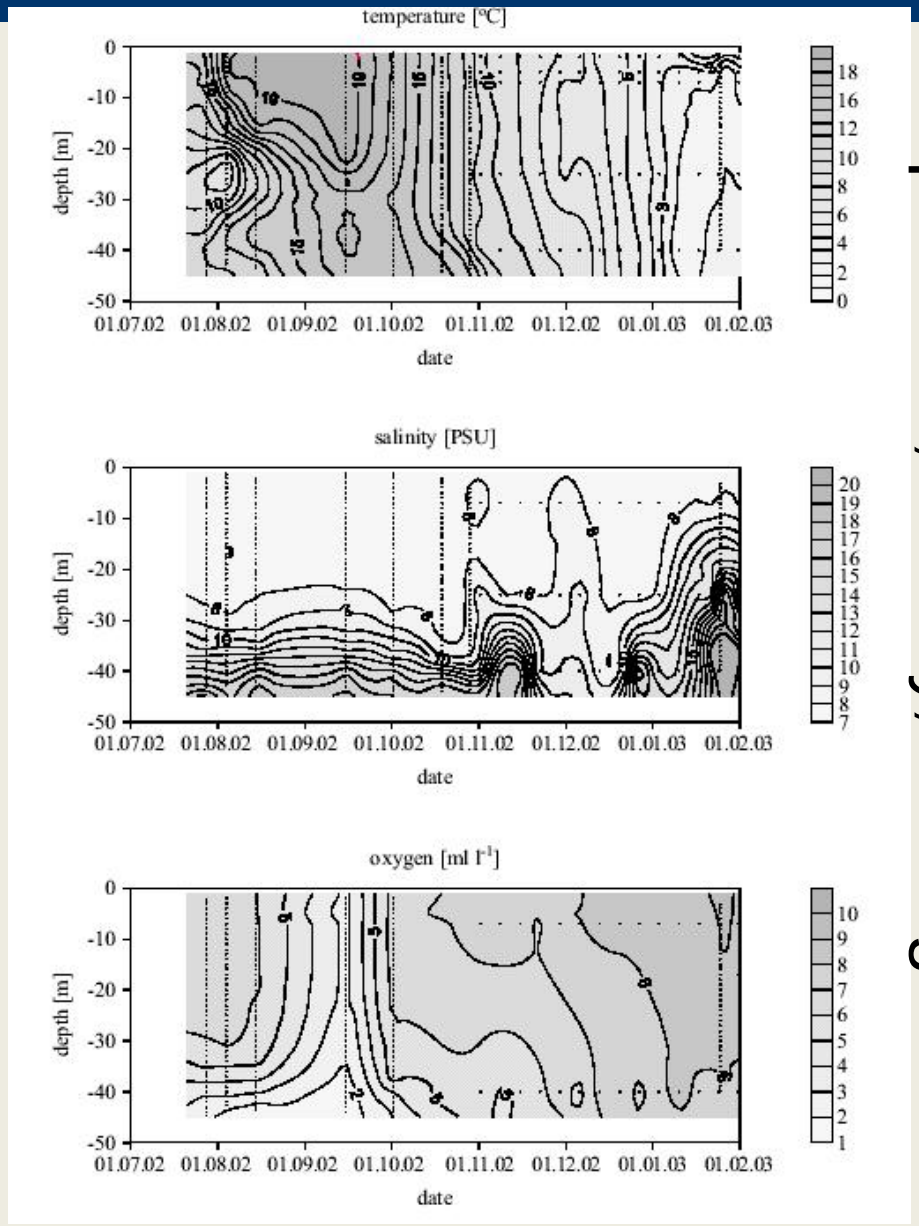
Apr 2003

Aug 2003

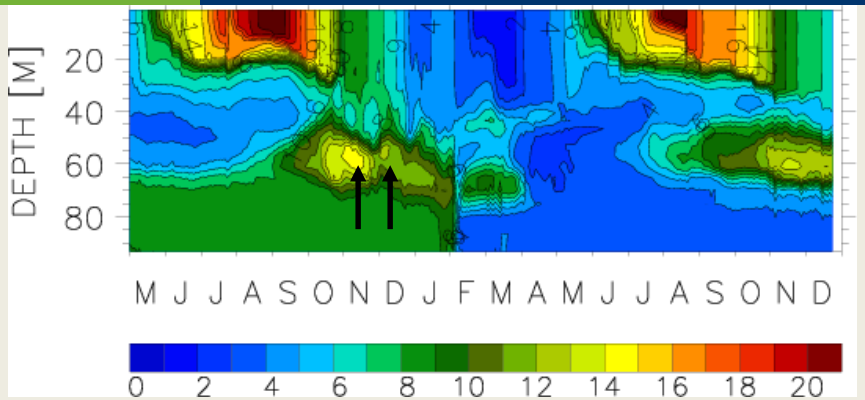


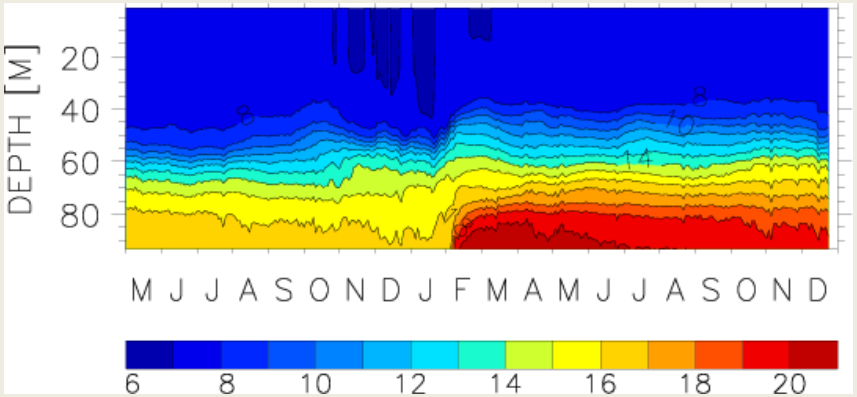


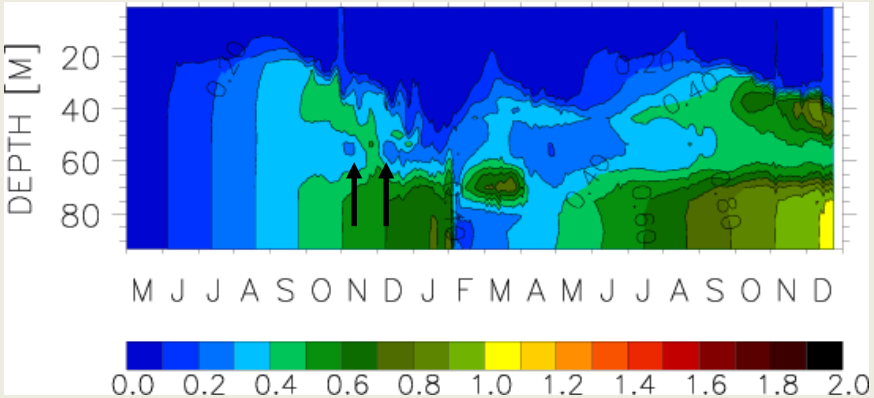


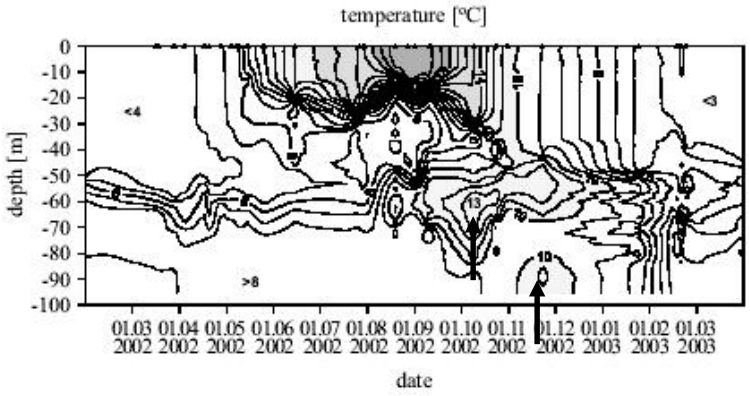


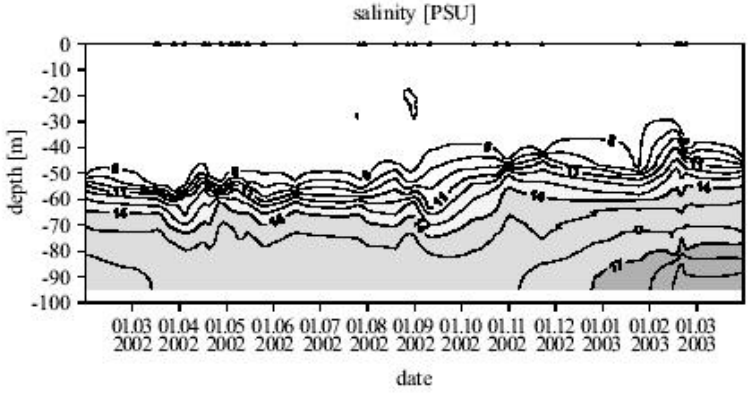
Temperature, salinity, and age at BY2

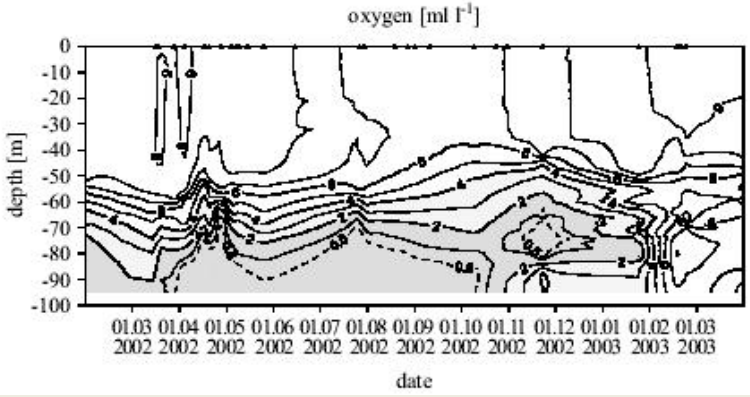




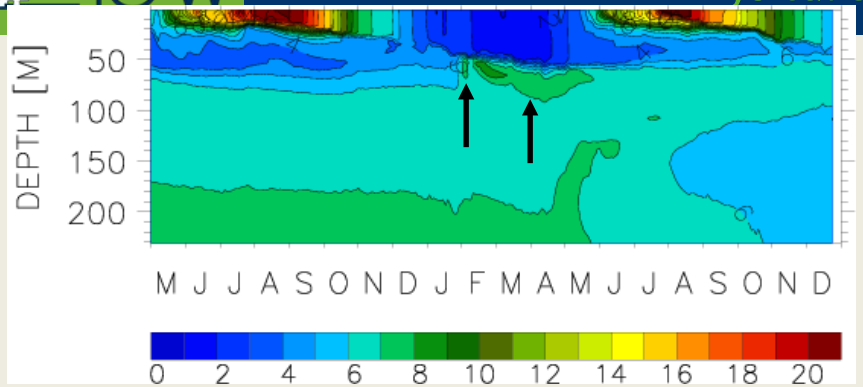


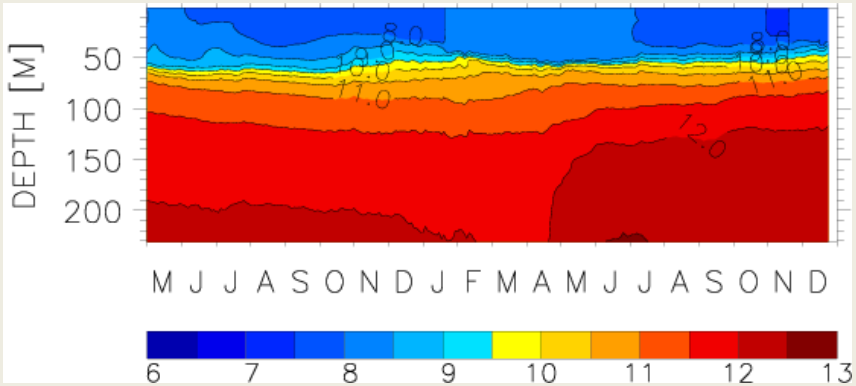


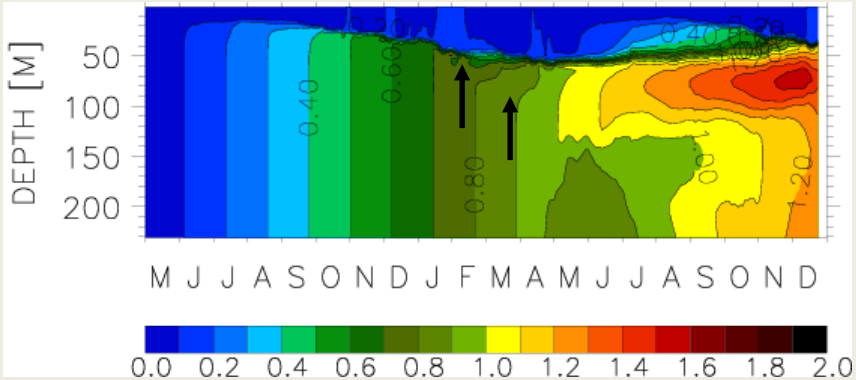


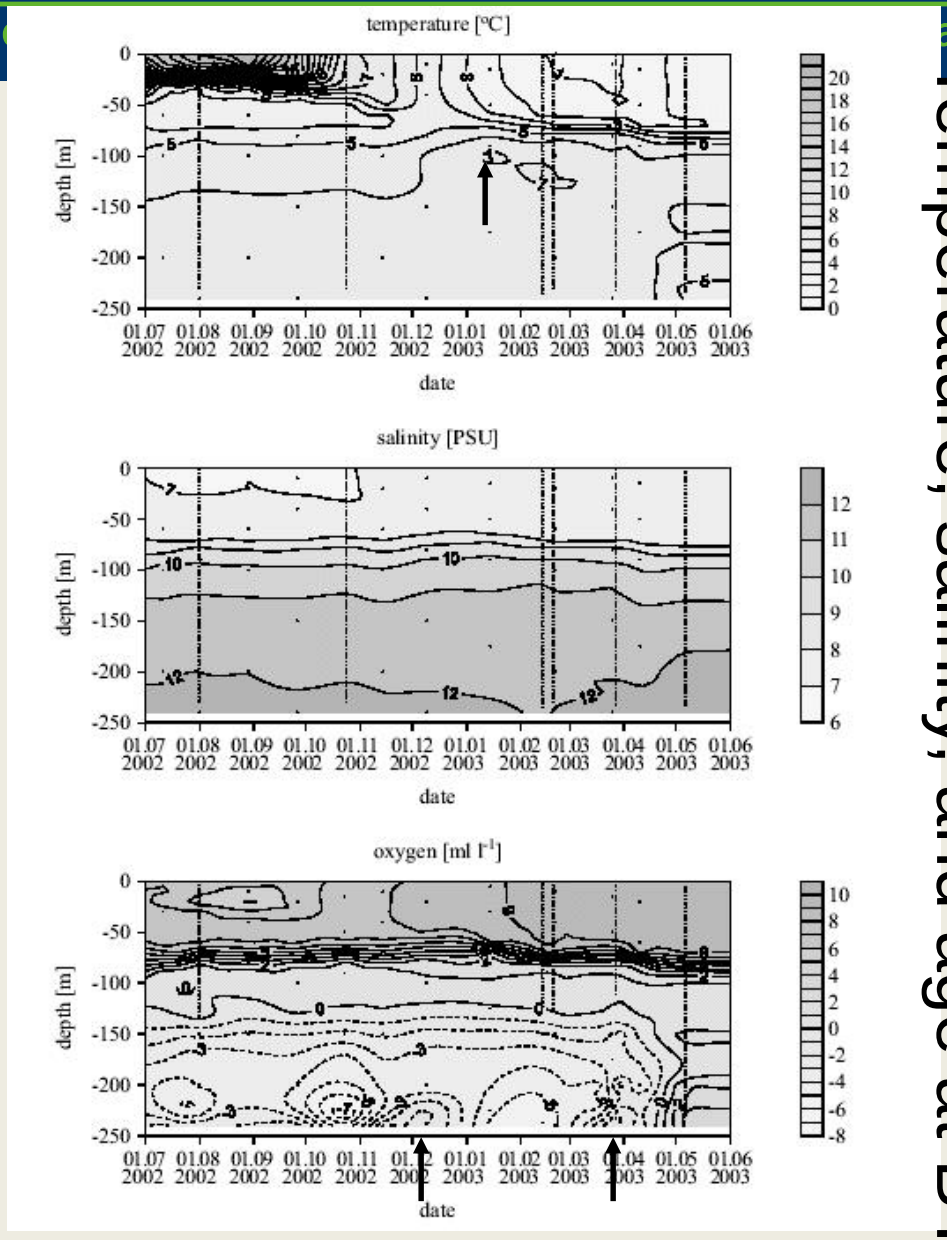


Temperature, salinity, and age at BY5









Temperature, salinity, and age at BY15

Characteristic periods of major Baltic inflows

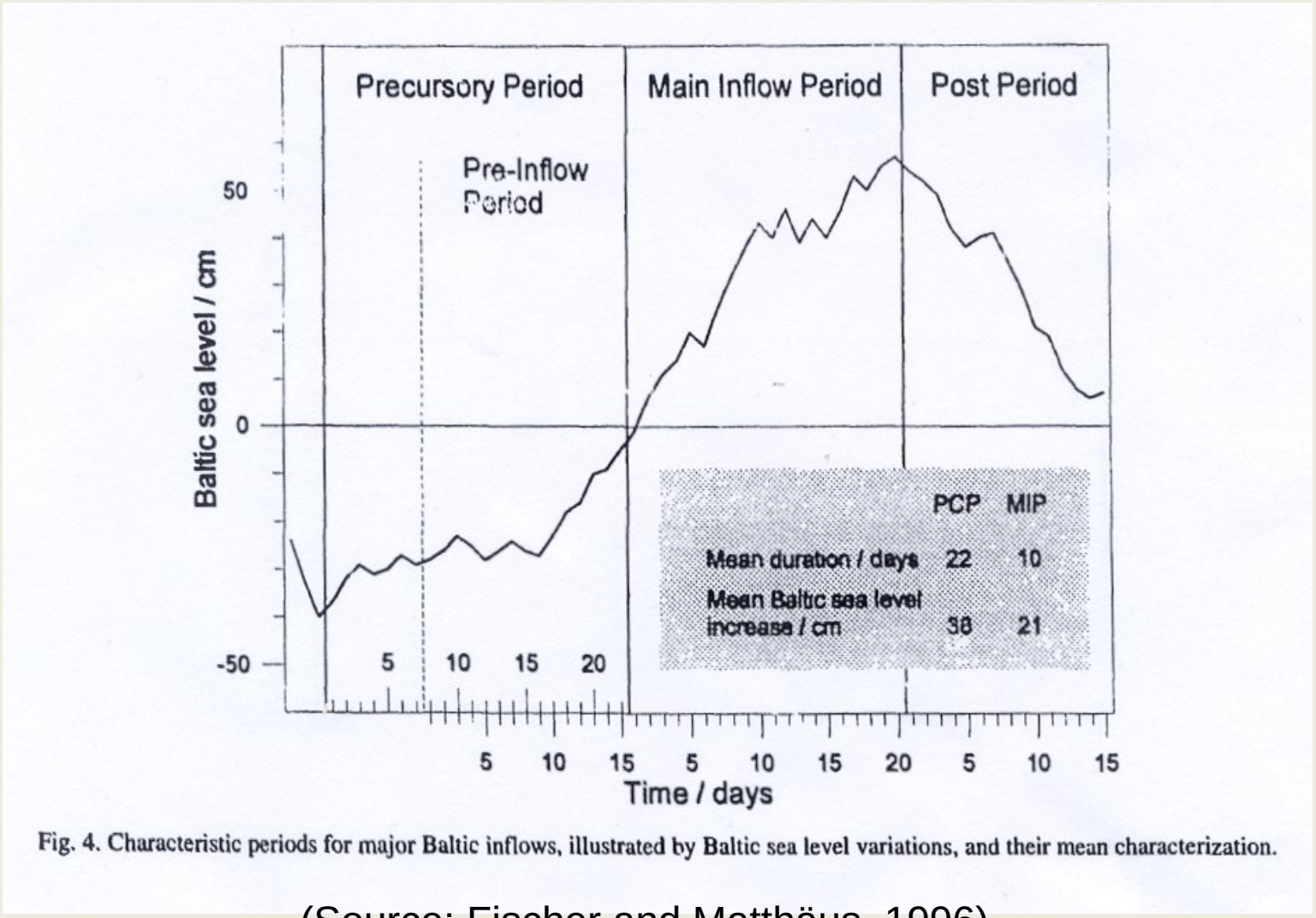


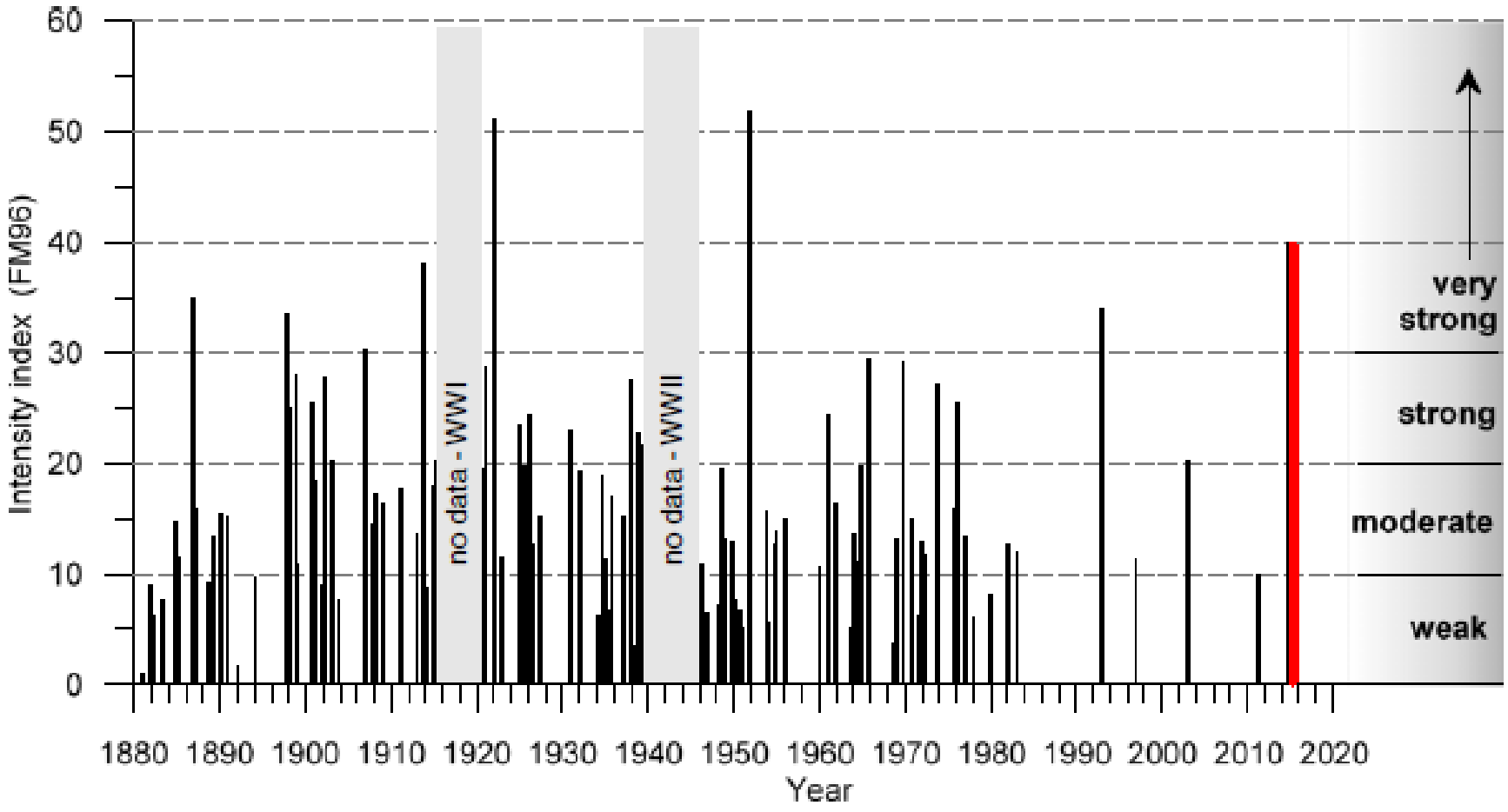
Fig. 4. Characteristic periods for major Baltic inflows, illustrated by Baltic sea level variations, and their mean characterization.

