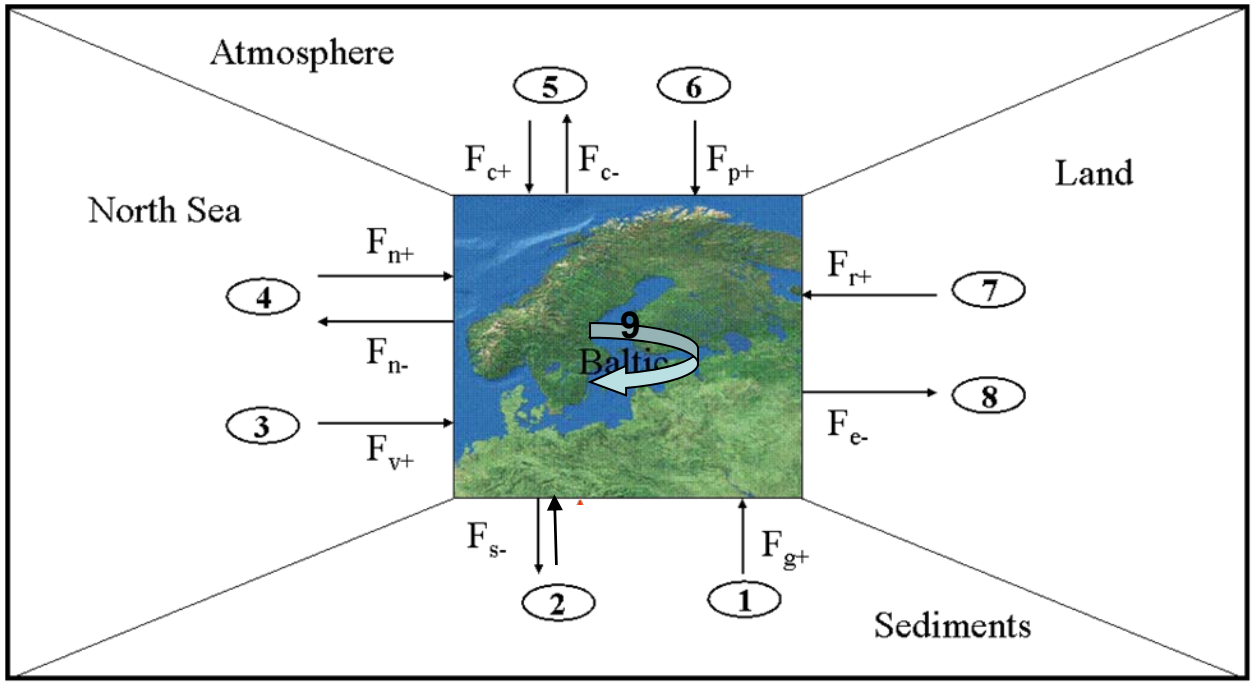
Baltic Sea carbon budget



1. Groundwater seepage
2. Sedimentation /**Return flux**
3. Ships discharge
4. North Sea + Baltic Sea water exchange
5. Air / Sea CO_2 exchange
6. Precipitation
7. Riverine runoff
8. Extraction

$F_{...}$ Carbon fluxes as a product of material fluxes and carbon concentration

Carbon fluxes in the Baltic Sea,

Pempkowiak 1977; Peltonen 2002; Thomas & Schnider,2000

Thomas et al. 2003a; Thomas et al. 2010; Smailys 2005;

