Abschlussbericht

ERANET BONUS: Verbundprojekt BONUS-112: INFLOW – Rekonstruktion von Änderungen der Einstromintensität salzreichen Nordseewasseres in die Ostsee während des Holozans, Reaktionen des Ökosystems und Zukunftsszenarien

Das diesem Bericht zugrundeliegende Vorhaben wurde teilweise mit Mitteln des Bundesministeriums für Bildung und Forschung unter den Förderkennzeichen 03F0496A gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren.

Project acronym: INFLOW - Holocene saline water inflow changes into the Baltic Sea, ecosystem responses and future scenarios

Reporting period: 2011 (2009-2011)

Project Partners

INFLOW (2009-2011) (http://projects.gtk.fi/inflow/index.html) was one of the BONUS research programme (http://www.bonusportal.org/) projects and it was funded by national funding agencies, the EU Commission and participating institutes. The Geological Survey of Finland (GTK) coordinated the INFLOW project that had nine partners in seven countries of the Baltic Sea Region:

Germany: **Leibniz Institute for Baltic Sea Research Warnemünde - IOW**,

Denmark: **Geological Survey of Denmark and Greenland - GEUS**,

Sweden: **Department of Earth and Ecosystem Sciences – Division of Geology, Lund University,** and **Swedish Meteorological and Hydrological Institute – SMHI**,

Poland: **Faculty of Earth Sciences, Department of Paleoceanology, University of Szczecin**,

Norway: **Unifob AS, Bjerknes Centre for Climate Research - BCCR**,

Russia: **A.P Karpinsky Russian Geological Research Institute – VSEGEI**,

Finland: **GTK, and Department of Geosciences and Geography, University of Helsinki**

Individual scientists that participated in the INFLOW project are shown in Appendix I

Project Structure

The INFLOW project consisted of 4 Work packages (WP); namely WP1-Sediment proxy studies, WP2-Modelling approach, WP3-Synthesis and WP4-Training and Education.

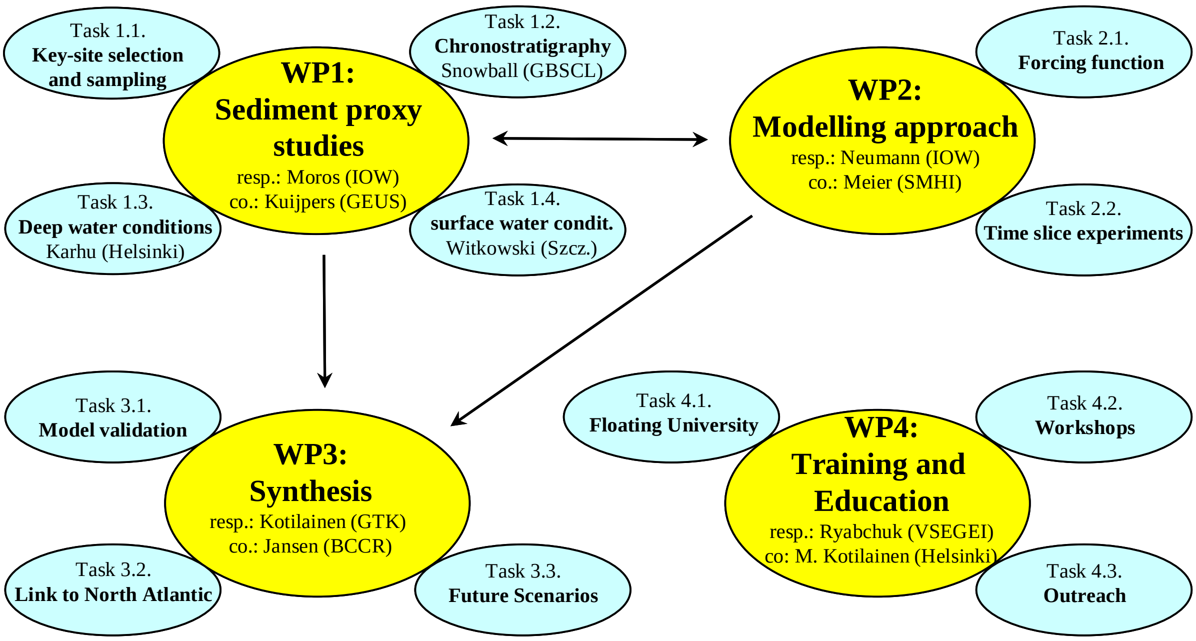

Figure 1. INFLOW Project Work packages (WP), Tasks and responsible persons.

Used resources

Used resources (person months) by each participating institute are shown in Appendix I.

Executive summary

Global climate change, growing population and increased activities in marine and coastal areas have threatened the marine environment worldwide. This deteriorating is valid also for the Baltic Sea, the European inland sea. The environmental problems of the Baltic Sea include e.g. eutrophication, seafloor hypoxia and increased chemical pollution. Considerable efforts to save and restore the condition of the Baltic Sea have been made during the past decades, but there is still work to do to ensure the health of our sea in future. In particular, it has been hypothesized that ongoing global warming and consequent climate changes may amplify the existing environmental problems that the Baltic Sea suffers from.

Effective and sustainable marine management and more plausible scenario simulations of the future Baltic Sea depend on improved understanding of the natural variability of the Baltic Sea ecosystem and its response to climate and human induced forcing.

The INFLOW project has used integrated sediment multi-proxy studies and modelling to reconstruct past changes in the Baltic Sea ecosystem (e.g. in saline water inflow strength, salinity, temperature, redox and benthic fauna activity) over the past 6000 years, concentrating on the last 1000 years that covers two natural climate extremes of the Little Ice Age and the Medieval Climate Anomaly; and the Modern Warm Period. The aim has been to identify the forcing mechanisms of those environmental changes, and to provide scenarios of the impact of climate change on the Baltic Sea ecosystem at the end of the 21st century AD.

Geological records of the Baltic Sea, especially sediments that have accumulated nearly continuously on the seafloor, provide unique information on past environmental changes. INFLOW has used a lot of efforts and resources to provide best possible material for sediment proxy studies. Several expeditions to the Baltic Sea have been organized during the project to collect material needed. Nearly hundred sediment cores were recovered during the expeditions from numerous carefully selected sites, along a transect from the marine Skagerrak to the freshwater dominated northern Baltic Sea.

INFLOW has studied ongoing and past changes in both surface (e.g. temperature and salinity) and deep water (e.g. oxygen and salinity) conditions and their timing. Sediment proxy studies included methods like TEX_{86} (a biomarker) for sea surface temperature, strontium isotopes ($^{87}Sr/^{86}Sr$) of bivalve shell carbonate and diatoms for salinity, and sediment fabric/trace fossils for benthic fauna activity reconstructions. In addition INFLOW has employed stable isotopes (O, C), Br, foraminera, dinoflagellate and mineral magnetic analysis among others. Geochemical methods included also XRF scans and ICP-MS analysis. Sound chronological control is crucial for high-resolution palaeoenvironmental reconstructions. Thus INFLOW has used multi-proxy dating methods, applying a range of different techniques, like (i) $^{210}Pb/^{137}Cs$ dating, (ii) AMS^{14}C dating, (iii) paleomagnetic dating, and (iv) OSL dating .

Modelling was done in close co-operation with sediment proxy studies. The regional climate model of the Rossby Centre (RCA3) has been used to downscale global climate simulations (ECHO-G) to the regional (the Baltic Sea) scale and to deliver lateral boundary conditions for the local ecosystem models. The better constrained ecosystem models (RCO-SCOBI and ERGOM) used in INFLOW provided simulated data (hydrographical and biogeochemical conditions) for extreme natural climatic conditions over the past thousand years (e.g. the Medieval Climate Anomaly and the Little Ice Age). These are partly forced with sediment proxy results such as a 2 K temperature change from the Little Ice Age towards the Modern Warm Period. Model experiments provided insight into the mechanisms triggering Baltic Sea ecosystem state changes as observed in sedimentary archives. Validated models have been used to provide scenarios of the Baltic Sea ecosystem state at the end of the 21st century for selected Intergovernmental Panel on Climate Change (IPCC) climate change scenario.

Results of natural past changes in the Baltic Sea ecosystem, received in the INFLOW project, provide a discouraging forecast for the future of the Baltic Sea: nutrients loads, among other, need to be reduced in the future too in order to minimise the effect of sea surface temperature changes

Sea surface temperature (SST) reconstructions, based on sediment proxy studies (TEX_{86} method), indicate 2-3 °C variability, between the Medieval Climate Anomaly, the Little Ice Age (1450-1850), and the Modern Warm Period. This variability is higher than expected. Oxic conditions in the Gotland Basin recorded in the sediments by various parameters have been also reconstructed by ecosystem models for the Little Ice Age. Around thousand years ago, during the Medieval Climate Anomaly, the sea surface temperature of the Baltic Sea was around at same level as today. An exception was the shallow water coastal environment where since the ending of the 20th century maximum temperatures appear occasionally to exceed those found for the Medieval Climate Anomaly. During the Little Ice Age the sea surface temperature of the Baltic Sea was 2-3 °C colder than today. The establishment of anoxic conditions in the deeper basins began parallel to the temperature rise from the Little Ice Age towards the Modern Warm Period. In shallower areas anoxic conditions were established much later. The INFLOW results highlight a strong effect of sea surface temperature changes on redox conditions in the central Baltic.

INFLOW's sediment studies reveal that the Medieval Baltic Sea was severely affected by oxygen depletion. On the other hand, seafloor oxygen conditions were improved during the Little Ice Age. Sediment records indicate an important new finding: during stable extreme conditions (warm: Modern Warm Period e.g. 1980-2010, Medieval Climate Anomaly, cold: peak Little Ice Age) there were less saline water inflows into the Baltic Sea. This is confirmed by modelling studies, where a proxy for saline water inflow events into the Baltic Sea, based upon sea level pressure gradients over the North Sea, is used to estimate changes of mean strength of inflow over the last millennium. It is obvious that saline water inflows increased in frequency and magnitude during climatic transitions. This might be linked to a change in the prevailing atmospheric North Atlantic Oscillation (NAO) system from a stable NAO+/- towards more unstable conditions. This aspect is still under investigation.

In addition, sensitivity studies of the Baltic Sea were performed with Baltic Sea models. It was shown that changes in the mean conditions do not have a large impact on bottom oxygen concentrations. This adds confidence that changes in the variability could have been more important for the increase of oxygen depletion in bottom waters during the Medieval Climate Anomaly than changes in the mean conditions. However, further studies are still necessary to elucidate the processes involved.

Future climate change is likely to affect the Baltic Sea marine environment. Modelling simulations suggest warmer air temperatures in the future, with an annual mean increase in the range of 2.7-3.8 K for 2070-2099 relative to 1969-1998 in the Baltic Sea region. It has been estimated also that the climate warming could increase precipitation (and river runoff) to the Baltic basin, as well as reduce the length of the ice season in the Baltic Sea. Oxygen depletion at seafloor has been estimated to expand, too. Furthermore, changes in hydrography and biogeochemical processes could affect the whole Baltic Sea ecosystem.

Anoxia/hypoxia is harmful for macro benthic fauna and flora. It also affects the ecosystem via internal loading. Extended seafloor anoxia could enhance the environmental problems by releasing toxic heavy metals and nutrients, like phosphorus, from the seafloor sediments, and thus intensify the harmful effects of eutrophication. These may affect marine ecosystem by reducing marine biodiversity as well as fish catch. However, reliable future scenarios on the effects of climate change to the Baltic Sea ecosystem and biodiversity are difficult to produce due to complicated ”cause–effect” relationships. Further studies are needed.

Socio-economic implications of climate change on Baltic Sea region need careful consideration, including effects on fisheries and possible reduced recreational values of the coastal areas. Summing up the climate change (IPCC scenarios of global warming), increasing human activities and human induced loading, the already taken measures are not enough. Further actions are needed including substantial nutrient load reductions also in the future in order to minimize the effect of sea surface temperature changes.

INFLOW has used integrated sediment and modelling studies to deepening scientific knowledge and understanding of the factors affecting the long-term changes in marine environment and of possible future changes of the Baltic Sea. That information will provide basis for improved management, implementation of policy strategies (e.g. the European Marine Strategy Directive) in Baltic Sea environmental issues and adaptation to future climate change.

INFLOW (2009-2011) was one of the BONUS Research Programme projects that generate new knowledge in support of decision-making in the Baltic Sea region. It was funded by national funding agencies (e.g. Academy of Finland), the EU Commission and participating institutes. Geological Survey of Finland (GTK) coordinated the INFLOW project that had 9 partners in 7 countries of the Baltic Sea Region: Finland, Russia, Poland, Germany, Denmark, Sweden and Russia.

Gained scientific results

Work packages WP1 "Sediment proxy studies", WP2 "Modelling approach" and WP3 "Synthesis"

Introduction

Growing population and increased activities in marine and coastal areas have enhanced use of the seas and seafloor worldwide. Such activities include fisheries, shipping, dredging, oil and gas exploitation, and more recently offshore wind farms and aquaculture (among others). Anthropogenic pressures are high also in the Baltic Sea region, because more than 85 million people live in the Baltic Sea discharge/catchment area.

The environmental problems of the Baltic Sea include eutrophication, occasional algal blooms, seafloor hypoxia and increased chemical pollution among others. Considerable efforts to save and restore the condition of the Baltic Sea have been made during the past decades, but there is still work to do to ensure the health of the sea in future. In particular, it has been hypothesized that ongoing global warming and consequent climate changes may amplify the existing environmental problems that the Baltic Sea suffers from.

To be able to provide more plausible scenario simulations of the future Baltic Sea, it is essential to improve understanding of the natural variability of the Baltic Sea ecosystem and its response to climate and human induced forcing. A deeper scientific knowledge and understanding of the factors affecting the long-term changes in marine environment and of possible future changes will provide a basis for improved management and implementation of policy strategies (e.g. the European Marine Strategy Directive) in the Baltic Sea environmental issues.

Geological records of the Baltic Sea, particularly those sediments that have accumulated nearly continuously on the seafloor, provide unique information on past environmental changes. The INFLOW project has used integrated sediment multi-proxy studies and modelling to reconstruct past changes in the Baltic Sea ecosystem (e.g. in saline water inflow strength, temperature, redox and benthic fauna activity) over the past 6000 years, concentrating on time period that covers two natural climate extreme of the Little Ice Age and the Medieval Climate Anomaly; and the Modern Warm Period. The aim was to identify the forcing mechanisms of those environmental changes and to provide scenarios of impact of climate change on the Baltic Sea ecosystem at the end of the 21st century AD.

Study area

Our study area covers the Baltic Sea Basin, from the marine Skagerrak to the freshwater dominated northern Baltic Sea and the eastern Gulf of Finland (Fig. 2).

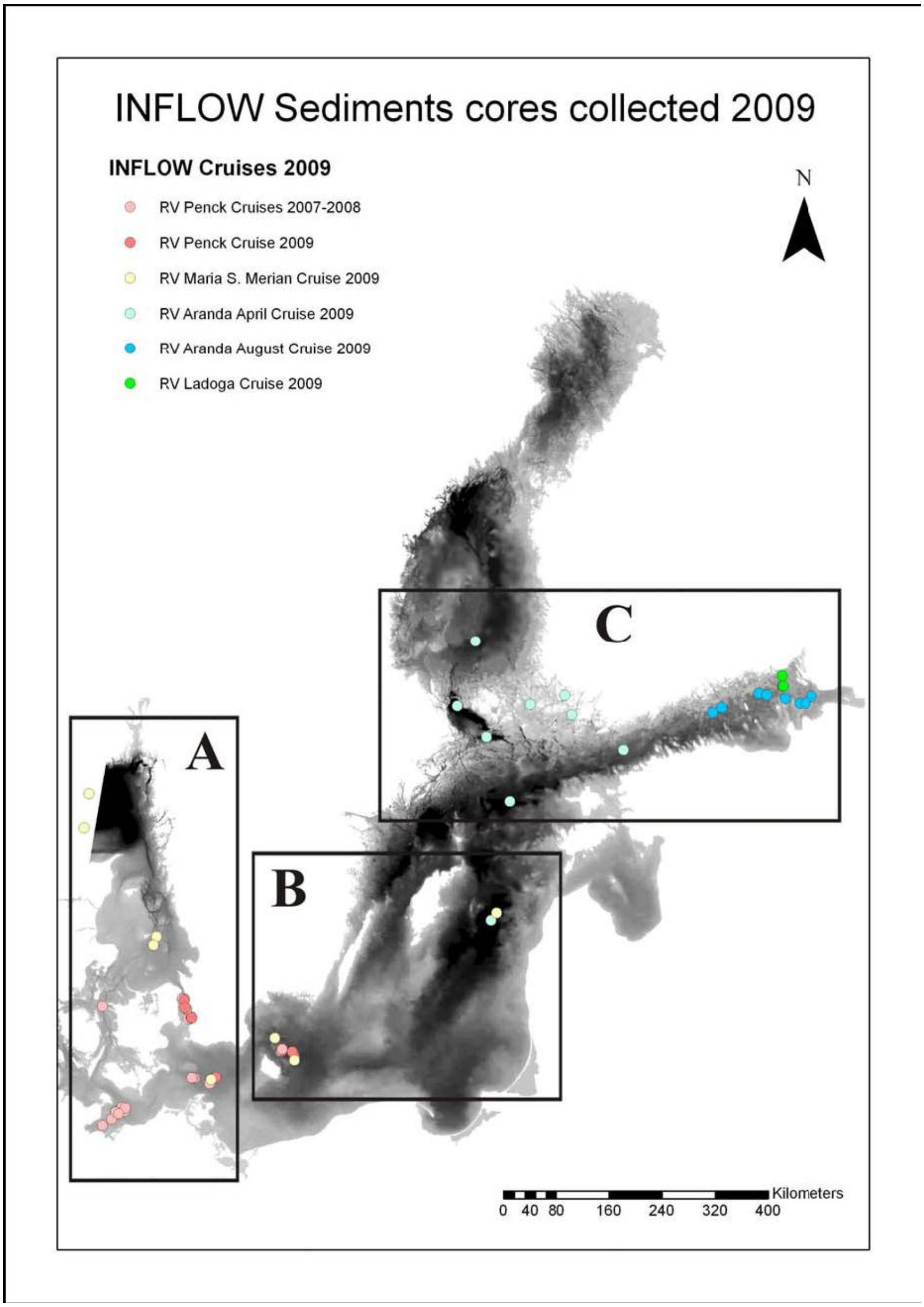

Figure 2. Bathymetric map of the Baltic Sea and the working areas (A=western Baltic Sea, B=central Baltic Sea and C=northern Baltic Sea) of the INFLOW project. Sediment coring locations indicated are also shown (colored circles, see legend for details). A bathymetric map is a product of BALANCE "Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning" Interreg IIIB EU-project.

Material & Methods

Field work and collected sediment material

The purpose of the field investigations was to collect the most suitable sediment records from the study area to sediment proxy studies. The key-site selection and sediment sampling were mainly realized during 2009 and 2010 (see INFLOW Annual Reports 2009 and 2010) (Table 1). The field investigations of the INFLOW project in 2009 concentrated on the whole INFLOW project study area: on a transect from the marine Skagerrak to the freshwater dominated northern Baltic Sea (Fig. 2). The field investigations in 2010 concentrated on the northern Baltic Sea and the Russian waters of the eastern Gulf of Finland.

Altogether five cruises onboard four research vessels (*RV Maria S. Merian, RV Professor Albrecht Penck*, *RV Ladoga, RV Aranda)* were carried out during year 2009. The INFLOW field expeditions were organized by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany (*RV Maria S. Merian, RV Professor Albrecht Penck*), A.P Karpinsky Russian Geological Research Institute (VSEGEI), Russia (*RV Ladoga*) and The Finnish Environment Institute (SYKE) (*RV Aranda*). These cruises were funded mainly by the institutes that organized cruises. In addition INFLOW participated in RV *Penck* HYPER cruise (chief scientist: Claudia Fellerhoff) and co-operated with BALTIC GAS RV *Poseidon* cruise December 2009 (chief scientist Rudolf Endler).

Two cruises were organized during year 2010. IOW organized *RV Professor Albrecht Penck* cruise (07PE1012) to the Northern Baltic Sea (June 2010). VSEGEI organized the field expedition to the Russian waters of the eastern Gulf of Finland in the summer 2010 (*RV Ladoga* and *RV Risk*).

In addition to those INFLOW Partners participated in the *RV Maria S. Merian* "BONUS Baltic Gas project" cruise to the northern Baltic Sea. Cruise was organized by the IOW (chief scientist Gregor Rehder).

Table 1. Cruises of the BONUS INFLOW project. * = Cruise Report available in the INFLOW website at http://projects.gtk.fi/inflow/index.html; # = cruise report available at IOW.

Research Vessel	**Date**	**Chief Scientist**	**Cruise Report**
Prof. Albrecht Penck	May–June 2007	Thomas Leipe (IOW)	#
Prof. Albrecht Penck	April 2008	Matthias Moros (IOW)	#
Aranda	April 2009	Harri Kankaanpää (SYKE)	*Available
Prof. Albrecht Penck	June 2009	Matthias Moros (IOW)	#
Ladoga	June 2009	Daria Ryabchuk (VSEGEI)	*Available
Maria S. Merian	September 2009	Falk Pollehne (IOW)	#
Aranda	August 2009	Harri Kankaanpää (SYKE)	*Available
Prof. Albrecht Penck	June 2010	Matthias Moros (IOW)	#
Ladoga and Risk	Summer 2010	Daria Ryabchuk (VSEGEI)	

The selection of key sites for sediment proxy studies is crucial. Site selection of the INFLOW project key-coring sites (Fig. 2) was based on high-resolution topographic information (multibeam echo-sounding data), shallow seismic, ecosystem modelling and other relevant data (from former projects) available at the participating institutes. The INFLOW project utilized also the consortiums long-term experience in working with the Baltic Sea sediments, ensuring the best possible knowledge base in Baltic Sea sediments. Participating institutes have collected marine geological and geophysical data for decades, and have used significant resources (and funding) to provide that information for the key site selection.

Sites were selected from the spatially very different hydrographic conditions in the Baltic Sea. The high sedimentation rates (approximately 1-2 mm/year, or more) at all selected sites (see Chapter “Key Sites studied in INFLOW”) provided an excellent opportunity to reconstruct ecosystem variability through time at decadal to centennial time scales.

Sediment material for proxy studies was collected using various sampling/coring techniques. Long sediment cores were recovered using (6 m long) piston corers and (6-9 m long) gravity corers (Fig. 3). Short surface sediment cores were recovered using mainly multicorer (that has 4 cores/ core liners) and a GEMAX twin barreled gravity corer.

Figure 3. IOW's 9 m long gravity corer in use onboard RV Aranda. Persons in picture are (from left): Juhani Rapo (FMI), Tuomo Roine (FMI), Michael Pötzsch (IOW) and Jyrki Hämäläinen (GTK). Photo: Aarno Kotilainen, GTK.

Sediment Proxy studies – methods

Sediment multi-proxy studies have been used to study and understand the natural elasticity of the ecosystem. We have studied ongoing and past changes in both surface (e.g. temperature and salinity) and deep water (e.g. oxygen and salinity) conditions and their timing. Sediment studies provided data also needed for modelling approaches (WP2). Sediment proxies have been studied from key-sites along a transect from the marine Skagerrak to the freshwater dominated northern Baltic Sea. As environmental conditions vary in different parts of the Baltic Sea, different proxy methods were used to reconstruct specific oceanographic/hydrographic parameters (Table 2). Some of the used methods have been described in the present report, and some methods have been described more detailed in publications referred to in the text.

Table 2. Sediment proxy and dating methods that have been used to reconstruct surface and deep water conditions in the hydrographically different working areas (Fig. 2) are shown in the table. (TF – transfer functions, * indicate a variety of geochemical studies which cannot be solely linked to surface or deep water processes, but which are essential to characterize the status of the ecosystem (such as redox stage).

Work Area	Proxy methods: surface water conditions	Proxy methods: deep water conditions	Dating method
A (western Baltic)	diatom (TF)	foraminifera (stable isotopes/trace elements), Sr-isotopes, grain size	$^{210}Pb/^{137}Cs$; AMS^{14}C (calcareous fossils)
	* Geochemical: TOC/N/S, XRF, Phosphorous, biogenic opal		
B (central Baltic)	diatoms and dinoflagellates (TF), $\delta^{13}C$, *Sea-ice cover*: diatoms, IP-25	benthic diatoms, Sr-isotopes, grain size, DNA on foraminifera test linings, trace fossils	$^{210}Pb/^{137}Cs$, OSL, paleomagnetic, AMS^{14}C (calcareous fossils, "soil approach" on bulk material, test linings)
	* Geochemical: TOC/N/S, XRF, Phosphorous, Ca/Mn, biogenic opal		
C (northern Baltic)	diatoms and dinoflagellates (TF), $\delta^{13}C$, *Sea-ice cover*: diatoms, IP-25	benthic diatoms, grain size, trace fossils, Sr-isotope	$^{210}Pb/^{137}Cs$, OSL, paleomagnetic, AMS^{14}C ("soil approach" on bulk material)
	* Geochemical: TOC/N/S, XRF, Phosphorous, Ca/Mn, biogenic opal		

Sediment descriptions and subsampling

All recovered sediment cores were digitally imaged, and first detailed lithologic descriptions were prepared onboard. Sedimentological descriptions of short surface sediment cores (e.g. GEMAX cores) were made both through the plastic core liner and from the split and trimmed sediment surfaces. A long sediment cores were cut normally into 100 cm sections and labelled. Then whole-core sections were split into two halves, archive and work halves. The work halves were described visually (e.g. sedimentary structures, sedimentary disturbances, colour) and photographed. Then work halves were run through magnetic susceptibility (MS) device, and stored in the cold store.

All surface sediment cores (GEMAX cores) and selected long sediment cores were subsampled (mainly) onboard. The surface sediment cores were sliced normally into 0.5 or 1 cm thick subsamples and packed in plastic bags and boxes. Subsamples of long sediment cores were taken from selected intervals for various analysis including microfossil (e.g. diatoms, forams), geochemical, sediment structure and palaeomagnetic studies.

Chronostratigraphy – methods

A key issue for understanding the temporal development of the Baltic Sea based on sediment archives is sound chronological control – or geochronology. Traditional geochronological methods provide results that are normally too uncertain to achieve high time resolution.The ^{14}C method has been used extensively for dating Baltic Sea sediments. The method is, however, prone to serious errors either due to a scarcity or lack of organic carbon, especially in early Holocene Baltic Sea sediments, from contamination by resuspended older organic material, and due to the ^{14}C deficiency of water (the so-called reservoir effect). The unknown radiocarbon reservoir effect in problematic in the Baltic Sea, especially as it varies in time and space.