(Source: Fischer and Matthäus, 1996)

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
- Latest, documented inflow events: 1983, 1993, 2003, 2014, 2015, 2016

Saltwater inflows during 1898-2017



(Matthäus & Franck 1992, Fischer & Matthäus 1996, Mohrholz et al. 2015)

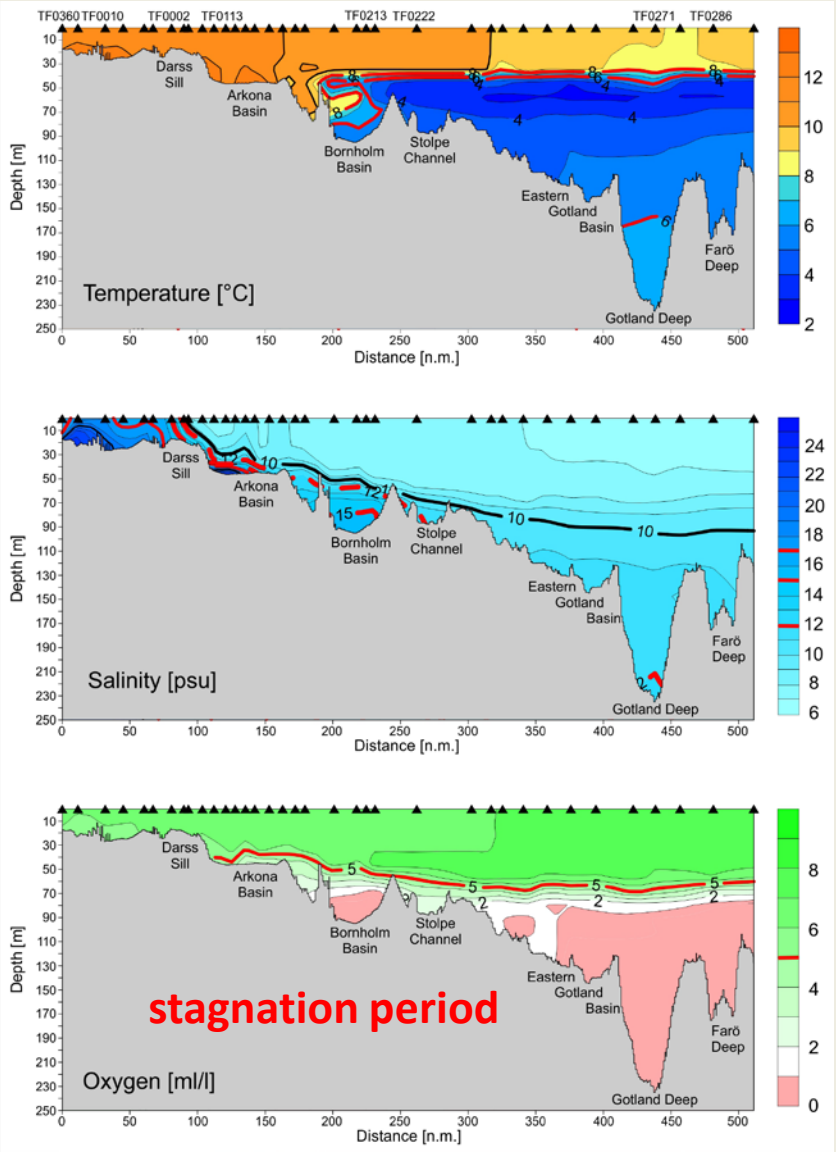
Die Salzwassereinstrom-Serie 2014-2016

Ergebnisse der Arbeitsgruppe Umweltüberwachung und Langzeitdaten am IOW

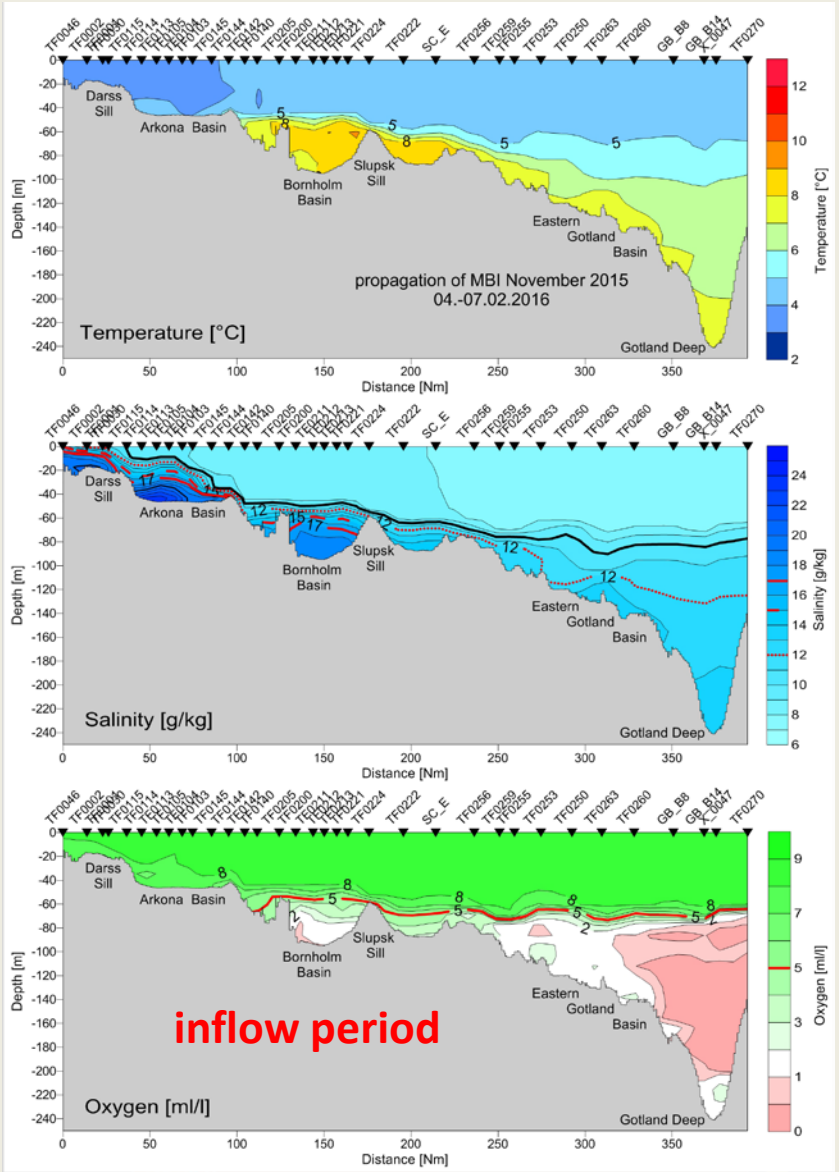
(Courtesy: Michael Naumann)

Situation zum Ende der Stagnationsphase 2004-2013 im Vergleich zur Ankunft eines Salzwassereinbruchs in der zentralen Ostsee (MBI vom 14.-22.11.2015)

1.-8.11.2013 (cruise: EMB-60)



3.-7.02.2016 (cruise: EMB-120)



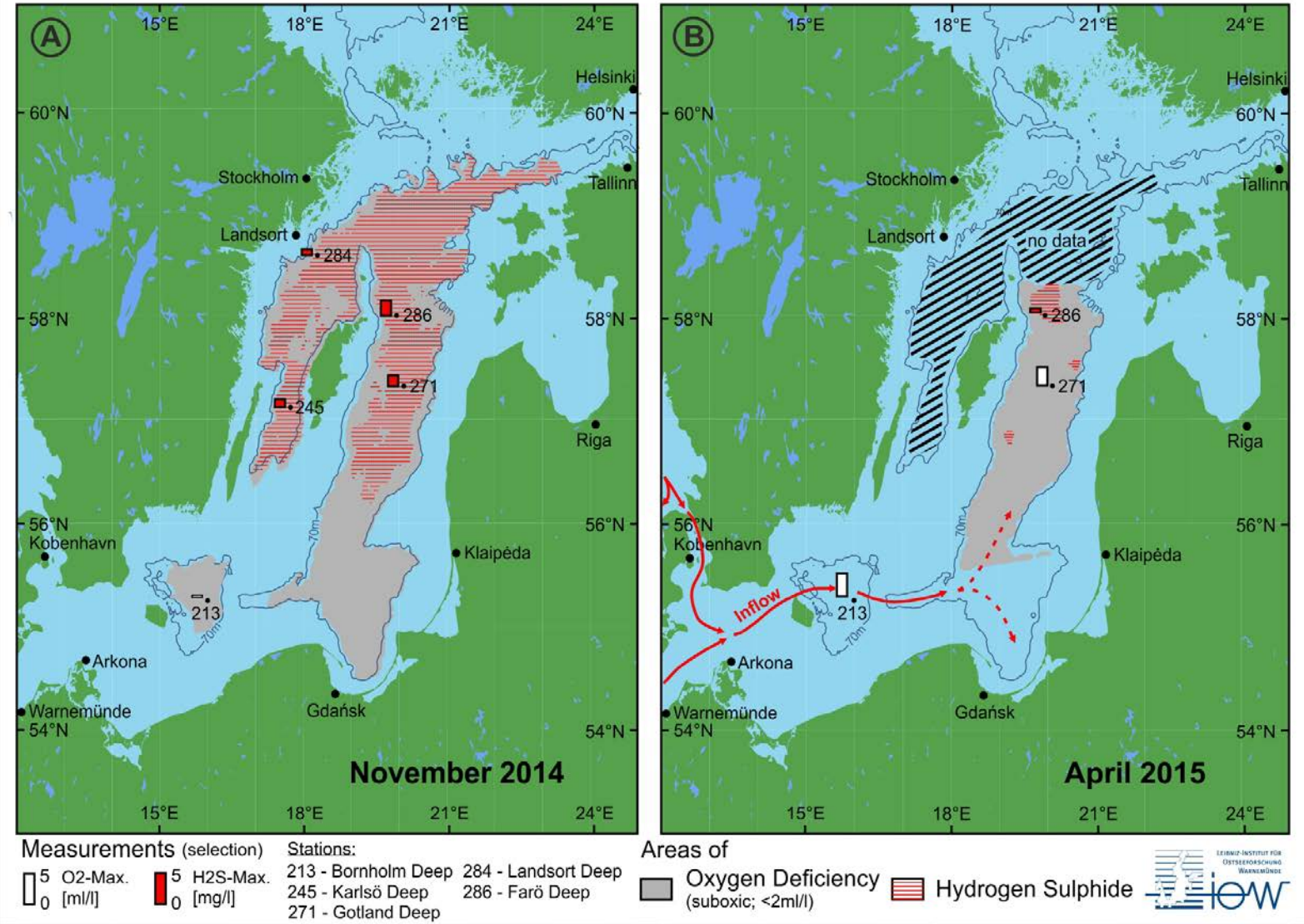
(Courtesy: Michael Naumann)

CTD transect Kiel Bight - Eastern Gotland Basin (Nov. 2013)

Mecklenburg Bight - Eastern Gotland Basin, eastern slope (Feb. 2016)