HELCOM 2004, 2006; SMHI 2003

Goeteborg, 19/20.09.2007

9. Primary production/mineralization

Budget approach to carbon cycling in the Baltic sea

Janusz Pempkowiak

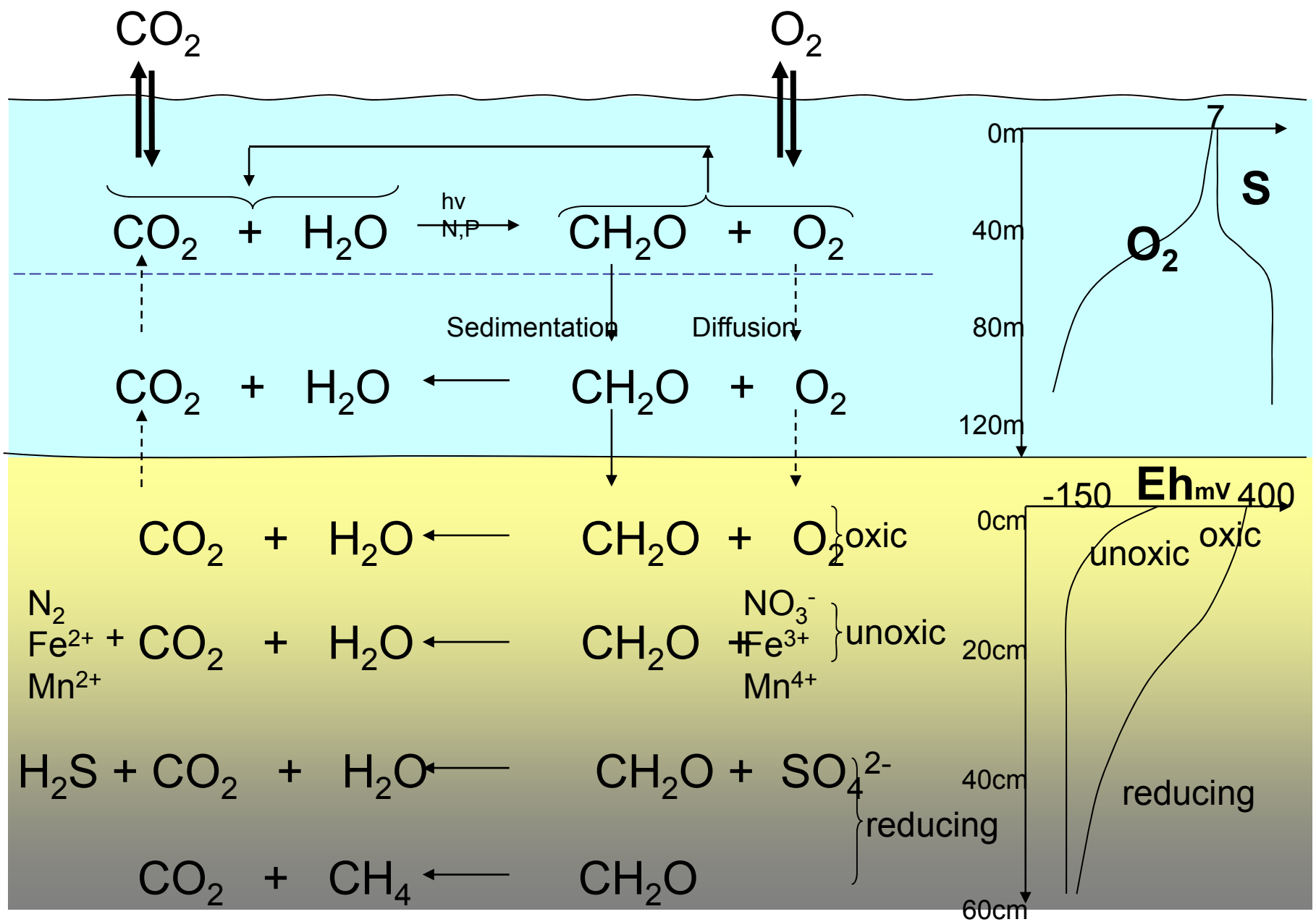
Inst.Oceanology, Sopot, Poland

Contents

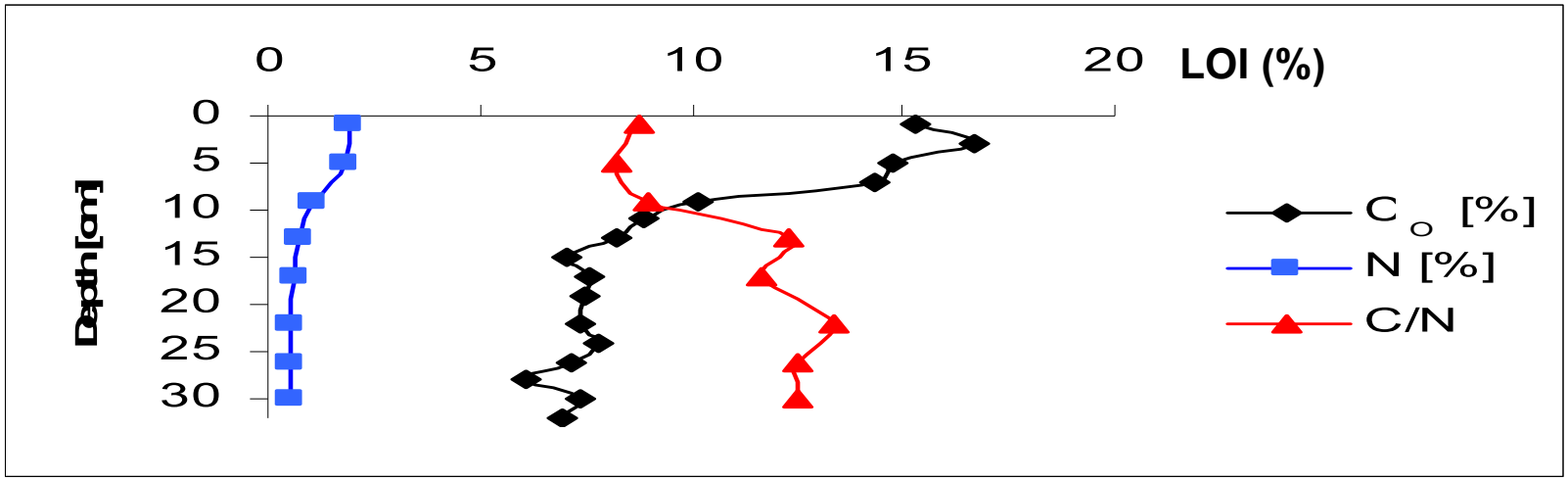
- Budget
- Sediments

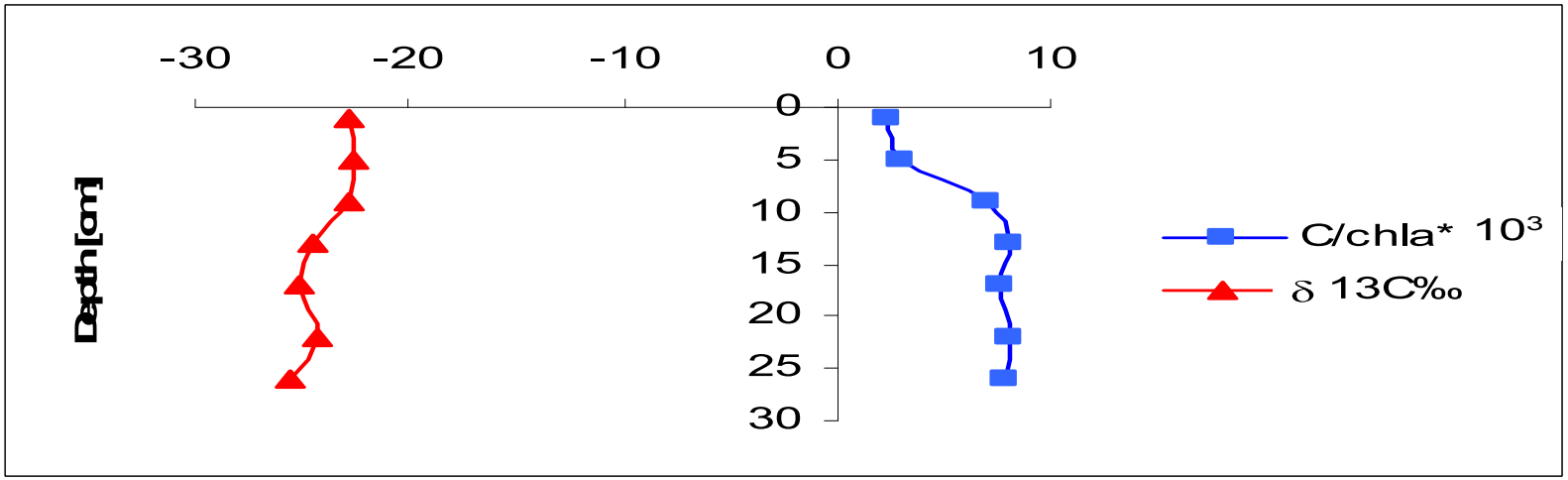
Processes

Goeteborg, 19/20.09.2007



SEDIMENTATION

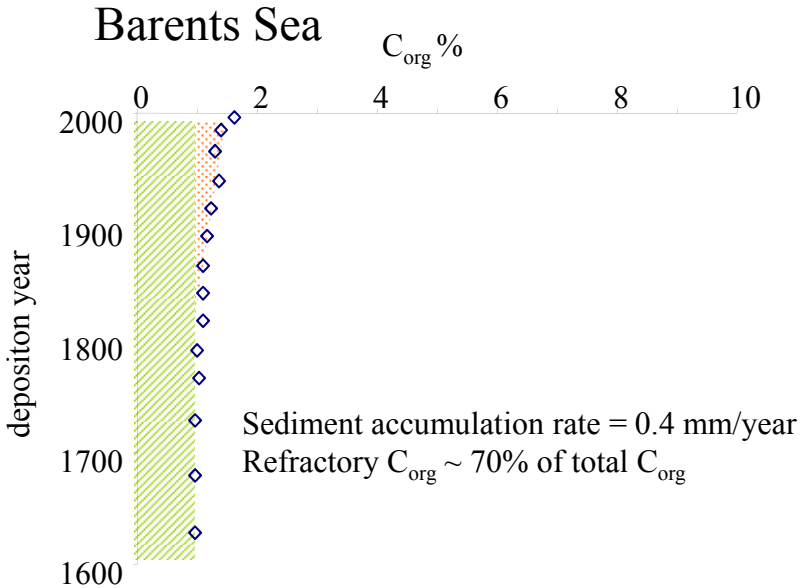


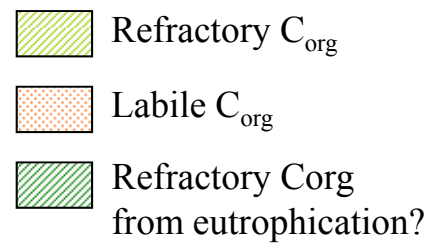


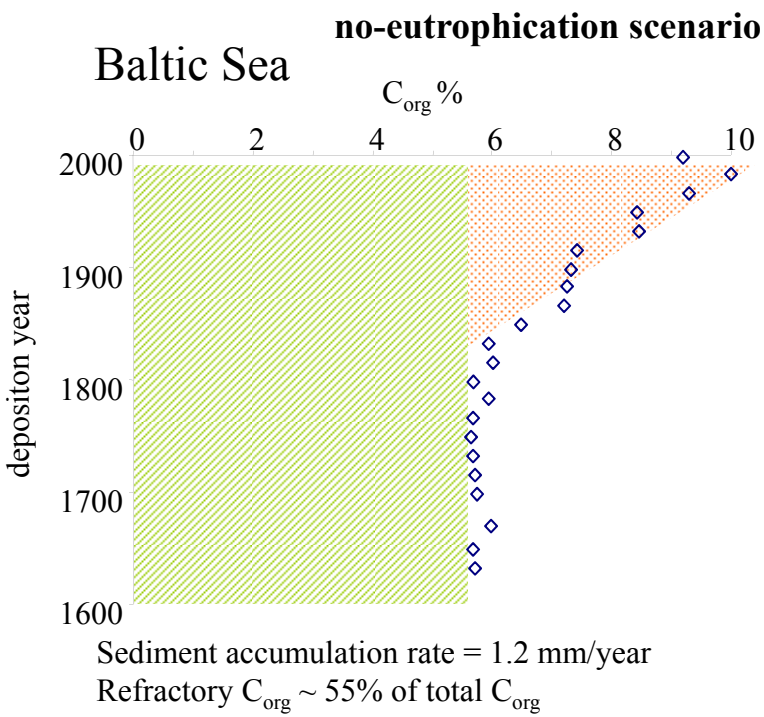
Goeteborg, 19/20.09.2007

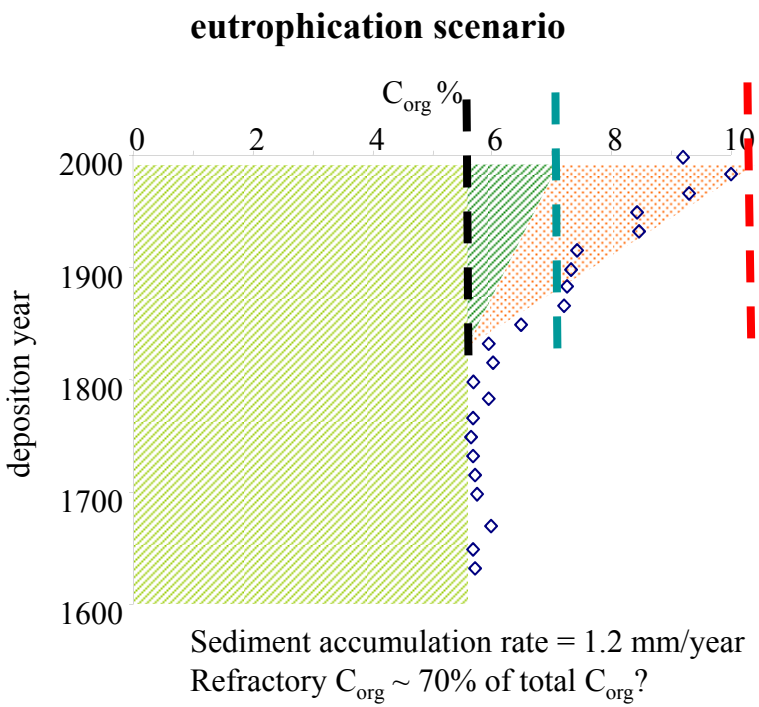
Fresh o.m. production impact on sedimentary organic carbon

Goeteborg, 19/20.09.2007





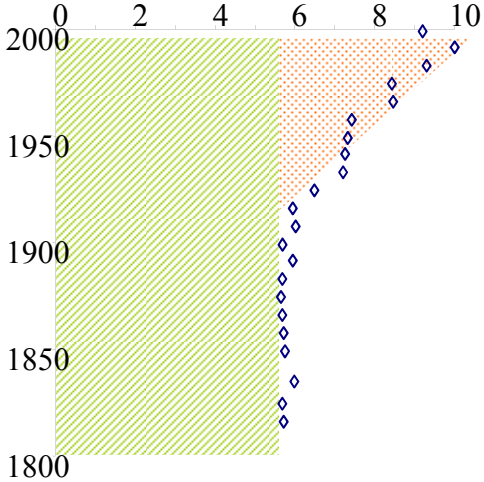




Baltic_C bussiness

Baltic-C: Building predictive capability regarding the Baltic Sea organic/inorganic carbon and oxygen systems

WP 4: Quantification of carbon species fluxes through sediment-water interface.



<u>Organic matter in the Baltic sediments</u>

- deposition rates
- remineralization rates
- burial rates

Baltic_C deliverables

Deliverables List

Del. No.	Deliverable Name	WP no.	Delivery date (month)
D1	Estimating environmental costs of change in the acid-base balance (pH).	1	12
D2	Assessment of Baltic Sea CO_2 system.	1	36
D3	The Baltic-C data base.	1	36
D4	Lecture and notes on the Baltic Sea CO_2 system under climate change.	1	12
D5	Seasonally resolved pCO_2 fields for the entire Baltic Sea.	2	12
D6	Seasonally resolved pCO_2 fields for the entire Baltic Sea: Update.	2	24
D7	Improved process parameterizations (biomass production, nitrogen fixation).	2	12
D8	CO_2 gas exchange balance.	2	24
D9	Concentrations of inorganic/organic carbon species in the major model sub-basins.	2	12
D10	Compilation of existing CO_2/carbon data.	2	6
D11	Trend analysis for CO_2/carbon variables.	2	12
D12	River inflow of: alkalinity, pH, total organic carbon, total inorganic carbon, and calcium: Initial database.	3	6
D13	River inflow of: alkalinity, pH, total organic carbon, total inorganic carbon, and calcium: Updated database.	3	18
D14	Calculate remineralisation rates of organic matter based on existing data.	4	6
D15	New stratified sediment samples collected covering Arkona Deep, Bornholm Deep, Gotland Deep, Coastal areas.	4	12
D16	Mineralization rates at the sediment water interface and in the deep water.	4	12
D17	Mineralization rate at different redox conditions.	4	12
D18	Collected cores analyzed.	4	18
D19	Mineralization rates established for a range of environmental conditions.	4	18
D20	Loads of carbon deposited to sediments and return flux of carbon from sediments for the entire Baltic Sea established.	4	24
D21	Carbon burial rates in the Baltic sediments established.	4	30

Deliverables List

Del. No.	Deliverable Name	WP no.	Delivery date (month)
D22	Data base consisting of C_T depth profiles measured in the central Gotland Sea.	4	36
D23	Report concerning mechanisms of carbon flux to the Baltic sediments.	4	36
D24	Improved parameterisation of the gas exchange transfer velocity.	5	18
D25	Measurements from the first 12 month of the project taken at the Östergarnsholm station.	5	18
D26	Acidic deposition for the Baltic Sea drainage basin.	5	8
D27	Compiled present and future scenario land use data for the Baltic Sea drainage basin.	5	12
D28	Set up and validation of the vegetation model with implementation of DOC export algorithm and coupling to river runoff model.	6	18
D29	Modelling present and past changes in vegetation, CO_2 exchange and DOC production on watershed basis for the Baltic Sea drainage basins.	6	18
D30	Modelling future changes in vegetation, CO_2 exchange and DOC production on watershed basis for the Baltic Sea drainage basis	6	24
D31	Data set on A_T, C_T, Ca and C_{org} inputs to the Baltic Sea.	7	6
D32	Model describing A_T, C_T, Ca and C_{org} inputs from 83 major watersheds for the period 1990-2000.	7	12
D33	Model runs and data set A_T, C_T, Ca and C_{org} fluxes from 83 watersheds as a function of land cover changes.	7	24
D34	Model runs and data set on N and P fluxes from 83 watersheds as a function of land cover changes.	7	24
D35	Model runs and data on N and P fluxes from 83 watersheds as a function land use changes.	7	24
D36	Modelling present and past changes of Baltic Sea CO_2 system.	8	18
D37	Modelling possible future changes in the Baltic Sea CO_2 system.	8	24

WP4 Most pressing deliverables_ Warnemunde, 2009

D.14 Calculate remineralization rates of organic matter basing on existing data ..... M 6
D.15 New stratified sediment samples collected M12
D.16 Mineralization rates at the sediment water interface and in the deep water M12
D.17 Mineralization rates for different environmental conditions M18

D.14 ➔Karol Kuliński will talk about remineralization rates
Aleksandra Szczepańska will show results of ‘data mining’
D.15 ➔Sediment cores collected (Aranda, Oceania), Anna Maciejewska
D.16 ➔Bernd Schneider
D.17 ➔in progress

WP4 Most pressing deliverables_Lund 2010

D.18 Collected cores analysed M18
D.19 Mineralization rates established for a range of environmental conditions M18
D.20 Deposition loads and return flux M24
D.21 Carbon burial rates established M30

D.18 ➔ Aleksandra Szczepańska has doubled no of analysed cores
D.19 ➔ Calculated for the newly analysed cores; in progress for surface sediments
A.Szczepańska
D.20 ➔ Karol Kuliński will talk about deposition loads and return flux
D.21 ➔ Karol Kuliński will talk about burial rates

Report on WP 4 activities_Nov.,2009- Nov.,2010:

1. Summary_Janusz Pempkowiak
   - carbon mineralization rates in sediments (Aleksandra Szczepańska)
   - DOC&POC modelling and experiments (Anna Maciejewska)