Thus, to tackle the reservoir age problem and establish how the reservoir age varied, and to provide the best possible age-depth models for individual core sites, the INFLOW project have applied a range of different techniques, like (i) ^{210}Pb210/^{137}Cs dating, (ii) AMS^{14}C dating of benthic foraminifers and bulk as well as humic acid and base residue organic carbon fractions, (iii) paleomagnetic dating, and (iv) OSL dating. In addition, oceanographic (e.g. Major Baltic Inflows 1993 and 2003) and biological monitoring data were used to identify further stratigraphic tie points during the Modern Warm Period. Also lead (Pb) content and stable isotope ratios ($^{206}Pb/^{207}Pb$) were tested for long sediment core dating.

Palaeomagnetic dating and Mineral Magnetic Analyses of sediment cores

The oriented sub-samples for paleomagnetic and mineral magnetic studies were taken from the splitted/cut and trimmed sediment core sections using oriented plastic sample boxes (size of 2 x 2 x 2cm). The plastic cubes (with a small hole drilled in the base for bleeding air during insertion into the sediment) were pressed into the sediment parallel to the trimmed sediment surface and one side of the cube oriented parallel to the long axis of the sediment core.

The magnetic susceptibility (MS) scans were carried out onboard cruises shortly after retrieval of core. Immediately after splitting of sediment cores (GEMAX and gravity) their surfaces were trimmed and covered with thin plastic film (©Elmukelmu). The MS scans were made (at 0.5 cm intervals) using a Bartington Instruments Ltd MS2E1 surface scanning sensor coupled to a TAMISCAN-TS1 automatic logging conveyor), which was interfaced to a PC.

Detailed palaeomagnetic and mineral magnetic analyses were performed in Lund/Sweden and in Espoo/Finland (at GTK). Magnetic susceptibility analyses of discrete subsamples were performed using a Geofyzica Brno KLY-2 Kappabridge. Natural remanent magnetization (NRM), anhysteretic remanent magnetization (ARM) and saturation isothermal remanent magnetization (SIRM) of discrete samples were measured using a 2D-Enterprises 755R superconducting rock magnetometer (SRM) coupled to an automatic degausser system (2G Enterprises)

Palaeomagnetic age/depth modeling was carried out (e.g. for cores 370530 and 370540) using statistical sequence slotting and independent core correlations using loss-on-ignition records. These methods are described in detail in Lougheed et al. (under revision) and later sections. A reconstruction of palaeomagnetic secular variations (PSV) with dates inferred from regional compilation based on multiple varved lake sediment sequences (Snowball et al., 2007).

Isotope dating

AMS ^{14}C dating was carried out on benthic foraminifera samples, mollusc shells, bulk sediments, as well as humic acid and base residue organic carbon fractions. Dating analyses were performed in different dating laboratories, namely Poznan Radiocarbon dating laboratory/Poland, Lund Radiocarbon dating laboratory/Sweden, Kiel Radiocarbon laboratory/Germany, and ETH Zurich.

^{14}C determinations on foraminifera samples were used to avoid the problems associated with ^{14}C dating of bulk sediment. Due to the scarcity of foraminifera in the Baltic Sea, some of samples were of very low mass and experimental ^{14}C analysis method (for the first time on foraminifera) was used (Lougheed et al. under revision) in ETH Zurich. This method involves the direct measurement of CO_2 from samples by a gas ion source. These measurements involved probably the smallest sample sizes ever used for ^{14}C determinations on calcareous material in an applied study (as low as 4 µg C). This experimental ^{14}C analysis may prove to be a useful in future studies where very little organic material is available.

^{210}Pb and ^{137}Cs dating of sediment samples were performed mainly at the Gamma Dating Center, Institute of Geography, University of Copenhagen. Some additional ^{137}Cs analyses were done also at GTK.

^{210}Pb and ^{137}Cs isotopes have very short half-lives, of 22.26 and 30 years respectively. Thus those isotopes have been used in the dating of lake and marine sediments spanning the last two centuries or so. ^{210}Pb dating has been used in the dating of sediments within time range of 1-150 years. In the sediment column the activity peaks of ^{137}Cs correspond to the fallout of the Chernobyl nuclear power plant accident of April 1986, and to the depositions from the nuclear weapons tests that occurred in the 1950s and 1960s.

At the University of Copenhagen sediment samples were analyzed for the activity of ^{210}Pb, ^{226}Ra and 137Cs via gamma spectrometry. The measurements were carried out on a Canberra low-background Ge-detector. ^{210}Pb was measured via its gammapeak at 46,5 keV, ^{226}Ra via the granddaughter ^{214}Pb (peaks at 295 and 352 keV) and ^{137}Cs via its peak at 661 keV. At GTK sediment samples were dated for ^{137}Cs by gamma spectrometry using an EG&E Ortec ACE™-2K spectrometer with a 4” NaI/TI detector.

Lead (Pb) content and stable isotope ratios ($^{206}Pb/^{207}Pb$) were tested for long sediment core dating, to detect lead deposition associated with atmospheric historical pollution peaks originating from continental Europe. Two of these production peaks are associated with the Medieval and Roman times and have been previously successfully used as age markers in the Baltic Sea (e.g.Zillén et al. in press).

Analyses were performed using ICP-MS by Durham University, UK and GTK, Finland. Discrete samples from MSM 16/1-052-04 were additionally measured for lead concentration at Lund University using a handheld NITON XRF scanner.

OSL dating (Helsinki)

Testing of the OSL-samples (and OSL dating) was performed at Helsinki University in close co-operation with the Nordic Laboratory for Luminescence Dating (NLL), Department of Earth Sciences, University of Aarhus, Risø National Laboratory, Roskilde, Denmark. Laboratory work included e.g. opening and sampling of the sediment cores for OSL-dating; chemical pre-treatment of the OSL-samples; final chemical etching, acid treatment (H_2SiF_6) of the samples and measuring the luminescence signal (Kotilainen et al. 2010, Kotilainen et al. in prep).

The sediment cores were split open under amber light conditions and the samples for OSL, water content and gamma measurement (dose rate) were taken from a 5 cm slice of one half of the core. Due to the fine-grained nature of the sediments the luminescence measurements were undertaken on the fine silt (4-11 µm) fraction. Pre-treatment of the samples included disaggregation in an ultrasonic bath (2 h), a Stokes' settling procedure (separation of 4-11 µm grains) and chemical purification: 10% HCl to remove carbonates and 10% H2O2 to remove organic material. Finally, the polymineral fraction was etched in hydrofluorosilicic acid (H2SiF6) for 3-5 days to provide a quartz-rich extract. The purity of the quartz extracts was confirmed by absence of a significant IRSL signal and OSL IR depletion ratios close to unity (Duller 2003).

A SAR protocol (Murray and Wintle 2000) was applied for equivalent dose determination. A preheat of 260°C for 10 s and a cut-heat to 220°C was used in these preliminary measurements. The quartz grains were stimulated for 40s with blue LEDS at 125°C. The quartz OSL signal is dominated by the fast component which makes this material very suitable for OSL dating. The equivalent doses (De values) range from 3.2±0.4 to 26.3±2.2 Gy for the upper sample at 22.5cm and the lowest sample at 331 cm respectively.

For dose rate determination the samples were dried, ground and cast in wax discs to retain radon and ensure a constant counting geometry. The discs were stored for at least three weeks to establish equilibrium between 222Rn and 226Ra. The radionuclide concentrations (238U, 226Ra, 232Th and 40K) were measured using high-resolution gamma spectrometry (Murray et al., 1987). The radionuclide concentrations were converted to dose rates using the conversion factors of Olley et al. (1996) and assuming an a-value of 0.04 for fine-grained quartz. The 'in situ' water content (weight of water / dry weight) was measured directly on all samples. These data were approximated by a straight line giving a dewatering rate of 0.3%/cm. This dewatering model was used to derive mean lifetime water contents of between 220 and 180% giving total dose rates of between 1.7 and 2.0 Gy/ka (Kotilainen et al. 2010, Kotilainen et al. in prep).

Methods for reconstruction of deep water conditions

Sedimentary-fabric analysis

Sedimentary-fabric analyses integrating sedimentologic and ichnologic methods were carried out on digital images and X-radiograph to reconstruct the history of oxygen and animal activity on the Baltic Sea floor. X-radiographs were prepared of the entire cores as described by Virtasalo et al. (2006, 2011a, 2011b). Plastic boxes of 50 × 5 × 2 cm in cross section were pushed into the sediment core sections, cut out and trimmed with a steel string and sealed. Some of the sediment (plastic) boxes were placed directly on X-ray film cartridges and X-rayed at GTK. The films were developed, scanned at a resolution of 1200 dpi and the contrast enhanced using regular image-processing software. Some of X-ray analyses were performed at the Laboratory of Microtomography, University of Helsinki, where high-resolution digital radiographs of the boxes were produced using a custom-made tungsten-anode micro-computed-tomography Nanotom device supplied by Phoenix|Xray Systems + Services GmbH (Wunstorf, Germany). X-ray source power settings were adjusted to 150 kV and 240 µA, and the detector to 750 ms exposure time and an averaging of 15 images per radiograph.

The digital images and X-radiographs were inspected for primary physical and biogenic sedimentary structures. Sedimentological examination was targeted to establish textural and compositional similarities and differences among various representative bed types. Ichnological structures were classified based on their two-dimensional (2D) projection on the X-radiograph to the ichnogenus level. The crosscutting relationships of the biogenic structures were recorded. The inside diameters of biogenic structures were measured and their vertical extents were calculated as the sine of their angle from horizontal multiplied by their length. In cases, where the structures extended outside the X-radiograph area, their length unavoidably was underestimated; nevertheless, the measurements are taken as rough estimates.

Grain size analyses
Physical grain size analyses were used to reconstruct changes in the inflow speed. Sediment samples for grain size analysis were taken at 1 cm intervals. Grain size analysis of sediments was carried out at the laboratory of Geoecology of the Atlantic Branch of the P. P. Shirshov Institute of Oceanology (AB IO RAS) using a Fritsch laser particle analyser ('Analysette-22 Compact', from 0.3 to 50 mm) and a Fritsch analytical sieve shaker ('Analysette-3', using sieves of 50, 63, 100 and 250 mm sell size). Organic matter was eliminated from the analysed samples by soaking them in a solution of H_2O_2. Sodium tripolyphosphate and ultrasonic cleaner "Laborette 17" were used for dispersing of particles. Grain size data were processed by means of Analysette 22 32-Bit software.

Benthic foraminifera studies of samples included counting, measurements of oxygen ($\delta^{18}O$), carbon ($\delta^{13}C$) and strontium ($^{87}Sr/^{86}Sr$) isotopes, as well as Mg/Ca analyses.

Benthic oxygen and carbon isotopes measurements of Uvigerina mediterranea from 372610 and of Bulimina marginata from 372680 were done in Bergen using a Finnigan MAT 253 mass spectrometer equipped with an automatic preparation line ("Kiel device"). All foraminifers used for the analysis were crushed and cleaned in methanol, using an ultrasonic bath, before being measured. The measurements were done on 2 or more specimens from the >100 micron fraction.

Mg/Ca analysis of Uvigerina medetterania from MUC372610 were done using a Thermofinnigan IRIS inductively coupled plasma optical emission spectrometer (ICP-OS) at the Department of Earth Sciences at the University of Bergen. The foraminiferal tests were crushed and cleaned of contaminating phases following the procedure developed by Barker et al. (2003).

Methods for reconstruction of surface water conditions

Sea surface temperature (SST) reconstructions were performed in the INFLOW project using sediment **biomarker TEX_{86} SST** measurements in NIOZ Texel (by IOW). TEX_{86}-analysis: 0.5-1g of the sediment samples were extracted using accelerated solvent extraction (DIONEX) with CH_2Cl_2:CH_4O (9:1;v/v) as solvent. The polar fraction was obtained from the extract by column chromatography and cleaned before analysis by high-performance liquid chromatography and atmospheric pressure chemical ionization-mass spectrometry (HPLC/APCI-MS) as described in Schouten et al (2007). Duplicate analyses revealed a standard analytical error of 0.2°C. Parallel to the TEX_{86} the BIT index (Hopmans et al. 2004) was determined as a proxy for the amount of soil-derived organic material.

Reconstruction of surface water salinity has been performed in INFLOW using **diatoms analyses** (University of Szczecin). Transfer functions (TF) were used to reconstruct paleoenvironmental conditions from fossil diatom assemblages. TF's based on the modern relationships between species distributions and environmental gradients in the Baltic Sea. Weighted averaging and maximum likelihood methods were used, as these are the most robust to spatial autocorrelation in the modern training sets (Telford and Birks, 2005).

Surface water conditions have been reconstructed in INFLOW also using **dinoflagellates** and $\delta^{13}C$ values. Changes in sea-ice cover were reconstructed using diatoms (*Pauliella taeniata, Fragilariopsis cylindrus*) and the newly developed **IP_{25}** (Belt et al. 2007) method. Also alkenones have been used for temperature reconstructions in Skagerrak cores.

Concentrations of bromine (Br) in sediments samples (Site F40) were measured as a proxy to bottom-water palaeosalinity. Measurements of bulk Br concentrations were performed at VSEGEI using an X-ray scanning crystaldiffractive spectrometer (SPEKTROSKAN-005). Prior to analysis, the samples were dried at 20°C and ground. This method was developed at VSEGEI based on the estimate of behaviour affinity of Cl and Br and a stable Cl:Br ratio of 230 in the water column and in pore waters of Baltic Sea sediments (Shishkina et al. 1969) and the assumption that this ratio remained fairly stable during sediment accumulation. Experimentally it was determined that for the eastern Gulf of Finland Cl:Br ratio is 204. The Br-based salinity (S) can be estimated using the empirical formula: S‰ = 0.115 + 1.80655 * (Br‰ – 0.0046‰) * 204, which was modified from the Cl-based formula S‰ = 0.115 + 1.80655 Cl‰ used by Snezhinsky (1951) and Lyahin (1994). The constant value of 0.0046‰ was determined as a regional background Br concentration in the minerals of silty-clayey sediment accumulated in freshwater basins. We note that Br can also be sorbed by organic carbon in particulate matter. A noticeable correlation was found between the downcore distribution of Br and TOC concentrations measured in core 303700-7 sediments sampled in the Gdansk Basin, which implies the possibility that Br distribution is partially controlled by the TOC concentration (Grigoriev et al., 2011). Nevertheless, estimated salinities based on Br concentrations measured in 13 samples of organic-rich, silty-clayey surficial (0 to 5 cm) sediments of the freshwater southern part of the Curonian Lagoon (near 1‰ salinity, 5 to 10% TOC; TOC concentrations from Emelyanov 2002).

Methods that cannot be solely linked to surface or deep water processes, but which are essential to characterize the status of the ecosystem

These methods include geochemical analysis such as **XRF–scanning (**at the Royal Netherlands Institute for Sea Research; the University of Cologne, and the Baltic Sea Research Institute), **TOC**/TIC/TC/S/N, **biogenic silicate**, P, Ca/Mn, and **Sr-isotope** measurements. **Loss on ignition (LOI)** was also measured from several long sediment cores. LOI was determined by ashing freeze-dried samples at 550 °C for three hours and calculating the resulting mass difference. These geochemical studies cannot be solely linked to surface or deep water processes, but which are essential to characterize the status of the ecosystem (such as redox stage).

Total organic carbon (TOC): After measuring the total carbon (TC) using the EA 1110 CHN analyser from CE Instruments and the total inorganic carbon (TIC) using the Multi EA-2000 Elemental Analyzer from Analytic Jena the TOC content was calculated as the difference between TC and TIC.

Biogenic Silicate (BSi): 0.1 g of sediment was used to extract BSi with 100 ml 1 M NaOH for 40 min. at 85°C. The extract was decanted after centrifugation and BSi was detected using the Molybdate-blue method, for the composition of for the composition of specific reagents see Ref. 11. 6 ml of molybdate reagent was added to 1 ml of extract and mixed for 5 min and then 6 ml of oxalic acid reagent and 6ml of ascorbic acid reagent were added and mixed for 15 min. BSi was detected with a SPEKOL 1100 photometer from “Analytik Jena” measuring the absorbance at a wavelength of 660 nm.

INFLOW has also used sediment proxy data from previous projects (e.g. BASYS), like geochemical data analyzed using a modified energy-dispersive X-ray fluorescence (EDX) techniques using radio-isotopes for characteristic X-ray excitation.

As a part of the sediment proxy studies within the INFLOW project, **the isotopic ratio of strontium (^{87}Sr/^{86}Sr)** of bivalve shell carbonate was used as an indicator of paleosalinity (e.g. Widerlund and Andersson 2006, 2011). The Sr-isotope composition of the biogenic carbonate reflects variations in the composition of dissolved Sr in the ambient water (Veizer, 1989), which is controlled by the mixing of two distinct end-members: North Sea water and freshwaters entering the various Baltic basins through river runoff. Being fully independent of variations in temperature and vital fractionation effects, the

$^{87}Sr/^{86}Sr$ ratio yields a pure salinity signal. The early stages of Sr-isotopic analyses were impeded by problems related to instrumentation, methodology and sample material. Automated ion chromatographic separation of Sr produced yields of only 15%, most likely due to necessary modifications to the eluent. Comparative mass spectrometric measurements on ICP-MS and TIMS instruments indicated stability issues within the ICP-MS technique that were subsequently resolved. The initial plan of producing a high-resolution Sr-isotope record on benthic foraminifers was rejected due to insufficiency of foraminifer abundance in sediment. The potential of $MnCO_3$-rich layers as records of Baltic Sea water palaeosalinity was explored with analysis of $^{87}Sr/^{86}Sr$ ratios in $MnCO_3$ (sediment core 370530 from the Gotland Deep). The results indicate contamination by silicate-derived Sr during the analytical leaching procedure, and possibly also during original precipitation of $MnCO_3$. Due to the contamination issues, the palaeosalinity reconstructions were based solely on mollusk shell carbonate Sr-isotope values.

Some INFLOW cores were also investigated using palynological methods (pollen analysis).

Modelling approach - methods

The regional climate model of the Rossby Centre (RCA3) has been used to downscale global climate simulations (ECHO-G) to the regional (the Baltic Sea) scale and to deliver lateral boundary conditions for the local ecosystem models. The better constrained ecosystem models (RCO-SCOBI and ERGOM) used in INFLOW provided simulated data (hydrographical and biogeochemical conditions) for extreme natural climatic conditions over the past thousand years (e.g. Medieval Climate Anomaly and Little Ice Age). These are partly forced with sediment proxy results such as a 2 K temperature change from the Little Ice Age towards the Modern Warm Period. Model experiments provided insight into the mechanisms triggering Baltic Sea ecosystem state changes as observed in sedimentary archives. Comparison with the simulated contemporary and future status allowed relating the expected changes to conditions in historical times. Validated models have been used to provide scenarios of the Baltic Sea ecosystem state at the end of the 21st century for selected Intergovernmental Panel on Climate Change (IPCC) climate change scenario. Transient simulations have been performed for a future climate (1960-2099) using RCAO/ECHAM5-A1B_3, RCAO/ECHAM5-A1B_1, RCAO/ECHAM5-A2 and RCAO/HadCM3-A1B combinations to force the Baltic Sea ecosystem models in co-operation with the BONUS-ECOSUPPORT project.

Results and discussion

Key Sites studied in INFLOW

Altogether, more than 90 sediment cores (including gravity cores, piston cores and different types of surface sediment cores) were recovered from the INFLOW project study areas of the Baltic Sea, during various expeditions (Fig. 2 and Table 1). Based on extensive additional INFLOW surveys and the preliminary results of post-cruise studies (e.g. the various scanning data, first AMS14C results), most suitable and representative "key cores" were selected for detailed high-resolution studies. The key sites of the INFLOW project are shown in Figure 4 and in Table 3. However, this list does not cover all sites studied in the project, and site/location information on those can be found from publications referred to in the text.

Table 3. Key sites studied in the INFLOW project. Sea area, sediment core IDd, coring locations, water depths (in meters), the types of coring equipment used, recoveries (i.e. length of sediment core in cm), sampling date and research vessel are shown in table.

Sea area	**Core ID**	**Latitude**	**Longitude**	**Water depth m**	**Gear**	**Recovery cm**	**Sampling date**	**Research vessel**
Skagerrak	372610	57°41.05	06°41.00	320	GC	550	01.09.2009	Maria S. Merian
Skagerrak	242940	57°40.520	07°10.000	316	GC	890	11.01.2002	Poseidon 282
Skagerrak	372650	58°29.76	09°35.91	550	GC	530	01.09.2009	Maria S. Merian
Kattegat	367270	56°41.282	11°46.679	41	GC	379.5	11.11.2009	Prof. Albrecht Penck
Mecklenburg Bay	317970	54°12.011	11°21.010	23	GC	758	28.03.2006	Maria S. Merian
Mecklenburg Bay	317990	54°18.596	11°25.571	23	GC	865	28.03.2006	Maria S. Merian
Arkona Basin	318340-3	54°54.765	13°41.444	47	GC	1104	04.04.2006	Maria S. Merian
Bornholm Basin	371080	55°20.37	15°26.76	93	GC	380	01.06.2009	Prof. Albrecht Penck
Gotland Basin	303600-3	56°55.01	19°20.01	170	GC	820	10.06.2005	Poseidon
Gotland Basin	370530-5	57°23.123	20°15.489	231	GC	498	24.04.2009	Aranda
Gotland Basin	370540-6	57°17.011	20°07.248	243	GC	650	24.04.2009	Aranda
Gotland Basin	372740	57°23.10	20°15.50	232	GC		01.09.2009	Maria S. Merian
Northern Central Basin (NCB)	370520-6	58°53,657	20°34,419	182	GC	480	23.04.2009	Aranda
Western Gulf of Finland (JML)	370510-5	59°34.907	23°37.572	80	GC	557	22.04.2009	Aranda
Eastern Gulf of Finland (F40)	MGML-2009-5	60°06.409	28°47.518	38	PC	454	06.08.2009	Aranda

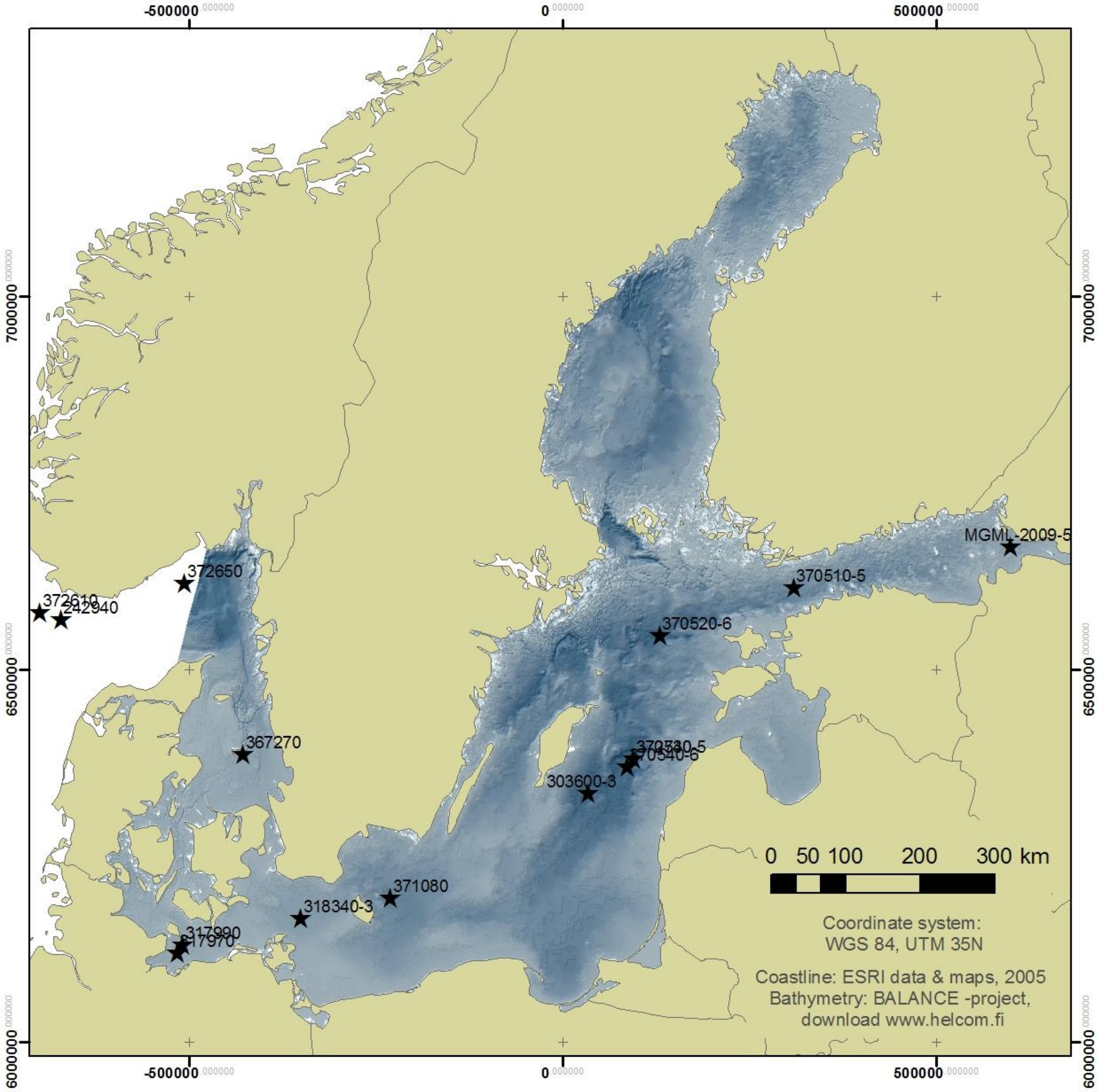

Figure 4. Key sites studied in the Baltic Sea during the INFLOW project. Sediment core id numbers are shown in figure. Detailed information on coring locations and water depths are shown in Table 3. Bathymetric map of the Baltic Sea is a product of BALANCE "Baltic Sea Management – Nature Conservation and Sustainable Development of the Ecosystem through Spatial Planning" Interreg IIIB EU-project.

Chronostratigraphy and mineral magnetic studies

Dating of surface sediment cores (MUC's ja GEMAX cores) from the key sites were performed using various methods like ^{210}Pb and ^{137}Cs dating (see Methods Chapter and Table 4).