Entwicklung der Sauerstoffmangelgebiete in der zentralen Ostsee

(Courtesy: Michael Naumann)

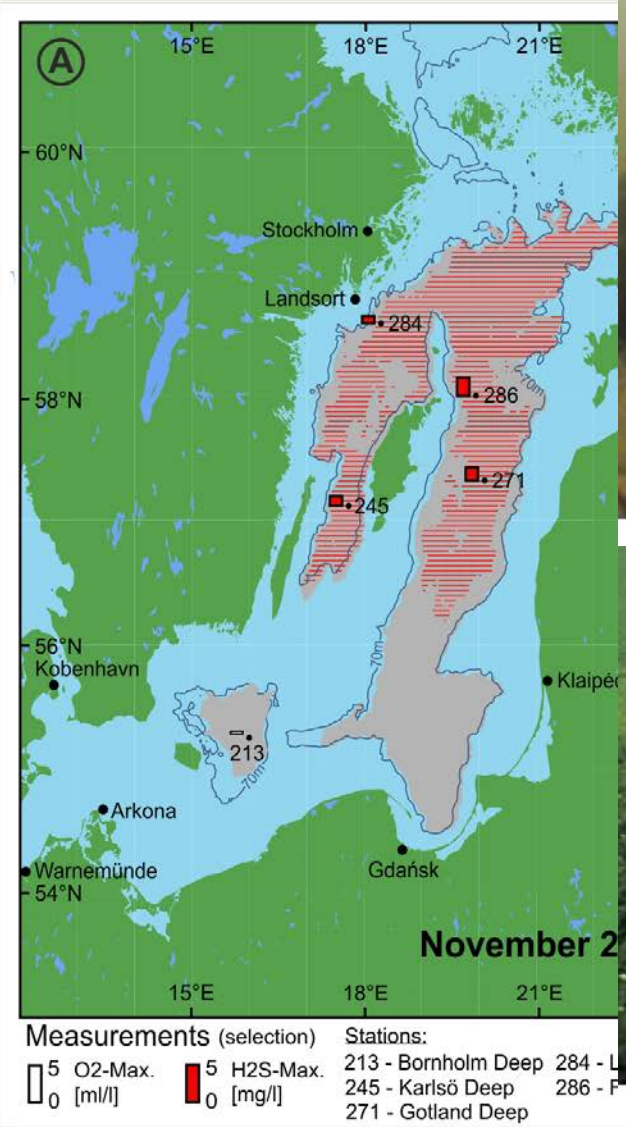


A: November 2014 - stagnation prior the MBI of December 2014 (cruise: EMB-89)

B: April 2015 - arrival of the MBI December 2014 (cruise: EMB-100)

Entwicklung der Sauerstoffmangelgebiete in der zentralen Ostsee

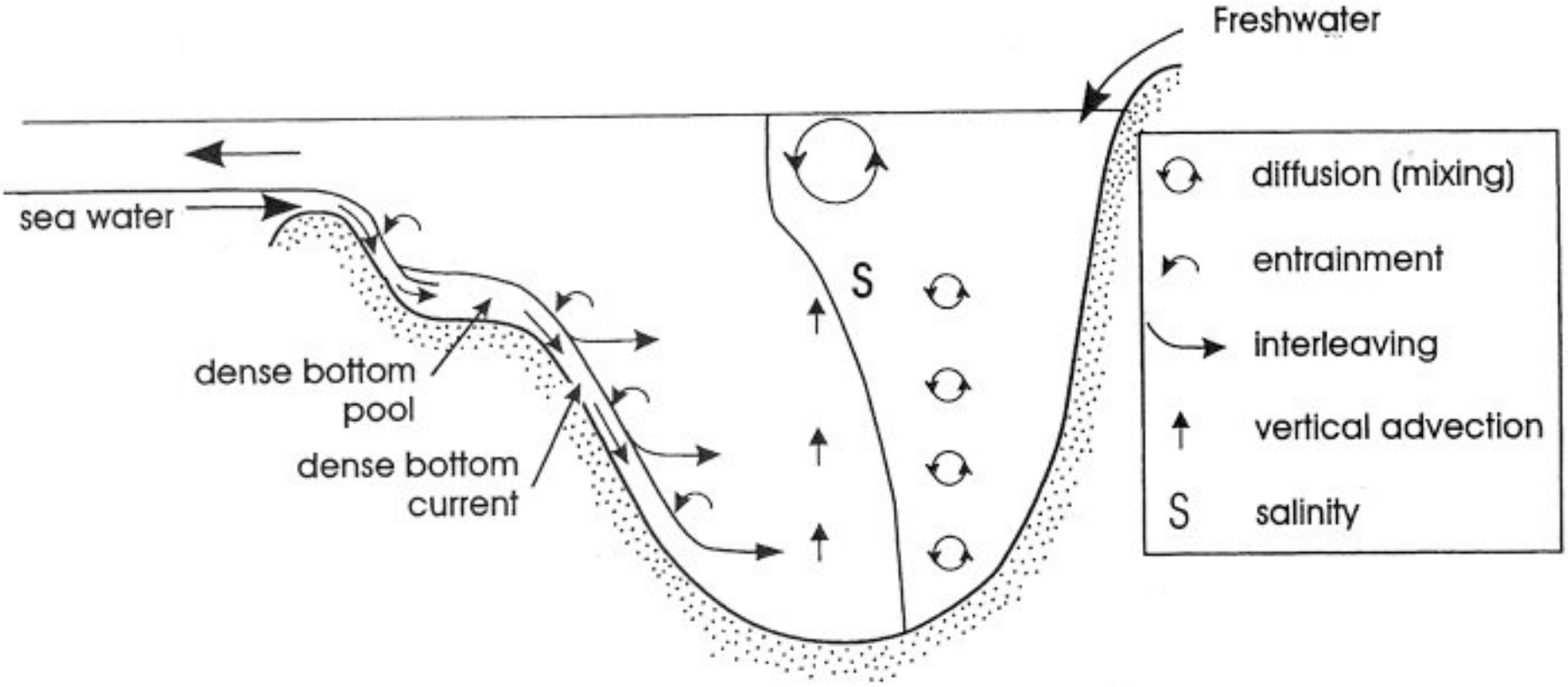
(Courtesy: Michael Naumann)



A: November 2014 - stagnation prior the MBI of December 2014 (cruise: EMB-89)

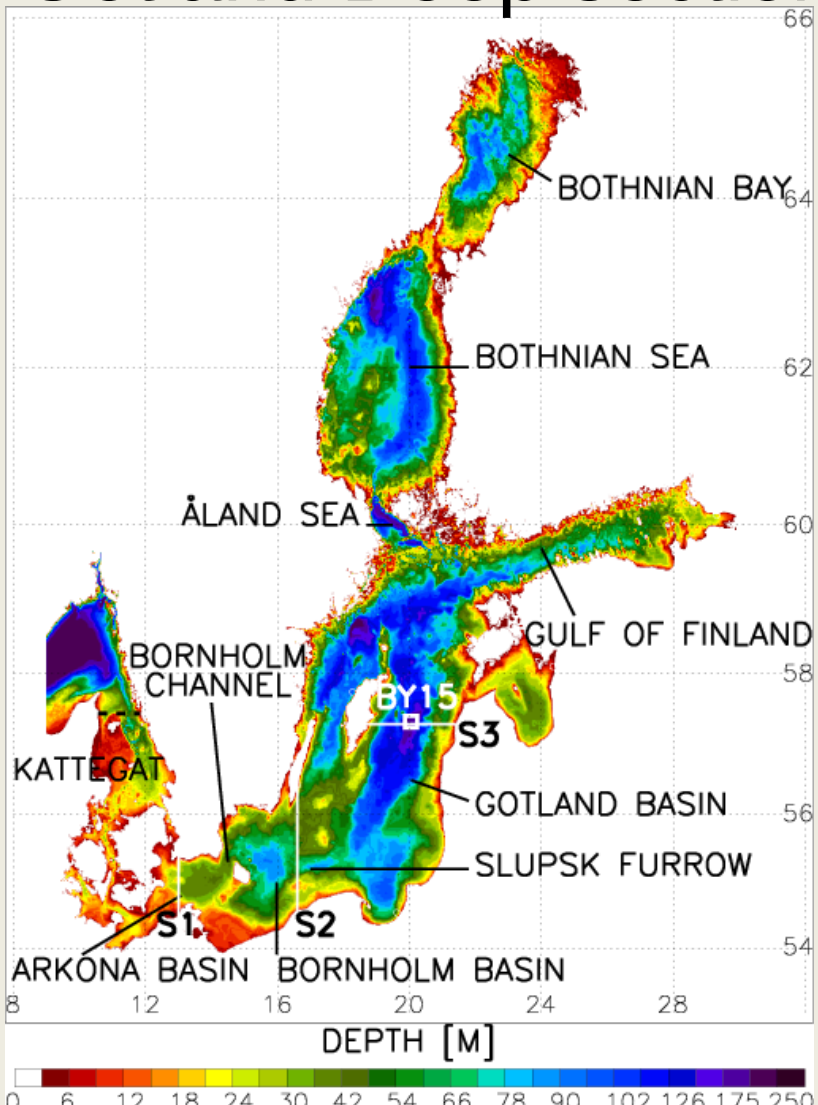
B: April 2015 - arrival of the MBI December 2014 (cruise: EMB-100)

Ventilation of the Baltic Sea deepwater

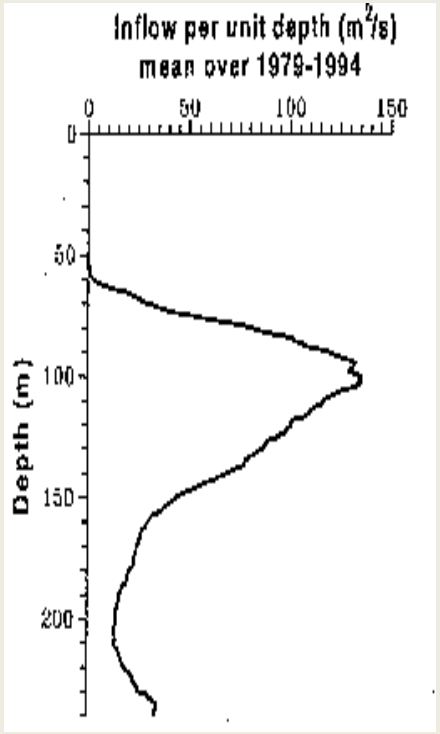


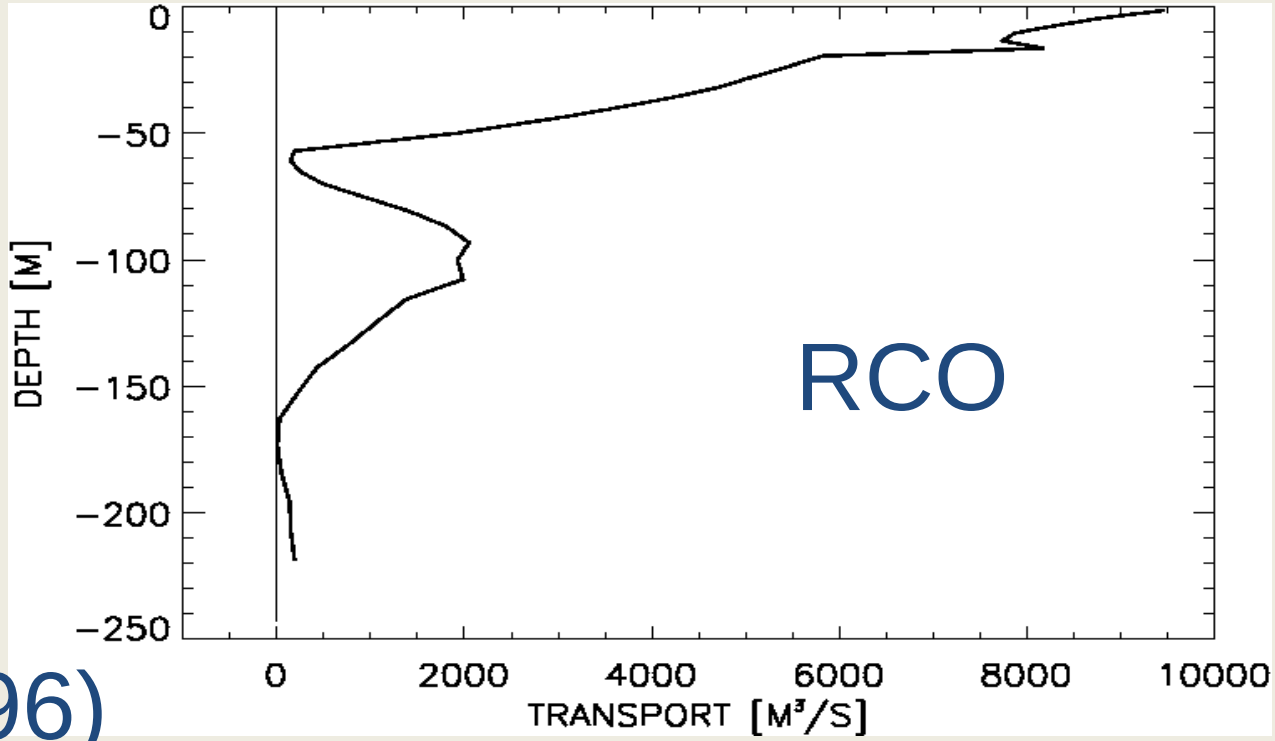
(Stigebrandt, 2001)

Horizontally integrated transport at the Gotland Deep section



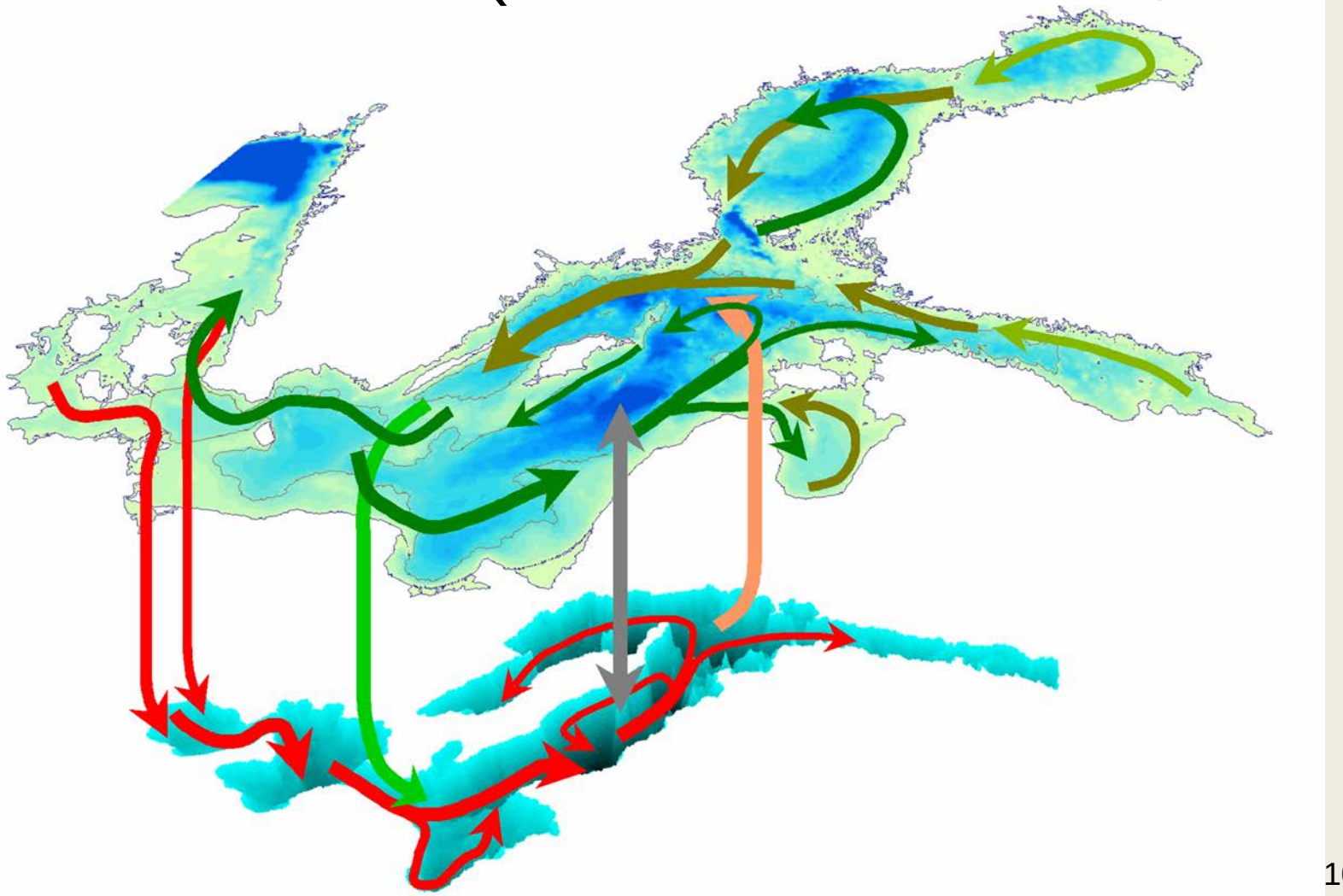
Horizontally integrated transport at the Gotland Deep section