2. Karol Kuliński_ Carbon burial rates

3. Beata Szymczycha_Carbon in seepage water discharges

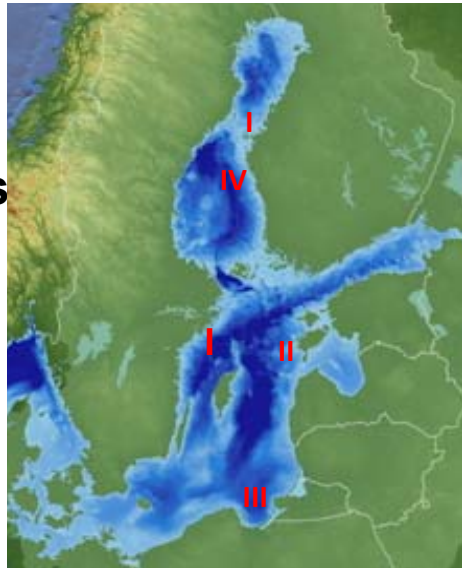
Carbon deposition/return flux

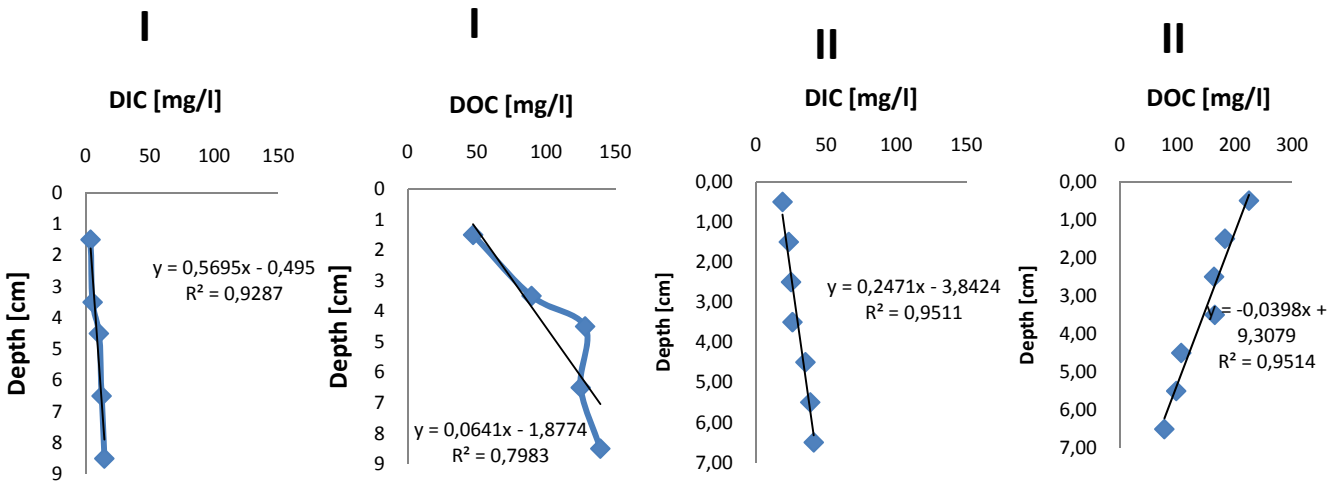
A.Szczepańska

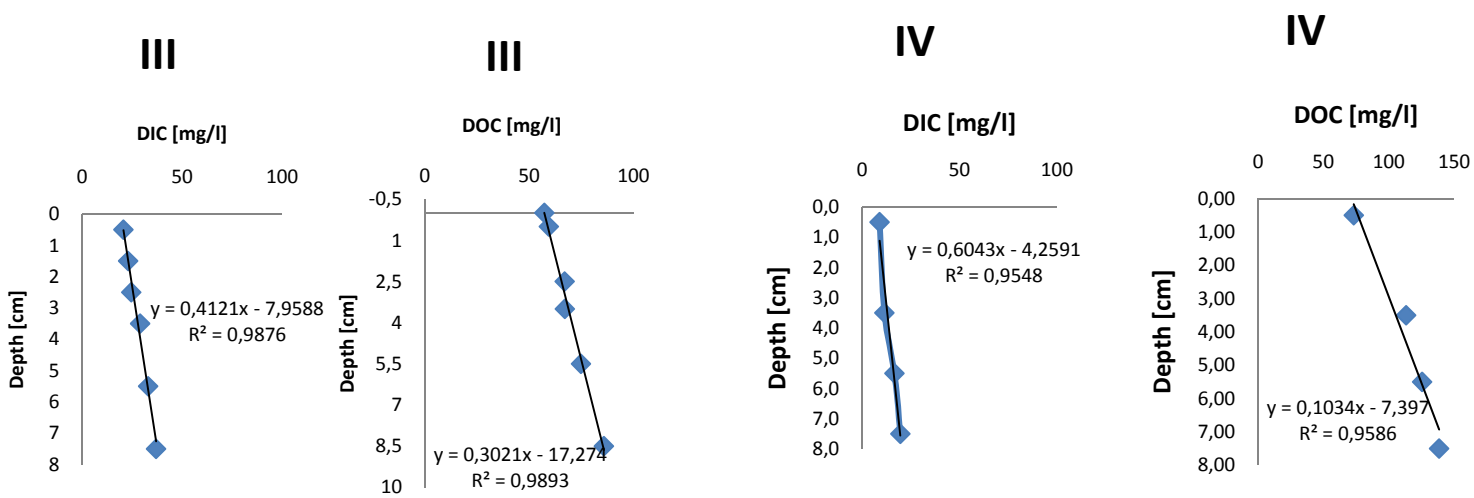
- collected cores analysed (D18)
- mnieralization rates (D19)

Carbon return flux estimation from the bottom sediments/1

- **DIC and DOC concentration gradient in the pore waters**







A.Szczepanska

Carbon return flux estimation from the bottom sediments/2

- **DIC and DOC concentration gradient in the pore waters**

Station	DIC return flux [g C m^{-2} $year^{-1}$]	DOC return flux [g C m^{-2} $year^{-1}$]
I	2,83	0,57
II	7,79	-
III	4,59	1,77
IV	3,71	0,62

A.Szczepanska

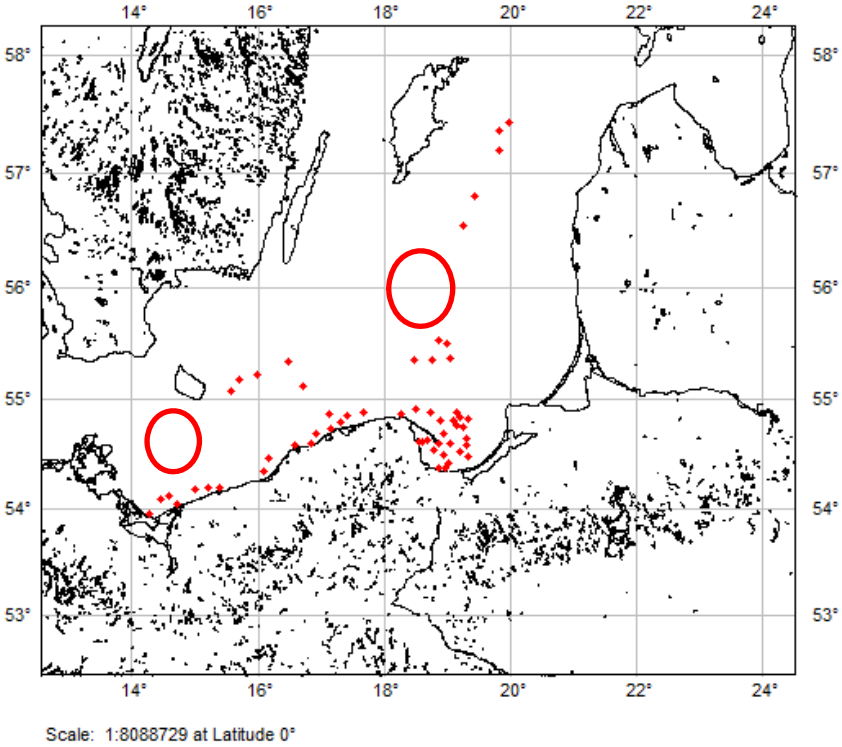
Mineralization rates for different environmental conditions

- **Determination of the labile carbon fraction in the surface sediments**

Incubation

$$v = dC/dt = k\,C_0$$

v –decomposition rate [mg C g^{-1} d.m. day^{-1}]
dC/dt – carbon concentartion gradient[mg C g^{-1} d.m. day^{-1}]
k –decomposition constant [day^{-1}]
C_0 – concentartion in „time 0”[mg C g^{-1} d.m.]