Table 4. Sediment cores that have been dated in the INFLOW project are shown in table. Also location and dating method is indicated.

Location	^{210}Pb, ^{137}Cs Dating	AMS^{14}C Dating	Palaeomagn. dating	Pb and $^{206}Pb/^{207}Pb$	OSL dating
	Core	Core	Core	Core	Core
Skagerrak	372610	372610 GC/MUC			
Skagerrak	372650	372650 GC/MUC			
Skagerrak	372660				
Kattegatt	372680	372680 MUC			
Kattegatt	367280	367280 GC/MUC			
Kattegat		367270 GC/MUC			
Mecklenburg Bay		317970-3 GC	317970 GC		
Bornholm Basin	371080				
Bornholm Basin		303770-3 GC			
Bornholm Basin		372720-3 GC			
Gotland Basin	370531	370530-5 GC 370531 MUC	370530-5 GC	370530-5 GC	
Gotland Basin	370540	370540-6 GC/MUC	370540-6 GC		
Gotland Basin	303600	303600N GC/MUC			
Gotland Basin	372740	372740 GC			
Northern Central Basin		349140 GC			
Northern Central Basin	377860				
Northern Central Basin	370520 B	370520-6 GC/MUC			
western Gulf of Finland (JML)	MGGN-2009-1	NN GC			
Eastern Gulf of Finland (F40)	MGGN-2009-21 GEMAX	MGML-2009-5	MGML-2009-5	MGML-2009-5	MGML-2009-5

An example of surface sediment dating of the core MGGN-2009-1, from the western Gulf of Finland (Site JML), is shown below.

Contents of unsupported ^{210}Pb in the upper part of the core MGGN-2009-1 are ~ 600Bq kg^{-1}, and there is a clear tendency for exponentially declining content with depth (Fig. 5). The calculated flux of unsupported ^{210}Pb is approximately 285Bq m^{-2} y^{-1} that is about three times higher than the estimated local atmospheric supply (based on Appleby 2001). This suggests that the JML site is subject to sediment focusing. The content of ^{137}Cs was high in the upper 8 cm of the core, and decreased to below detection limit at around 18 cm depth (Fig. 5).

CRS-modeling has been applied on the profile using a modified method (Appleby, 2001), where the activity below 26 cm is calculated on the basis of the regression. Based on the chronology, elevated contents of ^{137}Cs are found in layers dated to around 1987 and younger (Fig. 5). That is in excellent agreement with the expected Chernobyl-origin of this material (1986). This agreement and the clear tendency for exponential decline in unsupported ^{210}Pb with depth indicate that the chronology is reliable. However, the change in dry bulk density at around 18 cm (Fig. 5) the chronology below that level less certain.

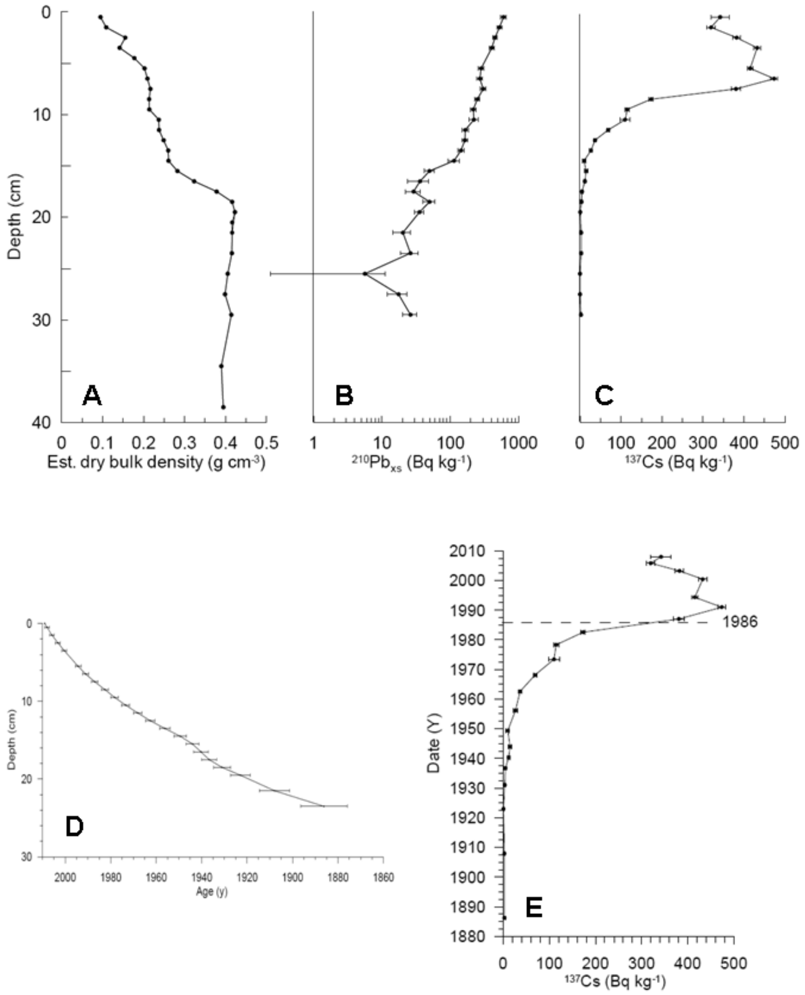

Figure 5. Dry bulk density (gcm-3) (A), ^{210}Pb (B) and ^{137}Cs (C) concentrations with depth in the western Gulf of Finland core MGGN-2009-1 are shown in figure. Age (year) – depth (cm) model is shown in Fig. 5D. The ^{137}CS activity with age (date, year) in the sediment core is shown in figure too. Dashed line corresponds to year 1986.

Long sediment cores that have been dated in the INFLOW project using multi-proxy dating methods are shown in Table 4.

Two separate geochronologies for the Gotland Deep (Gotland Basin) were constructed using ^{14}C determinations calibrated using OxCal computer modelling. These were based on data from three separate cores (370530-5, 370540-6, 372740-3) correlated in MatLab using Loss-On-Ignition (LOI) data (Lougheed et al. under revision). The first geochronology is based on a combination of atmospheric lead pollution isochrones (e.g. Brännvall et al., 2001; Stanton et al., 2010) and a reconstruction of palaeomagnetic secular variations with dates inferred from a regional compilation based on multiple varved lake sediment sequences (Snowball et al., 2007). The second geochronology is based on radiocarbon dating of foraminifera. A comparison of the two geochronologies allowed the inference of radiocarbon reservoir ages (Fig. 6)

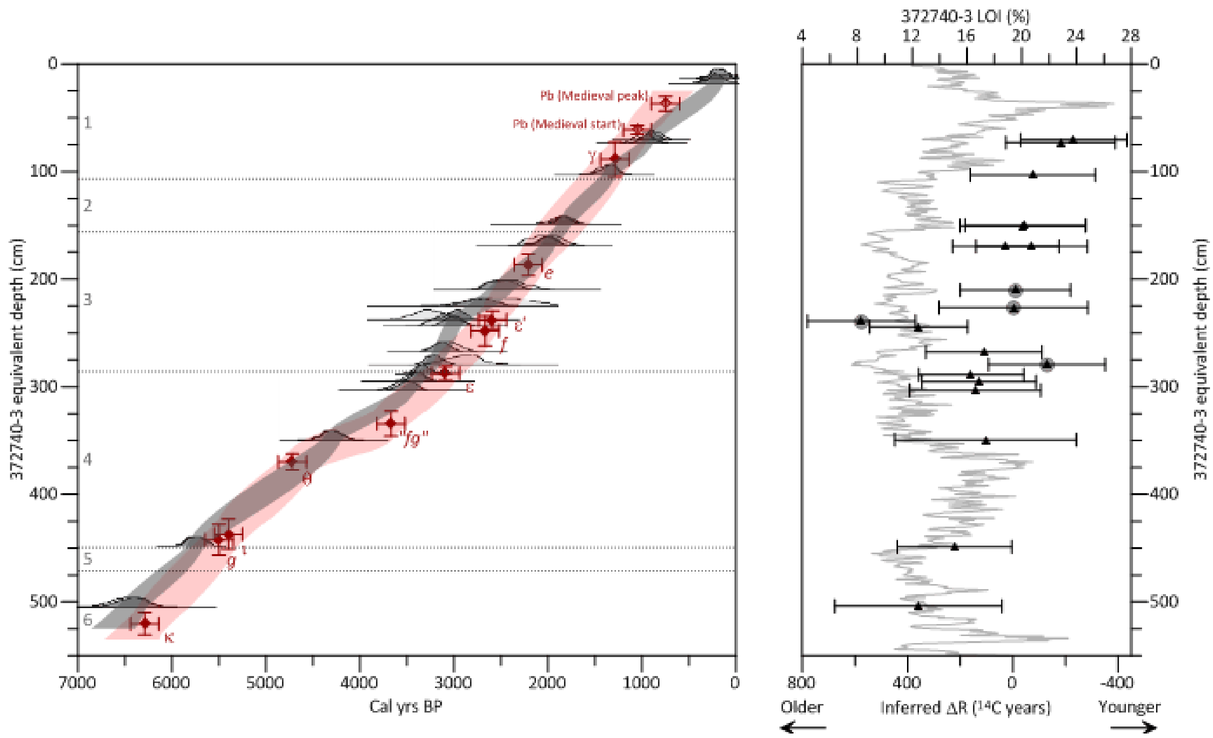

Figure 6. Left: 68.2% confidence interval for ^{14}C depositional P-sequence model whereby ΔR=0 (grey band) with calibrated date distributions (light grey mounds) and modelled date distributions according to OxCal P-sequence model (dark grey mounds). Also shown is 68.2% confidence interval for PSV and Pb OxCal P-sequence model (light red band) and associated PSV and Pb age constraints with 1-sigma errors (filled and open red diamonds, respectively). Numbered sedimentary units shown for reference (grey numbers and horizontal grey lines). Right: Inferred ΔR values for ^{14}C determinations with 1-sigma errors (black triangles). Filled grey circle denotes ΔR values based on ^{14}C determinations with a total sample mass of less than 200 µg. LOI% data (light grey curve) for core 372740-3 shown for reference. All data projected on 372740-3 depth scale. (From Lougheed et al., submitted)

Geochronology for the eastern Gulf of Finland Site F40 was constructed also using a combination of atmospheric lead pollution isochrones, a reconstruction of palaeomagnetic secular variations with tranferred ages from a Finnish PSV master curve, and radiocarbon dating of bulk sediments. Other long sediment cores were dated mainly using AMS-^{14}C dating (Table 4). Palaeomagnetic secular variations were possible to use for dating also in the Mecklenburg Bay sediment core.

The quality of the palaeomagnetic data was found to be very basin specific. The Gotland Deep cores did produce palaeomagnetic data of sufficient quality for palaeomagnetic dating. The Bothnian Sea cores analysed contain the best quality palaeomagnetic data, but this region was not the main site finally selected to meet the INFLOW deliverables and for which a high resolution chronostratigraphy was delivered (which was the Gotland Deep). There are many possible reasons why the sediment cores recovered from the other sediment basins packages did not produce a reliable palaeomagnetic signal. These reasons include, in order of diminishing importance (i) insufficient magnetic mineral concentrations and too coarse grain size, (ii) poorly consolidated sediments that cannot be accurately sampled, (iii) sediments physically disturbed post-depositionally due to sea currents or bioturbation, (iv) physical disturbance of the sediments during corer penetration and recovery and, (v) chemical alteration of the magnetic minerals during core storage that can cause some fine-grained iron oxides and iron sulphides to be transformed into paramagnetic minerals.

As a part of the dating package WP1, Task 1.2., we were developing fine grain methodology for a chronology based on ***optically stimulated luminescence (OSL) dating***. For OSL dating it is essential that any prior OSL signal of the grains is well zeroed or bleached before final deposition. This is known to be true in the Arkona Basin in the Baltic Sea (Kortekaas et al., 2007), to the south of our sampling location and is likely to apply at our sampling site at the outer Neva estuary (water depth 38 m), in the eastern Gulf of Finland (Site F40). This location is thought to record continuous sedimentation and a relatively high accumulation rate. The sediment consists mainly of bioturbated silty mud with laminated intervals.

The thermo luminescence (TL) signals IR50 and pIRIR225 from polyminerals of 12 samples demonstrated that the sediment grains have electrons (emitted as light) trapped in them and that the signals also formed a sensible smooth succession according the depth suggesting proper bleaching prior to sedimentation. Hence the Neva estuary fine grained marine sediment is suitable for luminescence dating. The optically stimulated luminescence was measured from 5 samples using the SAR procedure and fine-grained quartz grains. The limited number of samples was unavoidable since the purity test of the samples proved that all the polymineral samples were not pure quartz after 3 days of acid treatment (H_2SiF_6). However, the OSL signal of the measured samples was offset compared to IR50 and pIRIR225, probably due to thermal transfer. This problem has to be solved by preparing more samples and running more measurements. The dose rate determination is also essential before the measured signals can be transformed into ages. The sample preparation for the dose rate determination for all the 12 samples was completed, and one preliminary result received. The dose rate at the area seems to be rather high (reducing the age estimate). The water content of the sediment is very high too, which alters the interaction (by amplifying the age estimate). Eventually, both the OSL and TL signals are giving too old ages at this stage.

During the INFLOW project we tested three sedimentary environments for fine grain OSL dating: The Gotland Deep, GD (core 370540-7, water depth 243 m), North Central Basin, NCB (core 370520-7, water depth 182 m) and outer Neva estuary (core F40, MGML-2009-5, water depth 38 m). The test samples for GD and NCB were indicating incomplete bleaching, which led us to try the Neva estuary core instead. As stated before for OSL dating it is essential that any prior OSL signal of the grains is well zeroed or bleached before final deposition. Sedimentation process of the material into the basin has to able the bleaching with sufficient amount of day light during transportation. What we actually date is the moment when the bleaching capacity of solar energy fades out in the deep water, sedimentation of the well bleached material takes place and the crystal lattices in the grains start to charge due to the naturally occurring ionising radiation. It seems apparent that for the fine grained material the sedimentation process has to be well interpreted before the OSL sampling. Also for the fine grained sediments it seems that the water depth of the basin is a critical factor. Any possible re-deposition of the sediment interferes with the signal and thus alters the result of the OSL dating. However, the age-depth dependence of the OSL dates at the outer Neva estuary proves that the fine grained material there is suited for OSL dating. It is evident that this technique works for marine sediments and can be used as an independent dating method for marine fine grained sediments, but a lot more work is required for finalised results.

Mineral magnetic measurements show that the concentration of magnetic minerals in the Baltic Sea sediments is highly variable. One of the main new findings is that distinctly laminated sediment units with relatively high organic carbon content contain much higher concentrations of a fine-grained ferrimagnetic mineral, which contributes to the natural remanent magnetisation (and thus palaeomagnetic dating). It has already been established that sediments deposited in these locations prior to 6,000 years ago could contain high concentrations of an inorganically precipitated ferrimagnetic iron sulphide (greigite, Fe_3S_4). However, both our studies and complementary studies by the BALTIC GAS PhD student based in Lund (M. Reinholdsson) suggest that the formation of these particles is controlled by magnetotactic microbes, which use the organic carbon as an energy source.

Mineral magnetic properties were studied also from the eastern Gulf of Finland (F40 site) core MGML-2009-5 In the SIMR acquisition, all the samples were saturated (over 95 %) in low fields (<300 mT), which shows that the dominating magnetic mineral is a ferrimagnet, most likely magnetite, but greigite cannot be ruled out. The S-ratio is below –0.6 in the sediments underlying the erosional horizon at 190 cm, while the ratio reaches –0.4 or even higher above the erosional contact (Fig. 7). This indicates the presence of a higher coercivity mineral such as hematite as a minor magnetic component in the overlying sediments. Furthermore, the SIRM/K ratio decreases significantly just above the erosional horizon, indicating a higher magnetic grain size, but the increasing SIRM/K ratio indicates that the magnetic grain size decreases upward (Fig. 7).

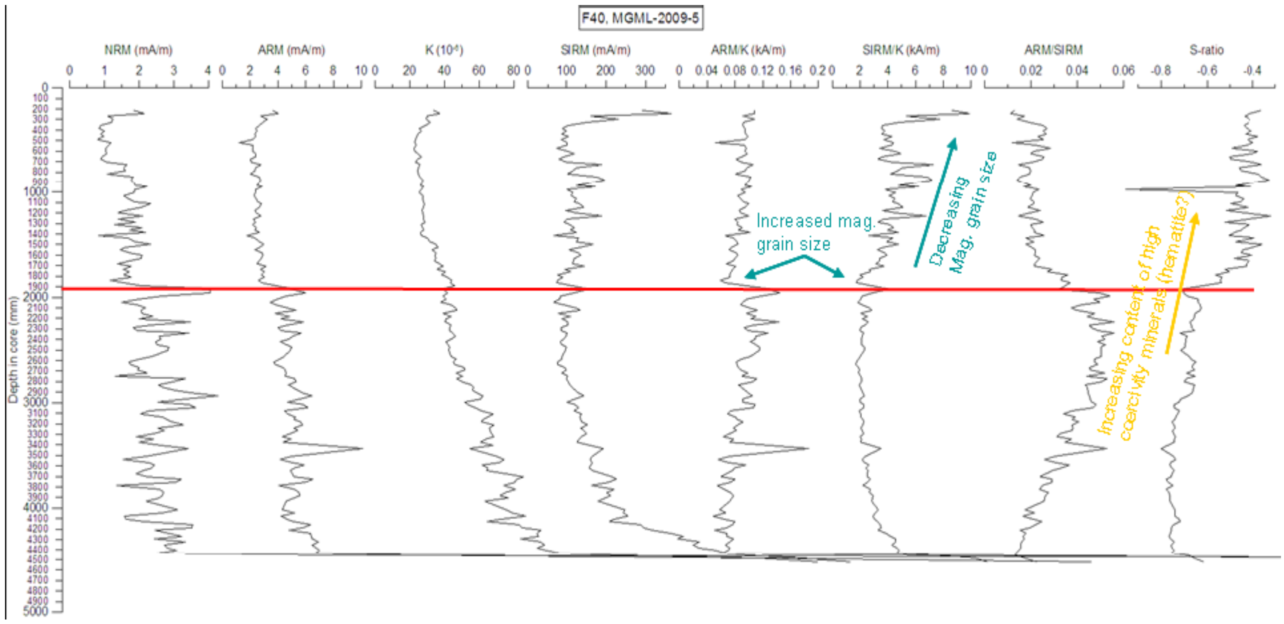

Figure 7. Mineral magnetic parameters determined for the core MGML-2009-5 from the eastern Gulf of Finland (F40 site). The red line indicates the erosional horizon at 190 cm.

Sedimentary fabric analysis

It was shown that the first saline inflows from the North Sea to the Baltic Sea arrived already during the postglacial lake phase of the Baltic Sea Basin, at approximately 10 000 years before present. This is revealed by the sulfur isotopic composition of pyrite framboids in the cores of pyrite concretions that were formed on the postglacial lake floor (Virtasalo et al. 2010). The sulfur isotopic composition (mean $\delta^{34}S$ = +20.22 ‰) is close to marine sulfate, and strongly indicates the North Sea as the sulfate source. These initial inflows were weak and had only a strongly attenuated effect on the lake ecosystem. Yet, they were a prelude to the stronger inflow activity that resulted in the establishment of brackish-water conditions and estuarine circulation in the Baltic Sea, and in oxygen deficiency in the deep areas of the basin beginning at 8000–7000 years before present.

Integrated sedimentological and ichnological analysis of sediment cores from the Gotland Deep, the central depression of the Baltic Sea, resulted in the recognition of sharply-laminated, biodeformed and burrow-mottled sedimentary fabrics in the sediments deposited after the establishment of brackish-water conditions (Fig. 8). The sharply-laminated and burrow-mottled fabrics dominate the cores as alternating long intervals, whereas the biodeformed fabrics occur as thin interbeds within the sharply-laminated intervals. The sharply-laminated fabrics record anoxia and the absence of macrofauna on the seafloor. The biodeformed interbeds record brief (few years to few decades) oxic–dysoxic conditions that punctuate the anoxic background conditions and permit sediment-surface grazing and feeding by a very immature benthic community restricted to the surface mixed tier. The likely biodeformers are meiofauna and nectobenthic pioneers passively imported with currents. The long burrow-mottled intervals are characterized by intensely bioturbated fabrics with discrete *Planolites*, rare *Arenicolites*/*Polykladichnus* and very rare *Lockeia* trace fossils, as well as bivalve biodeformational structures which represent shallowly penetrating endobenthic feeding and grazing strategies and permanent dwellings. These burrowed intervals represent longer periods (several years to few centuries) of oxic–dysoxic conditions that permitted maturation in the benthos by means of larval settling of opportunistic worm-like macrofauna and bivalves (Virtasalo et al. 2011b).

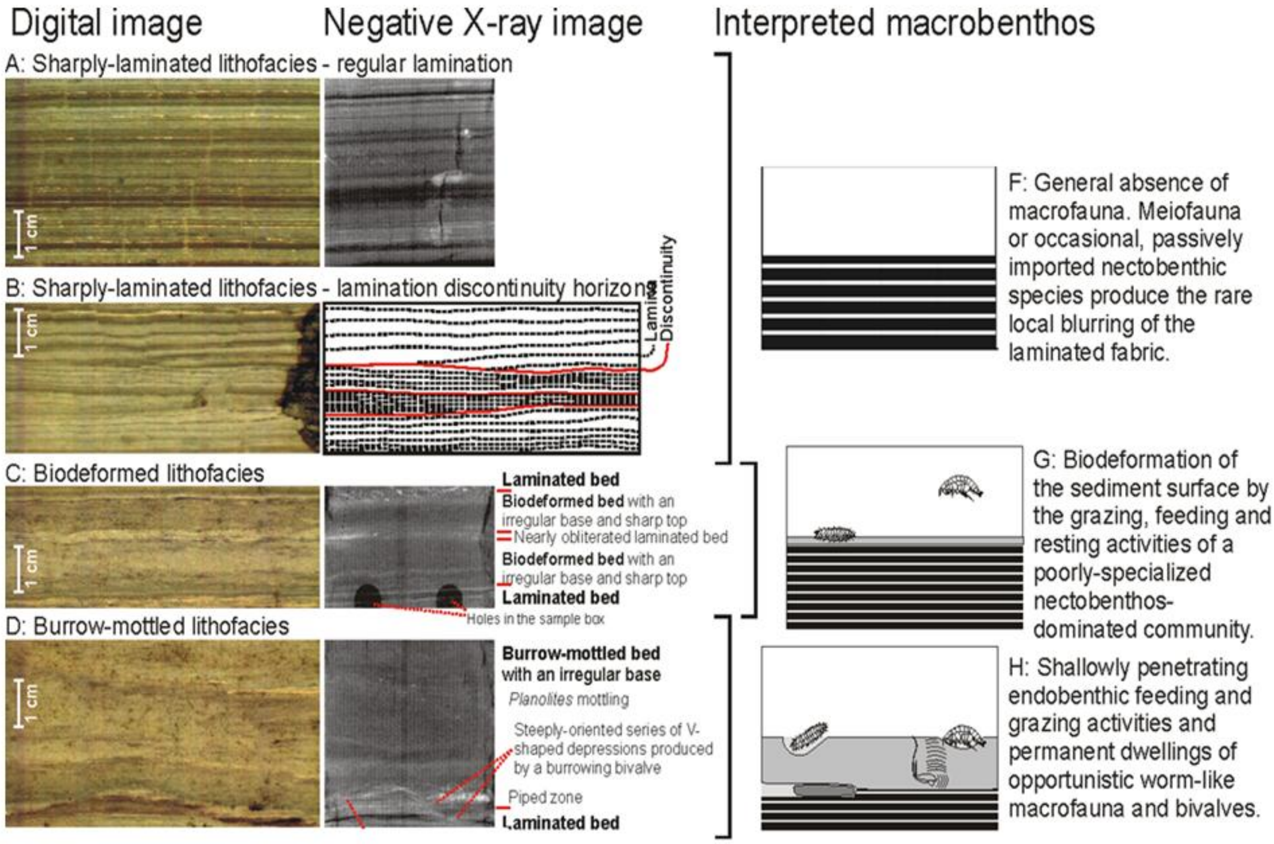

Figure 8. Digital images, negative X-radiographs and an interpreted line-drawing of the recognized lithofacies. (A) Sharply laminated mud with regular lamination. The occasional light-yellowish laminae are composed of Mn-carbonates. (B) Sharply laminated mud with lamination discontinuity horizons. Four beds of laminae of different inclination and thickness, separated by three lamination-discontinuity horizons are outlined in the interpreted line-drawing on the right. Note that the inclined laminae terminate towards the underlying layer. Also note the finer bedding of the second lowest bed compared with the other beds. (C) Biodeformed mud. Note the thin, nearly obliterated laminated bed in the middle between the two biodeformed beds. (D) Burrow-mottled mud. Note the Planolites-dominated mottling, and the shallow tubular burrows and the bivalve biodeformational structure in the basal piped zone. Vertical cracks in the images are due to sediment drying. Pale, needle-like sticks in the X-radiographs are gypsum crystals precipitated during the core storage.
Interpreted macrobenthos under different oxygen conditions are shown also: (F) Oxygen depletion and accumulation of laminated sediments. (G) Short-lived (oxic–)dysoxic conditions that permit biodeformation of the thin sediment surface mixed layer by the grazing, feeding and resting activities of a poorly specialized nectobenthos-dominated community. (H) Longer-lasting (oxic–)dysoxic conditions that permit the larval settling of endobenthic worm-like macrofauna and bivalves, leading to deeper bioturbation depths and transition-tier burrowmottling. Not to scale. Figure is modified after Virtasalo et al .2011b.

In order to explore lateral changes in the burrow-mottled fabrics along the well-known gradients in biodiversity, salinity and oxygen availability in the Baltic Sea floor, an integrated sedimentological and ichnological analysis of sediment cores was carried out along an open-water transect across the basin (Kattegat – Mecklenburg Bight – Arkona Basin – Gotland Deep – western Gulf of Finland – eastern Gulf of Finland) (Virtasalo et al. 2011a). It was shown that the diversity, diameter and vertical extent of trace fossils decrease along the Baltic Sea declining salinity gradient, mirroring the decreasing macrozoobenthic species size and richness and functional complexity (Fig. 9). Also oxygen deficiency controls the trace-fossil assemblages, suppressing the size, vertical extent and tiering of burrows in areas below the permanent halocline. These observations confirm the usefulness of trace fossils in characterizing past macrozoobenthic communities in the Baltic Sea.