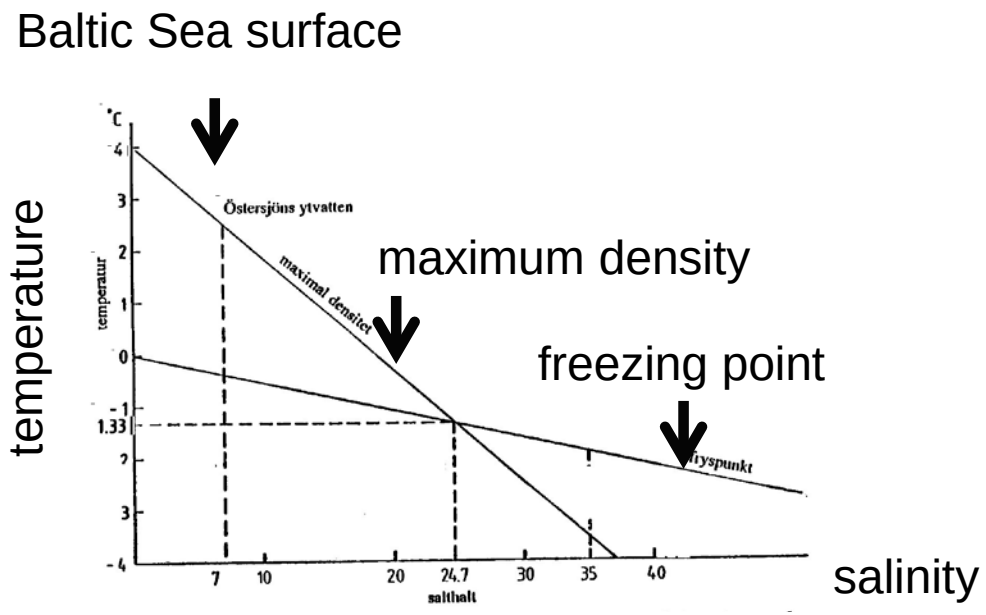




Elken (1996)

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





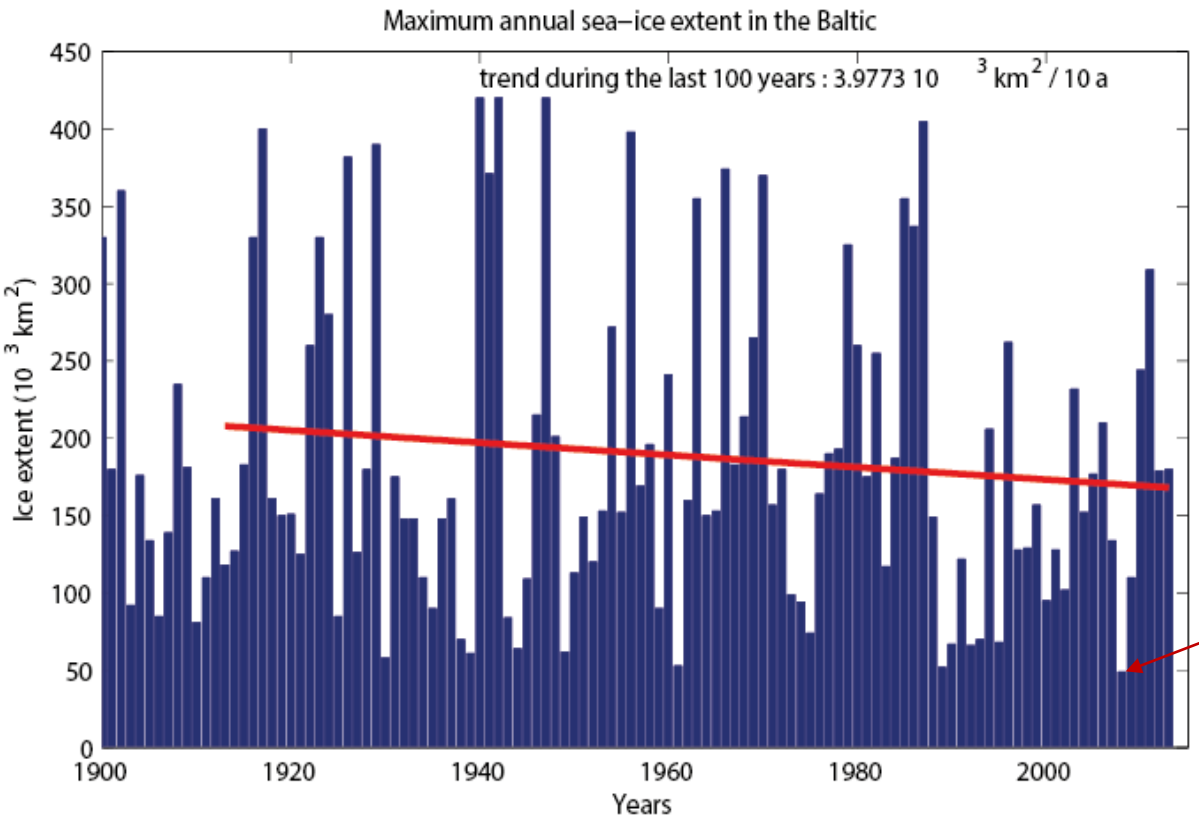
Freezing point temperature and temperature of maximum density as function of salinity

(Fonselius, 1996)

10. 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)

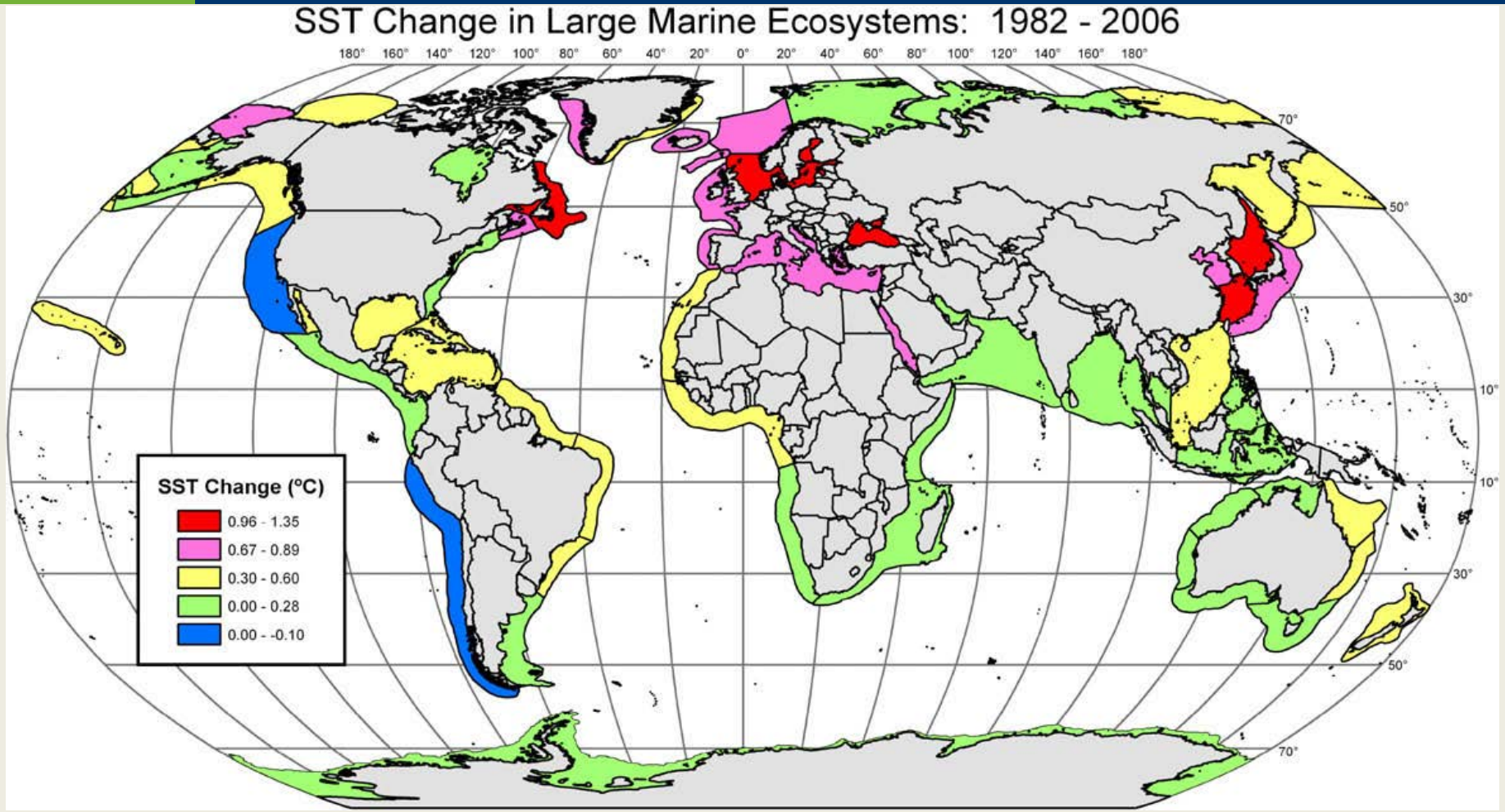
Sea ice cover



→ **Frequency of mild ice winters has increased**

Winter 2007/2008 lowest ever recorded ice cover

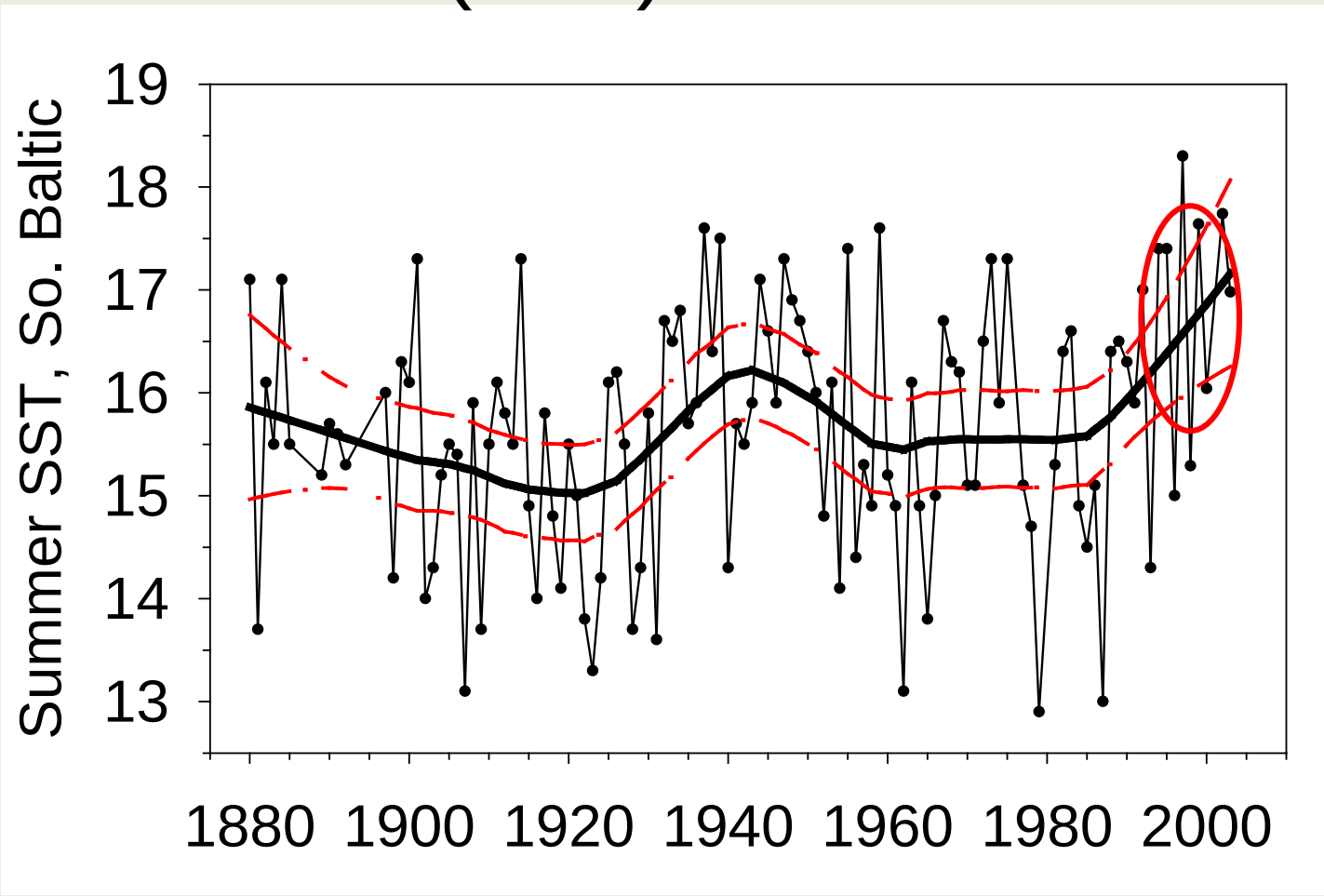
Fig. 8.3 The maximum extent of sea-ice cover in the Baltic Sea, 1900–2012. The red line shows a long-term declining trend of ~2% per decade



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

(Source: Belkin 2009)

Summer (JAS) SST 1880-2003

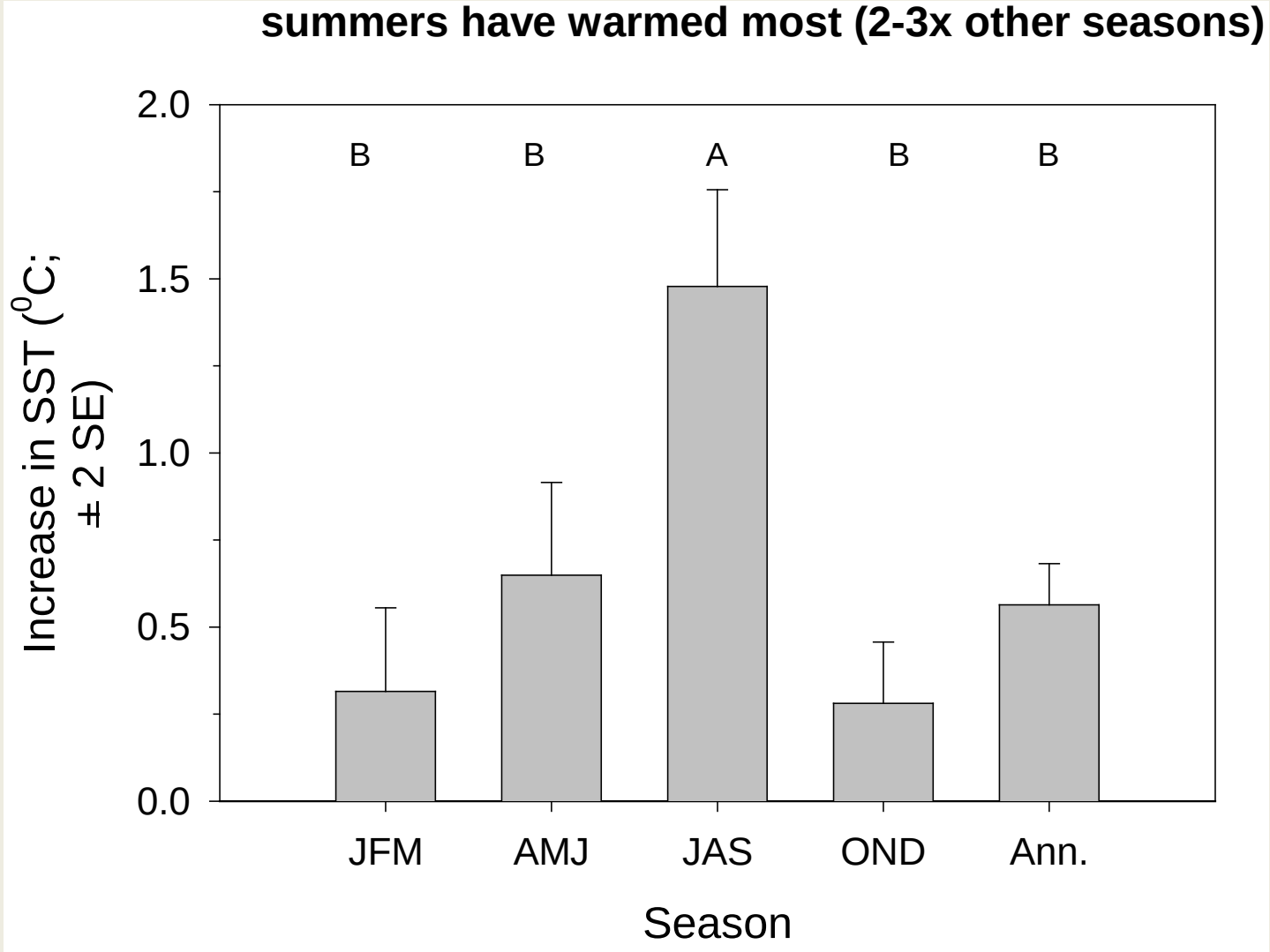


warm conditions during 1990s-2000s

(Source: MacKenzie & Schiedek 2007)

warming rates differ significantly among seasons

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



Temperature increase since 1985 in Baltic and North seas

(Source: MacKenzie & Schiedek 2007)