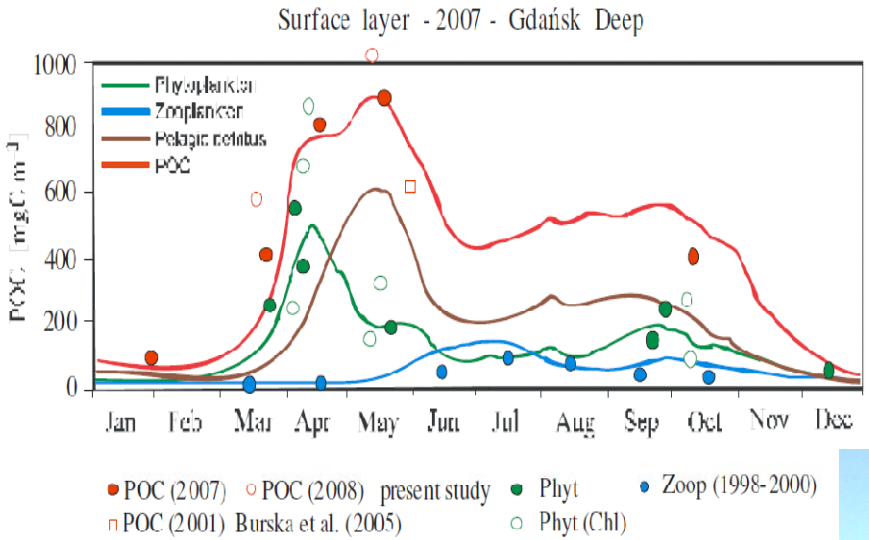
A.Szczepanska

Raport on measuring

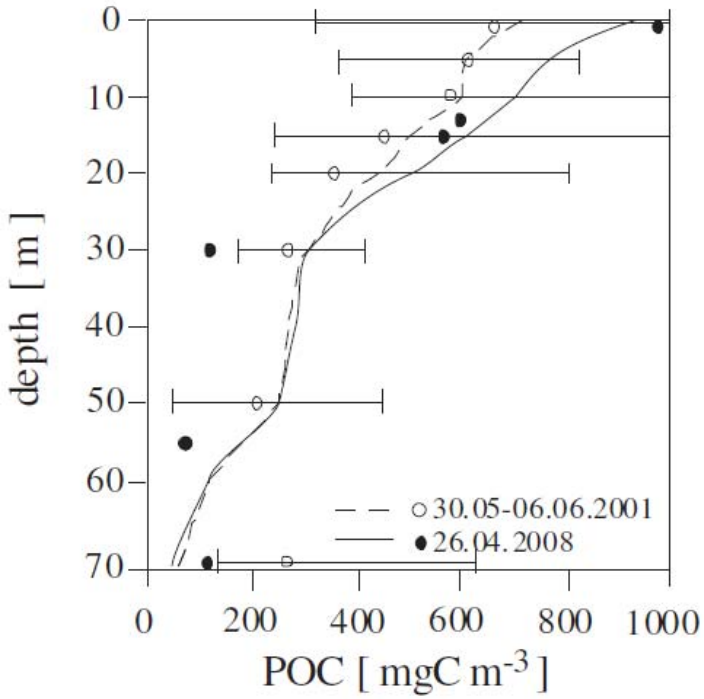
POC/DOC for model validation

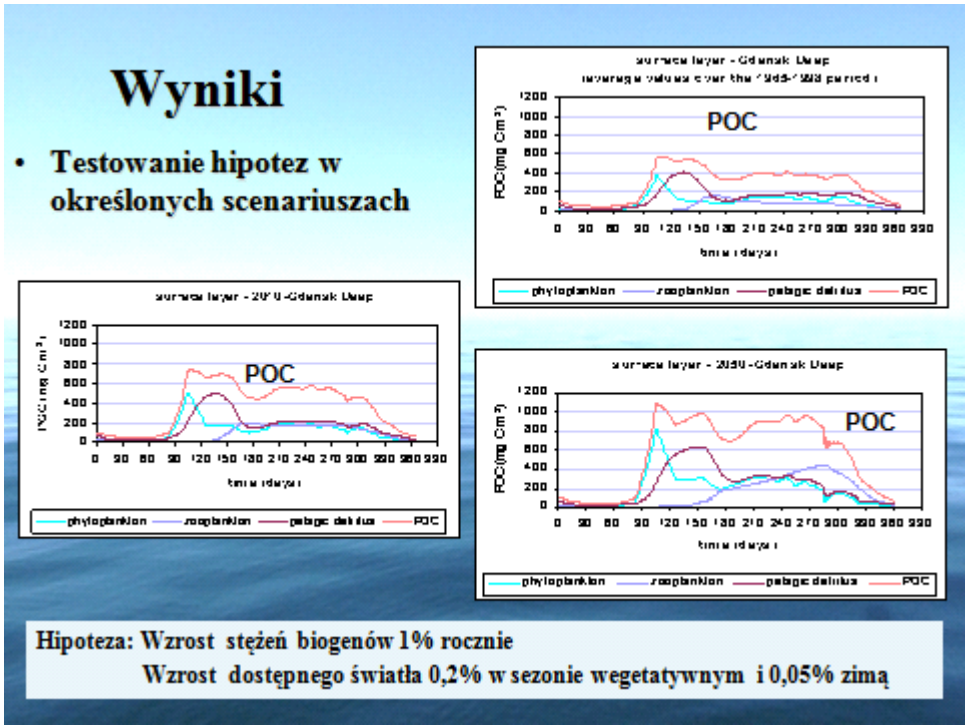
(primary production/mineralization)

A.Maciejewska



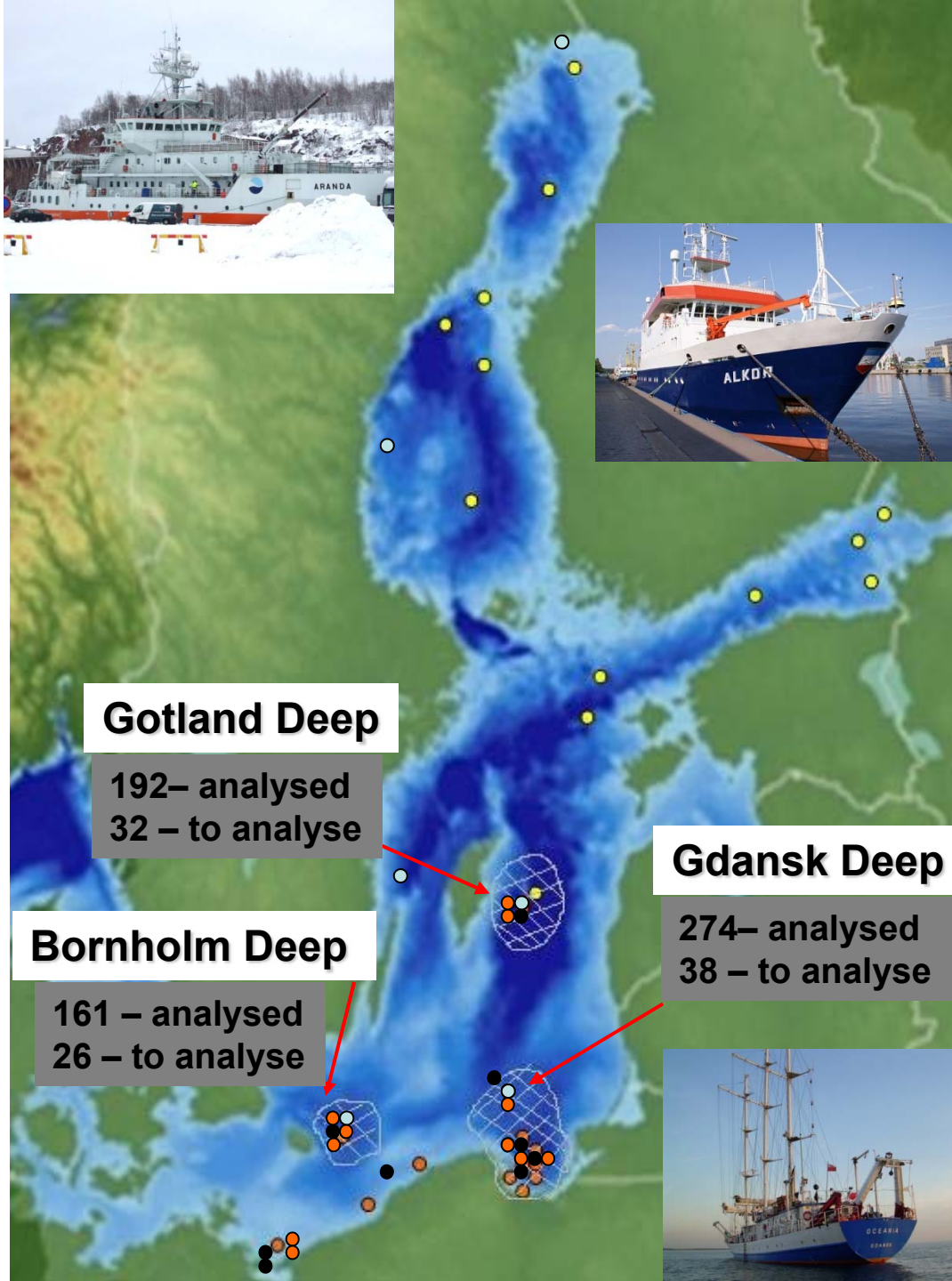
POC modeling ➔➔DOC modeling
-Maciejewska,
-Dziezbicka,
-Kuliński,
-Pempkowiak





Location of sampling station

- r/v **Oceania** cruise (March, April, October **2009** April **2010**) Samples: sediments and water
- r/v **Aranda** cruise (January **2009**) Samples: sediments and water
- r/v **Oceania** cruise (April/May **2008**) Samples: sediments and water
- r/v **FS Alkor** cruise (June/July **2010**) Samples: sediments and water



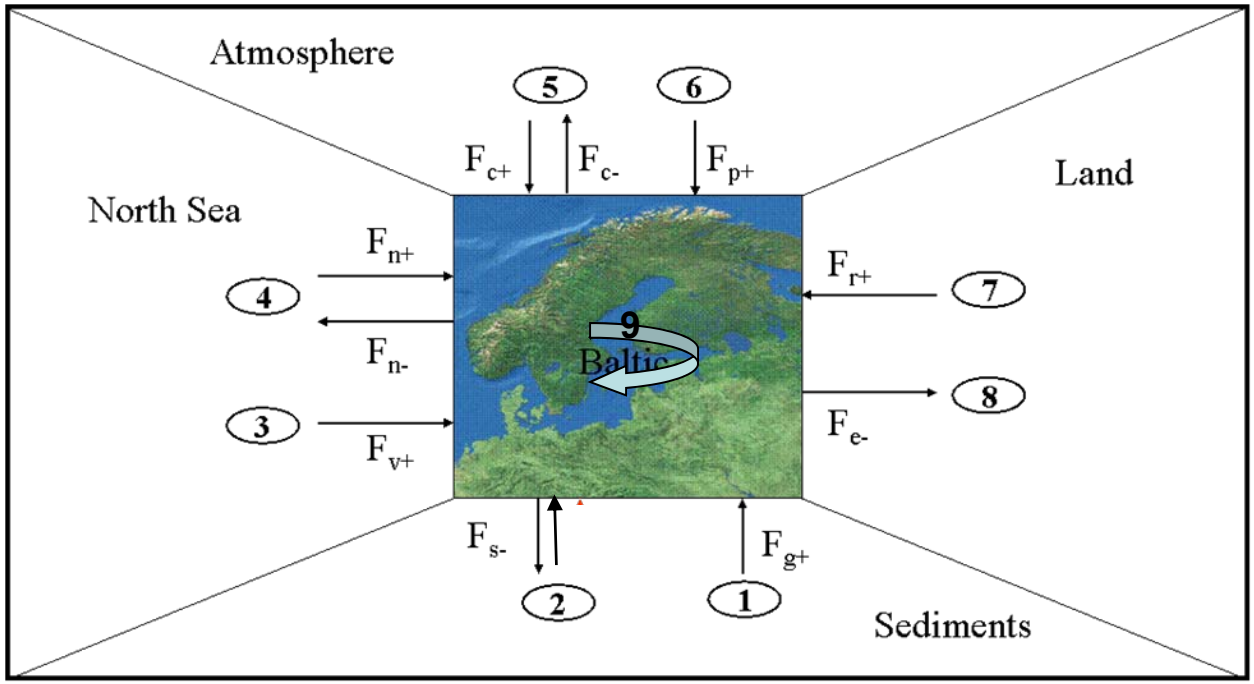
A.Maciejewska

POC/DOC/DIC Extensive measurments for model validation

Parameter	POC [mgC/l]			DOC [mgC/l]			DIC [mgC/l]		
Deep/Month	*Gdansk*	*Gotland*	*Bornholm*	*Gdansk*	*Gotland*	*Bornholm*	*Gdansk*	*Gotland*	*Bornholm*
January		surface - **0,15** w. column - **0,09**			surface - **3,22** w. column - **2,78**			surface – **21.23** w. column -23.**82**	
February				surface - **3,93**					
March	surface - **0,28** w. column - **0,15**	surface - **0,17** w. column - **0,13**		surface **- 3,38** w. column - **3,59**	surface - **3,47** w. column - **3,08**		surface - **19,38** w. column - **19,79**	surface - **18,82** w. column - **19,91**	
April	surface - **1,27** w. column - **0,52**	surface - **1,23** w. column - **0,56**	surface - **0,71** w. column - **0,41**	surface - **4,46** w. column - **4,14**	surface - **3,43** w. column - **3,35**	surface - **3,88** w. column - **3,87**	surface - **19,57** w. column - **20,06**	surface - **18,82** w. column - **20,01**	surface - **18,77** w. column - **19,12**
May	surface - **1,17**			surface - **5,35**					
June / July	surface - **0,88** w. column - **0,41**	surface - **0,72** w. column - **0,38**	surface - **0,54** w. column - **0,29**	surface - **4,98** w. column - **4,21**	surface - **3,87** w. column - **3,52**	surface - **4,01** w. column - **3,56**	surface - **19,32** w. column - **18,35**	surface - **17,56** w. column - **18,59**	surface - **17,58** w. column - **18,56**
August									
September	surface - **0,30**			surface - **4,00**					
October	surface - **0,22** w. column - **0,15**	surface - **0,34** w. column - **0,21**	surface - **0,17** w. column - **0,14**	surface - **3,89** w. column - **3,72**	surface - **3,34** w. column - **3,21**	surface - **3,65** w. column - **3,59**	surface - **20,78** w. column - **21,77**	surface - **21,39** w. column - **22,67**	
November									
December									

A.Maciejewska

Baltic Sea carbon budget



1. Groundwater seepage
2. Sedimentation /**Return flux**
3. Ships discharge
4. North Sea + Baltic Sea water exchange
5. Air / Sea CO_2 exchange
6. Precipitation
7. Riverine runoff
8. Extraction

$F_{...}$ Carbon fluxes as a product of material fluxes and carbon concentration

9. Primary production/mineralization

Carbon fluxes in the Baltic Sea,

Pempkowiak 1977; Peltonen 2002; Thomas & Schnider,2000 Thomas et al. 2003a; Thomas et al. 2003b; Smailys 2005; HELCOM 2004, 2006; SMHI 2003; Kuliński 2010; Szymczycha et al. in preparation

CONCLUSIONS

Amount returning to seawater as a consequence of organic matter decompositoion

Budget (10^6ton)