The above-described sedimentary fabrics and burrow properties provide, for the first time, a means of studying the past occurrences and magnitudes of sea-floor oxygenation and their benthic responses in the Baltic Sea on time scales longer than the past several decades covered by systematic oceanographic and zoobenthic studies. High-resolution age-models of sediment cores permit linking changes observed in these records to known Holocene climatic phenomena. The comparison reveals reduced macrobenthic communities and a higher tendency for laminated sediment accumulation in the Baltic Sea deep areas during the Holocene Thermal Maximum, Medieval Climate Anomaly and the modern eutrophic Baltic Sea. These results clearly demonstrate that climatic processes in the northern Europe and North Atlantic have strongly modulated the seafloor oxygen conditions and benthic life in the Baltic Sea during the Holocene. Anthropogenic eutrophication and associated oxygen-deficiency are manifested as the intensified accumulation of laminated sediments since approximately the 1950's. That has been documented not only in deep basins of the Baltic Sea, but also in the coastal regions like in the northern coast of the Gulf of Finland.

Benthic foraminifera counting

Benthic foraminifera counting results (Jentzen 2010) reveal a close link of the bottom water properties in Skagerrak and Kattegatt to the so-called "Matthäus-curve" of major Baltic saline water inflows. A decrease in frequency of the major Baltic inflows from the 1980s corresponds to depletion of oxygen in bottom waters of Skagerrak and Kattegatt. This suggests a close link of Baltic Sea inflow between changes to variations observed in the Skagerrak area.

Benthic foraminifera counts (number of foraminifera tests of Elphidium excavatum per ml sediment) of sediment cores from the Gotland Basin (Kabel et al. in prep) indicate strong natural variability at millennial to multi-decadal timescale (Fig. 10). As benthic foraminiferas occur when salinity is higher than 11-12 PSU, they are suggested to reflect changes in saline water inflow strength and variability (from the North Sea into the Baltic Sea).

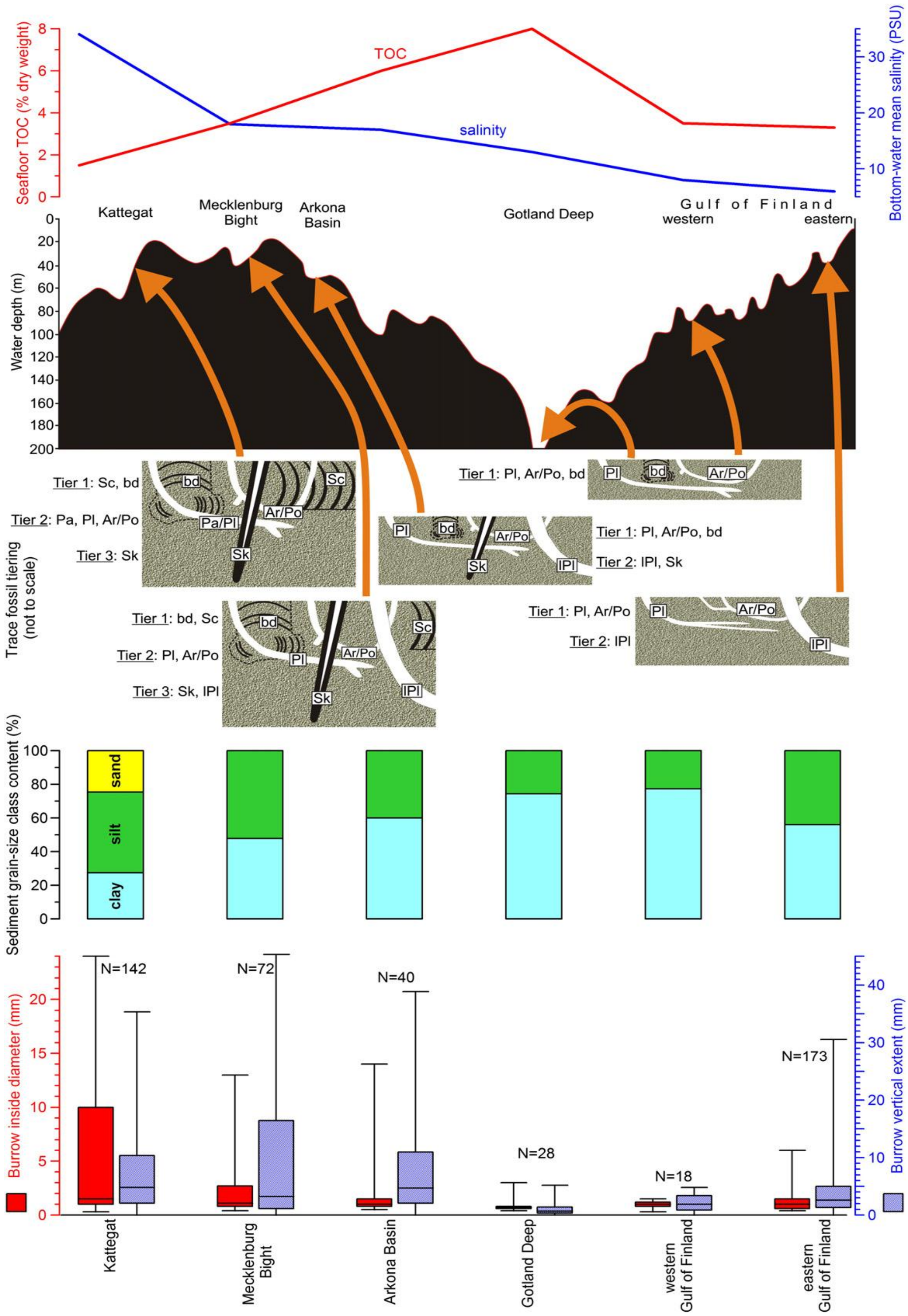

Fig. 9. Ichnological characteristics and environmental gradients along the studied open-water transect across the Baltic Sea. Sediment total organic carbon contents (% dry weight) in the uppermost 1–2 cm of the modern seafloor are from Leipe et al. (2011). Near-bottom water salinity (PSU) and the water depth profile are modified from Leppäranta and Myberg (2009). Ar=Arenicolites, bd=bivalve biodeformational structure, lPl=large Planolites, Pa=Palaeophycus, Pl=Planolites, Po=Polykladichnus, Sc=Scolicia, Sk=Skolithos. From: Virtasalo et al. 2011a.

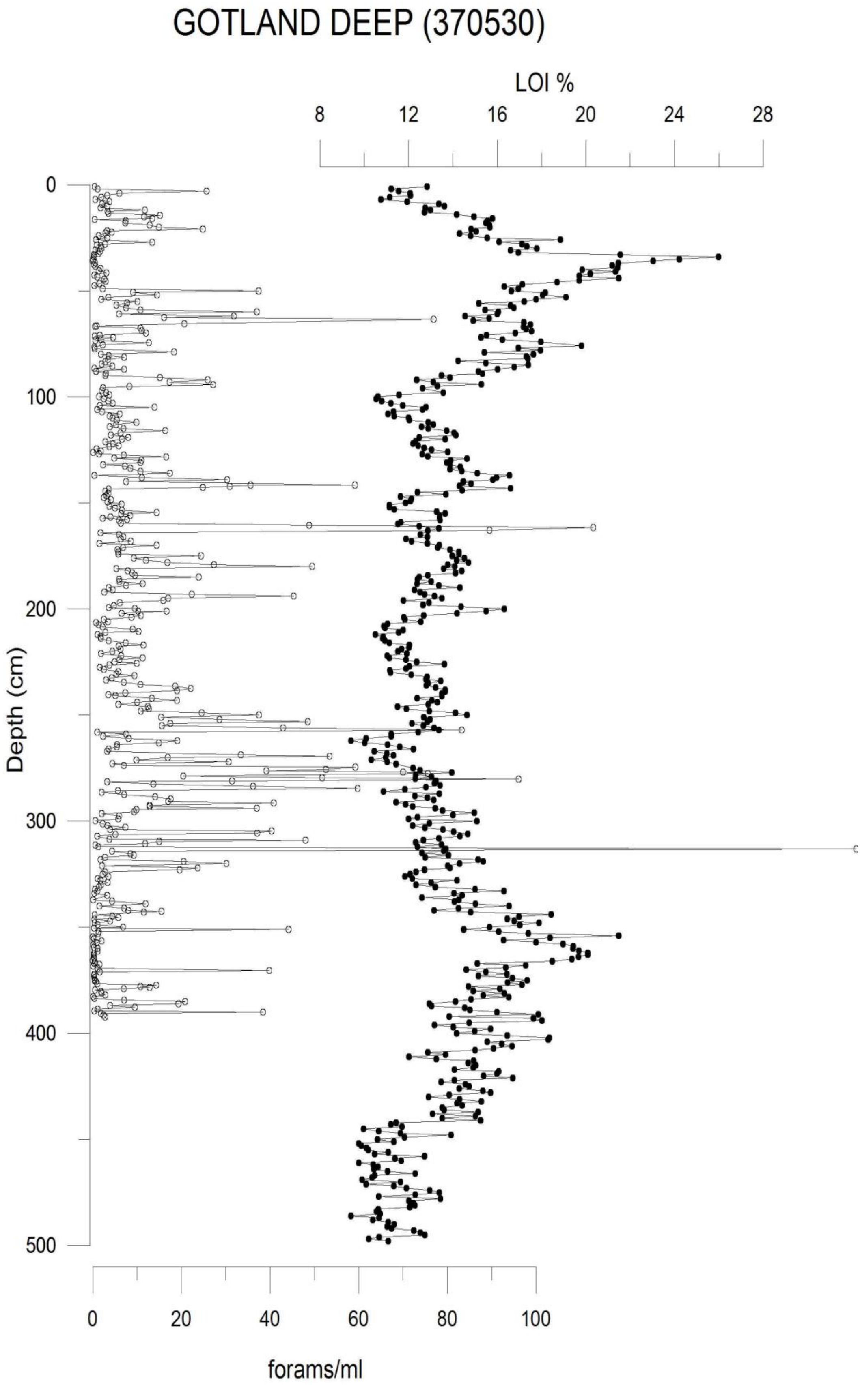

Figure 10. Benthic foraminifera counts (forams/ml) (open dot) and loss on ignition (LOI) concentrations (black dot) with depth in the Gotland Basin (Gotland Deep) sediment core 370530.

Stable isotope studies of benthic foraminifers

High-resolution stable isotope records (oxygen and carbon) were produced from three multicores from the Skagerrak and Kattegat (MUC372610, MUC372680 (B. marginata) and MUC242940 (U. mediterranea)). In MUC372610 three different species (U. mediterranea, B. marginata and M. barleeanum) were measured at all levels, and Mg/Ca is measured on U. mediterranea. Furthermore, oxygen and carbon isotopes are measured at every cm in gravity core GC372610 (U. mediterranea), providing a 5000 years long climate reconstruction from the Skagerrak area.

Comparing the oxygen isotope records from the last 40 years with instrumentally recorded temperatures and salinities shows a strong potential for high quality temperature reconstructions from Skagerrak; the benthic $\delta^{18}O$ provides a very good reconstruction of the instrumentally recorded temperatures (Fig. 11). Similar, warmer bottom water (ca 300 m) temperatures in Skagerrak, reconstructed and instrumentally measured, correspond with the positive phases of North Atlantic Oscillation (NAO) variability through the last 40-years, in agreement with suggestions from literature. Increasing the time scale, going back to 1850, the relationship between $\delta^{18}O$ in Skagerrak and predominant NAO forcing are still present at multi-decadal timescales. Hence, the record of the last 5000 years given by GC372610 has the potential to provide information on predominant atmospheric forcing in the area through the late Holocene. The record also shows a clear representation of the Medieval Climate Anomaly, the Little Ice Age, and the strong warming seen through the last decades, and will increase the knowledge on the dynamics behind these major climatic changes. In Kattegat, MUC 372680, a stronger relationship between the benthic $\delta^{18}O$ signal (40 m water depth) and salinity is indicated. However, relationship needs further investigation.

Comparing the benthic $d^{18}O$ (U. mediterranea) signature of the last 5000 years from the Skagerrak cores 372610 (this study) and 242940 (Moros and Jansen, unpublished data) with the planktic $d^{18}O$ signature from the Vøring Plateau core MD95-2011 (Risebrobakken et al., 2003) supports a clear linkage between the temperatures of the Norwegian Atlantic Current and the temperatures of the Atlantic water flowing into Skagerrak. However, it is also clear from this comparison that there are local differences within small areas in Skagerrak needs to be further investigated before major over-regional conclusions can be drawn from the data.

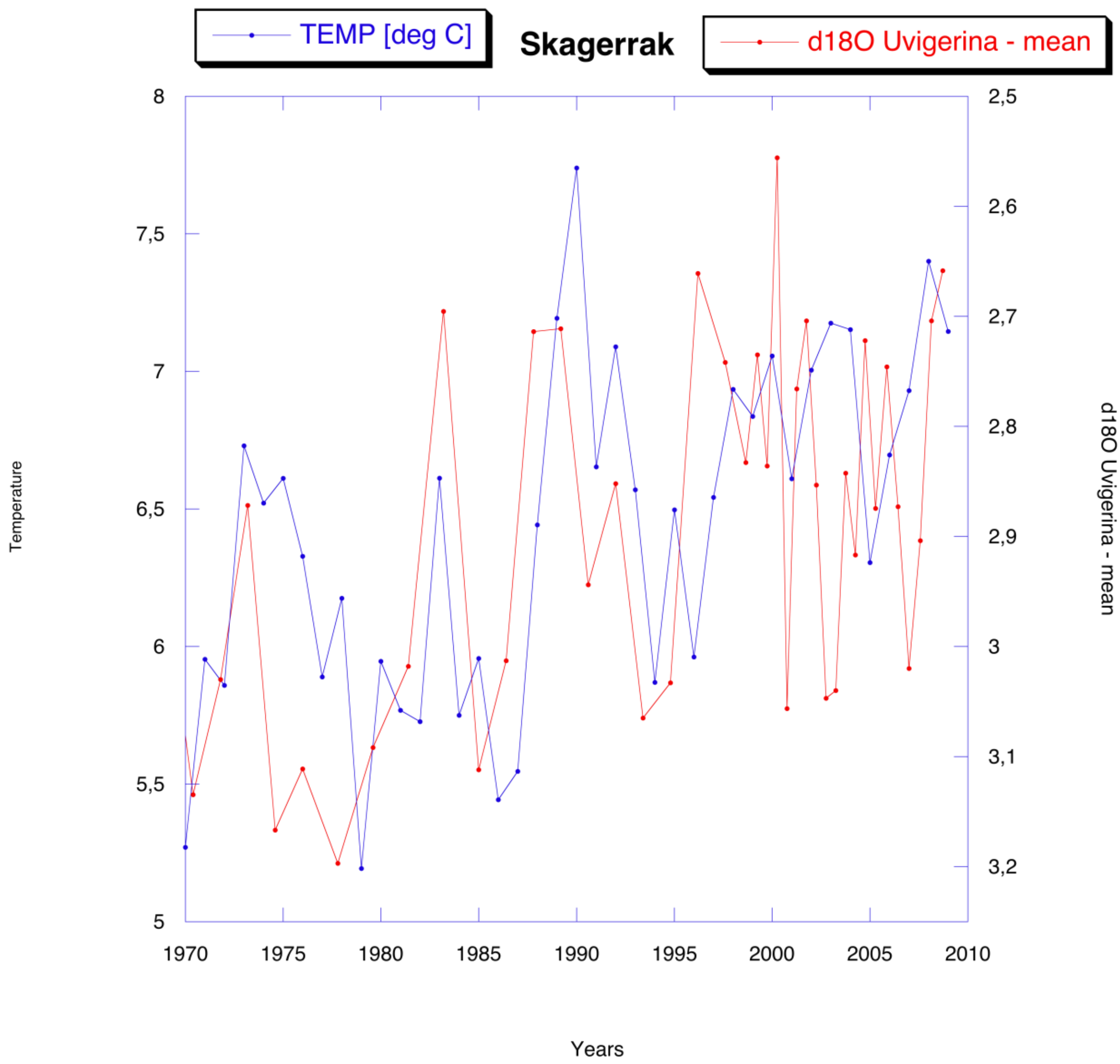

Figure 11. Uvigerina medeterranea $\delta^{18}O$ from MUC372610 and instrumentally recorded annual mean temperatures from corresponding water depth in Skagerrak (ICES 2011). Throughout the last 40 years (1970-2009) both main trends and amplitude of variability are comparable between the two records, emphasising the high potential of reconstructing past temperatures in Skagerrak using bethic $\delta^{18}O$.

$^{87}Sr/^{86}Sr$ studies

$^{87}Sr/^{86}Sr$ data were produced on 135 samples of biogenic carbonate of bivalve shells from sediment cores 371080, 317970 and 317990, and from raised beach deposits along the Finnish and Estonian coastlines. New freshwater end-member data was calculated for the Gulf of Finland, and reconstructions of surface water (down to 30 m depth) salinity were made for the Gulf of Finland, Gulf of Bothnia and Mecklenburgian Bay, while deep water salinities were studied in Bornholm basin. Surface water salinities in the Gulf of Bothnia have varied from 4 to 8 (±0.5) psu between ca. 6000 and 3000 cal yr BP. Compared to similar reconstructions from the Swedish coast (Widerlund and Andersson, 2011), the salinity estimates are 0-6 psu lower for the Finnish coastal area. The proxy salinities for the Gulf of Finland range from 0 to 10 (±0.5) psu between 7600 cal BP and the present day, with a maximum at 1700 cal BP, and a trend of declining salinities towards the present-day. The recent freshening of Northern Baltic waters was observed also by Widerlund and Andersson (2011). Reconstructed surface water salinities in Mecklenburgian bay display significant fluctuations, with recorded maximum salinity peaks of >20 psu at 7100, 6300, 1700, 1500 and 950 cal yr BP. Between 7800 cal BP and present-day, salinities have varied from 10±1 to 26 ± 6 psu. Both surface water records – from Mecklenburgian bay and Gulf of Finland – show the transition from Ancylus freshwater to the beginning of Litorina brackish water stage, with the timing of the transition in the Gulf of Finland lagging behind approximately 1000 years.

The Bornholm basin deep water salinity data represent the first direct quantitative evaluation of salinity variations in the deep water column. The single prior study on the subject, based on sediment chemical properties, estimated the Holocene maximum salinity at 18 psu (HuckriedeandMeischner 1996). According to the $^{87}Sr/^{86}Sr$ data, deep-water (water depth 90 m) salinities in the Bornholm basin have fluctuated mostly between 11±1 and 20 ± 4 psu during the past 4000 years. Two strong pulses of highly-saline water, with reconstructed salinities significantly above 20 psu, are recorded in shells at 160-170 cm and 270 cm depth below sediment surface, with preliminary, indicative dates of ca. 1.7-1.8 kyr and 3 kyr cal BP, respectively, based on depth-correlation to a nearby ^{14}C-dated core.

Biomarker TEX86 SST measurements

For the first time, biomarker TEX_{86} based sea surface temperature (SST) studies have been successfully applied on the Baltic Sea sediments (Adolphi 2010). Measurements have bee continued on multi-cores from the Northern Central Basin and Gotland Basin, and on key-long cores 370530 and 303600 from Gotland Basin (Kabel et al.). TEX_{86} measurements on a set of the Baltic Sea surface samples, multi-corer and trap material have been calibrated using instrumental data available for the last 50 years (collaboration with modellers). The new calibration was applied on the multi-corer and long core data.

Sea surface temperature (SST) reconstructions, based on TEX_{86} studies, indicate 2-3 °C variability, between Medieval Climate Anomaly, Little Ice Age (1450-1850), and Modern Warm Period (Fig. 12). This variability is higher than expected. Oxic conditions in the Gotland Basin recorded in the sediments by various parameters have been also reconstructed by ecosystem models for the Little Ice Age.

Around thousand years ago, during the Medieval Climate Anomaly, the average sea surface temperature of the Baltic Sea was around at same level as today. An exception is the shallow water coastal environment where since the ending of the 20th century maximum temperatures appear occasionally to exceed those found for the Medieval Climate Anomaly. During the Little Ice Age the sea surface temperature of the Baltic Sea was 2-3 °C colder than today. The establishment of anoxic conditions in the deep basin began parallel to the temperature rise from the Little Ice Age towards the Modern Warm Period (Fig. 12). In shallower areas anoxic conditions were established much later (Fig. 12). INFLOW results highlight a strong effect of sea surface temperature changes on redox conditions in the central Baltic.

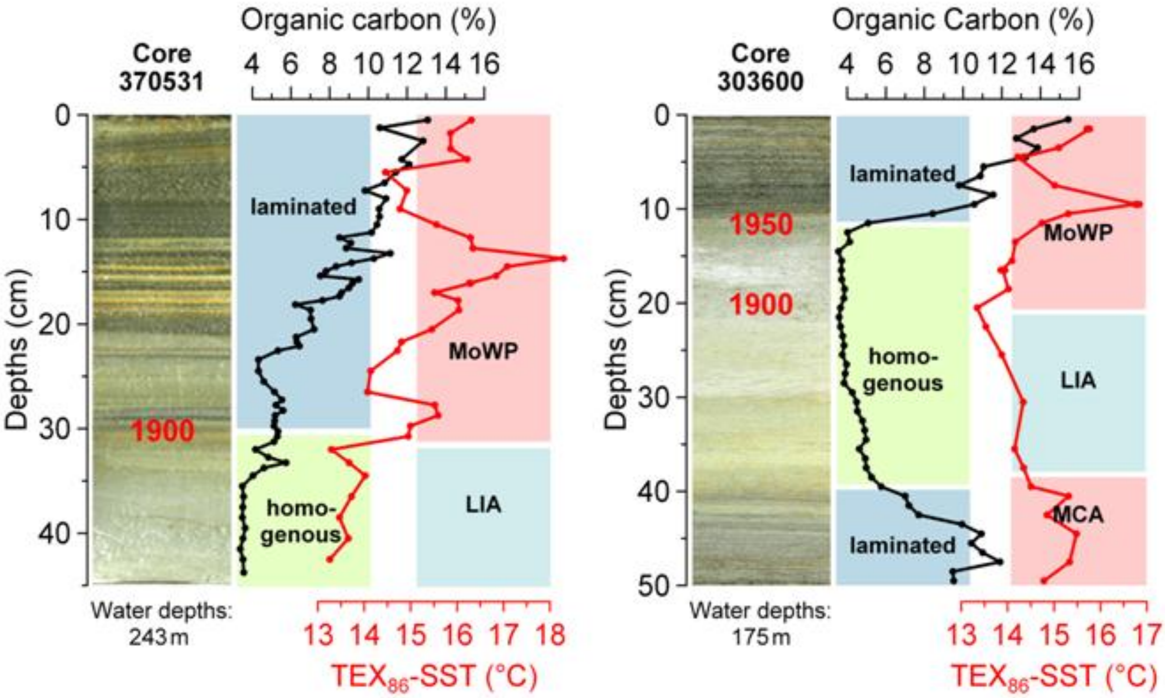

Figure 12. Photographs of sediment cores (370531 and 303600) from the Baltic Sea (Gotland Deep) (left), together with organic carbon (%) (black curve) and TEX_{86} estimated sea surface temperatures (ºC) (red curve). MoWP, LIA and MCA indicate Modern Warm Period, Little Ice Age, and Medieval Climate Anomaly, respectively. Also shown: estimated age-depth correlation (years 1900 and 1950) and water depths of sediment coring sites.

Diatom anylyses

For reconstruction of surface water salinity in the Baltic Sea during the last 6000 years several gravity and MUC's corers were sampled for diatoms analyses. In the first step, over 140 samples collected from several long cores were prepared (over 270 microscopic slides) and analyzed. The results provide an overview of the diatom preservation and quality of the environmental record to be expected. From core 370530 over 300 samples were prepared. Preliminary analyzes of samples show that the diatom preservation status below 105cm is very poor. All diatom samples from 370530 were analyzed under the light microscope, but only first 100 cm of core turns out useful for performing a diatom based salinity transfer function.

During preparation of salinity transfer function based of diatoms as indicators of surface water conditions it is necessary to provide calibration set, which is based on modern diatoms assemblages and measured, oceanographical data (salinity). To provide such calibration set the University of Szczecin constructed a training set for a salinity based transfer function for the Baltic Sea. During the project duration over 250 surface samples were been prepared (over 700 microscopic slides) and analyzed. Sample locations are shown on a map (Figure 13).

All samples from the sediment surface layers contained abundant siliceous microfossils dominated by diatoms and chrysophyceans. Ebridians and silicoflagellates also occur in examined samples. Examination of microscopic slides along the salinity gradient (from 32 psu in Skagerrak down to 3 psu in Bothnian Bay) of the Baltic Sea revealed substantial spatial differences in the distribution of the dominant diatom species (Fig. 14). Differences were also observed in the distribution of the ebridians, chrysophycean cysts and silicoflagellates , which occurred only in western part of the Baltic, where salinity was higher than 15 psu. Over 100 samples from surface station were chosen for inclusion in the calibration set. Altogether 519 diatom species and species variation were identified during surface samples examination under the light microscope. Maximum number of diatom species and species variation identified in one sample was 73. Average number of species in all samples examined for calibration set was 33.

Considering diatom species composition, distribution and statistical analyses performed on results gained from surface samples it was possible to distinguish modern diatom assemblages typical for specific Baltic Sea region. For statistical analyses Microsoft Excel; Primer ver. 6; and R - statistical software has been used. The statistical analysis of gained results allowed to the check potential of „calibration set" as a reference for planned reconstructions of environmental condition (salinity). Results of MDS analysis confirmed the differentiation of diatom species composition in surface samples (Fig. 15). Statistical tests were performed to assess the suitability of a calibration set for reconstruction of the salinity changes in the Baltic Sea based on the fossil material from sediment cores. For this purpose analysis WAPLS (Weighted Averaging Partial Least Square Regression) was performed. Conducting this analysis allowed calibration of data obtained from surface samples and the environmental parameters (salinity) (Fig. 16). Obtained calibration results were considered as a sufficient to use selected surface samples set to reconstruct the surface water salinity in the Baltic Sea.