Observed changes …

Sea water temperatures

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research

Baltic Earth

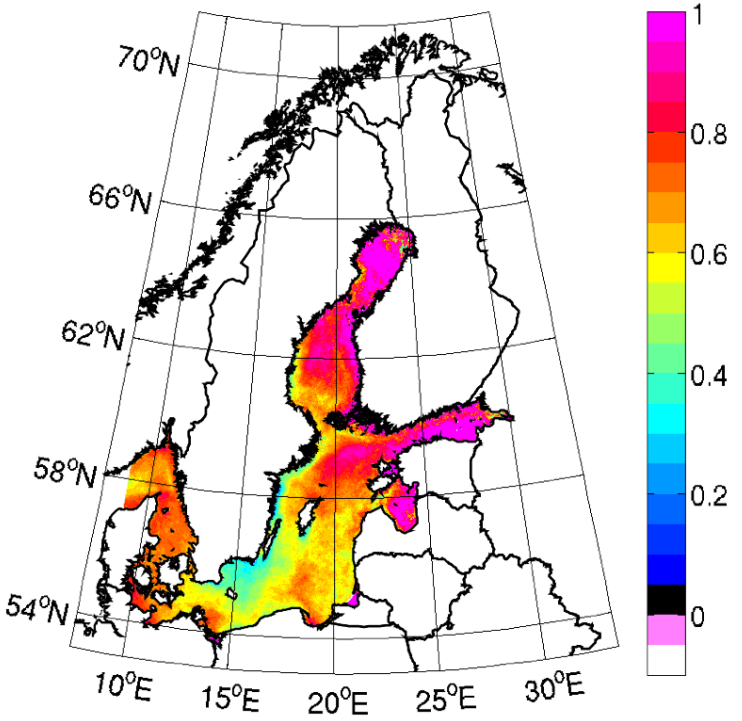
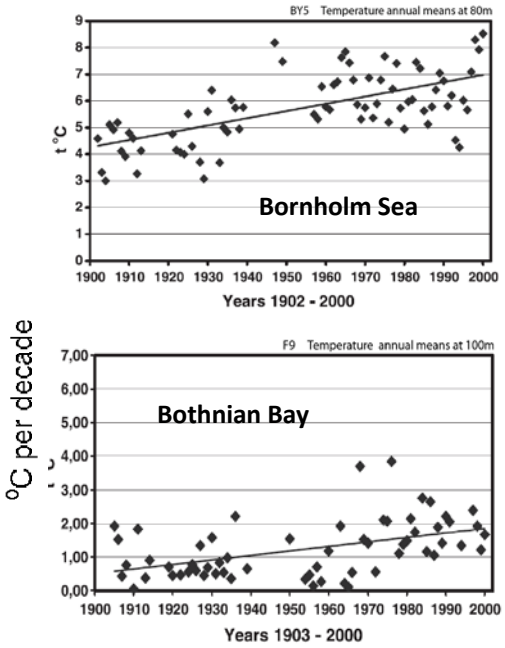


Fig. 7.2 Linear trend in annual mean sea surface temperature based on infrared satellite data (1990–2008) provided by the Federal Maritime and Hydrographic Agency (BSH), Hamburg (Lehmann et al. 2011)

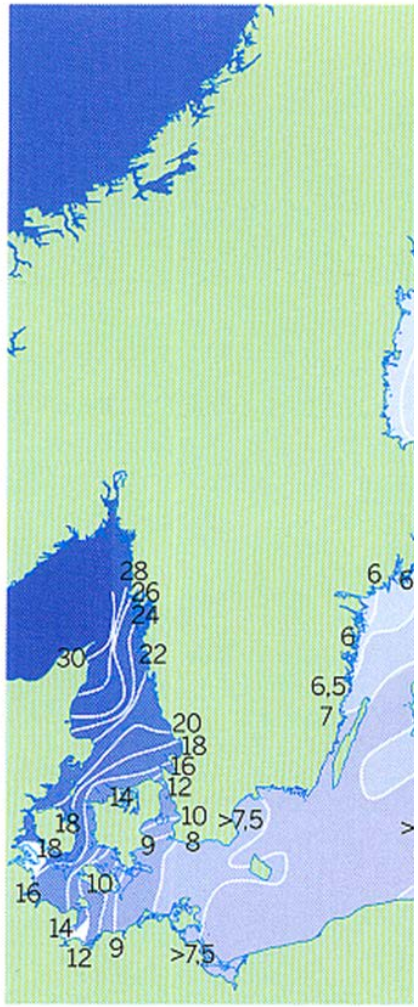


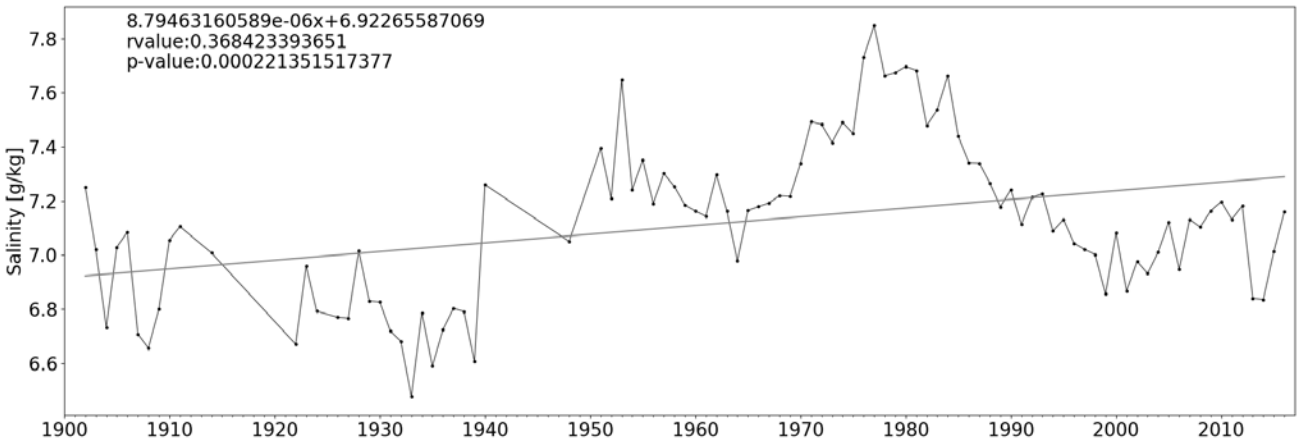
→ **Since 1990 strong surface warming in Bothian Bay and Gulf of Finland**

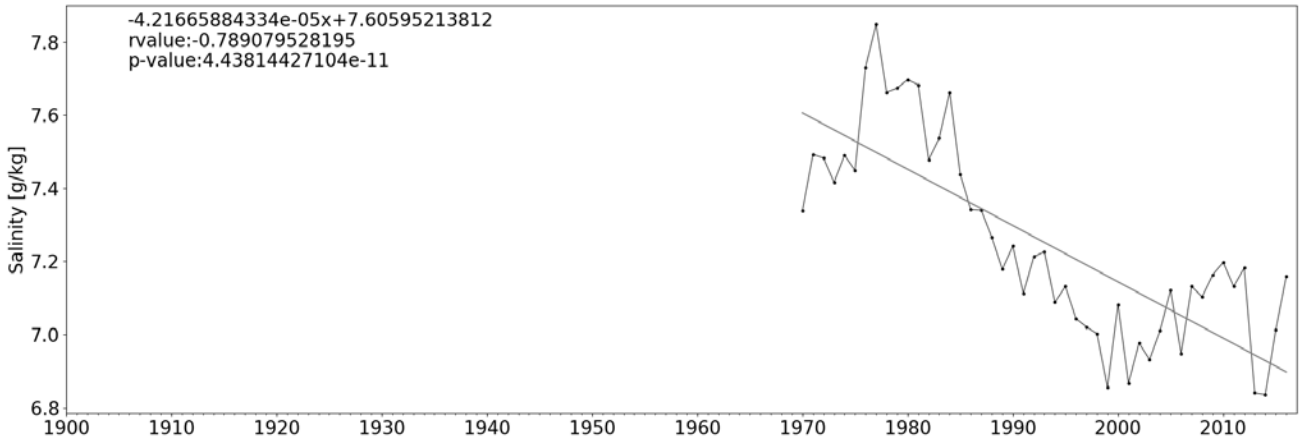
→ **Detectable warming of the Baltic Sea, surface and deep water**

BACC Ch. 3
BACC 2
Chapter 7

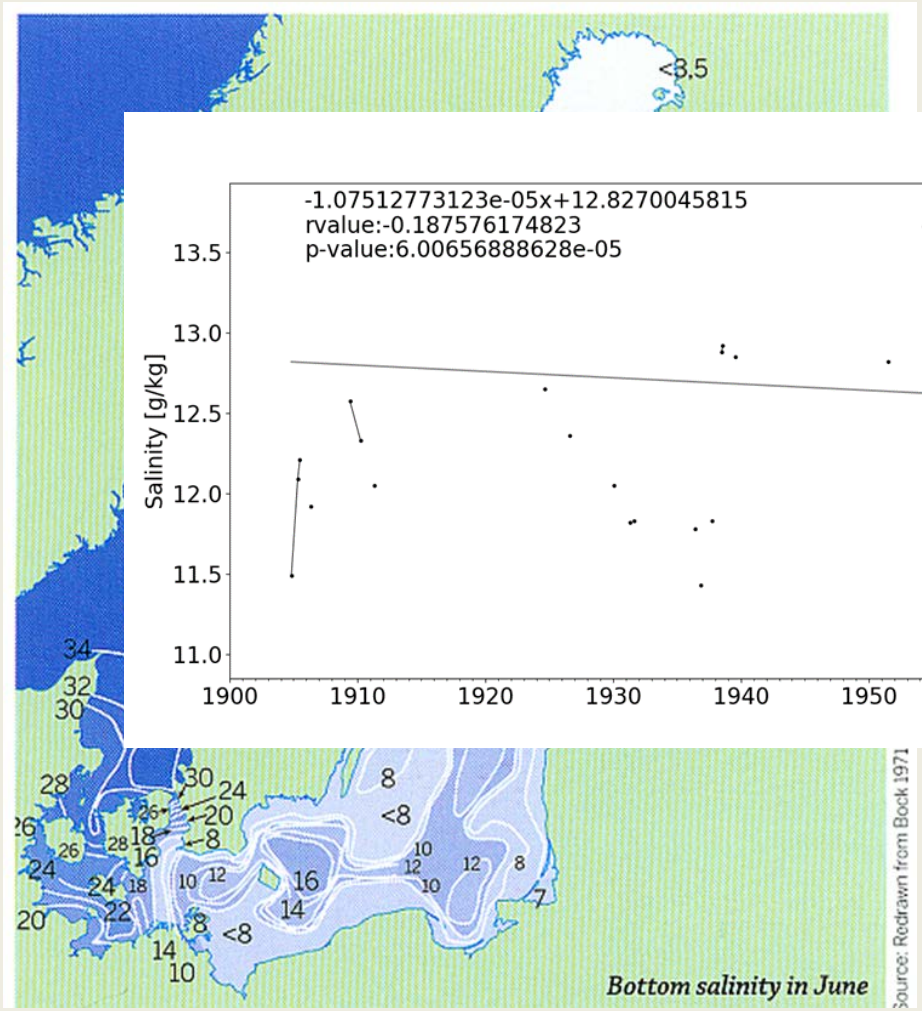
Mittlerer jährlicher Salzgehalt im Oberflächenwasser seit 1900 im Gotland-Tief

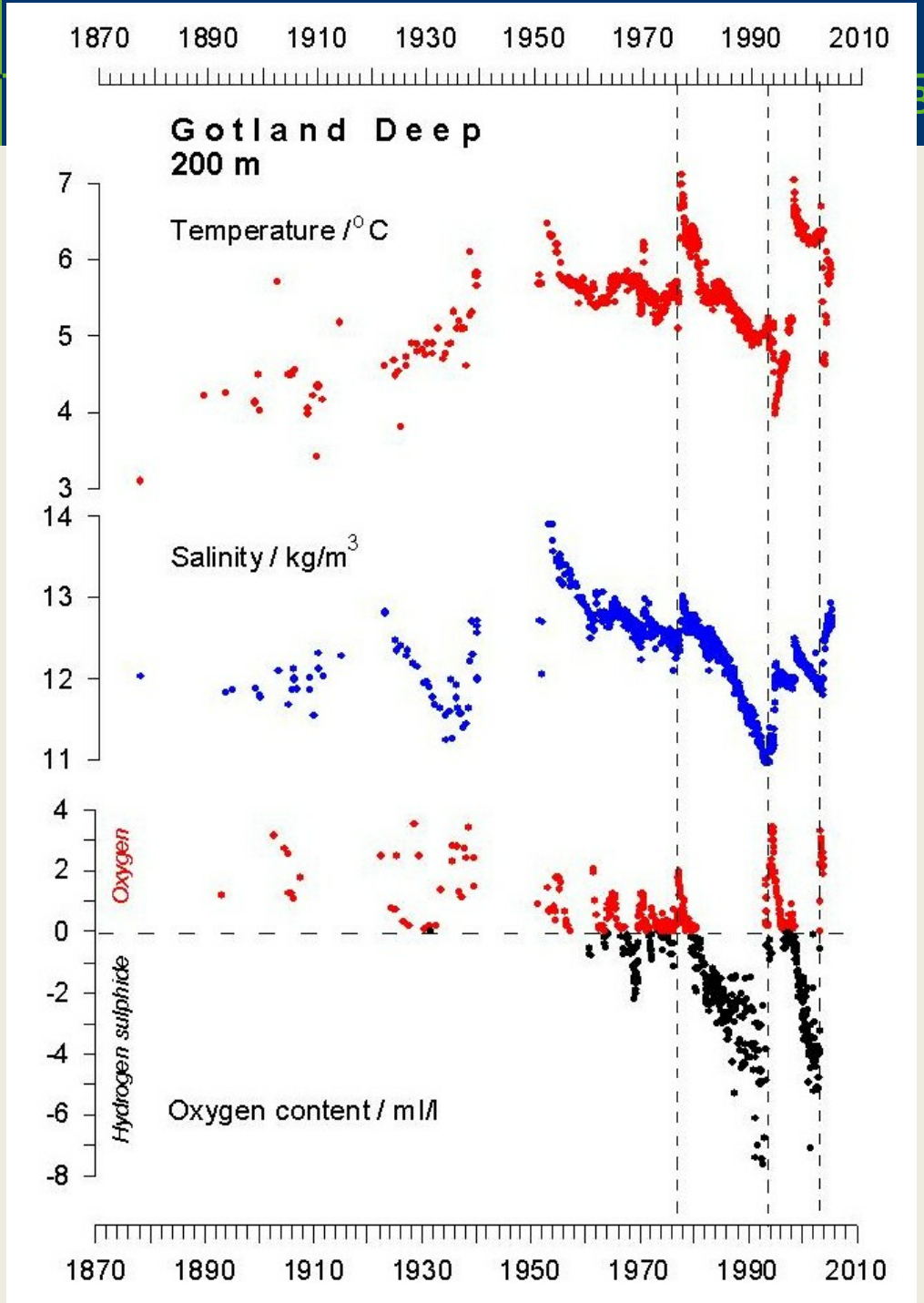






Monatsmittel des Salzgehalts in 224 m Tiefe seit 1900 im Gotland-Tief

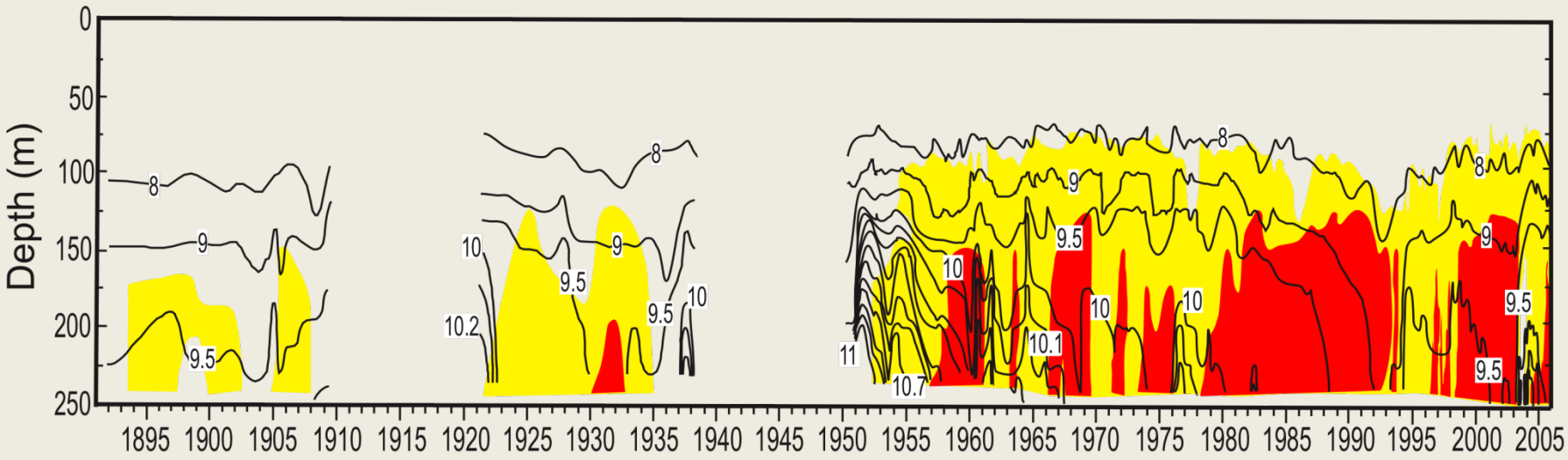




strong inflows: 1914, 1933, 1951, 1961, 1977, 1993

Elken and Matthäus (2008)

Oxygen and density at Gotland Deep 1890-2006



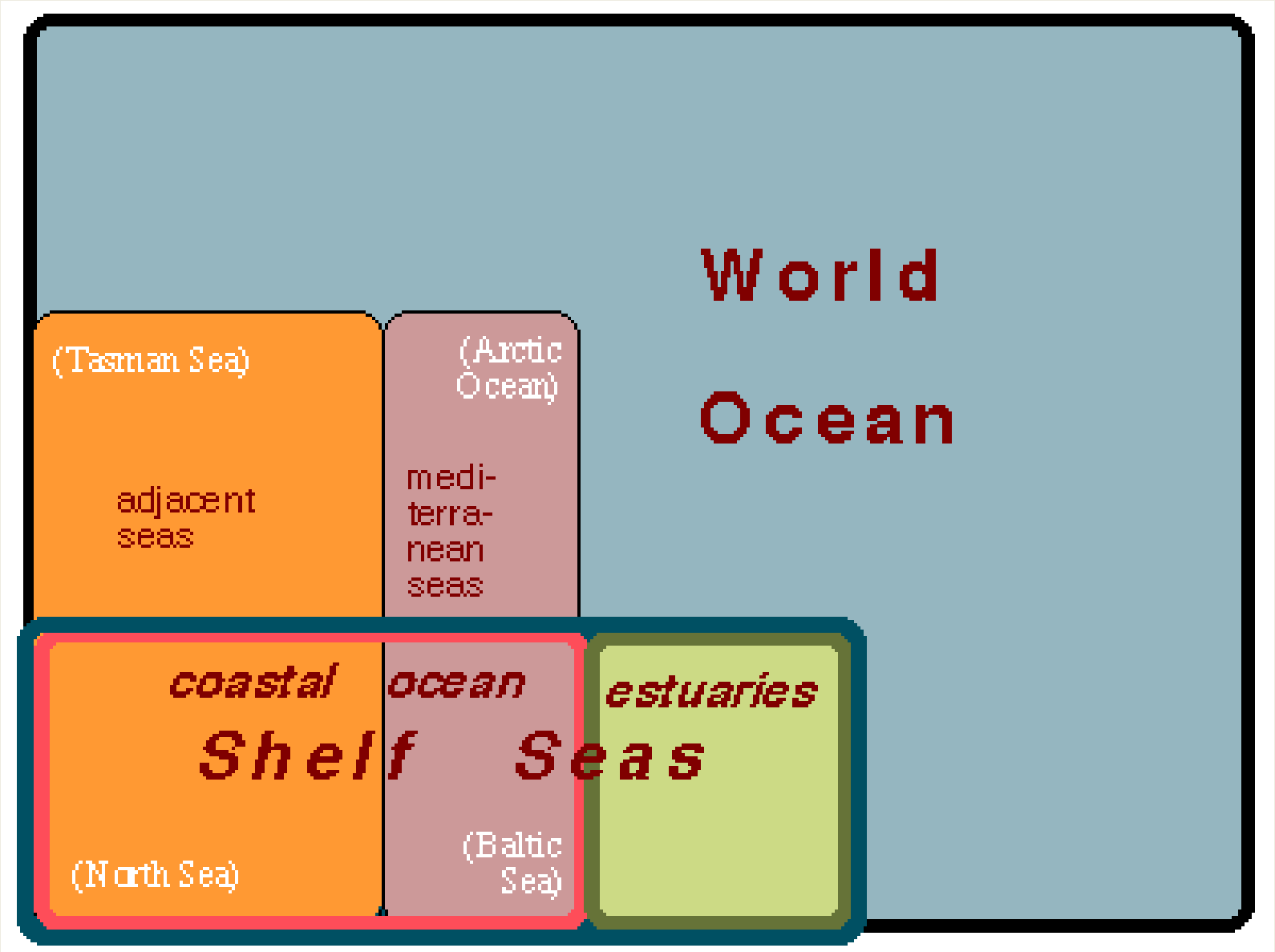
Isopycnals (– 1000 kg/m³) **(Source: Conley et al. 2009)**

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).