PROCESS	F	Flux			
		F_i		F_o	
		o	i	o	i
Sediment./Diff.	F_S	-	(1.38)	**3.89** ~~5.77~~	0.10
Dischar./extr.	F_D	0.21	0.02	0.41	0.00
Run-off	F_R	3.12	9.44	-	-
Prec./aeros	F_P	0.17	0.02	0.01	-
Water exch.	F_W	1.62	10.62	4.10	18.45
Seepage water	Fs1	0.06	0.43		
Total	ΣF	~~5.12~~ 5.18	~~20.10~~ 20.63	~~10.79~~ 8.41	18.55
		~~25.22~~ 25.81		~~28.84~~ 26.96	

Amount due to SGD

$F_g = \Sigma F$

$= -$ ~~3.62~~ 1.74 $\times 10^6$ t/a

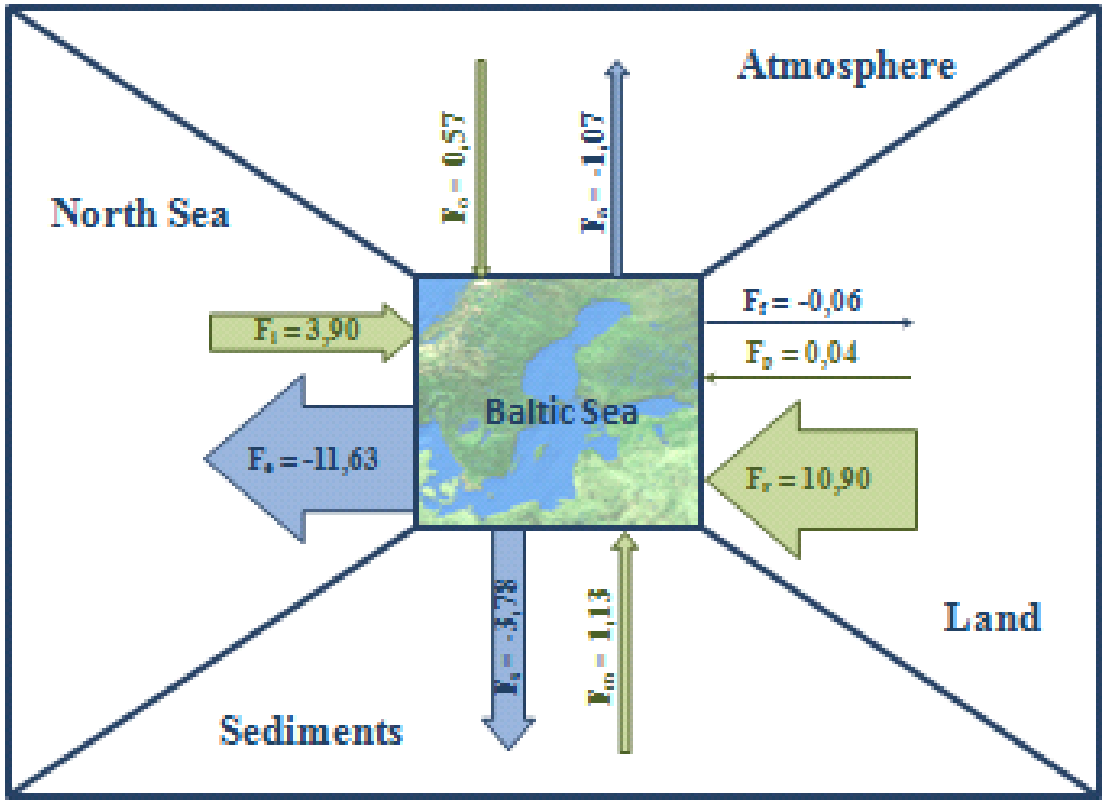
$=$ ~~9.43~~ 4.51 g/m²a

0.79 → 3.02 0.25mol/m2a **+/-0.3**

Estimated yearly carbon fluxes in the Baltic Sea,

Pempkowiak 1976; Peltonen 2002; Thomas et al. 2003a; Thomas et al. 2003b; Smailys 2005; HELCOM 2004, 2006; SMHI 2003 Kuliński,2010; Szymczycha et al. In preparation)

Baltic Sea carbon budget



F_e – carbon export to the North Sea;
F_i – carbon import from the North Sea;
F_o – precipitation;
F_f – fishery;
F_a – Net CO_2 exchange between Baltic and the atmosphere

F_p – wastewater;
F_r – river run-off;
F_m – carbon return flux from sediments
F_s – sedimentation

Burial rates

- Karol Kuliński

INSTITUTE OF OCEANOLOGY
POLISH ACADEMY OF SCIENCES

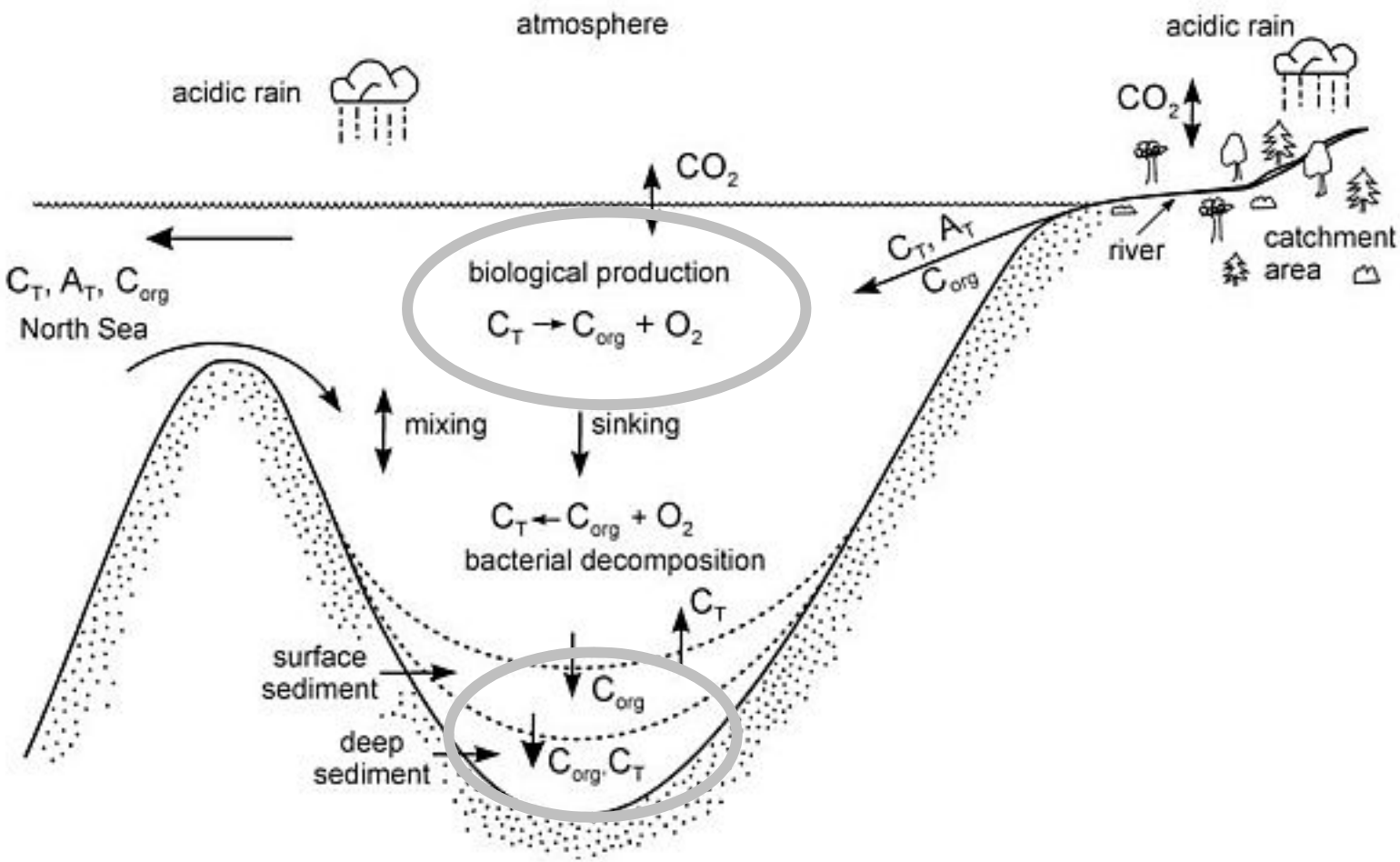
Carbon burial in the Baltic Sea sediments

Karol Kuliński, Janusz Pempkowiak, Anna Maciejewska, Aleksandra Szczepańska

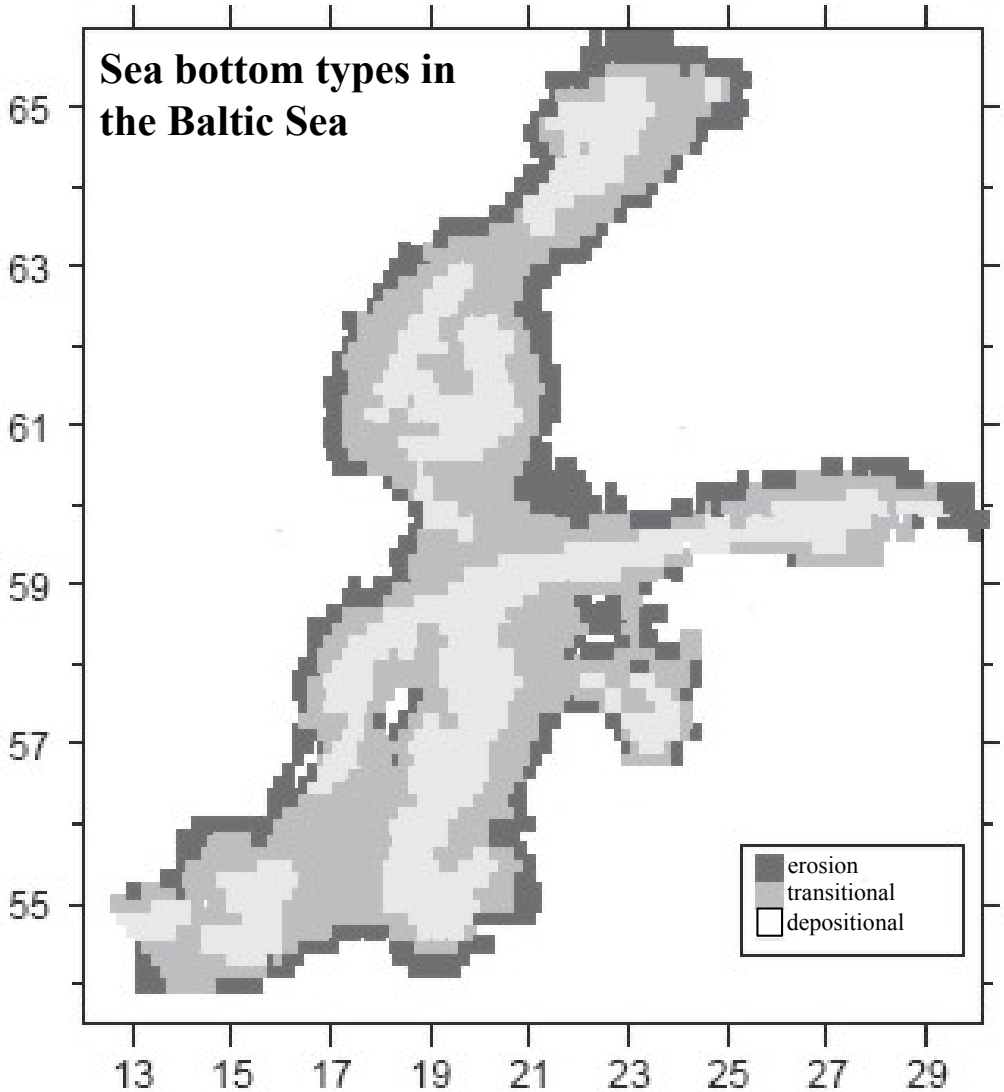
Marine Chemistry and Biochemistry Department