Reconstructions of environmental conditions was based on fossil material from the core no 370530. The core was sampled continuously from 0 cm down to 285.5 cm with samples interval from 0.3 cm to 1.3 cm. All together over 600 microscopic slides from more than 300 samples was prepared. Additionally, in order to obtain very high resolution data covering top 50 cm of the core, it was decided to provide diatom analysis on the core MUC 370530. Results of this analysis provided high resolution data on sediments from last few hundred years, and cover top most part of the „Master core" 370530 which could be destroyed due to the coring technology - gravity corer. The MUC core was obtained in the same location as a „master core". For the analysis 121 MUC core samples were taken from which 242 microscopic slides were prepared.

In order to carry out the reconstructions of the surface water salinity changes in the Baltic Sea diatomological analysis was performed on fossil material from cores MUC and GC 370530. Analysis of 370530 gravity core turn out that diatom preservation status below 105cm is very poor. All diatom samples from core 370530 has been analyzed under the light microscope, but only first 100 cm of core turns out useful for performing a diatom based salinity transfer function. During examination of fossil material 108 diatoms species and varieties were identified, chrysophyceans cysts, ebridians and silicoflagellates also occur in examined samples. Dominant taxon and species composition in examined samples are showed on Fig. 17 and Fig. 18

Based on gained results of diatomological analysis (recent and fossil material), and performed statistical analysis reconstruction of salinity changes in the Baltic Sea were performed. Results of the reconstructions were changes of the salinity in the Baltic Sea showed in „psu" digits (Fig. 19 and Fig. 20).

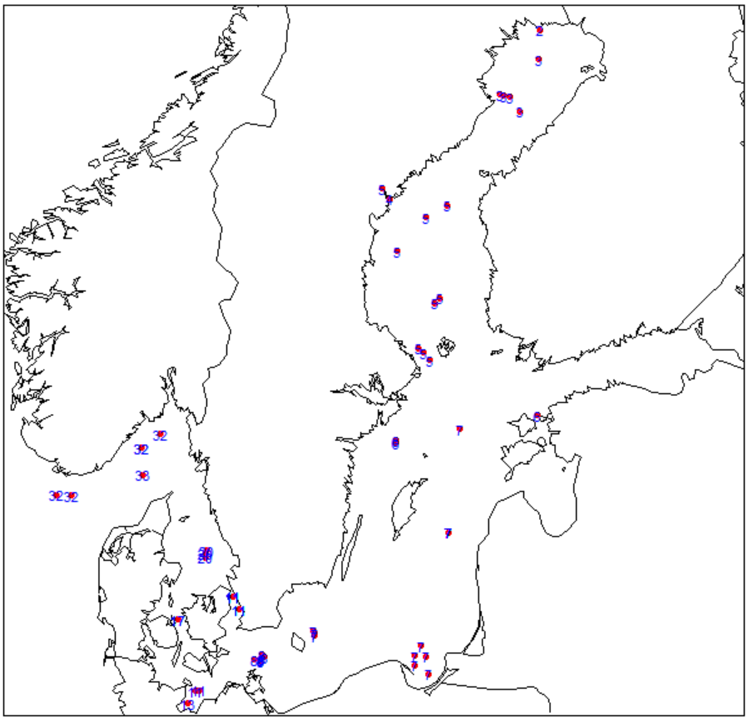

Figure 13. Map of the Baltic Sea showing locations of surface samples collected for „INFLOW" project and used for „calibration set".

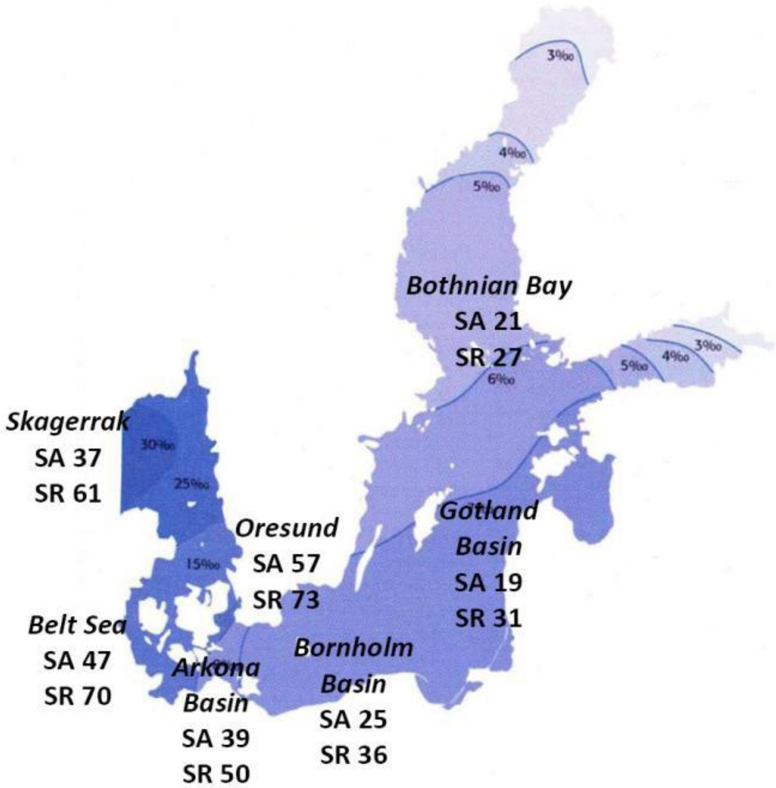

Figure 14. Average diatom species number (SA) and species richness (SR) in surface samples examined along salinity transect in the Baltic Sea.

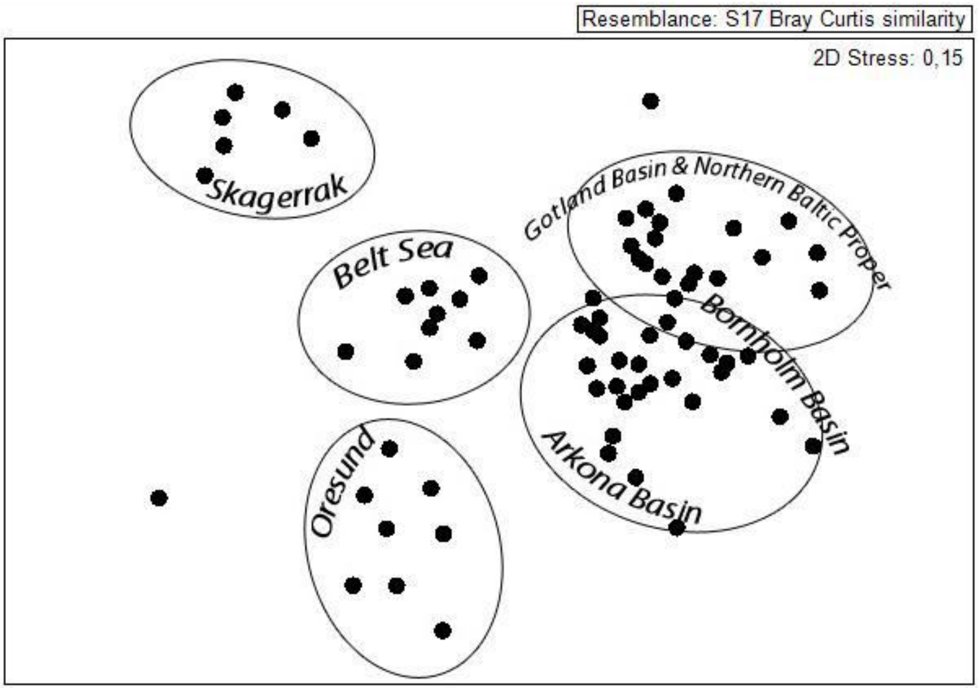

Figure 15. Results of MDS analysis for selected surface samples set.

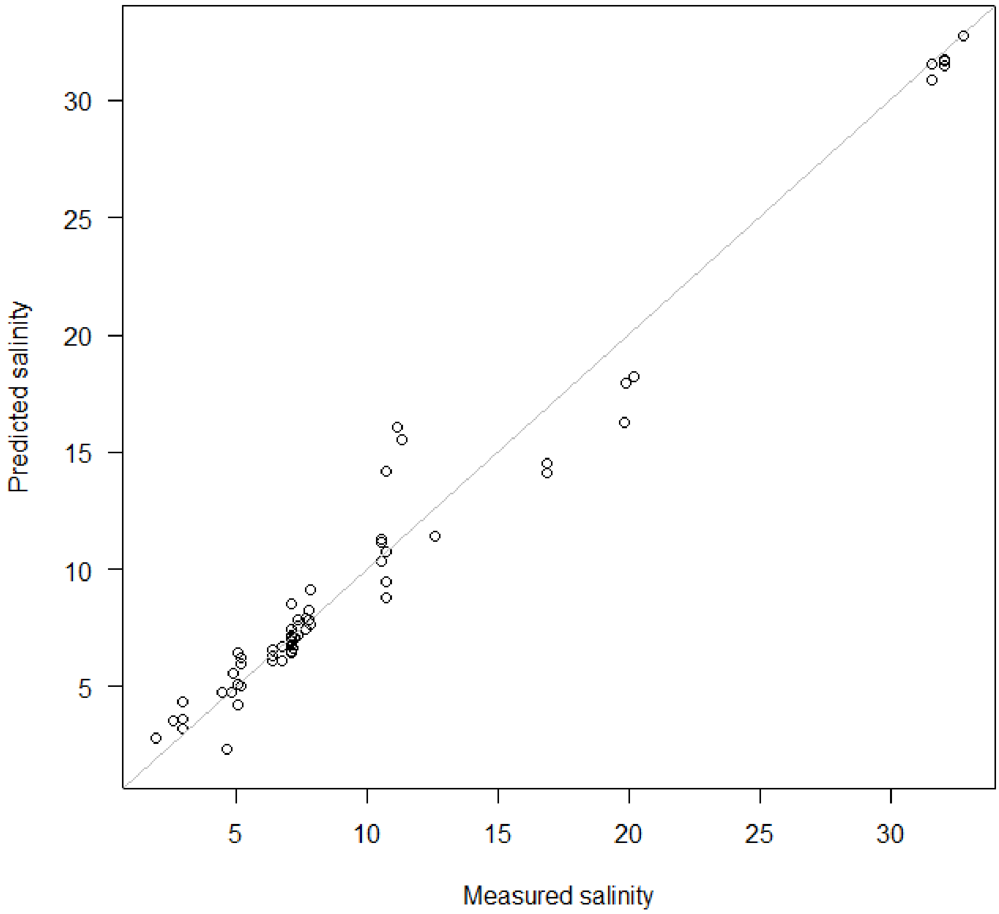

Figure 16. Results of WAPLS analysis for surface samples set. Salinity measured vs. predicted

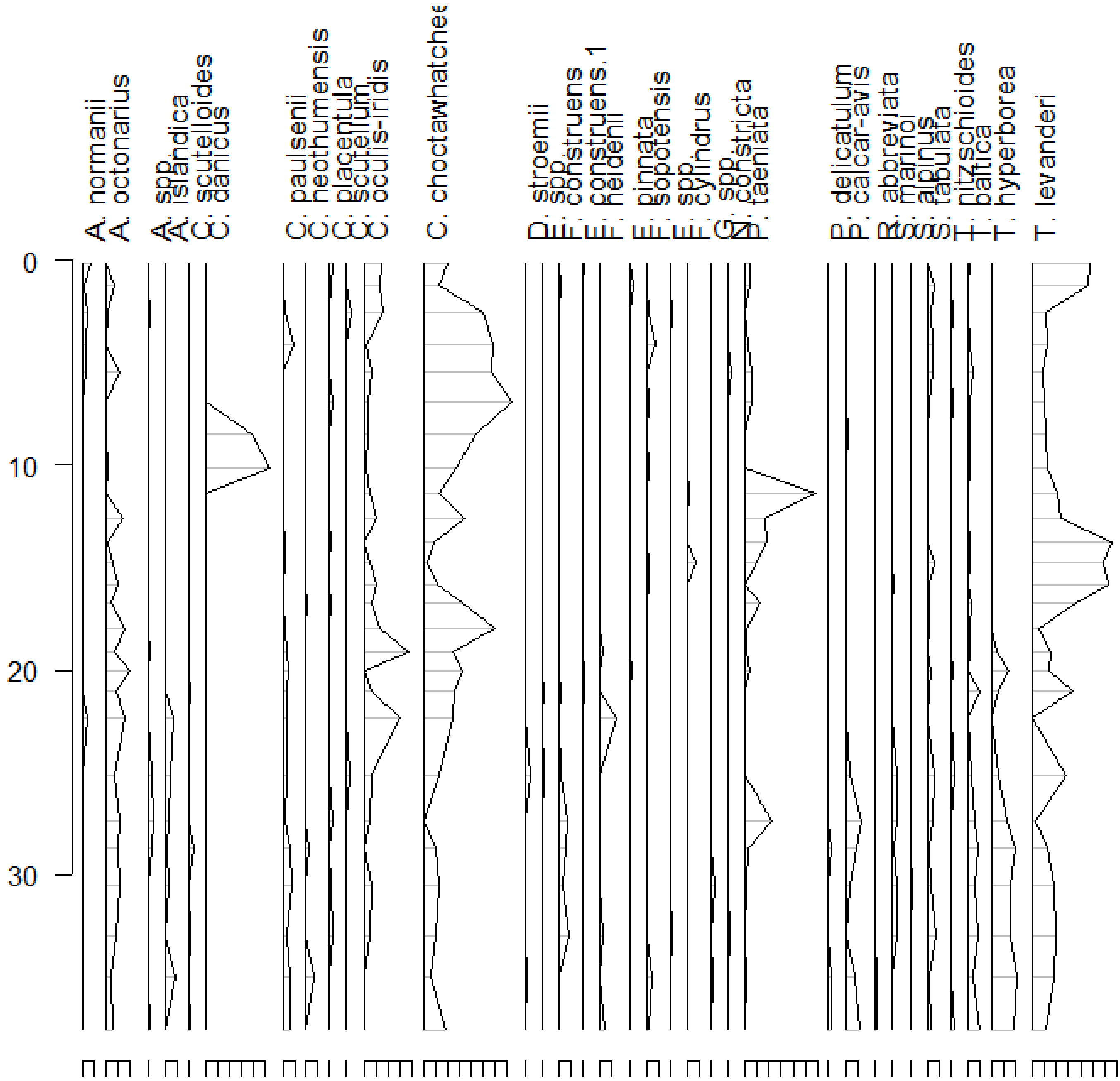

Figure 17. Dominant diatom species identified in the MUC 370530 sediment core from the Gotland Basin, the Baltic Sea.

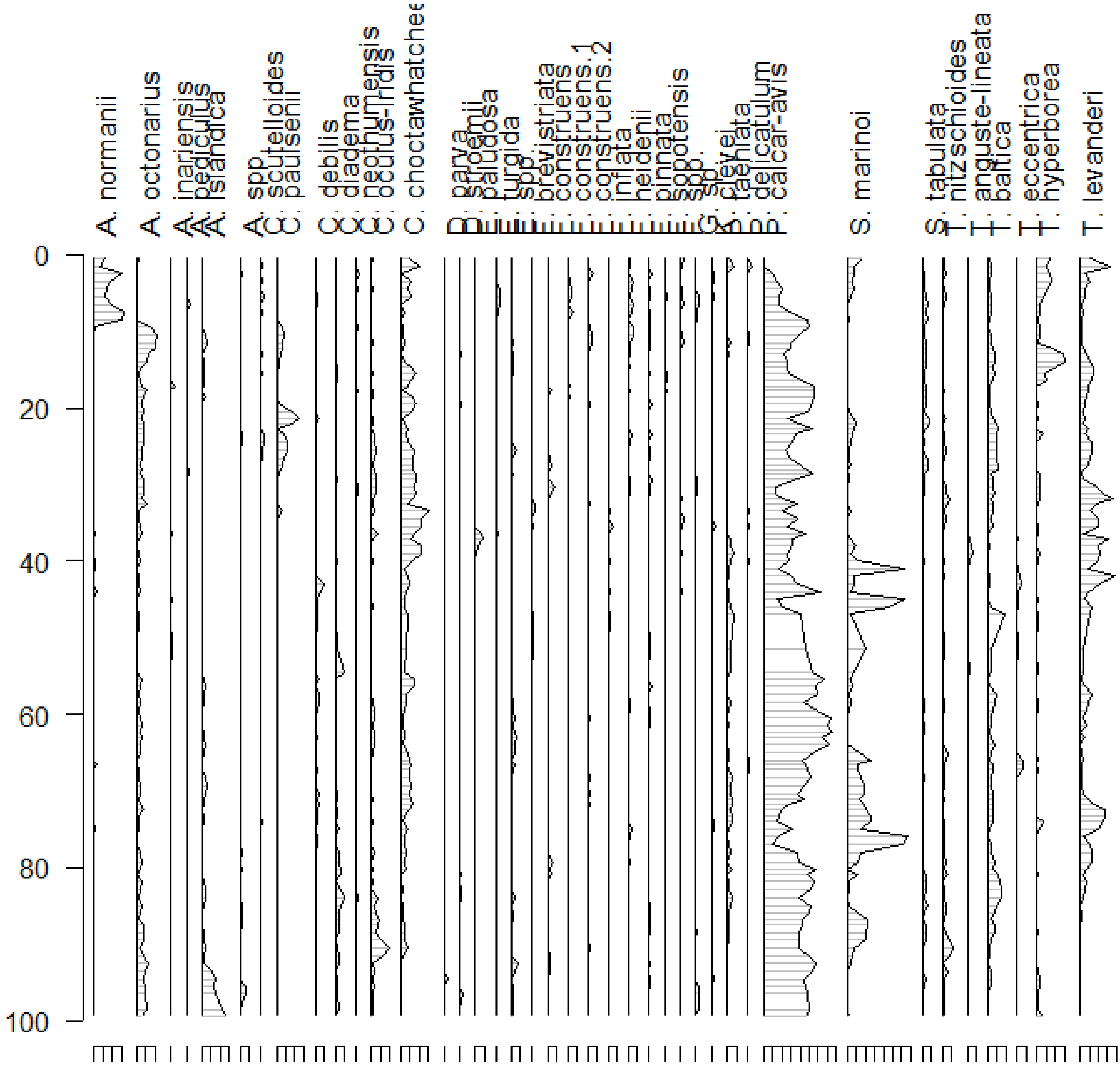

Figure 18. Dominant diatom species identified in the GC 370530 sediment core from the Gotland Basin, the Baltic Sea.

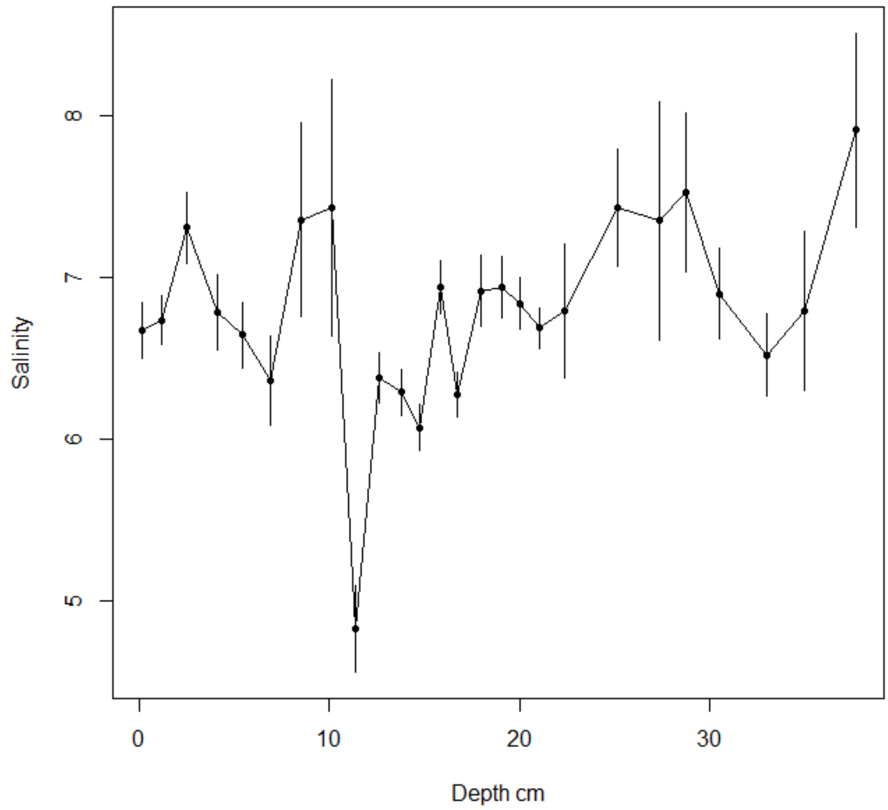

Figure 19. Result of salinity reconstruction [psu]; sediment core MUC 370530 from the Gotland Basin.

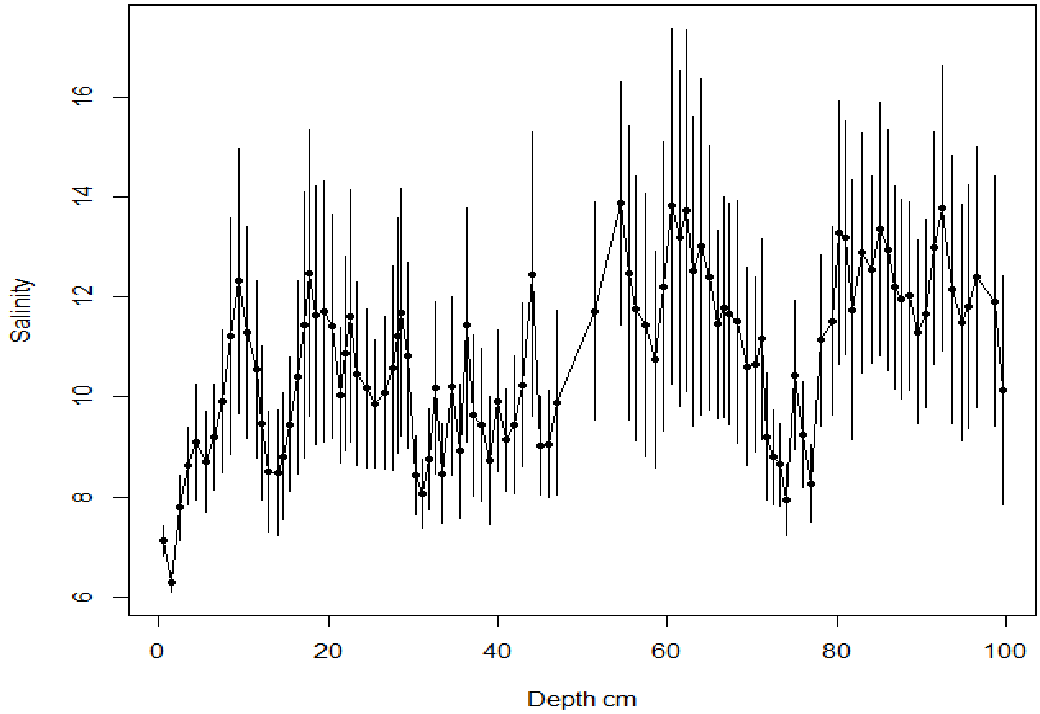

Figure 20. Result of salinity reconstruction [psu]; sediment core GC 370530 from the Gotland Basin.

To verify salinity reconstructions based on diatom „transfer function" method „traditional" - based on ecological preferences of diatoms species, salinity reconstructions were provided (Fig. 21).

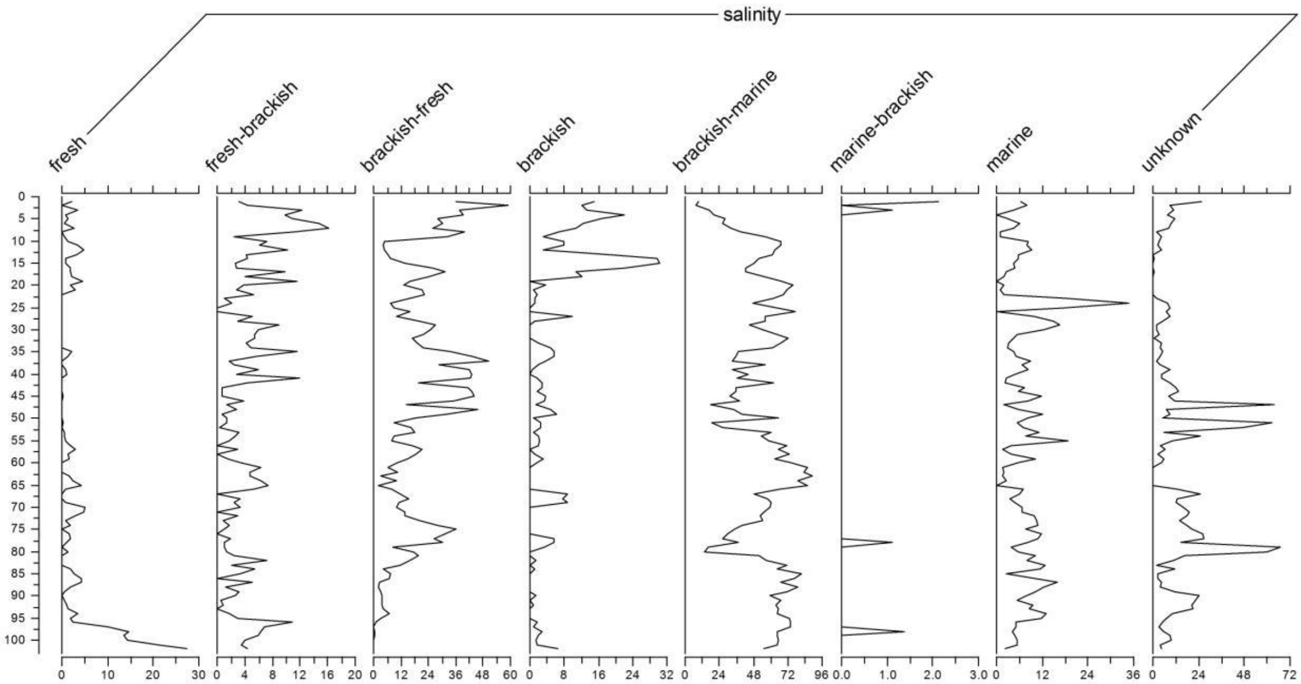

Figure. 21. Results of salinity reconstructions based on ecological preferences of diatom species; sediment core GC 370530 from the Gotland Basin, the Baltic Sea.