11. Comparison with other seas


World
Ocean
(Tasman Sea)
adjacent
seas
(Arctic
Ocean)
medi-
terra-
nean
seas
coastal
ocean
estuaries
Shelf Seas
(North Sea)
(Baltic
Sea)

Estuarine circulation

Matthias Tomczak (1998):
Shelf and Coastal Oceanography

http://www.es.flinders.edu.au/~mattom/ShelfCoast/

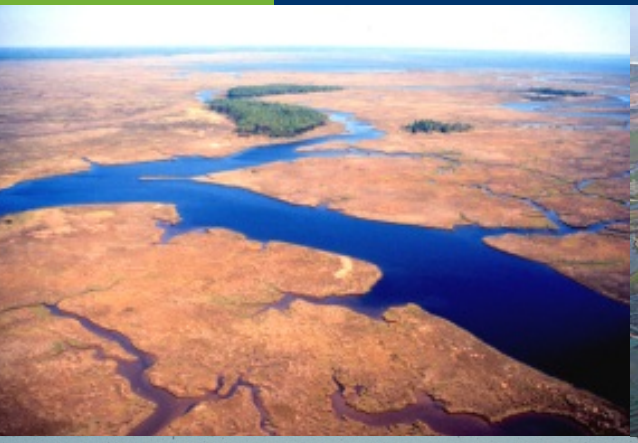
Definition:

An **estuary** is a narrow, semi-enclosed coastal body of water which has a free connection with the open sea at least intermittently and within which the salinity of the water is measurably different from the salinity in the open ocean.

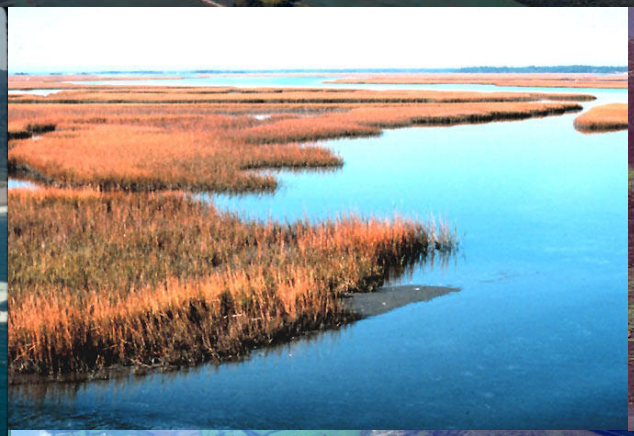
Leibniz Institute for Baltic Sea Research Warnemünde

Climate of the Baltic Sea Region

Physical Oceanography of the Baltic Sea and other regional seas







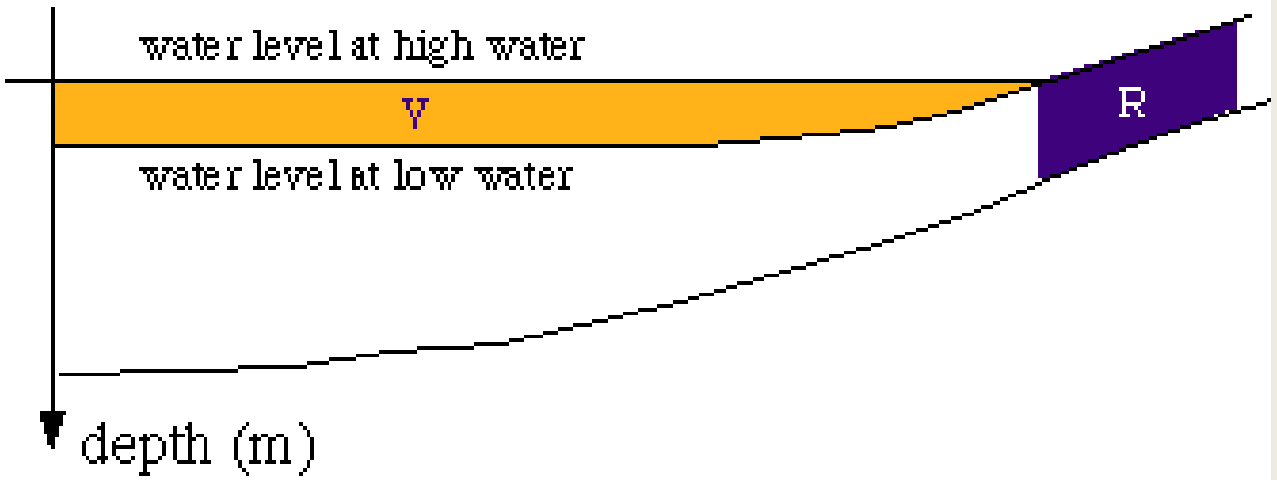


Definition:

An **estuary** is a narrow, semi-enclosed coastal body of water which has a free connection with the open sea at least intermittently and within which the salinity of the water is measurably different from the salinity in the open ocean.

Salt balance for a two-dimensional estuary

$$\frac{\partial(uS)}{\partial x} + \frac{\partial(wS)}{\partial z} - \frac{\partial}{\partial x}\left(K_h \frac{\partial S}{\partial x}\right) - \frac{\partial}{\partial z}\left(K_v \frac{\partial S}{\partial z}\right) = 0$$

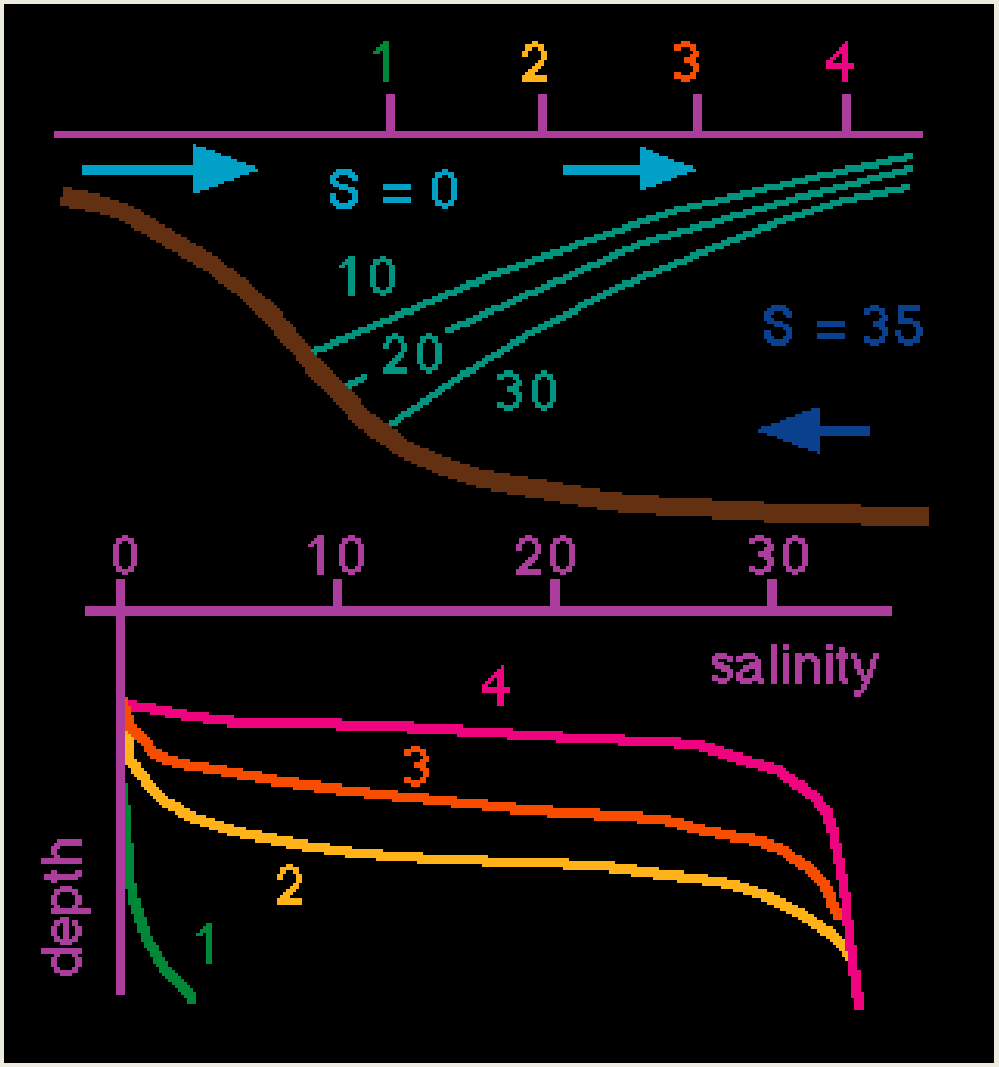


T tidal period

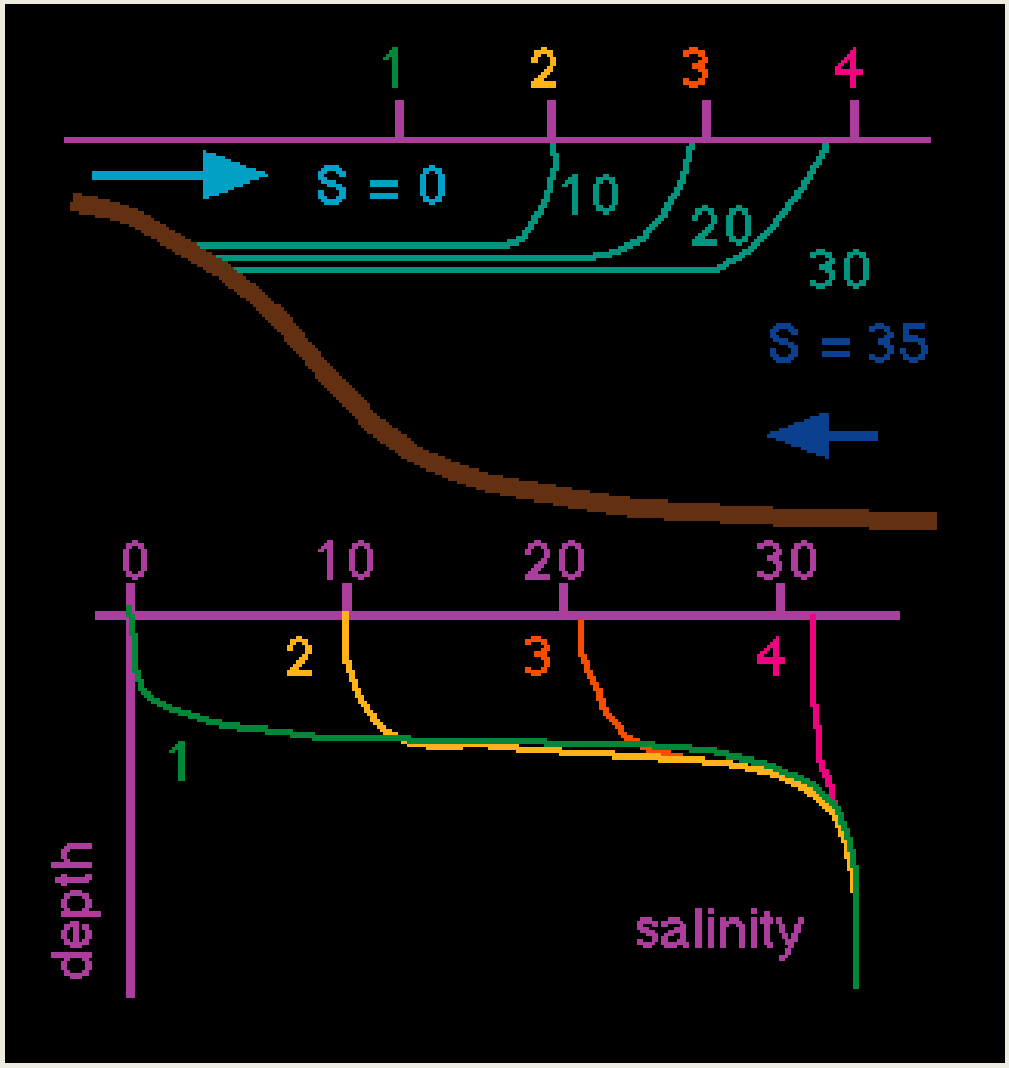
Tidal volume V

Fresh water volume R

1) 1 ≤ R/V salt wedge estuaries



2) 0.1 ≤ R/V ≤ 1 highly stratified (fjord) estuaries



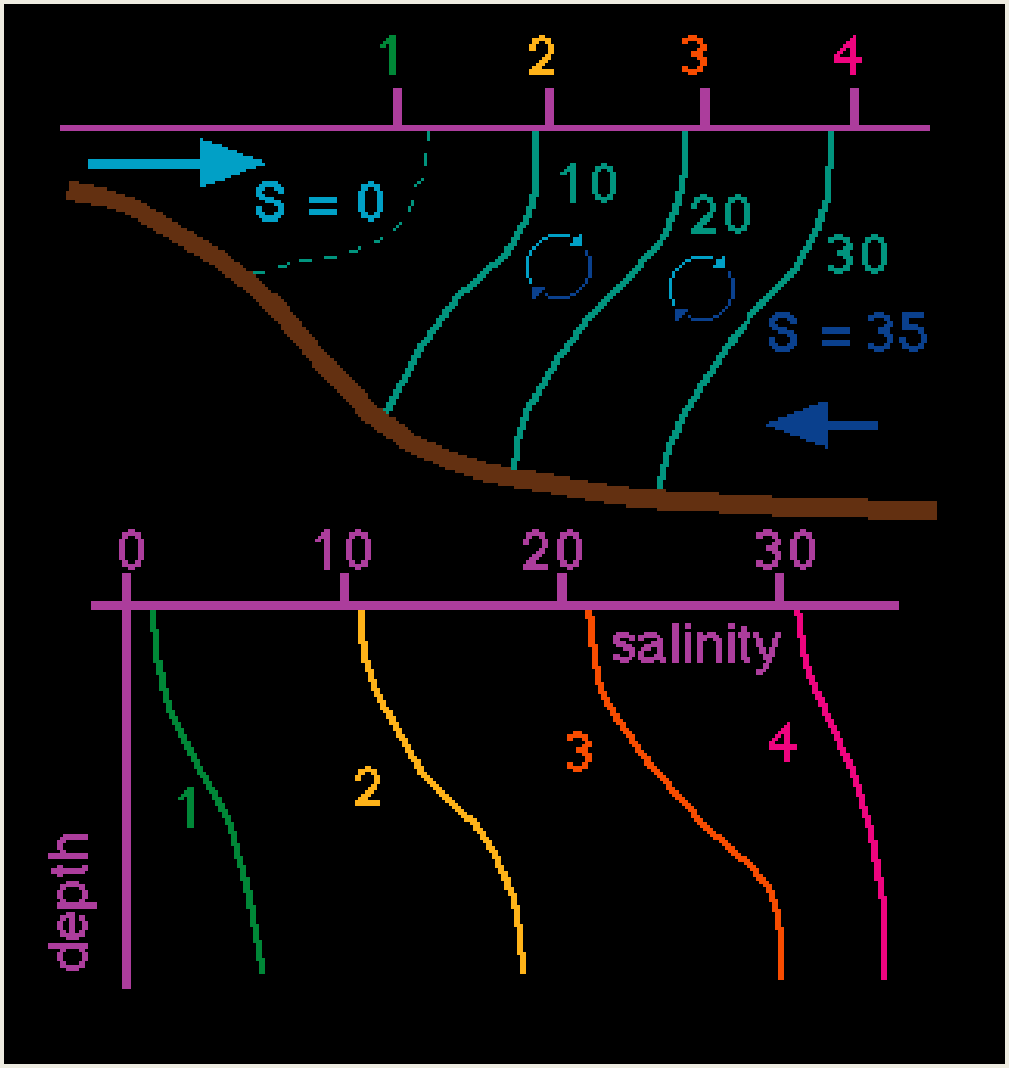
Salt balance for a two-dimensional estuary