Baltic-C Meeting
Lund, 8-10 November 2010

Carbon burial in the Baltic Sea sediments



Carbon accumulation in the Baltic Sea sediments

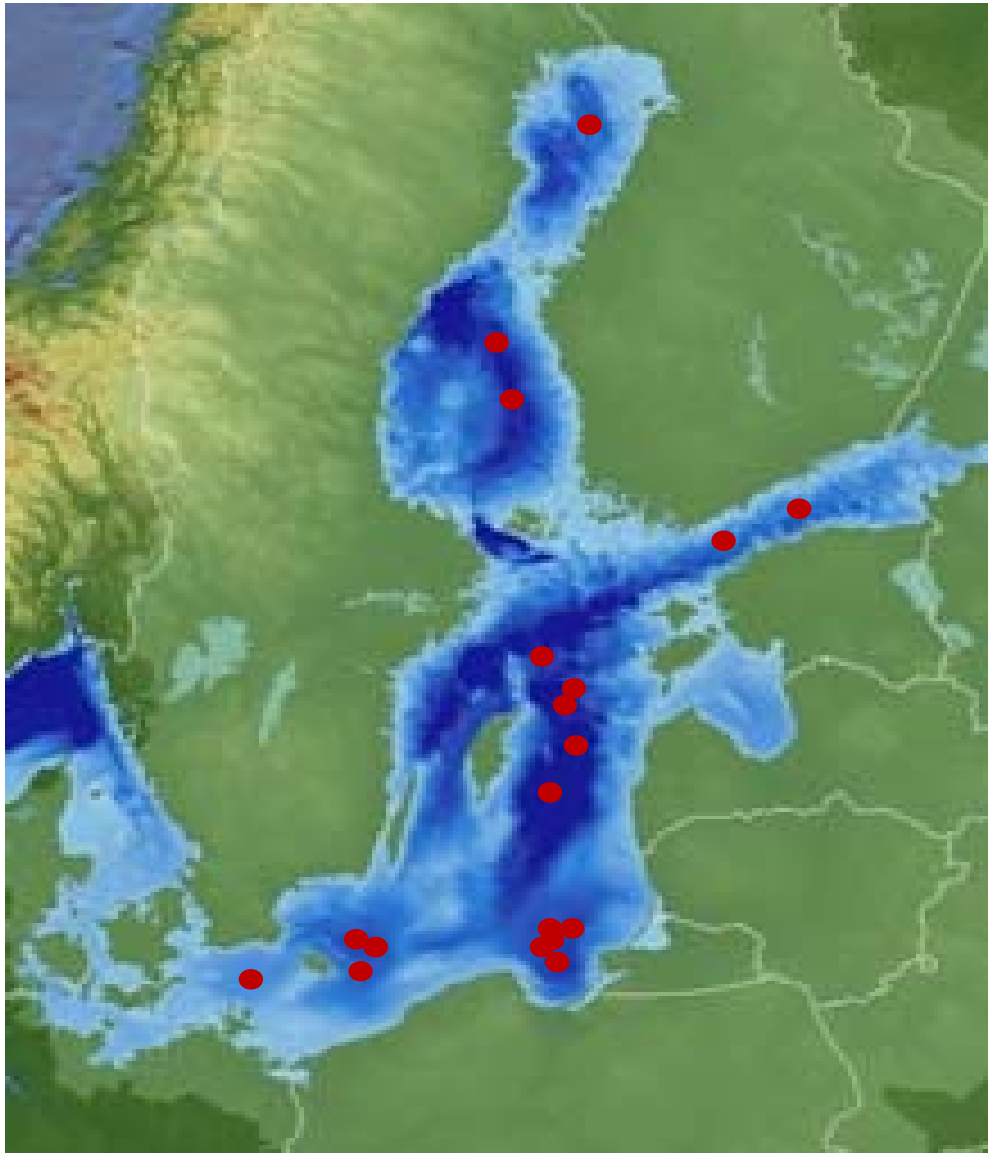


Jönsson et al., 2005

Surface of depositional areas and the organic carbon accumulation rates (^{210}Pb, C_{org}) are adopted from:

- Algesten et al., 2006
- Emeis et al., 2000
- Christoffersen et al., 2007
- PIG, 2005
- Błaszczyszyn, 1982

Carbon return flux from the Baltic Sea sediments



DOC and DIC fluxes from sediments are calculated using Fick's First Law

DIC, DOC

DIC, DOC

$$J = -\phi D_{sed} \frac{\Delta C}{\Delta x}$$

J – diffusion flux

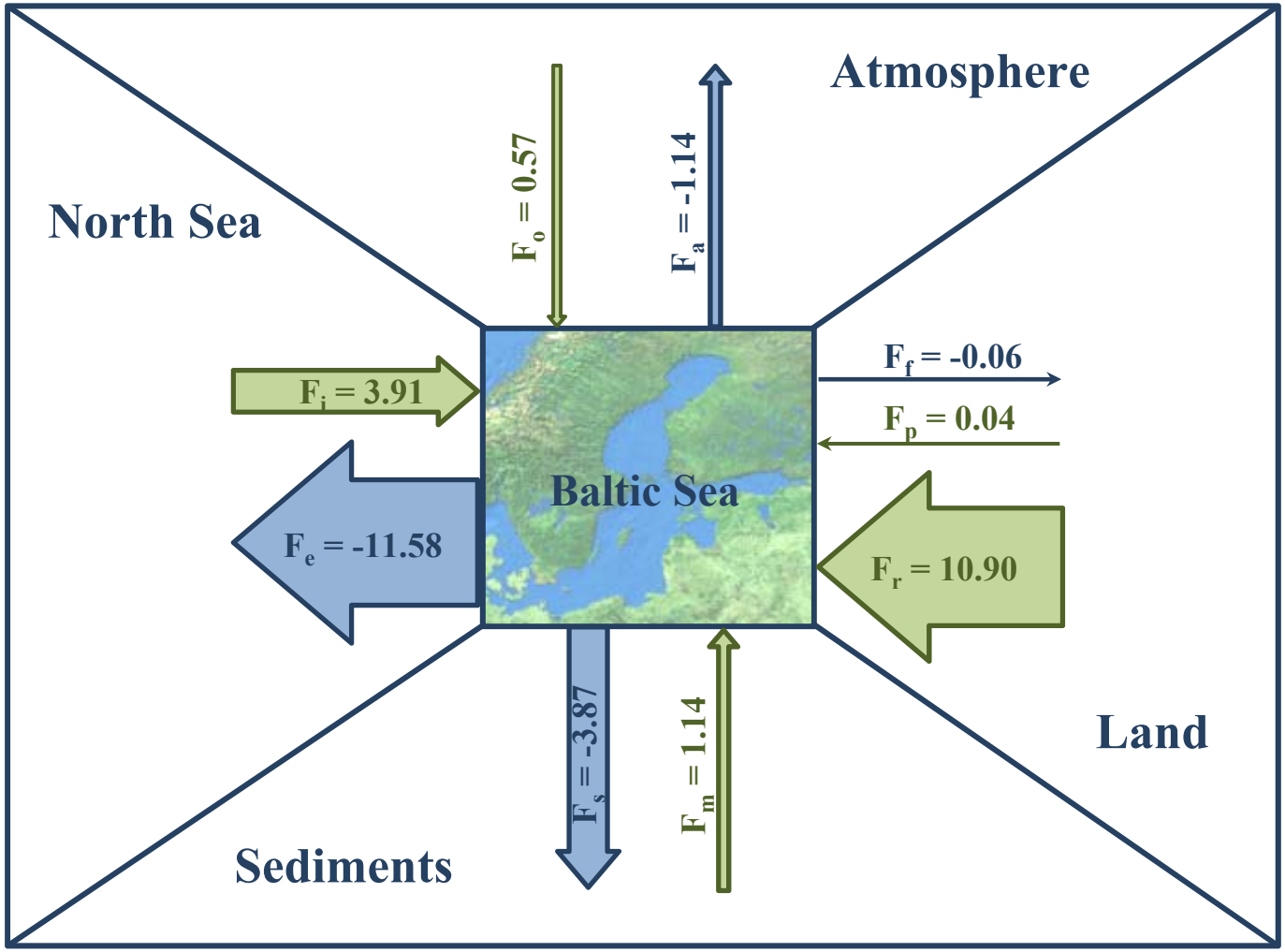
ϕ – porosity

D_{sed} – sediement diffusion coefficient

$\frac{\Delta C}{\Delta x}$ – carbon concentrations gradient

Ullman & Aller, 1982

Carbon budget of the Baltic Sea



River run-off
IC: 62%
OC: 38%

Import from the North Sea
IC: 95%
OC: 5%

Export to the North Sea
IC: 83%
OC: 17%

Return flux from the sediments
IC: 91%
OC: 9%

Values are in Tg (10^{12} g) C yr^{-1}

Inputs – positive

Outputs - negative

Carbon burial in the Baltic Sea -2.73 Tg C $year^{-1}$

Primary production in the Baltic Sea

	Primary production [g C m^{-2} $year^{-1}$]	
Basin	**Kaiser et al., 1981**	**Wasmund et al., 2001**
Kattegat/Danish Straits	90-120	190
Baltic Proper	90-125	200
Gulf of Riga	80-100	261
Gulf of Finland	70	82
Bothnian Sea	70	52
Bothnian Bay	18	17
Baltic Sea - mean	84	150

Wasmund & Siegel, 2008 after Kaiser et al., 1981 and Wasmund et al., 2001

Baltic Sea surface excluding Kattegat 385 000 km^2

Total primary production in the Baltic Sea 57.75 Tg C $year^{-1}$

Carbon burial in the Baltic Sea sediments

Total primary production in the Baltic Sea	57.75 Tg C $year^{-1}$
Carbon burial in the Baltic Sea	-2.73 Tg C $year^{-1}$

Carbon burial in the Baltic Sea	**4.7%**

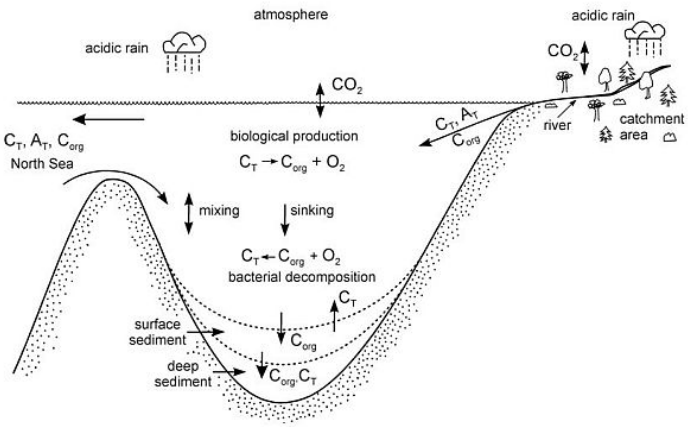
Carbon burial in the Gulf of Bothnia sediments

Total primary production in the Gulf of Bothnia	4.76 Tg C $year^{-1}$
Carbon burial in the Gulf of Bothnia	-0.66 Tg C $year^{-1}$

Carbon burial in the Gulf of Bothnia	**13.8%**

Carbon burial in the Gulf of Bothnia sediments

Total primary production in the Gulf of Bothnia	4.76 Tg C year^{-1}
River input of C_{org} to the Gulf of Bothnia	1.50 Tg C year^{-1}
Carbon burial in the Gulf of Bothnia	-0.66 Tg C year^{-1}