Salinity reconstructions from both, surface sediment core (MUC 370530) and long sediment core (GC 370530) show high variability with depth (through time). In the surface sediment core salinity varied from ca 5 to 8 PSU in the upper 40 cm of sediment column (Fig. 19). In the long sediment core salinity varied from ca 6 to 14 PSU in the upper 100 cm of sediment column (Fig. 20). Age models suggest that in the sediment core MUC 370530 the surface layer corresponds to present day (2009) and the depth of 30 cm corresponds to year 1900 AD. In the long sediment core (GC 370530) the depth of 100 cm corresponds to ca 1500 cal years BP.

Dinoflaggelate, alkenone and IP25 studies.

Dinoflagellate cyst analysis of sediment core material from the Gotland Basin and foraminiferal studies of sediment core material from the Kattegat has continued at GEUS. In addition, ongoing work has focused on a high-resolution temperature reconstruction for the Isefjord (southern Kattegat) based on alkenones and IP25 (sea ice indicator). Furthermore, efforts were made in linking Baltic hydrographic changes at the Medieval Climate Anomaly / Little Ice Age transition (MCA / LIA) to large-scale circulation changes in the North Atlantic.

The main conclusions from above (dinoflaggelate, alkenone and IP25) studies demonstrate a clear link between large-scale North Atlantic circulation and Baltic Sea inflow activity. This applies both for the MCA / LIA transition as well as for earlier (mid-Holocene) changes of respective circulation regimes. A shift in the large-scale North Atlantic ocean and atmosphere circulation near 4000 BP is also clearly reflected in the Baltic inflow/outflow pattern as recorded by the foraminiferal fauna in Kattegat sediments. Mid- to late Holocene (atmospheric) temperature changes recorded in the shallow Isefjord, southern Kattegat, coincide with above shifts in the hydrographic regime, and reflect ocean-atmosphere interaction patterns at various time scales. Higher Isefjord temperatures in the past 2000 years prevailed during the MCA and preceding Roman Warm Period, with an absolute maximum during modern warming having been reached during the past 2 decades. During the same periods sea level in the Kattegat was relatively high due to local sea level response to generally dominating strong zonal (west wind, positive NAO index) circulation. From other studies it is known that strong zonal circulation over the North Atlantic and central Europe favours Baltic inflow processes, which are, amongst others, also dependent on the relative difference in sea level between the Kattegat and western Baltic. Such conditions thus prevailed during the MCA leading probably to enhanced inflow activity and consequently stronger stratification resulting in oxygen deficiency problems in the Baltic proper. Furthermore, in the Gotland Basin a rising halocline leads to increased availability of nutrients in the photic zone, which together with generally higher MCA temperatures may have led to increased cyanobacterial summer blooming. Sediment geochemical records provide evidence that deeper water masses of the Bornholm Basin and Gotland Basin experienced significant changes in salinity. Such changes are also documented for surface water masses as inferred by virtue of the dinoflagellate cyst record from the Gotland Basin sediments.

Methods such as **XRF scanning**, **EDX**, ICP-MS, ICP-AES, Leco (C, N, S) were also used for geochemical analysis of sediment cores. **Loss on ignition (LOI)** measurements were performed on surface sediment cores (MUCs) and long sediment cores from about 40 sites (Kattegatt, Mecklenburgian Bight, Arkona Basin, Bornholm Basin, Gotland Basin, Northern Central Basin, western Gulf of Finland, eastern Gulf of Finland) (Fig. 22). Parallel total organic carbon (TOC) measurements were performed to allow a conversion LOI to TOC.

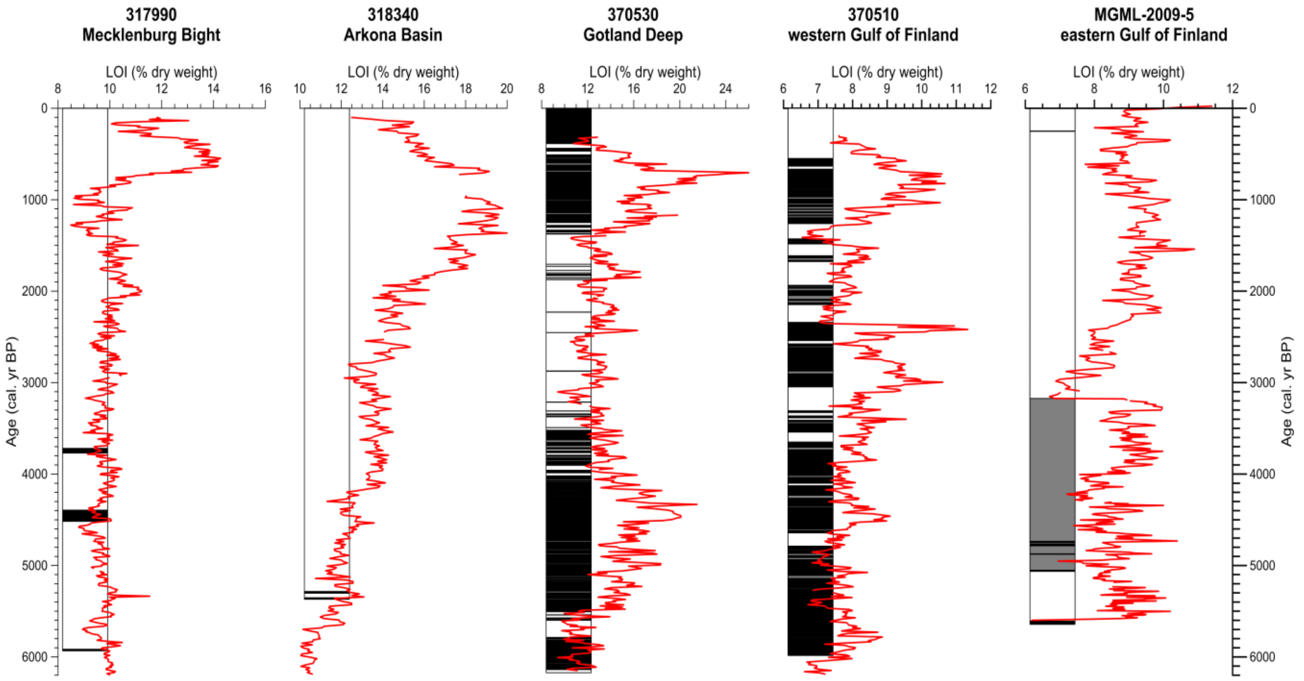

Figure 22. Loss on ignition (LOI) (%) versus age (cal years BP) from selected sediment cores from Mecklenburg Bay, Arkona Basin, Gotland Deep, western Gulf of Finland and eastern Gulf of Finland. Laminated (black), biodeformed (grey) and burrow-mottled (white) lithofacies are indicated in the sediment columns.

Eastern Gulf of Finland studies

Detailed study of core 09-BI-3, recovered from the local sedimentation basin in Vyborg Bay (60º17.506 N, 28º 03.405 E, depth 40 m) has a great importance for understanding of the Late Pleistocene – Holocene geological history of the region. Visual description of the core enabled to distinguish three major lithostratigraphic units: brownish-grey badly laminated clay corresponded to the Baltic Ice Lake period (the core depth of 129-246 cm), grey, sometimes black, silty clay with black micro-inclusions of amorphous iron-sulphides presumably formed during the Ancylus Lake period (the core depth of 104-129 cm), and laminated, olive-grey, silty-clayey sediment accumulated during Littorina and Post Littorina stages (the core depth of 96-0 cm). At the core depth of 96-104 cm there is a very special sediment layer called "blue clays", which is rarely observed in the sediment sequence of the Eastern Gulf of Finland, and it is poorly studied from palaeoenvironmental point of view. The upper core interval (6-0 cm) is represented by unsorted clayey-silty-sandy sediment containing spheroidal Fe-Mn concretion up to 2 cm size. According to our previous investigations of concretions growth rate the age of spheroidal concretion of 2 cm diameter is in the range 650-820 years (Zhamoida et al. 1996). Accordingly silty-clayey sedimentation was changed in this area for non-sedimentation conditions at least 650-820 years ago. Grain-size and chemical analyses allowed receiving information on sediment dynamics and water salinity in the north-western sedimentation basin of the Russian part of the Eastern Gulf of Finland (Fig. 23). In particular our data suggest four significant salinity maxima during the Littorina Sea - Post Littorina stages including initial Littorina transgression.

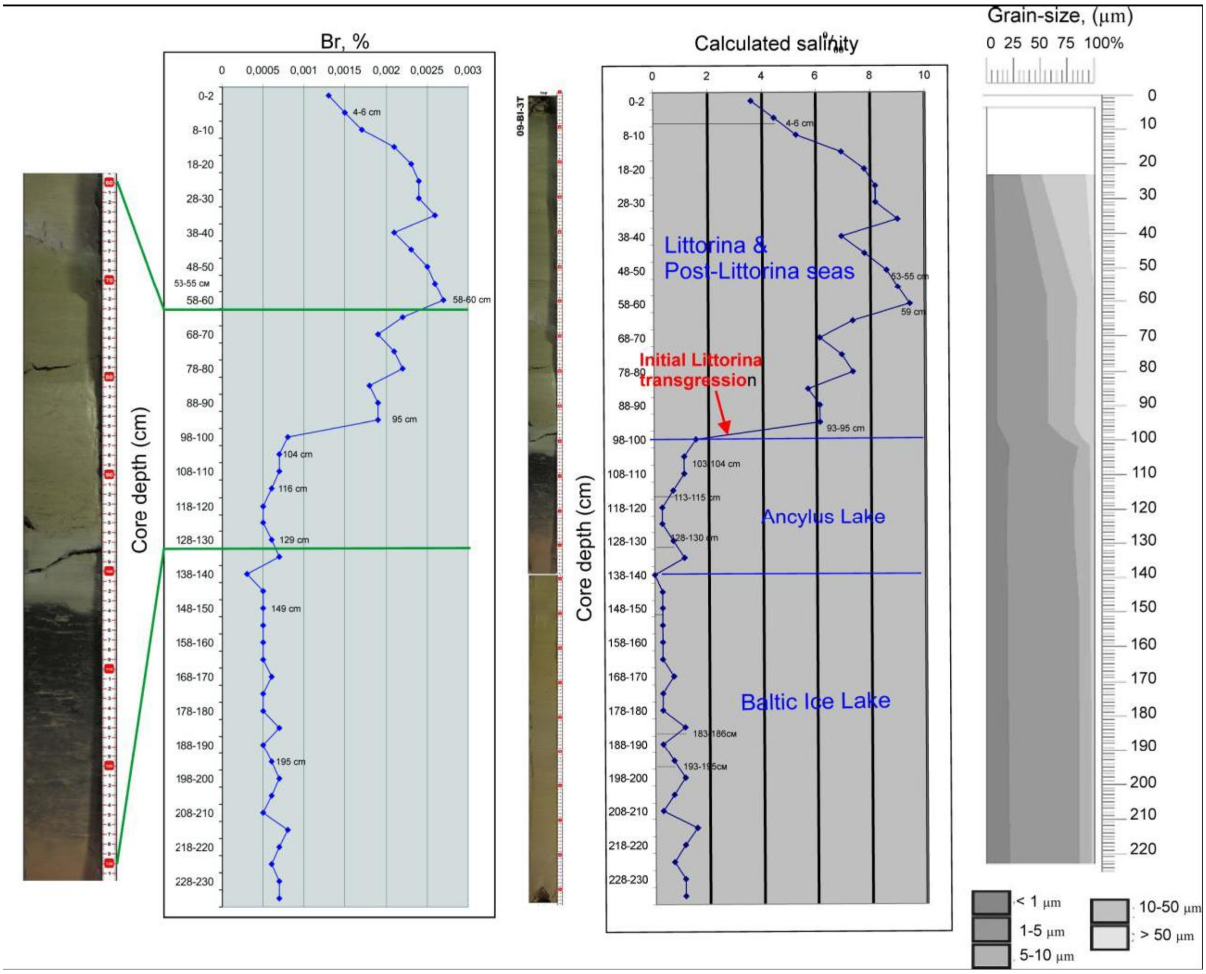

Figure 23. Photograph of the sediment core 09-BI-3 (the eastern Gulf of Finland), together with bromium (Br) content (%), calculated salinity (PSU) and grain-size. Different phases of the Baltic Sea history are indicated in figure too (namely Baltic Ice Lake, Ancylus Lake, and Littorina and Post-Littorina Seas).

Dating analysis of Site F40 sediment core allowed establishing the most significant events of Middle and Late Holocene history of the eastern Gulf of Finland. Distribution of Br concentration and grain-size distribution have suggested such events as (i) beginning of the Littorina transgression; (ii) six sub-cycles (transgression-regression) within Littorina Sea; (iii) the onset of the Neva Riva; (iv) Medieval Climate Anomaly; and (v) Little Ice Age (Fig. 24).

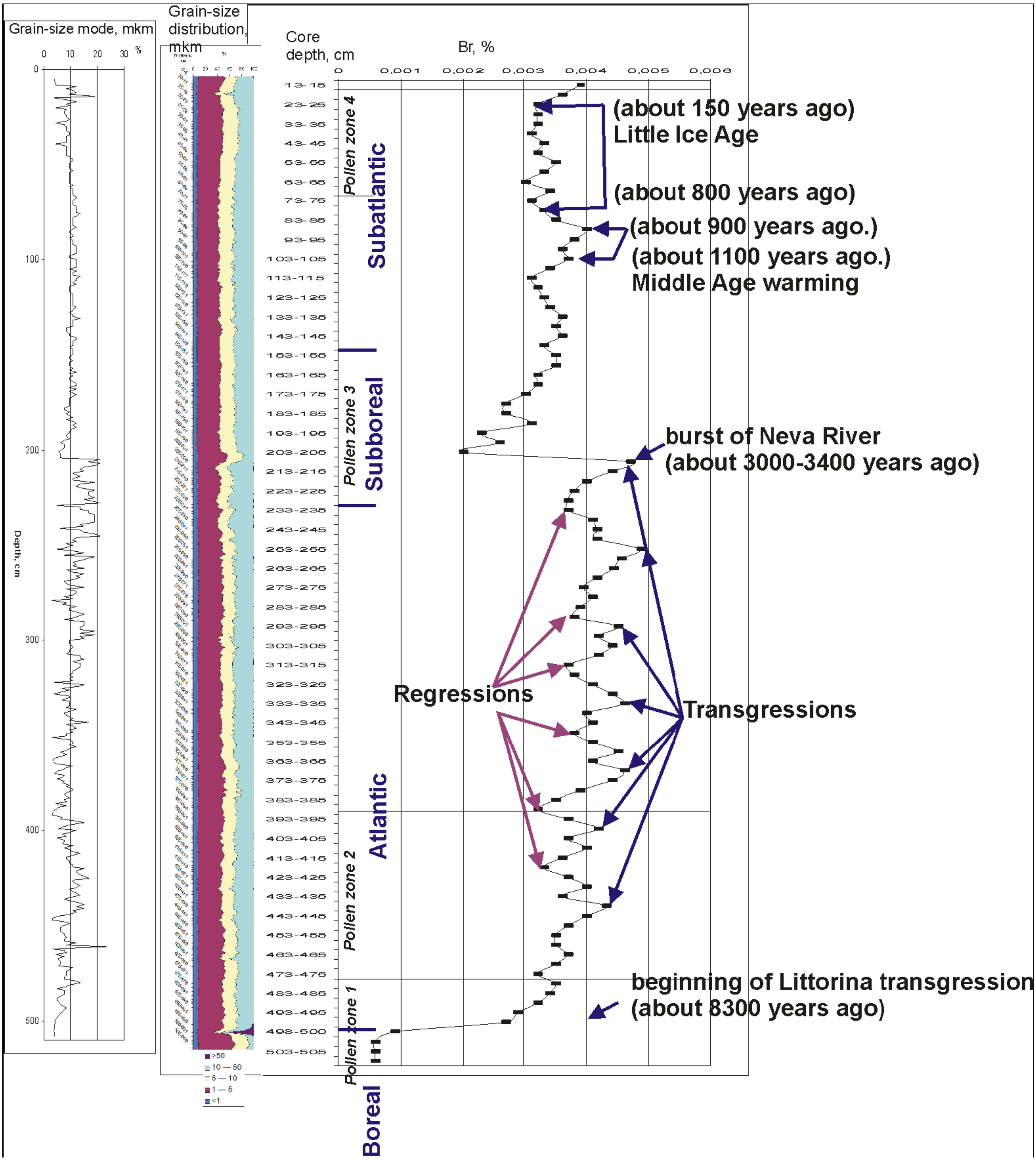

Fig.24. Grain-size mode, grain-size distribution and bromium (Br) content (%) in the sediment core MGML-2009-6 from the eastern Gulf of Finland site F40.

Upper unit of the core MGML-2009-6 (0-50 cm) is represented by dark olive grey clayey silt (the average content of clay particles is 47.3%, silt particles – 52.6%). There is no sand except of upper horizons (5-7 cm), where sand particles value reaches 1.62%. The next sediment unit (50-205 cm) consists of laminated olive gray clayey silt, bioturbated in the interval 148-167 cm. The average content of clay is 44%, silt - 46%, sand – 0.004%.

At the core depths of 205-212 cm there is a layer which upper part differs from the lower part of sequence by grain-size distribution. Coarse particle content increases to 63.4% for silt, and 0.44% for sand.

Sediment unit at the core depths of 212-249 cm is represented by dark olive grey laminated clayey silt with average content of clay particles 45.1% and silt particles 54.9%. Within upper (212-221 cm) and lower (242-249 cm) subunits there are no sand particles, but in the middle part average sand content grows to 0.35%.

Within the unit of laminated very dark olive grey clayey silt from the core interval of 249-391 cm, average clay content is 47.6%, silt – 52.3%, sand – 0.13%. The next unit at the core depths of 391-495 cm is represented by dark olive grey partly laminated clayey silt (48.5% of clay, 51.4% of silt, 0.13% f sand).

The unit at the core depths of 495-500 cm characterizes the “border” between Littorina Sea and Ancylus Lake. The content of clay particles decreases from the top of the unit to the bottom of the unit from 50.9% to 32,7%, silt - from 47,6% to 26,5%, content of sand particles increases from 2.45% at the depth 4.95-4.96 m to 40.8% at the depths 4.99-5.00 m). Thus the average contents of clay, silt and sand are 45.0%, 41.2%, and 13.8%, respectively.

Sediments of Ancylus Lake (down 9 cm of the core - interval 500-509 cm) differ from the Littorina and postLittorina deposits, as they are represented by brownish grey silty clays with 65.5% of clay particles and 35.5% of silt, and with no sand.

Analyses of grain-size (hydraulic size) mode (left graph, fig.10) have shown that sediments of Ancylus Lake were formed without active hydrodynamics impact. Sedimentation environment during forming the deposits between the core depths of 205-500 cm was active and variable. During the deposition of sediments at the core depths between 40 and 205 cm, hydrodynamic conditions were much calmer. The upper part of the sediment core was formed under the influence of near-bottom currents again.

The most interesting results from the eastern Gulf of Finland studies were received using analyses of the trend of Br-concentration changing (right graph, fig.24). The trend of Br concentration shows a drastic change (increase) of water salinity at the depth 495-500 cm, which is interpreted as the onset of the Littorina transgression. Six distinct alterations of Br-concentration occurred in the interval of 205-495 cm, which can possibly be interpreted as the transgressions and regressions of the Littorina Sea.

At the depth 205-212 cm there is a drastic significant decrease of Br-content, which can be interpreted as the onset of the Neva River (see also the results of mineral magnetic and sediment fabric analyses). In the post-Littorina sediment sequence it is possible to find peaks that can be explained as Medieval Warming and Little Ice Age.

The dates of events were preliminary estimated using the linear sedimentation rate between modern surface (the strong increase in the ^{137}Cs activity in the sediment core at the depth of 6 cm corresponds to the fallout of the Chernobyl nuclear power plant accident of the year 1986) and the onset of the Littorina transgression that was estimated approximately 8300 years ago. Later these dates were corrected according to 14C- and palaeomagnetic -dating.

Received results have a great importance for palaeogeography of the Eastern Gulf of Finland as there is no uniform opinion about the timing and number of Littorina transgression.

As for the timing of the onset of Neva River, according to many scientists (Sevastianov et al., 2001) it is still one of the most interesting and unclear questions of Holocene geological history in spite of many research and publications (Kvasov, 1979; Saarnisto, 1996; Subbeto et al., 1998). According to most part of scientists, this event took place in Middle or Late Holocene, 4000-4500 years ago according to A.Yakovlev and U.Ailio (1926), 2000 years ago according to O.Znamenskaya et al. (1970), 2300-1300 years ago according to D.Kvasov (1979), and 3100 years ago according to M.Saarnisto (1970; 1996). Besides there is another point of view, supported by some specialists (Verzilin et al., 2003) the Neva is much "older" and formed in the Pleistocene. It should be mentioned that all data for these hypotheses were obtained from terrestrial deposits. Sediments of the Eastern Gulf of Finland have never studied from this point of view.

An age-model developed for the site F40 core in the INFLOW project, suggests that the onset of the Neva River took place ca 3100 cal years BP. These results received in the range of the INFLOW project will help to solve the problem of the onset of the Neva Riva, and the palaeoenvironmental history of the Gulf of Finland.

Modelling

Forcing data for time slice experiments

Global climate simulations (ECHO-G) were downscaled for the Baltic Sea Region for 950-1849 using the regional climate model RCA3. A forcing data set for the LIA (Little Ice Age, Maunder minimum from 1657 to 1704) has been reconstructed based on the delta-change approach. In co-operation with the BONUS-ECOSUPPORT project, transient simulations have been performed for a future climate (1960-2099) using RCAO/ECHAM5-A1B_3, RCAO/ECHAM5-A1B_1, RCAO/ECHAM5-A2 and RCAO/HadCM3-A1B model combinations to provide forcing for the regional Baltic Sea ecosystem models. In addition, a statistical model has been developed to calculate runoff and sea level data from the output of the regional climate model for both future scenario simulations and the long past climate simulation.

Time slice experiments -simulation of the Baltic Sea ecosystem

The validation of the ecosystem model (ERGOM) was done by comparison of the reference model results with instrumental data for the time period of 1961 to 2007. The instrumental data sets consist of up to four million single values depending on the particular parameter, which were adapted to the model's spatial and temporal resolution. Results of the validation are shown in Figure 25. The data were standardized before analysing. The spearman rank correlation coefficient of phosphate, oxygen, salinity, and temperature is in the range of about 0.7 and 0.95. For these parameters the ratio of the standard deviation is nearly one or something less and the deviation in the centred RMS is about one half of the standard deviation.

For the Little Ice Age period (Maunder minimum from 1657 to 1704) and the Medieval Climate Anomaly (MCA) changed signals for several model variables along a transect (see Fig. 26) are shown in Figure 27. The water temperature changed according to the alteration of the atmospheric temperature, while the salinity increased about 1 PSU during the LIA scenario and decreased about 0.5 PSU during the MCA scenario. The oxygen concentration increased up to 6 $ml \cdot l^{-1}$ in depths greater than 70 m during the LIA scenario, which is likely a result of the lower temperature and the reduced nutrient loads. During the MCA scenario the oxygen concentration is increased as well, but not as high as during the LIA. The deep areas of the Baltic Sea are mostly anoxic during the MoWP, hypoxic to oxic during the MCA and oxic during the LIA scenario. In the deeper parts of the Baltic Sea ammonium is reduced while nitrate increases. This reflects the oxygen conditions in the deeper part of the Baltic Sea. Phosphate is reduced in the whole Baltic Sea, especially in the deeper areas. Therefore the whole productivity of the Baltic Sea is affected by the climate variations of different time periods. Another aspect of the climate impact on the Baltic Sea is the ice cover. During the LIA scenario the maximum ice extent even the Danish streets are covered with an ice sheet, whereas during the MCA wide areas of the Baltic Sea are free of ice. The delta change approach is an appropriate method to simulate former states of ecosystems such as the Baltic Sea, but it has some weaknesses such the inability to change the pattern of the atmospheric forcing fields, which may have a significance impact on important processes of the ecosystem. That is quite important to simulate transition periods between the quasi stable states.

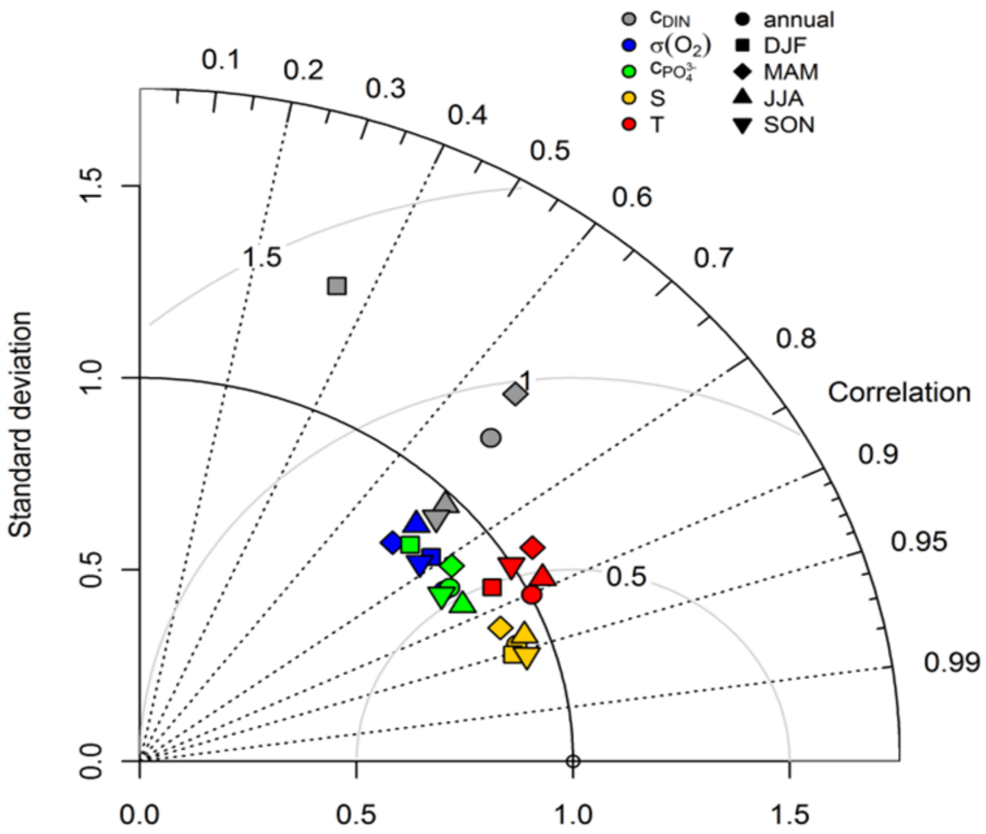

Figure 25. Taylor diagram, which shows differences in chosen variables of the model and observations. The circular arc around the point of origin prescribes the normalized standard deviation, whereas the observational data set are represented by a dot on the abscissa at normalized standard deviation of 1.0. The grey circles around this reference point shows the deviation of the centred root mean square (cRMS) and the dotted lines refer to the rank correlation coefficient by Spearman. The shapes of the points represent the different periods and the shades correspond to the different variables (c_{DIN}: Dissolved Inorganic Nitrogen, $\sigma(O_2)$: oxygen concentration, cPO_4^{3-}: phosphate concentration, S: salinity, T: temperature).