$$\frac{\partial(uS)}{\partial x} + \frac{\partial(wS)}{\partial z} - \frac{\partial}{\partial x}\left(K_h \frac{\partial S}{\partial x}\right) - \frac{\partial}{\partial z}\left(K_v \frac{\partial S}{\partial z}\right) = 0$$

w entrainment velocity

1) salt wedge and 2) highly stratified estuary

3) 0.005 ≤ R/V ≤ 0.1 Partially mixed estuaries

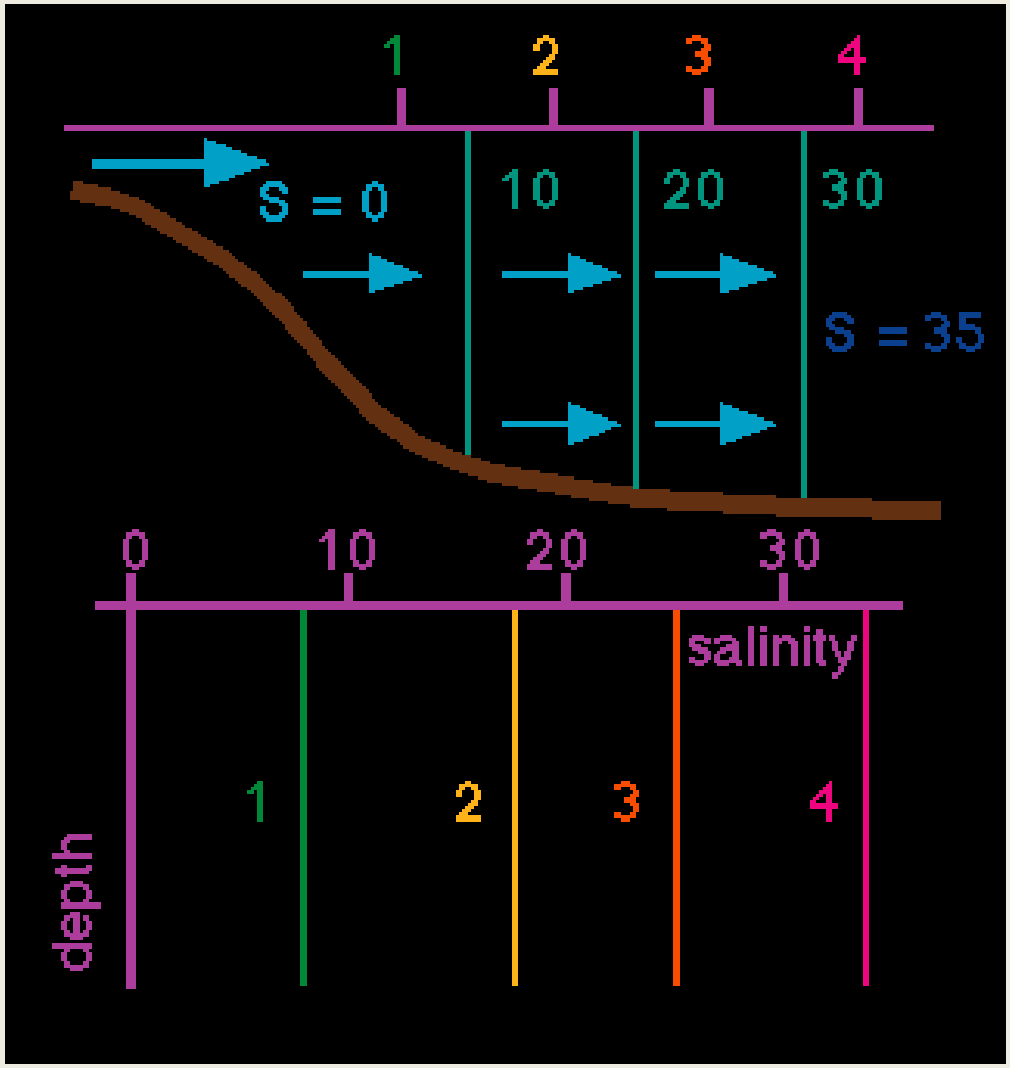


Salt balance for a two-dimensional estuary

$$\frac{\partial(uS)}{\partial x} + \frac{\partial(wS)}{\partial z} - \frac{\partial}{\partial x}\left(K_h \frac{\partial S}{\partial x}\right) - \frac{\partial}{\partial z}\left(K_v \frac{\partial S}{\partial z}\right) = 0$$

3) partially stratified estuary

4) R/V ≤ 0.005 vertically mixed estuaries

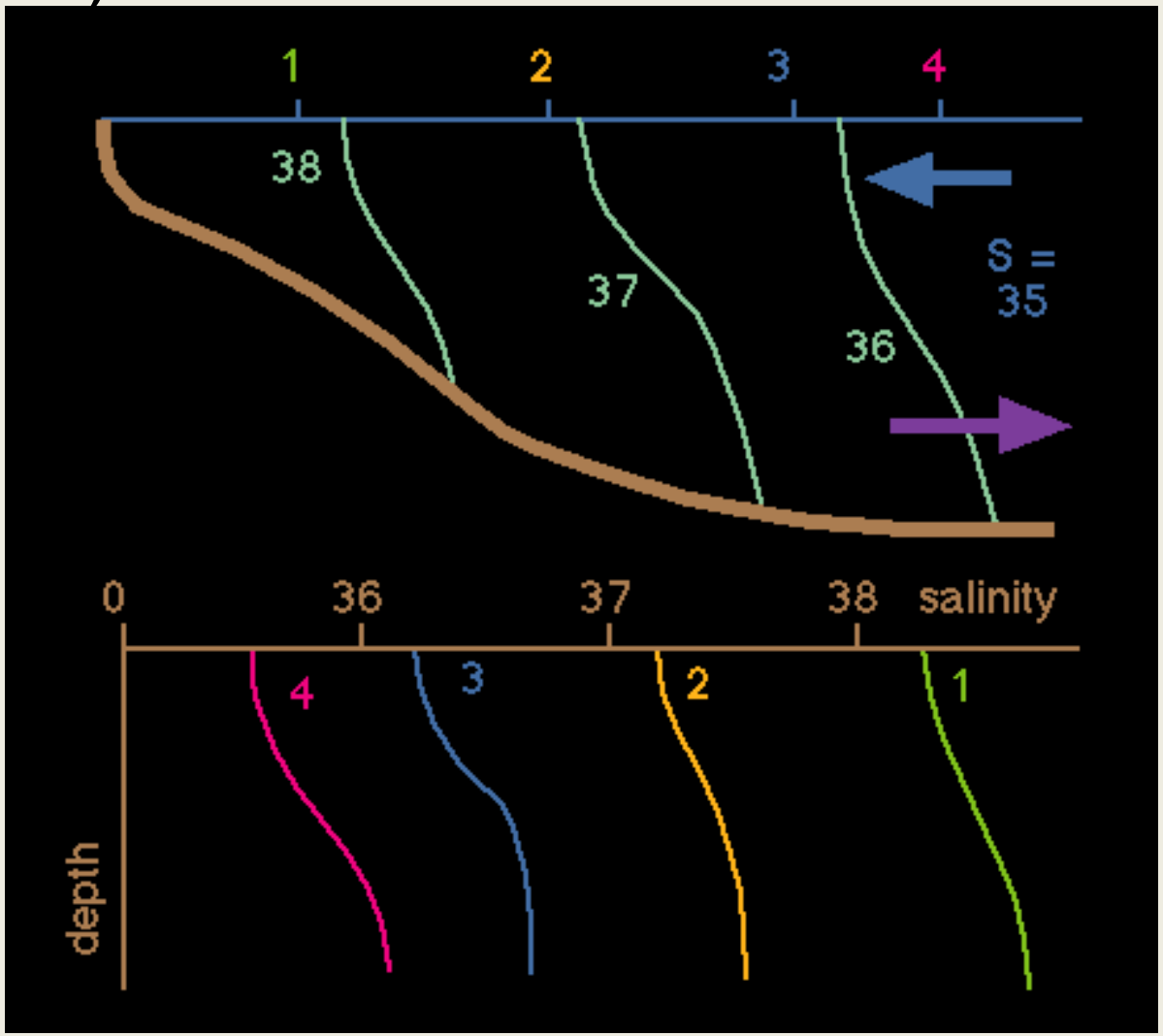


Salt balance for a two-dimensional estuary

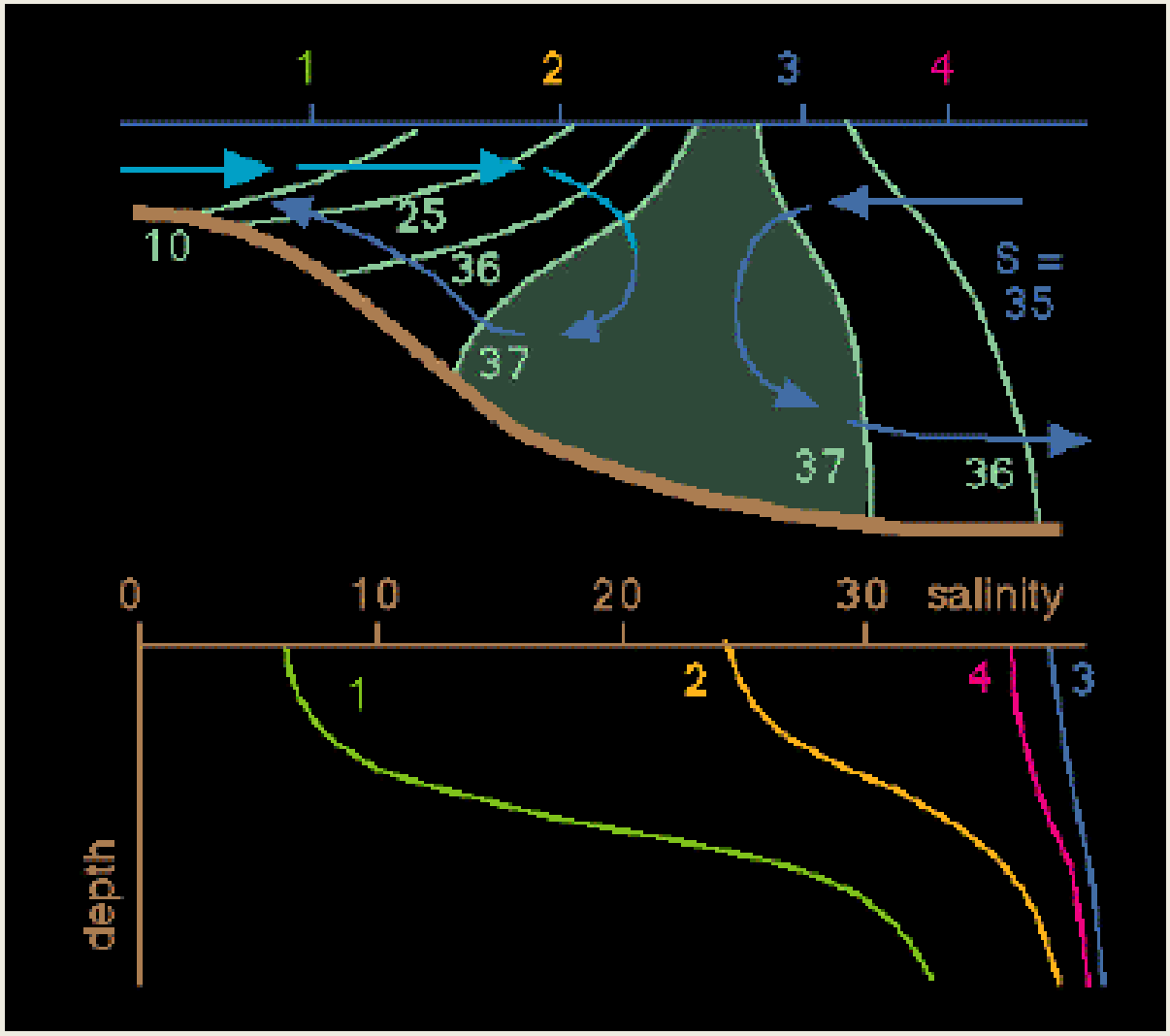
$$\frac{\partial(uS)}{\partial x} + \frac{\partial(wS)}{\partial z} - \frac{\partial}{\partial x}\left(K_h \frac{\partial S}{\partial x}\right) - \frac{\partial}{\partial z}\left(K_v \frac{\partial S}{\partial z}\right) = 0$$

4) vertically mixed estuary

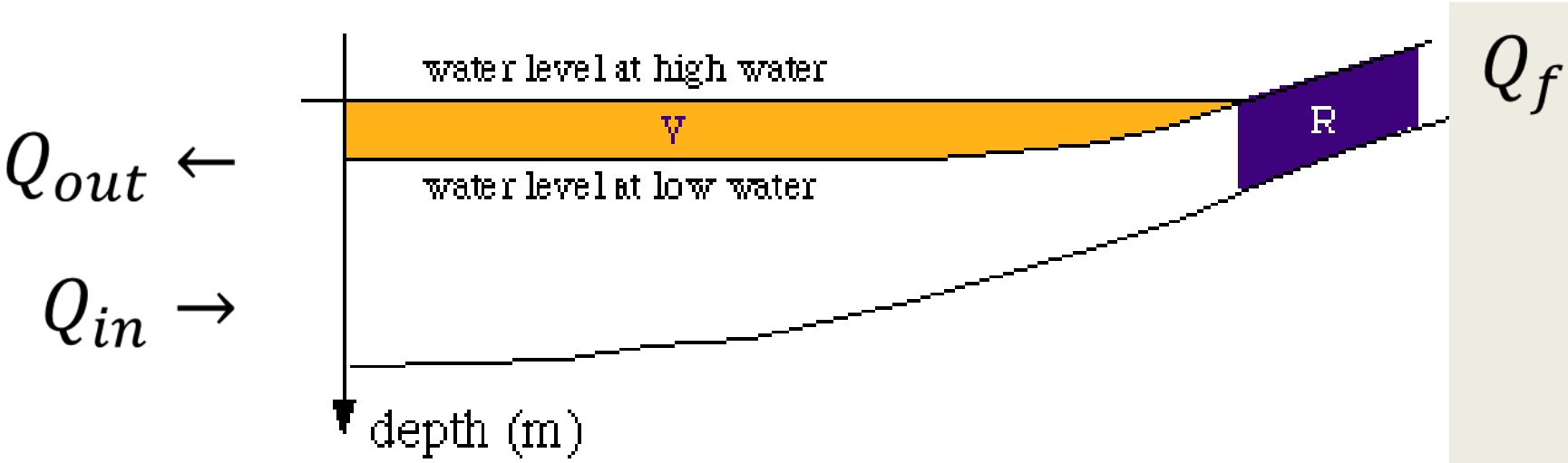
5) R/V ≤ 0 inverse estuaries



6) R/V ≈ 0 salt plug estuaries



7) The intermittent estuary is characterised by the temporary disappearance of the thermohaline forcing and, as a consequence, changes more or less regularly from an estuary to an oceanic embayment and back.