Carbon burial in the Gulf of Bothnia **10.4%**

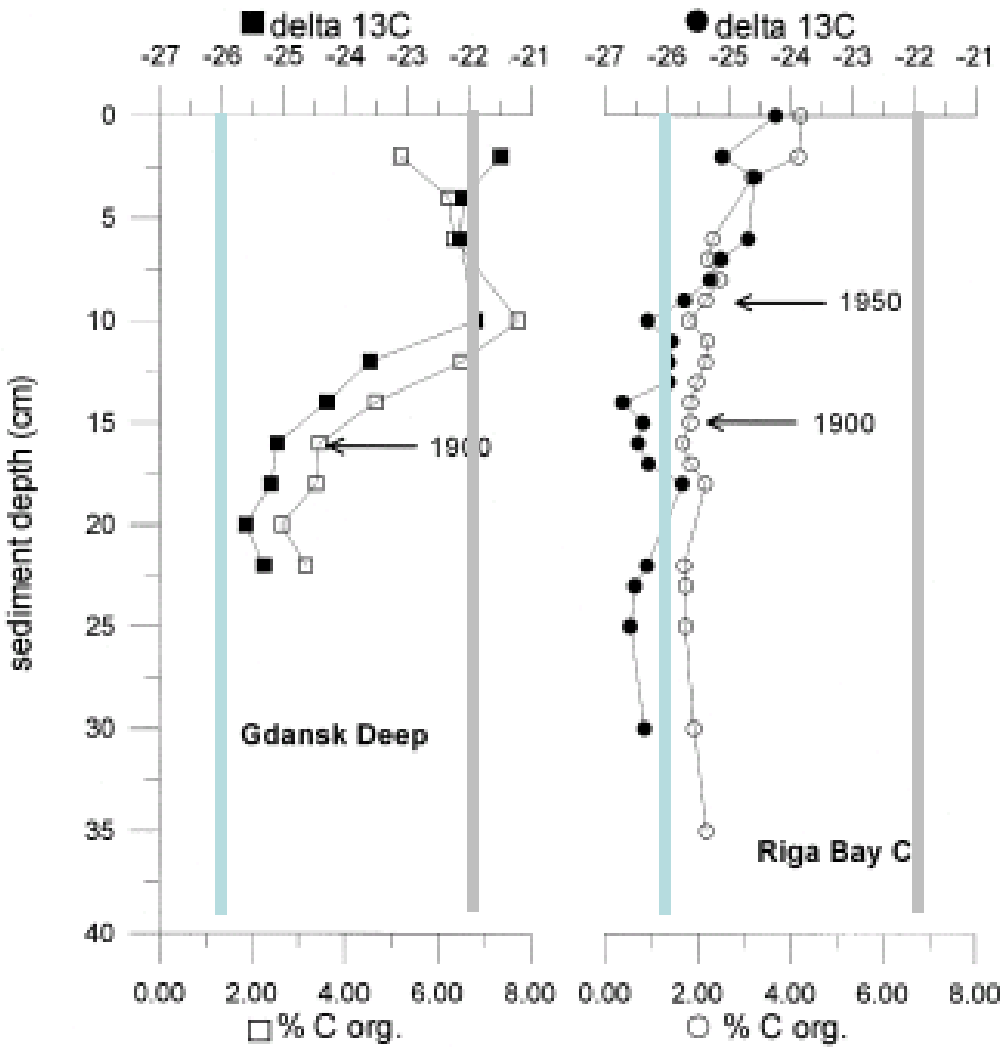
Carbon burial in the Baltic Sea sediments

Total primary production in the Baltic Sea	57.75 Tg C $year^{-1}$
River input of C_{org} to the Baltic Sea	4.09 Tg C $year^{-1}$
Carbon burial in the Baltic Sea	-2.73 Tg C $year^{-1}$

Carbon burial in the Baltic Sea	**4.4%**
Global oceans	**0.01-1%**
Shelf seas	**0.5-6%**

Liu et al., 2010
Schulz & Zabel, 2006

Contribution of the terrestrial C_{org} in the bottom sediments



Voss et al., 2000; Emerson & Hedges, 1988; Fontugne & Jouanneau, 1987; Maksymowska et al., 2000

IRMS Delta V advantage, Thermo

Conclusions

- 3.87 Tg C $year^{-1}$ are accumulated in the Baltic Sea sediments

- Carbon return flux from the Baltic Sea bottom sediments amounts to 1.14 Tg C $year^{-1}$

- 2.73 Tg C $year^{-1}$ (4.4-4.7%) is buried in the Baltic Sea sediments

- It is essential to calculate the contribution of the terrestrial C_{org} buried in the bottom sediments

DIC and DOC fluxes to the Baltic Sea -originating from the Submarine Groundwater Discharge (SGD).

Extrapolation based on the Bay of Puck study.

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Submarine groundwater discharge to the marine environment

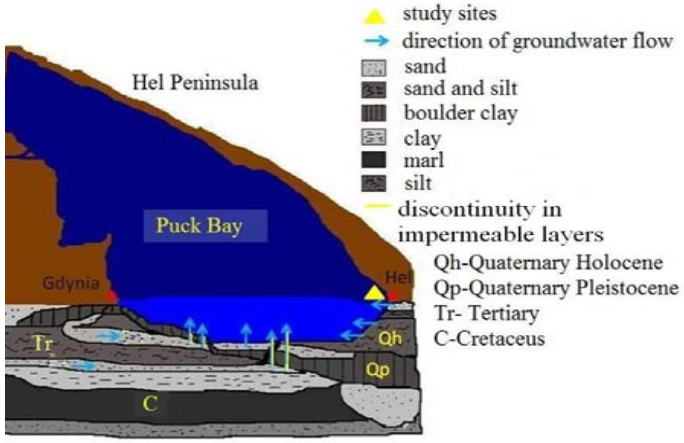


Fig.1 Hydrogeological layers of the study area (modified after Piekarek-Jankowska H. i in., Oceanologia. 1994).

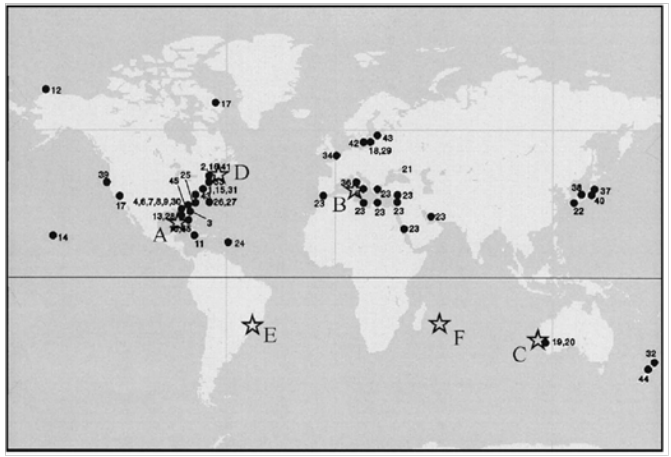


Fig.2 SGD study areas**.** Burnett et al., 2006.

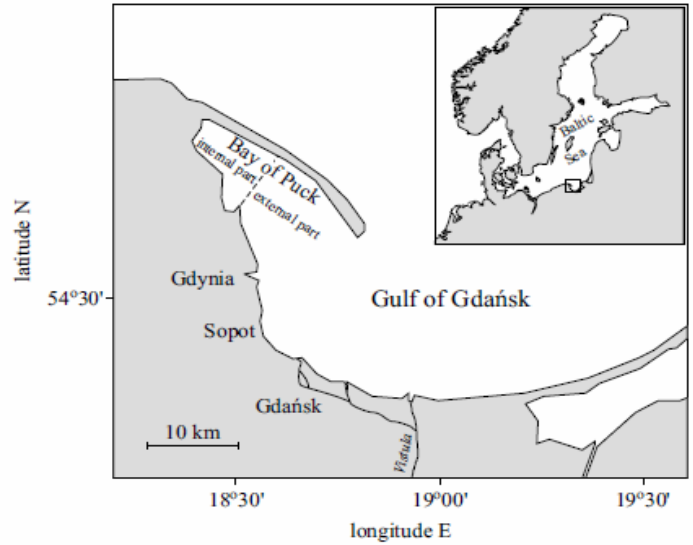


Fig.3 The study area.

Main goals:

- Measuring concentrations of listed below water components:
  - Selected trace metals: **Cr, Cu, Co, Ni, Mn, Zn, Pb, Cd, Hg** and metals: **Na, K, Ca, Fe,**
  - Nutrients: **NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, SiO_2,**
  - **DIC, DOC**: (dissolved inorganic carbon and dissolved organic carbon).

- Investigating speciation dynamics of the measured substances in the mixing zone between groundwater and sea water.

- Quantification the geochemical fluxes connected to seepages.

Details of sampling campaigns and methods of samples collection

Study area	Date	Samples type / samples amount
The Bay of Puck	23-26.03.09	Seepage water, sea water, interstitial water, groundwater/12
	31.08.09-04.09.09	Seepage water, sea water, interstitial water, groundwater/60 Sediment cores/4
	3-6.11.09	Seepage water, sea water, interstitial water, groundwater/60 Sediment cores/4
	27-29.02.10	Seepage water, sea water, interstitial water, groundwater/60 Sediment cores/4
	4-7.05.10	Seepage water, sea water, interstitial water, groundwater/40 Sediment cores/4

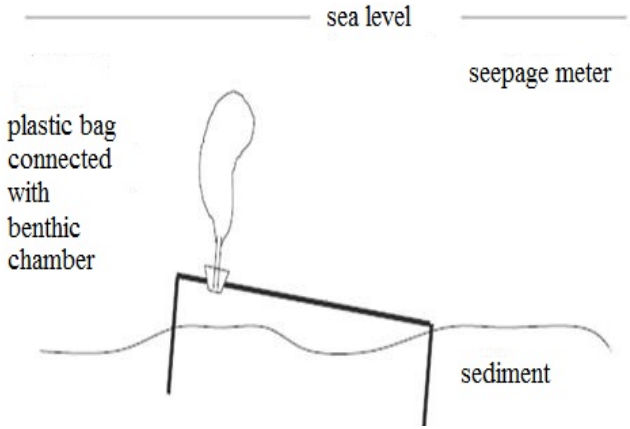


Fig.5 Seepage meter, (modified after Lee, 1977).

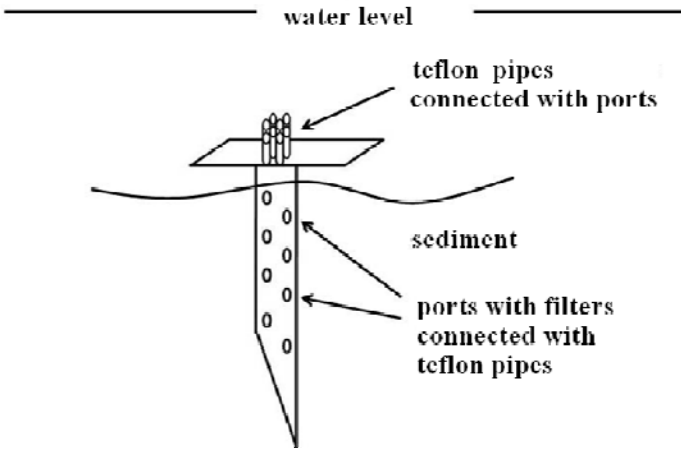
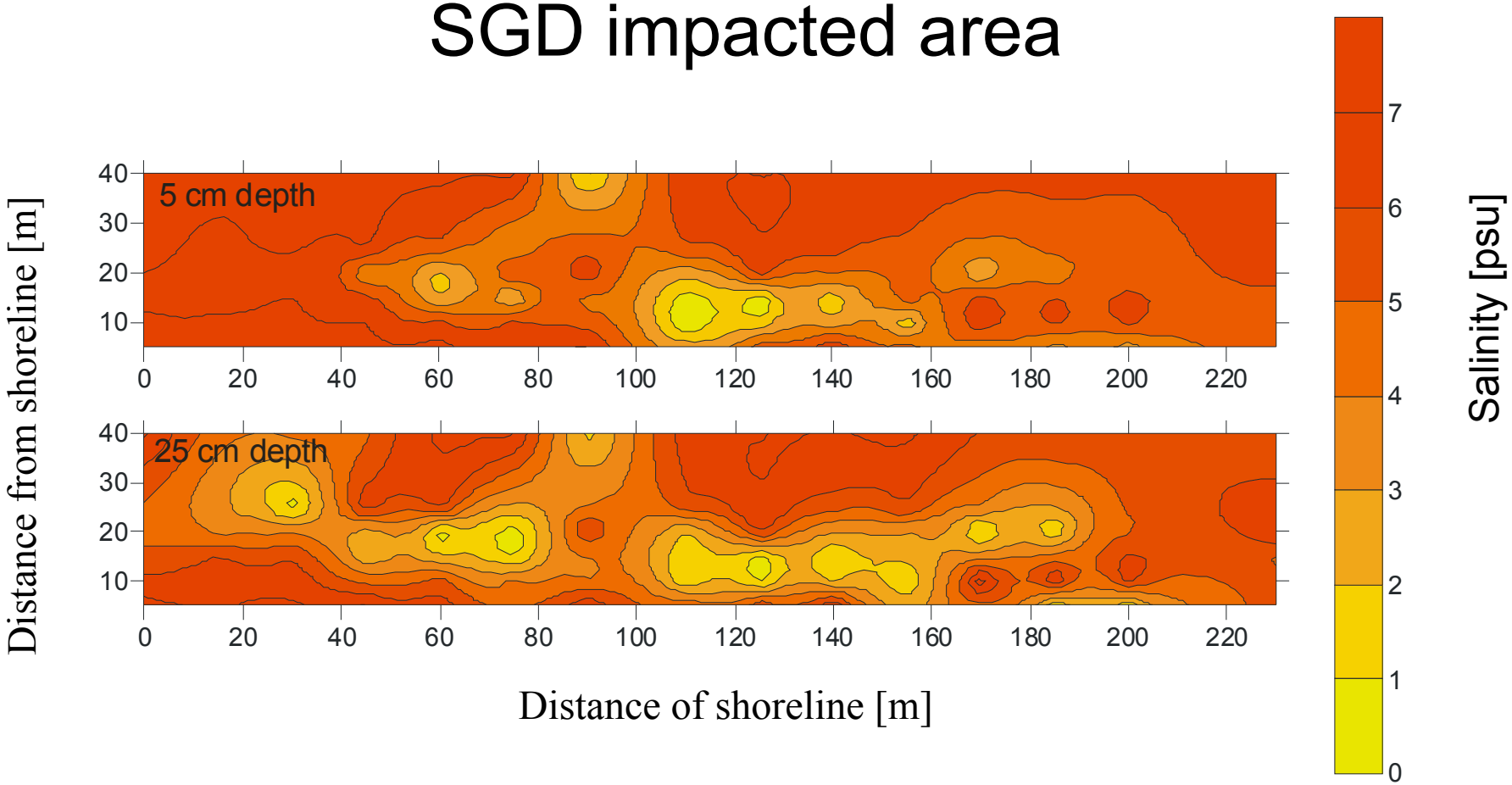