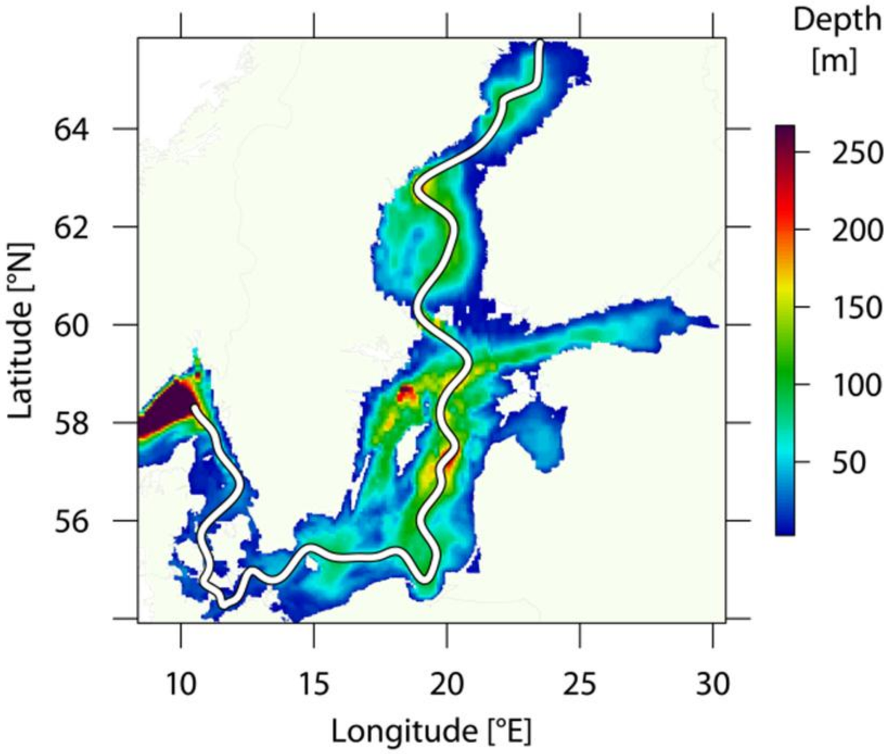

Figure 26. Overview of the chosen transect (white line) through the topographic map of the Baltic Sea model, which includes the main basins and sills.

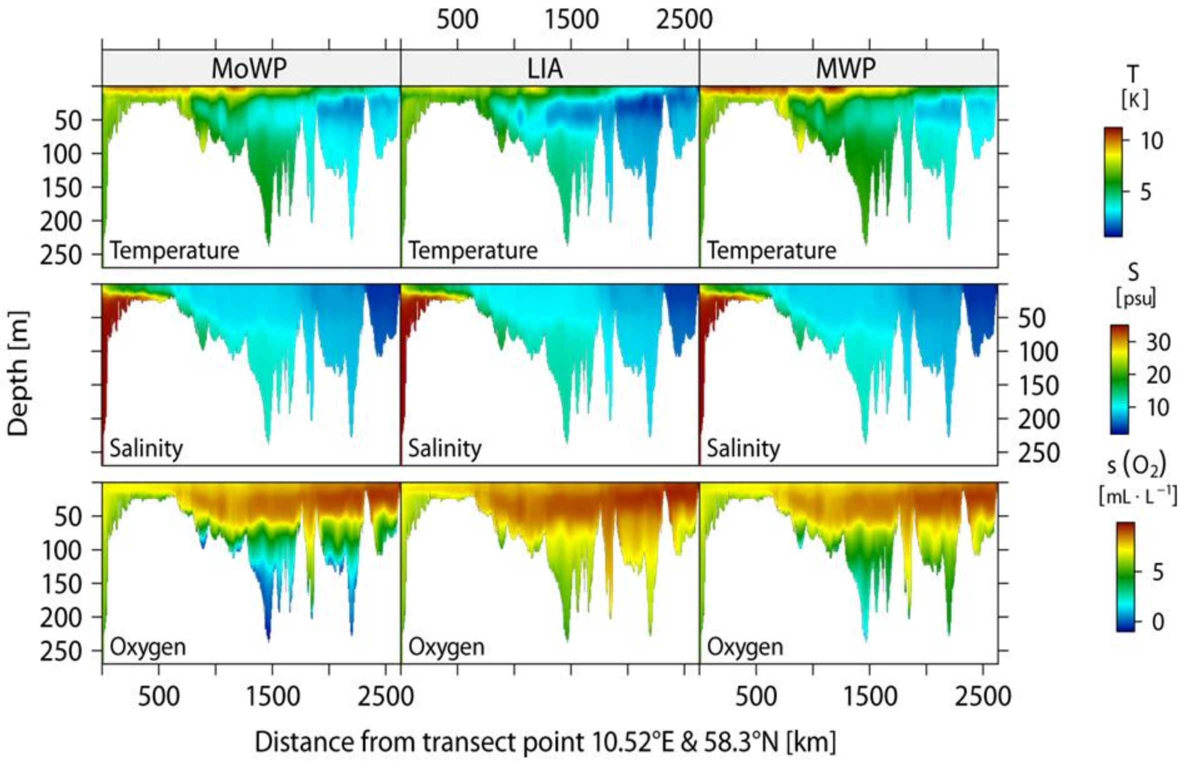

Figure 27. Median temperature, salinity, and oxygen concentration change between Modern Warm Period (MoWP), Little Ice Age (LIA), and Medieval Climate Anomaly (MWP) scenarios along a transect through the Baltic Sea (cf. Fig. 2). Calculated for 47 simulated years per scenario.

Future scenario simulations for 1961-2099

Future scenario simulations for 1961-2099 have been performed (Meier et al., 2011). Results for temperature changes from RCO-SCOBI are shown in Figure 28. Independently of the applied model we found the largest temperature changes in the Bothnian Bay and Bothnian Sea during summer. The increased water temperatures cause decreased oxygen concentrations in the entire water column (not shown) because the oxygen saturation concentration decreases with increasing water temperature. As the bottom water is ventilated by surface water on a decadal time scale, also the bottom oxygen concentrations will decrease in future climate with up to 2 ml/l in a A1B scenario. However, the bottom oxygen concentration will not decrease in areas where the stratification is decreasing due to increased freshwater supply from the rivers. These areas are for instance regions where the permanent halocline hits the topography in present climate.

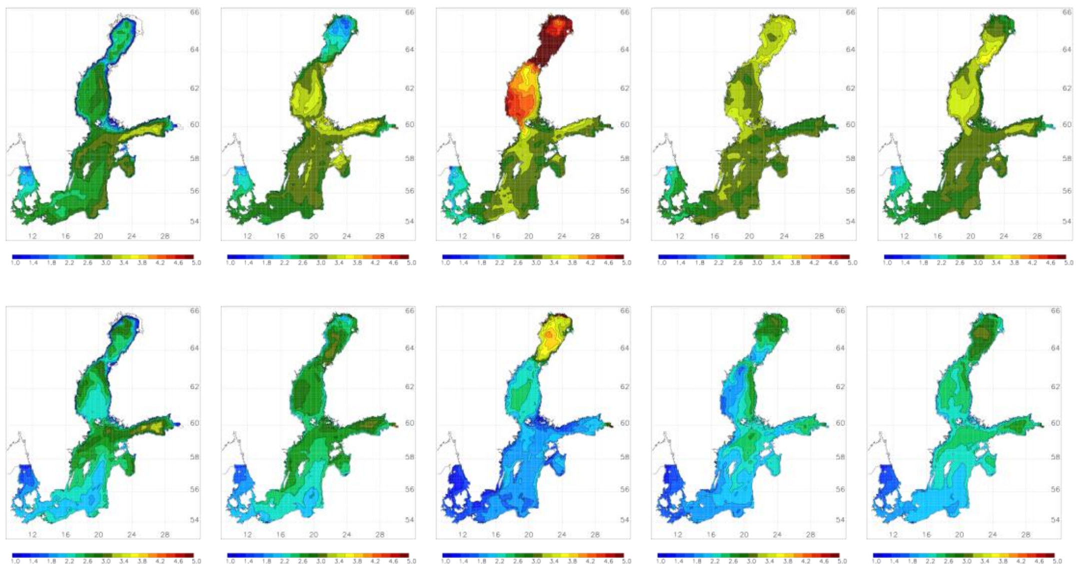

Figure 28. Annual and seasonal mean sea surface temperature changes (in°C) between 2070-2099 and 1969-1998 in RCO-SCOBI forced with RCAO-HadCM3_ref A1B_3 (upper panels) and RCAO-ECHAM5 A1B (lower panels). The columns show from left to right winter (December through February), spring (March through May), summer (June through August), autumn (September through November) and annual mean changes, respectively**.**

First steps have been made towards an uncertainties assessment of climate projections for the Baltic Sea. In figure 29, the sea surface temperature based on a 3 member ensemble for the A1B scenario is shown. The ensemble members are based on one Baltic Sea model forced with different combinations of global and regional atmospheric climate models. As seen from Fig 29 the strongest changes can be expected in summer in the northern Baltic similar to the findings indicated in Fig 28. The lower panels in Fig 30 show the range of the ensemble simulations, that means the difference between the maximum and minimum of the ensemble realisations. Largest uncertainties appear in summer in the northern Baltic.

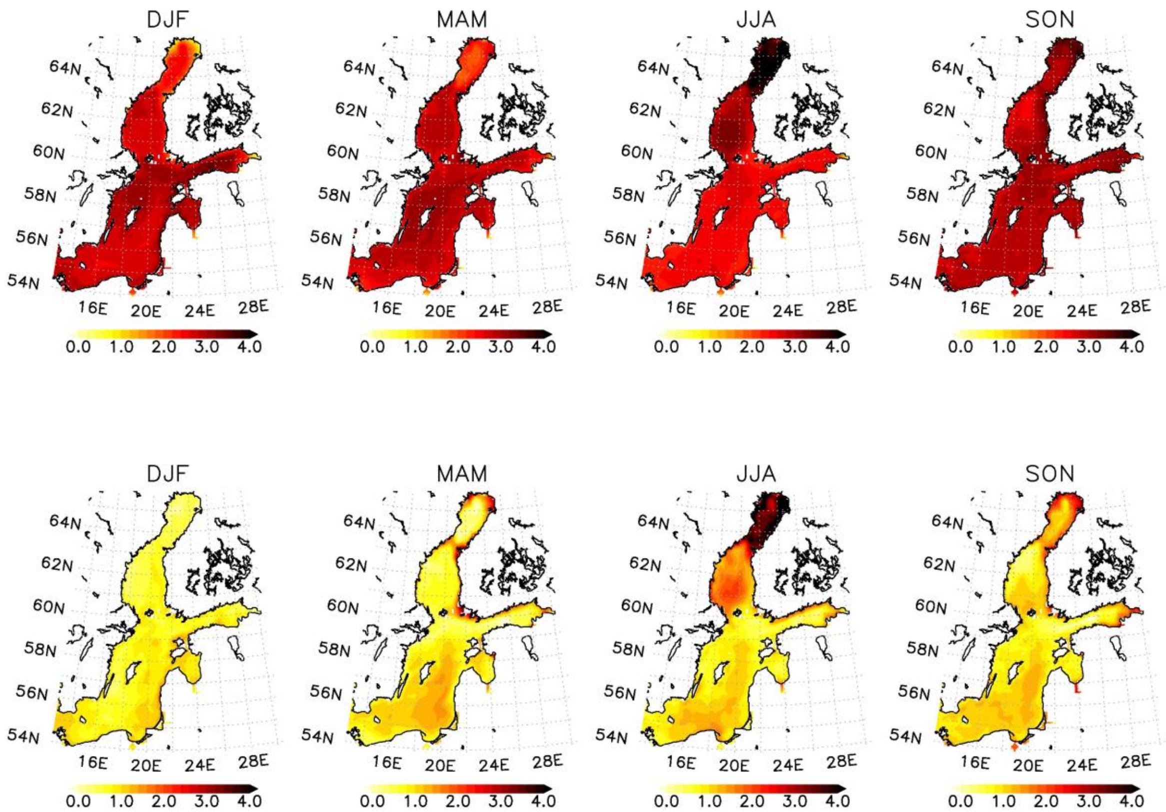

Figure 29. Upper panels show the sea surface temperature change between 2070-2100 and 1970-2000 based on an ensemble simulation of 3 members for the A1B scenario. In the lower panels the range of the ensemble simulation is shown. Each column of the figure represents a season.

The model results for future climate were compared with model results from the Medieval Warm Period and the Little Ice Age. For this purpose a dynamical downscaling approach has been performed to generate atmospheric and hydrological forcing fields for the two coupled physical-biogeochemical models of the Baltic Sea, RCO-SCOBI and ERGOM. Using the regional atmosphere model RCA3 with a horizontal resolution of 50km data of the global model ECHO-G have been downscaled for the Baltic Sea Region for the period 950-1849. Further, a statistical model has been developed to calculate monthly runoff and daily sea level data from the output of the regional climate model RCA3 for both future scenario simulations and the long past climate simulation. Results for air temperature and precipitation averaged over Sweden are shown in Figure 30. During the Medieval Warm Period, especially winter mean air temperature and winter mean precipitation are significantly higher compared with corresponding values during the Little Ice Age.

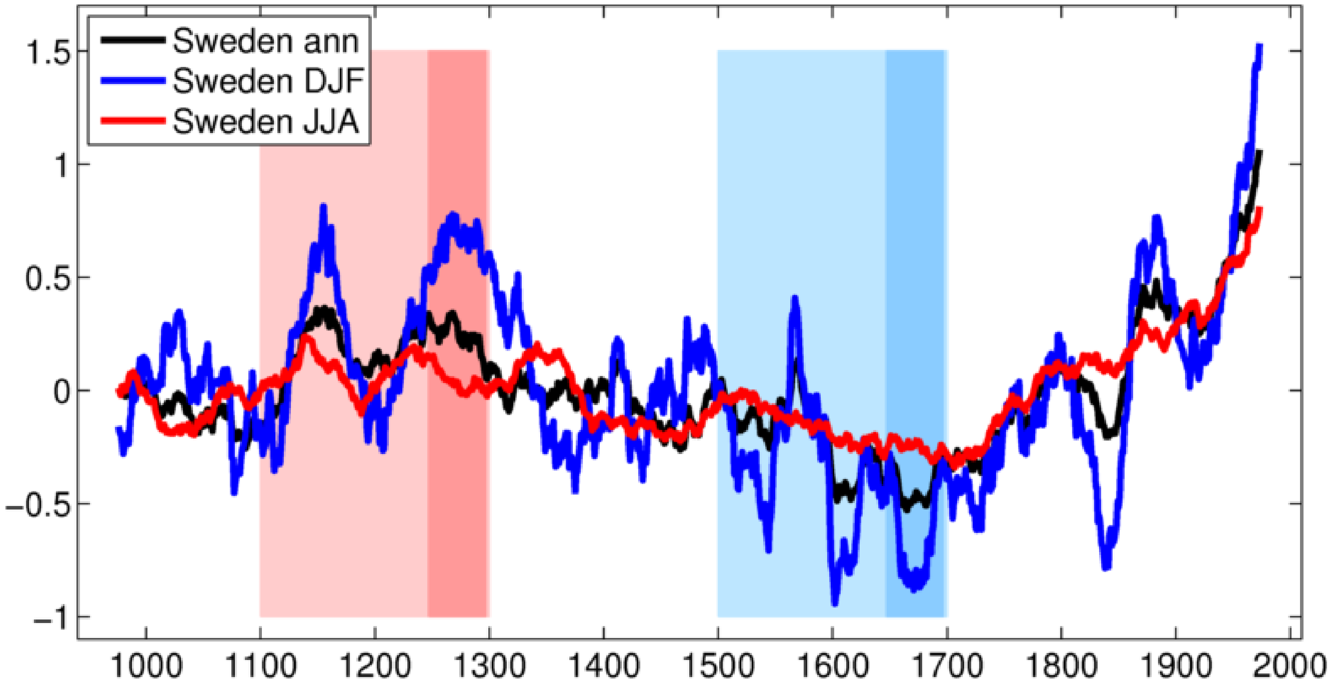

Figure 30. The temporal evolution of the temperature over Sweden for the complete simulation ranging from 950 A.D. until 1998 A.D. Winter (blue), summer (red) and annual (black) means are illustrated as 50-year running means. The defined periods of the Medieval Climate Anomaly (pink/red) and the Little Ice Age (light blue) are highlighted. From: Schimanke et al. 2011.

Conclusions and key results

INFLOW has used integrated sediment and modelling studies to deepening scientific knowledge and understanding of the factors affecting the long-term changes in marine environment and of possible future changes of the Baltic Sea. That information will provide basis for improved management, implementation of policy strategies (e.g. the European Marine Strategy Directive) in Baltic Sea environmental issues and adaptation to future climate change.

Changing sea surface temperatures and anoxia in the past

Sea surface temperature (SST) reconstructions, based on sediment proxy studies (e.g. TEX_{86} method), indicate 2-3 °C variability, between the Medieval Climate Anomaly, the Little Ice Age (1450-1850), and the Modern Warm Period (Figures 31 and 12). This variability is higher than expected. Oxic conditions in the Gotland Basin recorded in the sediments by various parameters have been also reconstructed by ecosystem models for the Little Ice Age (Figure 31). Around thousand years ago, during the Medieval Climate Anomaly, the sea surface temperature of the Baltic Sea was around at same level as today. An exception was the shallow water coastal environment where since the ending of the 20th century maximum temperatures appear occasionally to exceed those found for the Medieval Climate Anomaly. During the Little Ice Age the sea surface temperature of the Baltic Sea was 2-3 °C colder than today. The establishment of anoxic conditions in the deeper basins began parallel to the temperature rise from the Little Ice Age towards the Modern Warm Period (Figure 12 left). In shallower areas anoxic conditions were established much later (Figure 12 right). The INFLOW results highlight a strong effect of sea surface temperature changes on redox conditions in the central Baltic.

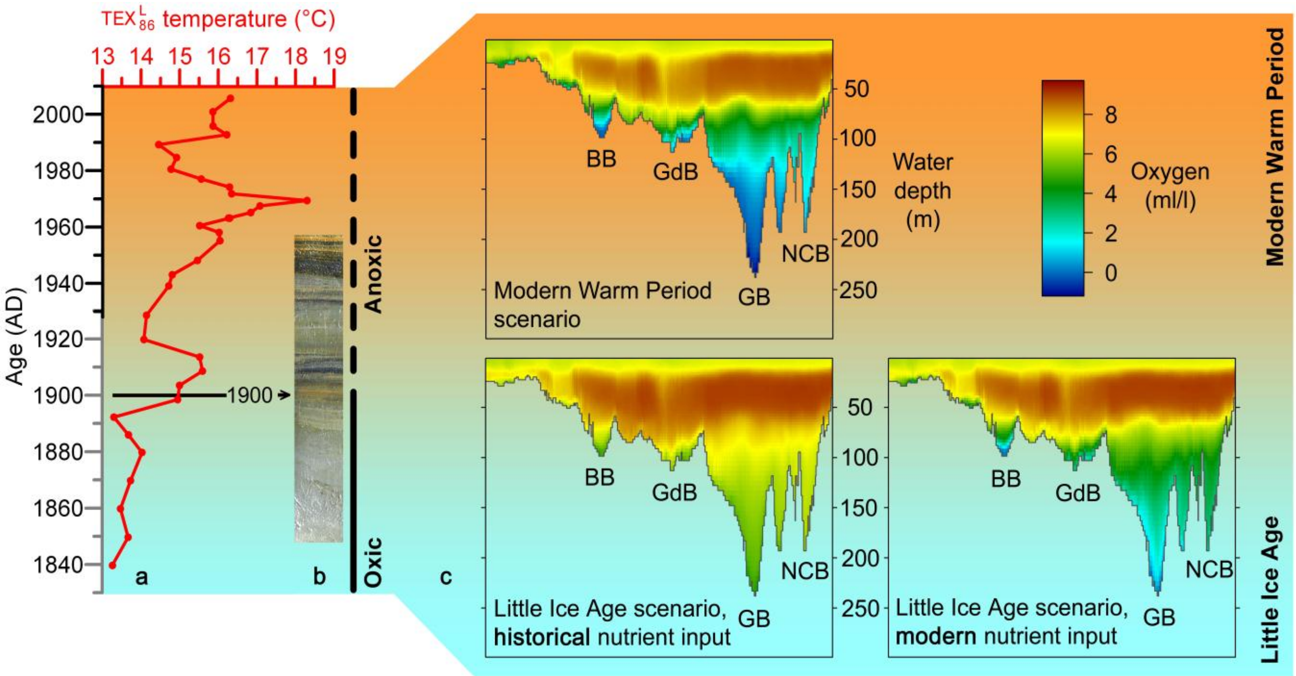

Figure 31. Left: TEX_{86} (biomarker) reconstructed sea surface temperatures (ºC) (red curve) from the Baltic Sea (Gotland Deep) sediment core, over the past 150 years. Anoxic periods at seafloor can be seen in sediment photograph as laminated structures, and more oxic conditions as homogeneous structures. In the middle: Ecosystem modelling simulations show similar seafloor anoxic conditions for the Modern Warm Period (upper). Simulations for the Little Ice Age, with historical (preindustrial) nutrient input, show well oxygenated seafloor conditions (lower). Right: Simulations for the Little Ice Age with modern nutrient input produce anoxic/hypoxic conditions at the seafloor.

Past saline water inflow changes, temperature and oxygen depletion

INFLOW's sediment studies reveal that the Medieval Baltic Sea was severely affected by oxygen depletion. On the other hand, seafloor oxygen conditions were improved during the Little Ice Age. Sediment records (e.g. foraminifera counts and XRF scans) indicate an important new finding: during stable extreme conditions (warm: Modern Warm Period e.g. 1980-2010, Medieval Climate Anomaly, cold: peak Little Ice Age) there were less saline water inflows into the Baltic Sea (Figure 32). This is confirmed by modelling studies, where a proxy for saline water inflow events into the Baltic Sea, based upon sea level pressure gradients over the North Sea, is used to estimate changes of mean strength of inflow over the last millennium. It is obvious that saline water inflows increased in frequency and magnitude during climatic transitions. This might be linked to a change in the prevailing atmospheric North Atlantic Oscillation (NAO) system from a stable NAO+/- towards more unstable conditions. This aspect is still under investigation.

In addition, sensitivity studies of the Baltic Sea were performed with Baltic Sea models. It was shown that changes in the mean conditions do not have a large impact on bottom oxygen concentrations.
This adds confidence that changes in the variability could have been more important for the increase of oxygen depletion in bottom waters during the Medieval Climate Anomaly than changes in the mean conditions. However, further studies are still necessary to elucidate the processes involved.

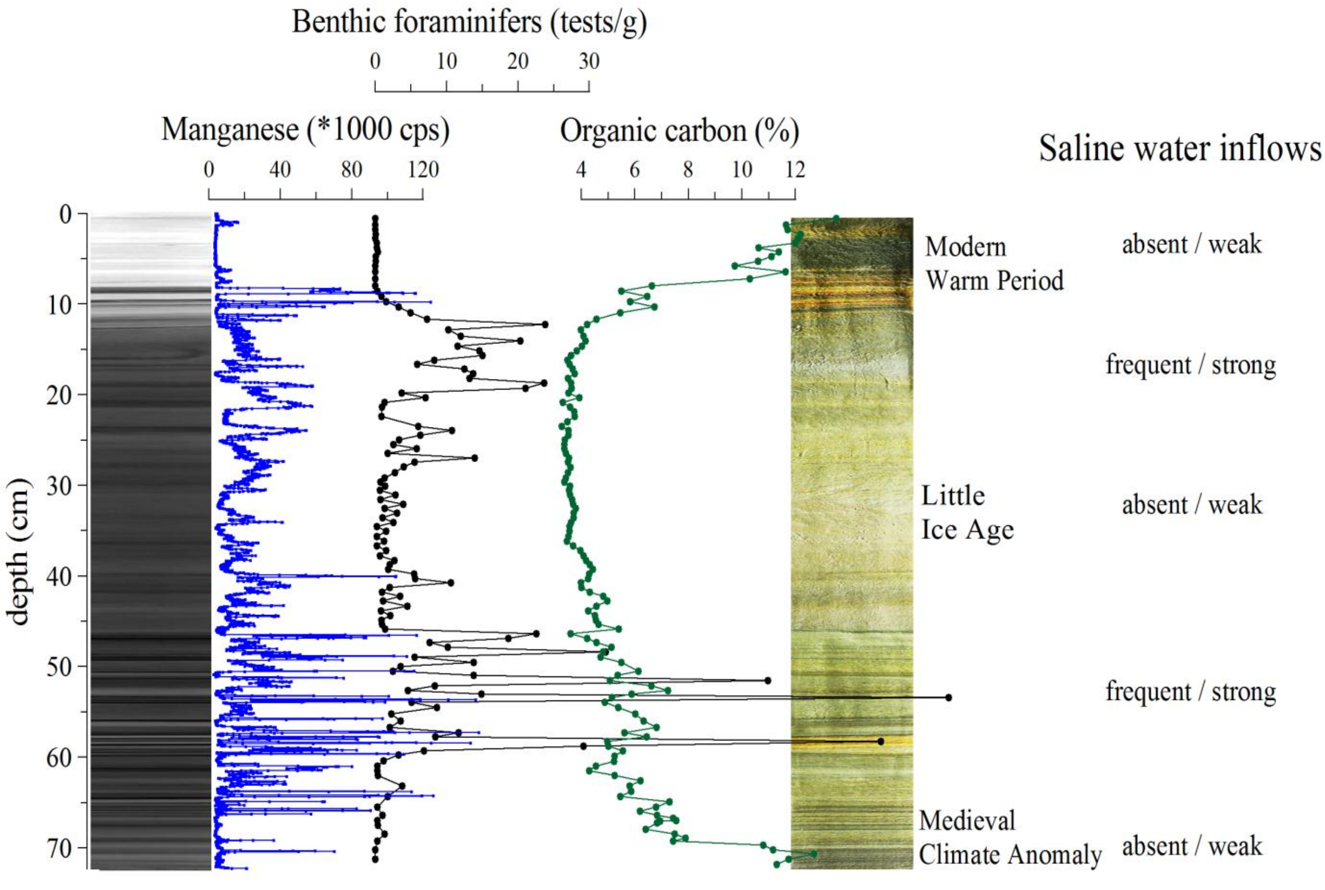

Figure 32. X-ray photograph of sediment core from the Baltic Sea (Gotland Deep) (left); manganese concentration of sediment core (blue curve), number of benthic foraminifers (tests/g) (black curve), organic carbon (%) content of sediment core (green curve), and photograph of sediment core. Also shown: Modern Warm Period, Little Ice Age and Medieval Climate Anomaly, as well as estimated frequency/strength of saline water inflows.