T tidal period

Tidal volume V

Fresh water volume R

Knudsen´s hydrographical theorem

$$Q_{in} + Q_f = Q_{out}$$

Knudsen´s hydrographical theorem

$$Q_{in} + Q_f = Q_{out}$$

$$Q_{in}S_{in} = Q_{out}S_{out}$$

Knudsen´s hydrographical theorem

$$Q_{in} + Q_f = Q_{out}$$

$$Q_{in} S_{in} = Q_{out} S_{out}$$

$$Q_{in} = \frac{Q_f S_{out}}{S_{in} - S_{out}} \qquad Q_{out} = \frac{Q_f S_{in}}{S_{in} - S_{out}}$$

Knudsen´s hydrographical theorem

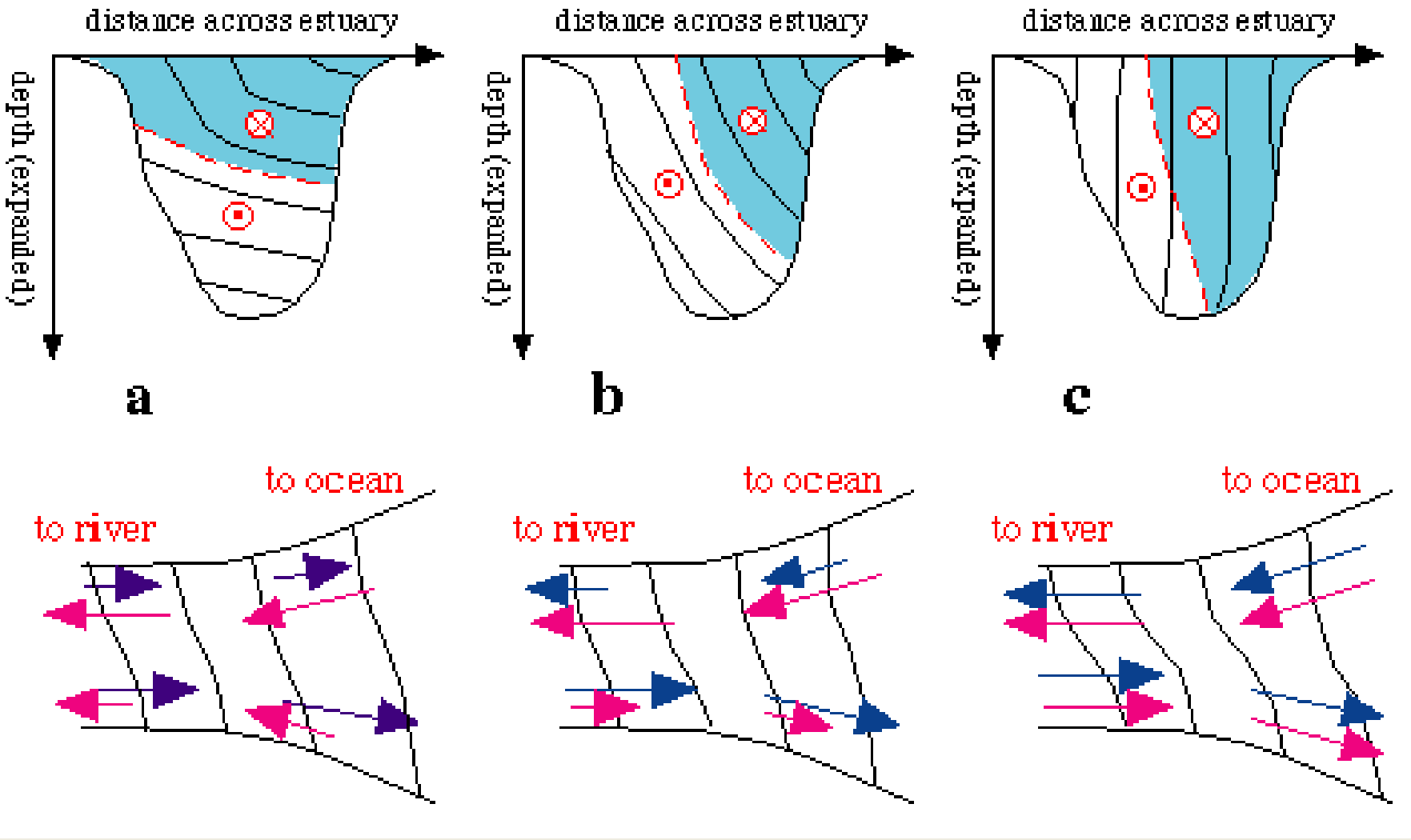
$$Q_{in} + Q_f = Q_{out}$$

$$Q_{in}S_{in} = Q_{out}S_{out}$$

$$wA = Q_{in} = \frac{Q_f S_{out}}{S_{in} - S_{out}} \qquad Q_{out} = \frac{Q_f S_{in}}{S_{in} - S_{out}}$$

R/V can change in time as a result of variations in rainfall over the catchment area of the rivers

Horizontally inhomogeneous, three-dimensional estuaries (when the Coriolis force becomes important)


distance across estuary
depth (expanded)
a
distance across estuary
depth (expanded)
b
distance across estuary
depth (expanded)
c
to ocean
to river
to ocean
to river
to ocean
to river

Schematic of different vertical circulation patterns

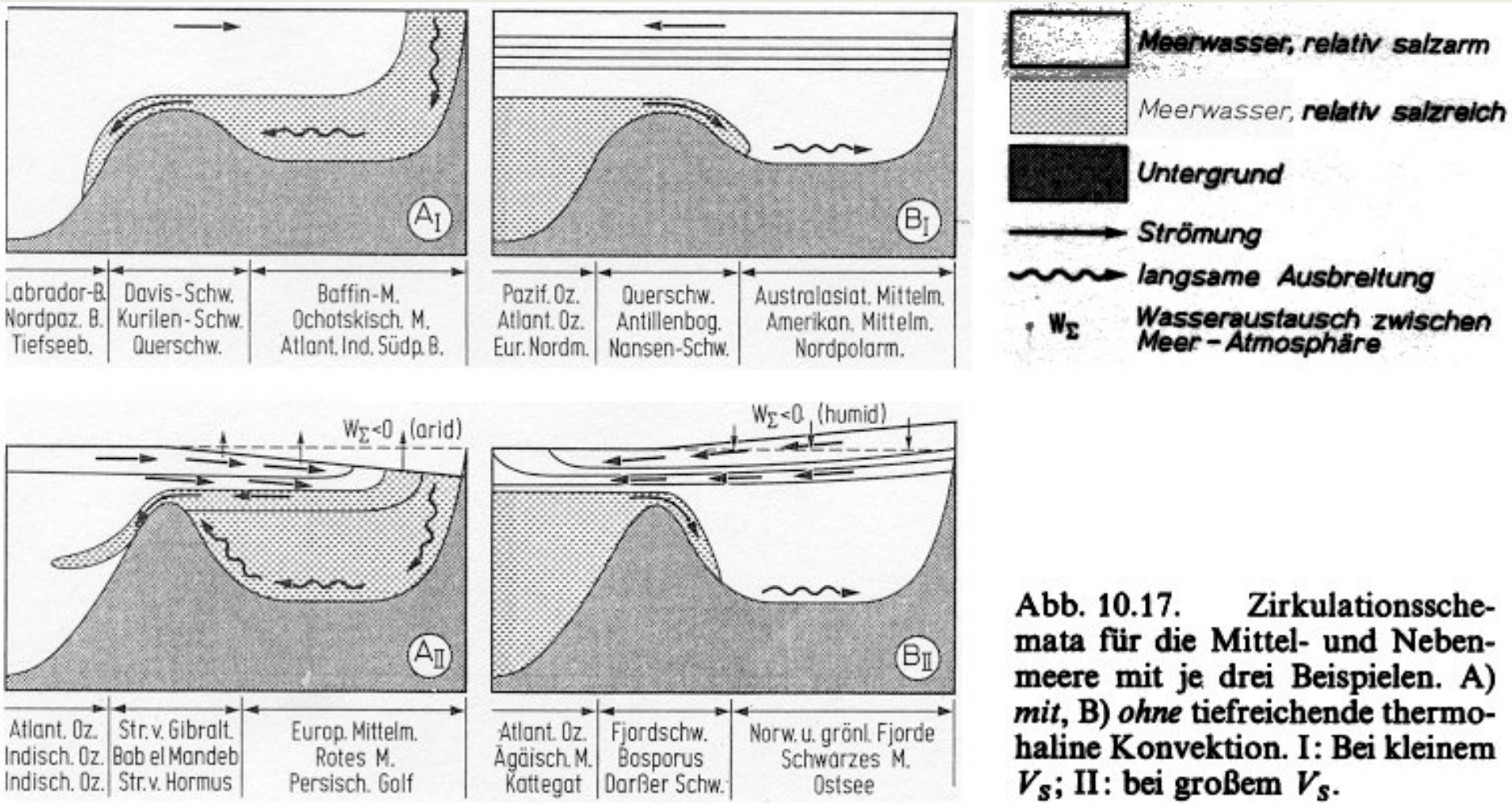
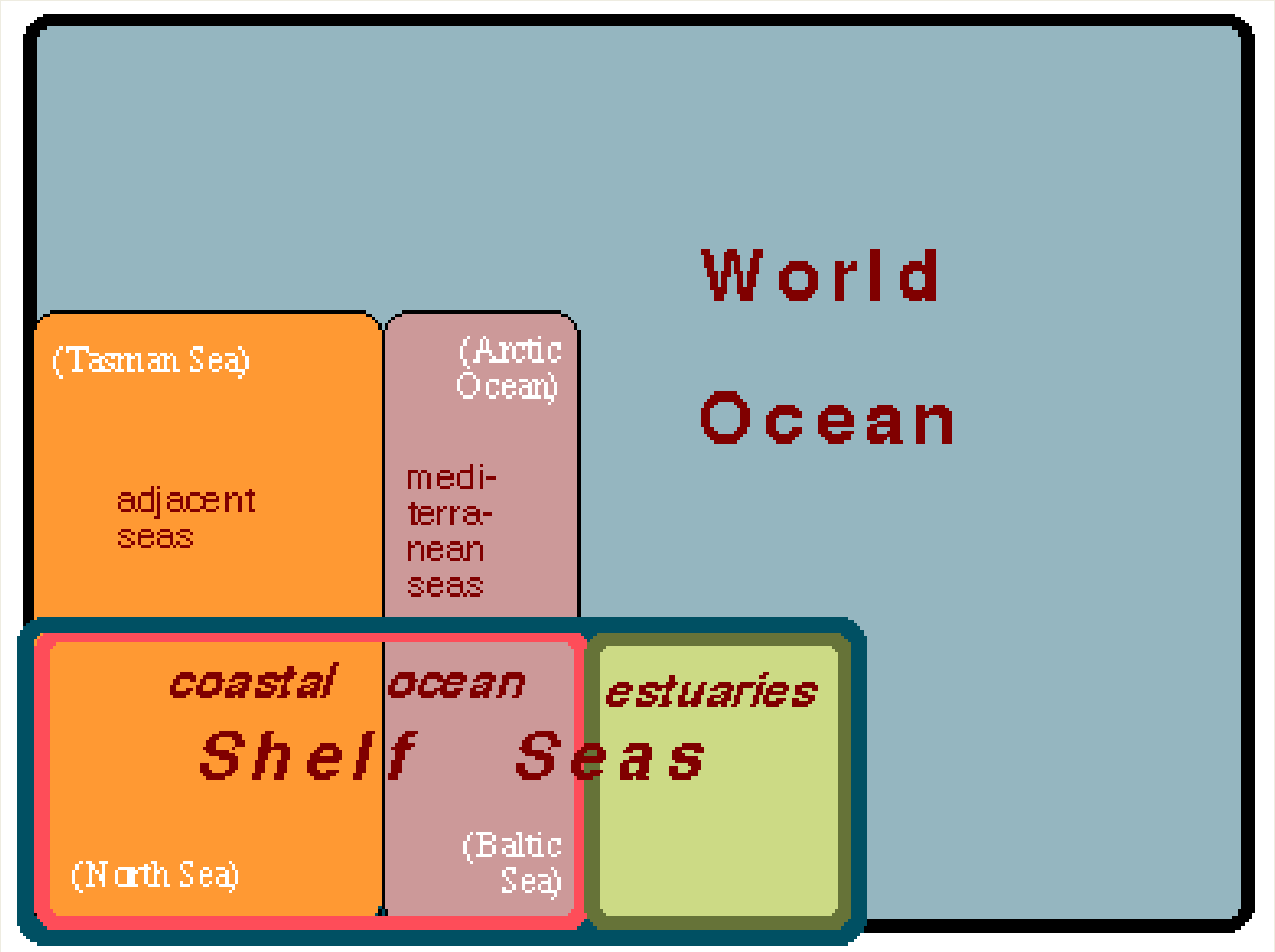


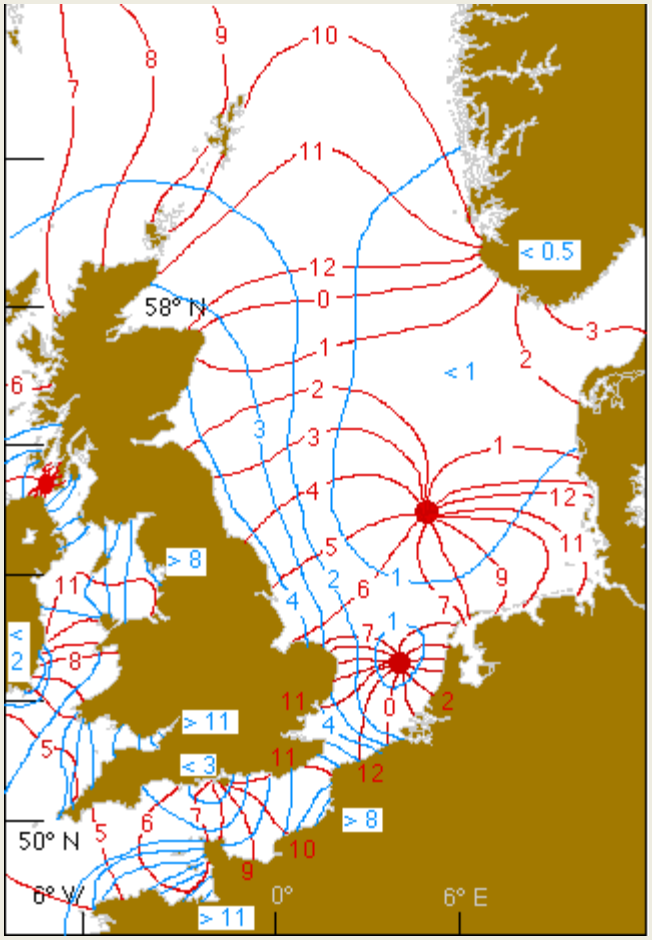
Abb. 10.17. Zirkulationsschemata für die Mittel- und Nebenmeere mit je drei Beispielen. A) *mit*, B) *ohne* tiefreichende thermohaline Konvektion. I: Bei kleinem V_S; II: bei großem V_S.

(Source: Dietrich et al., 1975)


World
Ocean
(Tasman Sea)
adjacent
seas
(Arctic
Ocean)
medi-
terra-
nean
seas
coastal
ocean
estuaries
Shelf Seas
(North Sea)
(Baltic
Sea)

North Sea

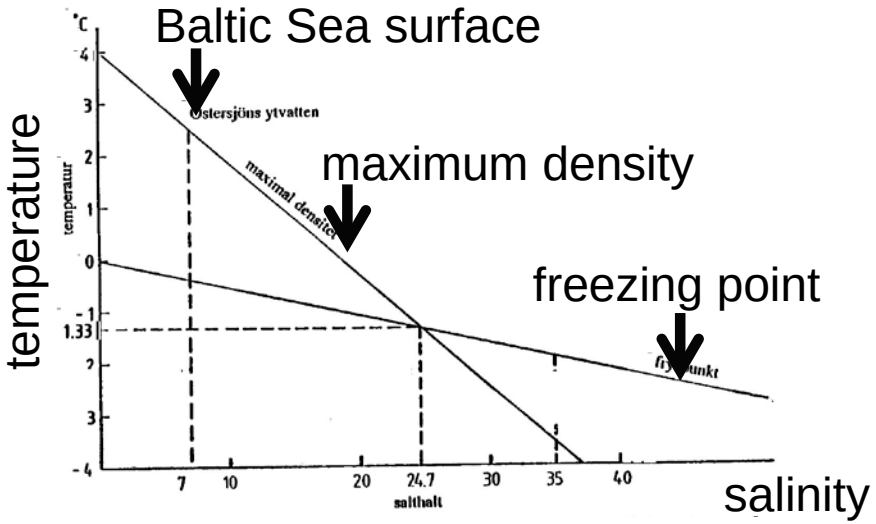
(Source: NASA)



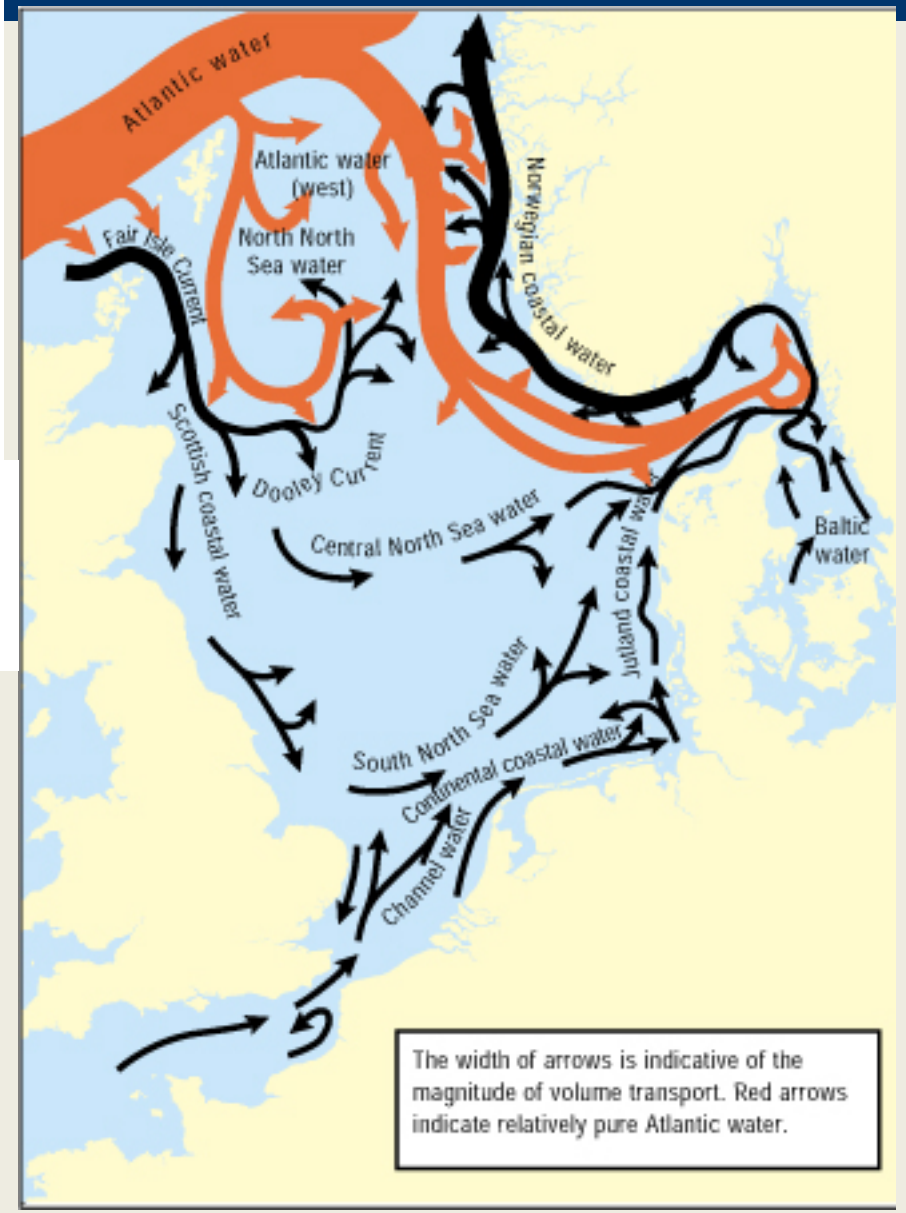
Co-phase (in hours) and co-range lines (in metres) for the semidiurnal tides M_2+S_2

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

NOSCCA North Sea Region Climate Change Assessment



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



North Sea

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)

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Thank you very much for your attention!