Fig.6 Groundwater lance.

Salinity of interstitial water collected from layers 5 cm and 25cm deep in sediments
SGD impacted area



Szymczycha, May, 2010.

Salinity influence on DIC and DOC concentrations

Date	November, 2009		February, 2010			May, 2010	
Salinity [psu]	**2.1-2.8 (2.45)**	**7.1-6.9 (7)**	**0.4-1 (0.7)**	**6.9-7.2 (7.05)**	**Well 170m 0.2**	**0.6-1 (0.8)**	**6.9-7.1 (7)**
DIC [mgC/l]	**63.6-313**	**21-32**	**44-64**	**0.3-23.5**	**40**	**61.8-73.4**	**18.3-19.3**
DIC [µmol/l]	**5300-26083**	**1750-2666**	**3666-5333**	**25-1958**	**3333**	**5150-6117**	**1525-1608**
DOC [mgC/l]	**3.8-12.59**	**2.98-3.16**	**x**	**x**	**x**	**x**	**x**
DOC [µmol/l]	**316.7-1049**	**248.3-263.3**	**x**	**x**	**x**	**x**	**x**

- groundwater

- sea water

- water from well 170m

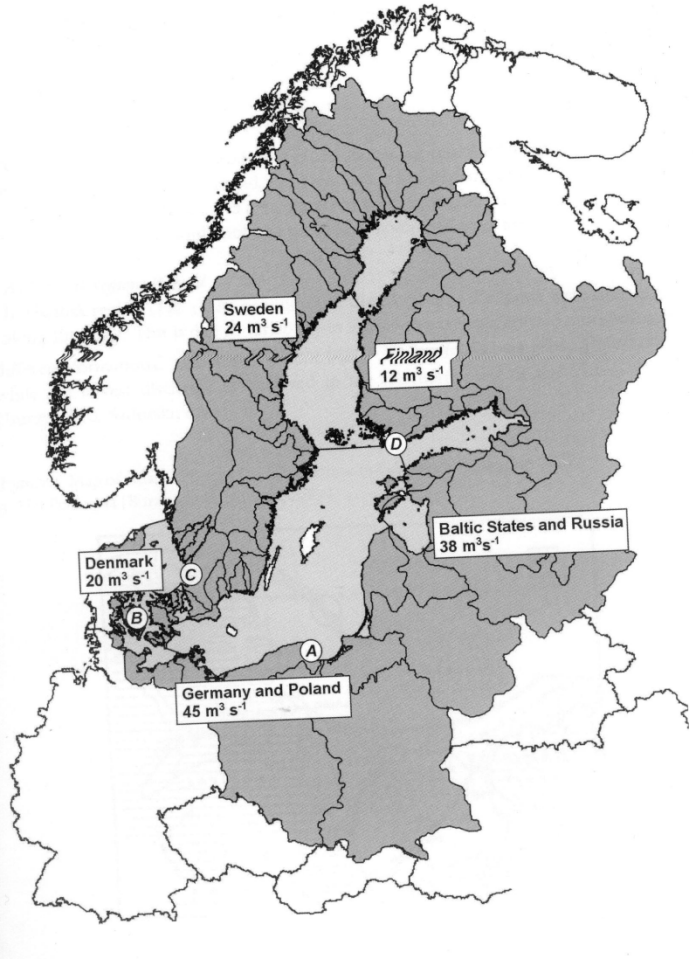
X- analysed but not calculated

Salinity influence on other water components

Chemical components of water	31.08.09-04.09.09		3-6.11.09	
	1,1-2,8 psu	7,2 psu	1,1-2,8 psu	7,2 psu
Cr [µmol/l]	$4,4 * 10^{-3}$	$0,2*10^{-3}$	0,1	$8,7*10^{-3}$
Co[µmol/l]	$1,1*10^{-3}$	$0,8*10^{-3}$	$6,8*10^{-3}$	$0,7*10^{-3}$
Mn[µmol/l]	1,9	0,02	1,9	0,1
Cu[µmol/l]	0,5	0,5	0,06	$2,2*10^{-3}$
PO_4^{3-}[µmol/l]	45	0,4	64	12
NO_3^-[µmol/l]	0,325	0,8	1,5	3
NO_2^-[µmol/l]	0,228	0,6	0,8	0,4
NH_4^+[µmol/l]	264,5	49	115,9	15
SiO_2[µmol/l]	801	9	71	18

Approximate SGD to the Baltic Sea

Fig. 5 Approximate direct groundwater inflow to the Baltic Sea. Peltonen, 2002.



Approximate SGD to the Baltic Sea	m^3/s	m^3/h	km^3/yr
Puck Bay[1]	0.97	3500	0.03
Germany and Poland[2]	45	162000	1.4
Baltic states and Russia[2]	38	136800	1.2
Finland[2]	12	43200	0.4
Sweden[2]	24	86400	0.8
Denmark[2]	20	72000	0.6
$\sum^2$	139	500400	4.4

[1]Piekarek-Jankowska. 1994

[2] Peltonen. 2002

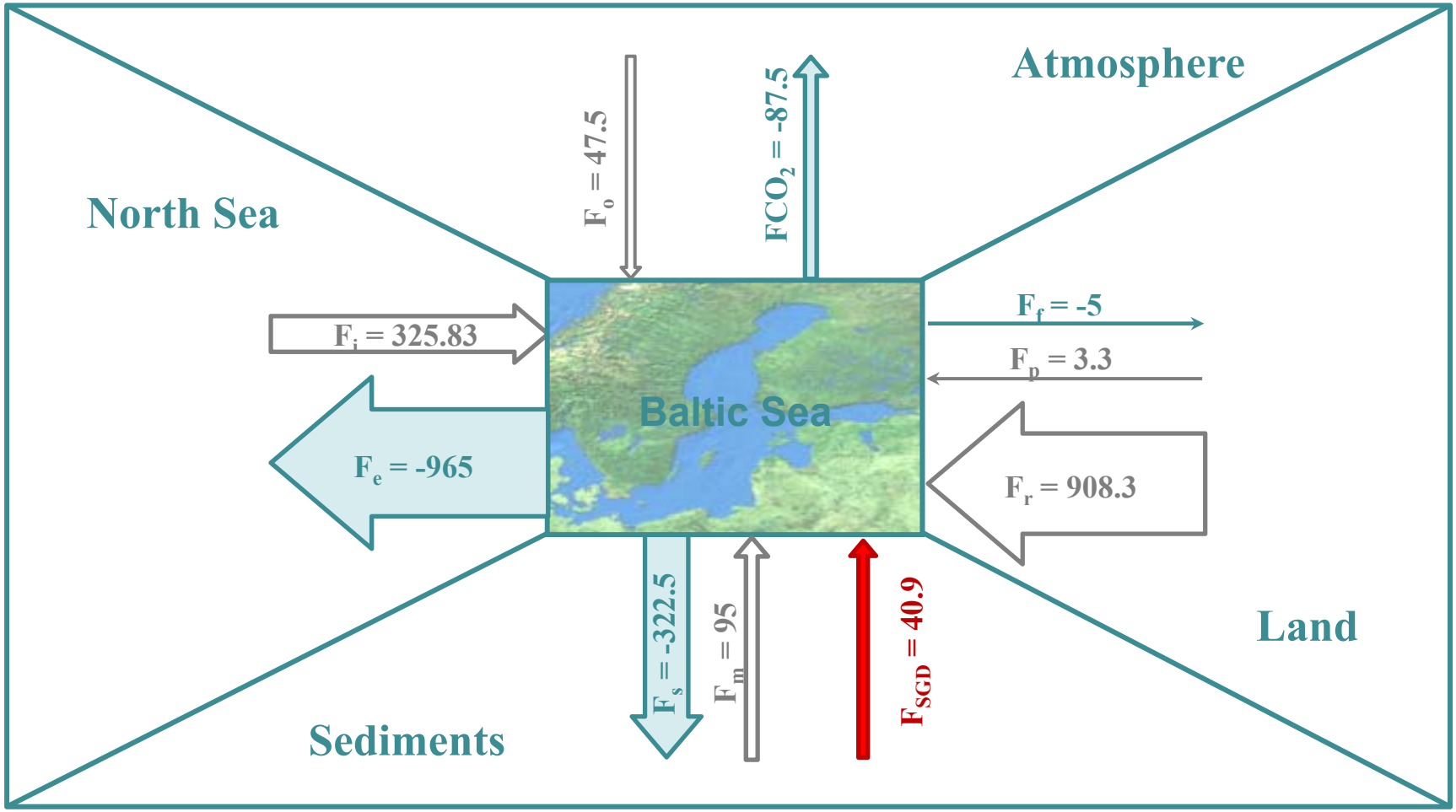
DIC and DOC fluxes to the Puck Bay and Baltic Sea

	SGD [km³/yr]	DIC [µmol/l]	DOC [µmol/l]	DIC Gmol/yr	DOC Gmol/yr	∑ DIC+DOC [Gmol/yr]
Puck Bay[1]	0.03	8608.2	682.85	0.3	0.02	0.3
Germany and Poland[2]	1.4	8608.2	682.85	12.1	1	13
Baltic states and Russia[2]	1.2	8608.2	682.85	10.3	0.8	11.1
Finland[2]	0.4	8608.2	682.85	3.4	0.3	3.7
Sweden[2]	0.8	8608.2	682.85	6.9	0.5	7.4
Denmark[2]	0.6	8608.2	682.85	5.2	0.4	5.6
∑ 2	4.4	8608.2	682.85	37.9	3	40.9

[1]Piekarek-Jankowska, 1994.

[2] Peltonen, 2002.

The quantitative carbon circulation for Baltic Sea



(modified after Kuliński, 2010).

Conclusions

- Submarine Groundwater Discharge is the important flux influencing geochemical cycle of elements in marine environment, especially the coastal areas.
- Carbon flux via Submarine Groundwater Discharge should be taken into account while speaking about the carbon budget.

I thank you for your attention