Future Baltic Sea
Future climate change is likely to affect the Baltic Sea marine environment. Modelling simulations suggest warmer air temperatures in the future, with an annual mean increase in the range of 2.7-3.8 K for 2070-2099 relative to 1969-1998 in the Baltic Sea region (Figure 33). It has been estimated also that the climate warming could increase precipitation (and river runoff) to the Baltic basin, as well as reduce the length of the ice season in the Baltic Sea. Oxygen depletion at seafloor has been estimated to expand, too. Furthermore, changes in hydrography and biogeochemical processes could affect the whole Baltic Sea ecosystem.

Anoxia/hypoxia is harmful for macro benthic fauna and flora. It also affects the ecosystem via internal loading. Extended seafloor anoxia could enhance the environmental problems by releasing toxic heavy metals and nutrients, like phosphorus, from the seafloor sediments, and thus intensify the harmful effects of eutrophication. These may affect marine ecosystem by reducing marine biodiversity as well as fish catch. However, reliable future scenarios on the effects of climate change to the Baltic Sea ecosystem and biodiversity are difficult to produce due to complicated ”cause–effect” relationships. Further studies are needed.

Socio-economic implications of climate change on Baltic Sea region need careful consideration, including effects on fisheries and possible reduced recreational values of the coastal areas. Considerable efforts to save and restore the Baltic Sea condition have been made during past decades. However, when combining the climate change, increasing human activities and human induced loading, the already taken measures are not enough. Further actions are needed including substantial nutrient load reductions also in the future in order to minimize the effect of sea surface temperature changes.

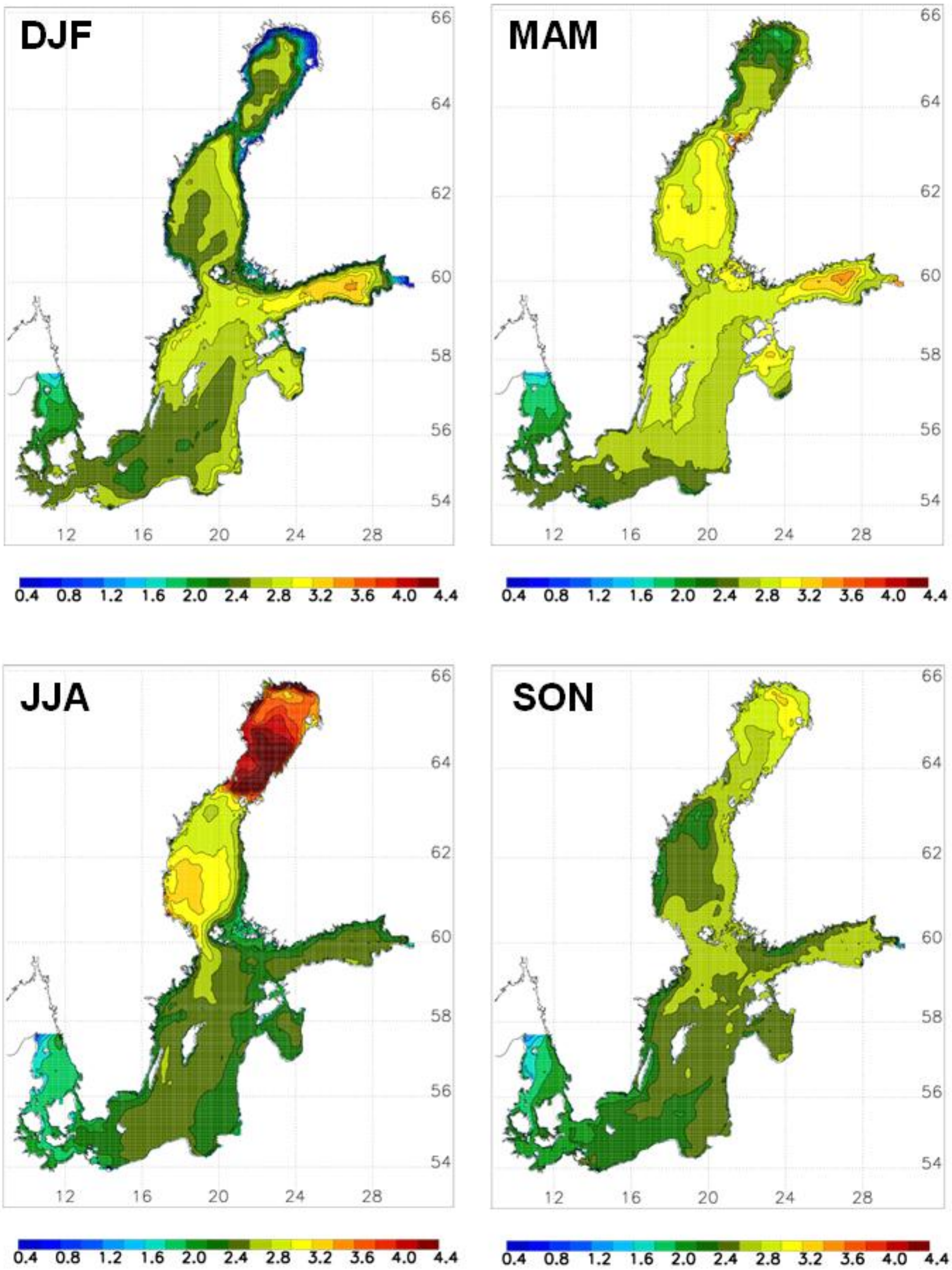

Figure 33. Seasonal mean sea surface temperature changes (in ºC) between 2070-2099 and 1978-2007 in RCO-SCOBI simulations driven by regionalized GCM results. DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November.

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Work package WP4 “Training and education”

Floating University (Task 4.1)

Floating University was organized during the RV Aranda SEDU 2009 Cruise 22.-29.4.2009. For more detailed information see INLOW Interim Reports 1 (Kotilainen et al. 2009) and 2 (Ryabchuk and Kotilainen 2009).

Workshops (Task 4.2)

Altogether five workshops were organized in 2009:

- INFLOW kick-off workshop, Helsinki, Finland, 15th January 2009 (GTK)
- small INLOW workshop during RV Aranda cruise (April 2009) (GTK, IOW, Lund, Szcecin, VSEGEI, Helsinki)
- ``The marine ecosystem in changing climate - on the added value of coupled climate-environmental modeling for the Baltic Sea", Norrköping, Sweden, 16 October 2009 (SMHI, IOW)
- INFLOW national workshop for Finnish Partners, Helsinki University, Department of Geology, 2.10.2009 (Helsinki, GTK).
- INFLOW workshop and subsampling party, Warnemünde, December 2009 (IOW)

Altogether three workshops were organized in 2010:

- INFLOW Annual Meeting (and workshop), Vilnius, Lithuania, 19th January 2010 (GTK)
- INFLOW workshop, Małkocin, Poland, 18th – 20th June 2010 (Szczecin University)
- INFLOW workshop in the range of 10th Baltic Marine Geological Conference, St.Petersburg, Russia, 27th August 2010 (VSEGEI).

Altogether three workshops were organized in 2011:

- INFLOW workshop 2011, Simlångsdalen, Sweden, 1st – 2nd Feb. 2011
- internal INLOW meeting during BSSC 2011 St. Petersburg, August 2011.
- INFLOW Final workshop in Rostock Warnemünde, Germany, 29th to 30th Nov. 2011.

Outreach (Task 4.3.)

INFLOW Partners disseminated the project actively during 2009-2011. Altogether 12 peer reviewed articles were produced, so far. In addition to that altogether more than 80 conference and seminar presentations as well as invited lectures were given.

Peer reviewed articles

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Ryabchuk, D., Kotilainen, M. 2009. Floating University Report, the RV Aranda 22.-29.4.2009. INFLOW Interim Report No. 2. Espoo: GTK. 7 p. http://projects.gtk.fi/inflow/Reports/INFLOW_Interim_Report_No_2_2009.pdf

Ryabchuk, D., Spiridonov, M., Zhamoida, V., Grigoriev, A., Sergeev, A., Kropatchev, Y., Kotilainen, A., 2010. INFLOW Cruise Report, FYTO 2009, the RV Ladoga 4.-7.7.2009. INFLOW Interim Report No. 6. St.Petersburg: VSEGEI. 14 p. Electronic publication. Available at http://projects.gtk.fi/inflow/index.html

S. Schimanke, E. Kjellström, G. Strandberg, H.E.M. Meier , 2011. A regional climate model simulation over the Baltic Sea region for the last Millennium, SMHI reports in oceanography, No. 111.

Virtasalo, J., Moros, M., Ryabchuk, D., Kotilainen, A. 2009. High-resolution sediment cores covering the past 6000 years. INFLOW Interim Report No. 4. Espoo: GTK. 18 p. http://projects.gtk.fi/inflow/Reports/INFLOW_Interim_Report_No_4.pdf

Other presentations (e.g. seminars)

Porsche, C. The influence of climate change on the Baltic Sea ecosystem - comparison of variability from the last 2k years with the expected changes in the next 100 years. Seminar at the Baltic Sea Research Institute Warnemünde, Germany, 12th November 2009.

Kaskela, A. INFLOW-, EMOGE-, ja FINMARINET – hankkeiden esittely. Seminar "Työelämäorientaatio" for geology students of Helsinki University, GTK, Espoo, Finland, 27 November 2009.

Kotilainen, A. INFLOW and other marine geological research projects in GTK. Internal Seminar of Research Programmes, GTK, Espoo, Finland, 9.6.2009.

Neumann, T. Scientific Advisory Board of IOW, 3rd Mar. 2011, IOW, Rostock, Germany.

Neumann, T., Porsche, C. University of Rostock – Marine Biology, 26th Dec. 2011, Rostock, Germany.

Porsche, C. Diplomanden - Doktoranden Seminar, 5th May 2011, IOW, Rostock, Germany.

Porsche, C. DPG (Deutsche Physikalische Gesellschaft) Summer School – Physics of the Oceans . 11th – 17th Sep. 2011, Bad Honnef, Germany.

Kabel, K. and Porsche, C., Moros, M., Neumann, T., Andersen T.J., Sinninghe Damsté, J.S.: The impact of climate variability on the Baltic Sea analysed combining sediment proxy and model studies. Talk for Scientific advisory board of IOW (talk). 2011.

Kotilainen, A., “Towards understanding the forcing mechanisms of environmental changes of the Baltic Sea and future scenarios”. Presentation in ”Towards bilateral cooperation in geosciences (Russian Academy of Sciences and Academy of Finland)” seminar, 17.3.2011, Helsinki,.

Kotilainen, A., "INFLOW". Presentation in "BONUS Forum for stakeholders” event, 24.10.2011, Gdansk, Poland.

Kotilainen, A., "We know that the Baltic Sea is crucially dependant on the inflow of saline North Sea water. How intense this inflow was in the past?” and “When did the bottoms of the Baltic Sea die?” presentations in “BONUS+ highlights to the European community" event, 8.11.2011, Bruessels, Belgium.

Kotilainen, A., "Pohjamudista tulevaisuuden kuviin – minne olet matkalla Itämeremme?”. Presentation in Geological Society of FInland, 8.12.2011, Helsinki.

Lectures

2009:

Invited lecture for graduate students at the International BALTEX summer school on ``Threats and challenges for the Baltic Sea environment under climate change", Nexö, Bornholm, Denmark, 27 July - 5 August, 2009: Regional climate simulations and uncertainties of scenario simulation (8 lecture hours) (M. Meier)

Invited lecture for graduate students at the International BALTEX summer school on “Threats and challenges for the Baltic Sea environment under climate change”, Nexö, Bornholm, Denmark, 27 July - 5 August, 2009: Regional climate simulations and uncertainties of scenario simulation (8 lecture hours) Modelling the Baltic Sea Ecosystem (6 lecture hours) (T. Neumann).

Invited lecture in Russian Academy of Sciences “Towards understanding the causes of the Baltic Sea environmental changes over the past 6000 years and future scenarios -INFLOW project”. 20th October 2009 (A. Kotilainen).

Invited lecture for graduate students at the St. Petersburg University, Department of Geology, Russia, 21st October 2009 (2 lecture hours) (A. Kotilainen).

2010:

Kabel, K., 2010. Reconstruction of Baltic Sea surface temperatures using Tex86 paleothermometry. Baltic Sea research Institute Seminar, 25.11.2010, Rostock, Germany.

Kabel, K. and INFLOW partners, 2010. The BONUS project INFLOW and planned foraminiferal research in the Skagerrak-Kattegat region. Workshop at Aarhus University, 2.2.2010-4.2.2010, Aarhus, Denmark (oral presentation).

Kotilainen, A., 2010. Marine geological research and mapping in Finland - a submarine view to the Gulf of Finland. Gulf of Finland Trilateral Meeting, 7.-8.12.2010, Helsinki, Finland.

Meier, H.E.M., A. Höglund, R. Döscher, H. Andersson, U. Löptien and E. Kjellström, 2010.

Quality assessment of atmospheric surface fields over the Baltic Sea of an ensemble of regional climate model simulations with respect to ocean dynamics. BONUS+ program cluster workshop on "Uncertainties of scenario simulations", Norrköping, Sweden, 14 October 2010.

Meier, H.E.M., 2010. Impact of changing hydrography on biogeochemical cycles in future climates of the Baltic Sea (invited presentation). International workshop on ``Effects of climate change on the marine environment" organized by the Nordic Council of Ministers, Copenhagen, Denmark, 9-10 March, 2010.

Moros, M., 2010. The Baltic Sea as a recorder of Holocene climatic changes in the North Atlantic region. Australian National University Nov. 2010, Canberra. Australia. (talk)

Leipe T. and Moros, M., 2010. Sediments and Seabeds as archives of the Baltic Sea. 35th DEUQUA Conference Sept. 2010, Greifswald (oral presentation).

Leipe, T., Moros M., Tauber F., 2010. Sediments and seabeds as archives of the Baltic Sea history. In Eislandschaften in Mecklenburg-Vorpommern editors: Lampe R and Lorenz S., Excursion guide. 35th DEUQUA Conference Sept. 2010, 164pp.

Ryabchuk, D., 2010. Lecture to the students of Russian State Hydrometeorological University (RSHU)

Sławomir D., 2010. Presentation of Phd thesis assumption in frame of Faculty of Geoscience Council meeting. University of Szczecin, November 2010.

INFLOW in Media (e.g. TV, radio, newsparers):

- 13.1.2009, INFLOW –project presentation (in Finnish) (Kotilainen A./GTK) in BONUS Programme Press conference, Espoo, Finland.
- 13.1.2009, press Release of INFLOW – project (in Finnish, Swedish, English) (Academy of Finland, GTK).
- 2.2.2009, Article of INFLOW – project in Helsingin Sanomat magazine (in Finnish).
- March 2009, Article "Itämeren ympäristömuutosten salat ja tulevaisuuden kuvia. BONUS – ohjelman INFLOW –projekti." in Geologi – magazine (Kotilainen 2009)
- May 2009, Article of INFLOW – project in Saaristo –magazine (in Finnish).
- June 2009, Article "Look back - and learn" in Baltic Rim Economies –magazine (Kotilainen 2009).
- June 2009, Article ”Pohjasedimenteistä näkyy Itämeren tulevaisuus” in Geofoorumi –magazine (in Finnish) (Harriet Öster).
- August 2009, Article "Itämerta ei hymyilytä" in Kotilaisten suku –magazine.
- 10.8.2009 12:30pm, INFLOW –project in Russian Television Channel 5 News, "Marine mud and climate change", during INFLOW project RV Aranda Cruise visit in St.Petersbug (http://www.5-tv.ru/).
- Radio interview http://sverigesradio.se/sida/artikel.aspx?programid=406&artikel=4870469 (Meier, M.)
- 15.2.2011 INFLOW related "Science Breakfast for journalists" ("Toimittajien tiedeaamiainen" in Finnish) in the Academy of Finland. Presentation ”INFLOW **-** Itämeren suolapulssit ja niiden vaikutus Itämeren ekosysteemiin holoseenin aikana sekä tulevaisuuden skenaariot” (Kotilainen). Press release in finnish, swedish and english. Several INFLOW news/articles in media (e.g. verkkouutiset, kauppalehti, kouvolansanomat, hs.fi/kotimaa).
- 15.2.2011 Articles in GTK's webpage: ”Happikato vaivasi Itämerta jo keskiajalla”**, ”**Mediaeval Baltic Sea severely affected by oxygen depletion” ja ”Svår syrebrist i Östersjön redan under

medeltiden".

- 15.2.2011 Radio interview (Radio Suomi, Ajantasa, 02:03 pm, (Kotilainen, A.,)
- 15.2.2011 BONUS News: BONUS+ project in spotlight: INFLOW, Baltic Sea was severely affected by oxygen depletion already in medieval times. http://bonusportal.org/maps_and_elements/news/bonus_project_in_spotlight_br_inflow.html
- 12.4.2011 Article about INFLOW "Pohjasedimentit kertovat Itämeren kehitykserstä" (Jarmo Wallenius) in Turun Sanomat (newspaper).

Finalized Master / Diploma Thesis within INFLOW

Adolphi, Florian, 2010. Holocene temperature reconstruction in Baltic Sea sediments for the last 2000 years, using the biomarker TEX86. Diploma Thesis, The faculty for Geosciences, Geoengineering, and Mining, Technical University Bergakademie Freiberg. 92pp.

Alenichev, Alexey, 2010. Paleoreconstruction of sedimentation environment in the Eastern Gulf of Finland during Late Pleistocene – Holocene. Baccalaurean thesis. The Geological Faculty, Department of Marine Geology, St. Petersburg State University, Russia.

Häusler, Katharina, 2011. Reconstruction of Paleoenvironmental Changes during the last 200 Years using Micro-fabric Studies of Surface Sediment Cores from the Central Baltic. Diploma Thesis. Greifswald University, Germany.

Jentzen, Anna, 2010. Benthic foraminifera-based reconstruction of Palaeoenvironmental changes in Skagerrak and Kattegat during the last 500 years. Master Thesis. Ernst-Moritz University Greifswald, Institute of Geography and Geology, Greifswald. 94pp.

Other activities:

- Planning and organization of, and attending the Young Scientists Club meeting of the BONUS-programme (held 14.1.2009 at the Department of Geology, University of Helsinki) (LA/Helsinki).
- 10.2.2009 BONUS –projects (INFLOW, BALTIC GAS, HYPER) meeting on cruise sampling site selection, Department of Geology, Helsinki University, Finland, hosted by ALE/GTK.
- AKU/GESU has established contact for future collaboration with Kiel University (Prof. R. Schneider) where a recent initiative 'Mid-Holocene climate variability in Northern Germany and surrounding oceanic regions' will involve study of high-resolution sediment cores from the Skagerrak and Kattegat focusing on the period 7000-4000 yrs BP.
- 15.6.2009 participating in "The 1st meeting of the Forum of Project Coordinators", Academy of Finland, Helsinki, Finland (ALE/GTK).
- 16.6.2009 participating in "Joint meeting with the BONUS EEIG Steering Committee and Advisory Board", Academy of Finland, Helsinki, Finland (ALE/GTK).
- Crown prince of Denmark visit in October 2010 (see INFLOW homepage) – news and brochure
- Lougheed has constructed and maintained an online Baltic Sea Radiocarbon Database,

information accessible via: http://www.geol.lu.se/inflow/

- Other work of INFLOW scientists include also serving as members or observers in stakeholder and scientific committees like

- Prof. Eystein Jansen, Lead scientist in Working Group 1 of Contribution to the IPCC (Intergovernmental Panel on Climate Change) Fifth Assessment Report.

- Prof. Ian Snowball, ESSAC/IODP National Delegate (Sweden). ESSAC is the Science Support and Advisory Commitee of ECORD (the European Consortium of Ocean Reseach Drilling).

- Lougheed continued to maintain an online Baltic Sea Radiocarbon Database, information accessible via http://www.geol.lu.se/inflow/ .

- 15.6.2011, participating in ”Forum of Project Coordinators" meeting that was held in Helsinki.(Kotilainen).

- 16.6.2011, participating in ”Joint triple meeting with the BONUS EEIG Steering Committee and Advisory Board" meeting that was held in Helsinki.

Co-operation with other BONUS projects

- Cruises (and co-operation with other BONUS Projects) along inflow transect
  - RV Aranda INFLOW Cruise in April 2009 with BALTIC GAS (floating university)
  - RV Penck HYPER Cruise in June 2009
  - RV Poseidon BALTIC GAS Cruise in December 2009 (sediment cores provided to INFLOW)
- ECOSUPPORT close co-operation in modeling
- Providing expertise for Site selection (BALTIC GAS, HYPER)
- Preparation of seabed substrate data to IBAM –project for modelling (ALE/GTK)
- BALTIC GAS:
  - The INFLOW Partners (BLO, JVV) participated in the R/V Maria S. Merian "BONUS Baltic Gas project" cruise to the northern Baltic Sea in July-August 2010. Cruise was organized by the IOW
  - Providing expertise for Site selection (ALE, JVV)
- HYPER: key-core samples were measured at Lund University for biogenic opal (D. Conley)
- The measurement of stable lead isotopes to identify known atmospheric pollution peaks is reported in a study by Zillén et al. (in press). Zillén was a Lund-based scientist associated with the parallel BONUS HYPER project, but she now works for the Swedish Geological Survey

(SGU). Idea transfer between Zillén and Lougheed helped to improve our methods and produce new results.

- It was quickly identified by the work undertaken by Lougheed (INFLOW) and a parallel study by another PhD student in Lund (LU faculty salaried M. Reinholdsson, who worked within the BALTIC GAS project) that sections of relatively organic-rich laminated sediment, which is a signal of past anoxia, contain much higher concentrations of ferrimagnetic minerals than non-laminated sections. Lougheed and Reinholdsson have made complementary magnetic comparisons of INFLOW and BALTIC GAS cores using the same magnetic techniques. Lougheed concentrated on the INFLOW deliverable, while Reinholdsson's subsequent mineral magnetic studies aided Lougheed in the interpretation of his palaeomagnetic data. Microbial action is probably responsible for the controlled precipitation of these nano-metre scale magnetic particles (studies are continuing as part of BALTIC GAS).

Practical implementation of project outputs (performance statistics 1-4)

INFLOW project and its results have been disseminated actively both in national and international forums (see list above).

Project partners served as members of following scientific committees:

Members (Aarno Kotilainen, Finland; Markus Meier, Sweden) of the Scientic Committee of the 8th Baltic Sea Science Congress (BSSC) 2011 “Joint research efforts for sustainable ecosystem management" St.Petersburg, Russia, 22-26 August, 2011

Convener of the theme session “Impact of changing climate and human induced pressures on the Baltic Sea Ecosystem" proposed by the BONUS+ program by Markus Meier (Sweden), Joachim Dippner (Germany), Aarno Kotilainen (Finland) at the Baltic Sea Science Congress (BSSC), St.Petersburg, Russia, 22-26 August 2011.

Convener of the theme session “Late Quaternary geological development of the Baltic Sea: paleorecontructions – links to modern climate change “at the Baltic Sea Science Congress (BSSC), St.Petersburg, Russia, 22-26 August 2011. Aarno Kotilainen (Finland)

Chairman (Aarno Kotilainen, Finland) of Scientific Committee of the GeoHab 2011 Conference, Marine Geological and Biological Habitat Mapping, 3–6 May, 2011, Geological Survey of Finland, Espoo.

Comparison with the original research and financial plan

The Steering Committee decided on 18 June 2008 on 16 BONUS+ projects proposed to be funded. As the BONUS+ programme’s financial volume was limited there was a need to make budget cuts. Inflow budget was cut from 1 948 004 Euros to 1 563 857 Euros.

Despite the budget cuts, the INFLOW project was able to follow mainly the original research plan, and planned products were produced. That was enabled by additional resources (in kind contributions) received from Participating Institutes.

Statement if the research plan and schedule of deliverables had to be adapted

Consortium Agreement between BONUS EEIG and Project Partners remained unsigned relatively long. That was due to prolonged negotiations between the German national funding agency and the BONUS EEIG. Despite this delay, the INFLOW project was executed more or less as planned in the Full Research Plan. However, due to prolonged contractual negotiations between the Danish Natural Research Council (FNU) and the BONUS EEIG management, an official (financial) start of GEUS activities was delayed until September 1st 2009. Consequently, the originally scheduled work in scheme for 2009 underwent major revision which had an impact on the 2010 work plan of GEUS as well. This implies, amongst others, a c. 8 months delay for the appointment of the (dinoflagellate) post-doc researcher, who originally should have started by January 1st 2010.

Further research and exploitation of the results

INFLOW project has used integrated sediment and modelling studies to deepening scientific knowledge and understanding of the factors affecting the long-term changes in marine environment and of possible future changes of the Baltic Sea. That information will provide basis for improved management, implementation of policy strategies (e.g. the European Marine Strategy Directive) in Baltic Sea environmental issues and adaptation to future climate change.

Despite the new findings of the INFLOW project, several research topics need to be further studied in future. Those include ^{14}C dating problem of the Baltic Sea sediments due to radiocarbon reservoir effect. Also fine grain OSL dating method needs to be further developed. One of findings of the INFLOW project was that saline water inflows enhanced during climatic transitions. That might be linked to a change in the prevailing atmospheric North Atlantic Oscillation (NAO) system from a stable NAO+/- towards more unstable conditions, but that need to be studied further. Precipitation changes over the past thousand years in the Baltic Sea region, and it effects on the Baltic Sea ecosystem remains still unsolved. Future scenarios on the effects of climate change to the Baltic Sea ecosystem and biodiversity are difficult to produce due to complicated ”cause–effect” relationships, and further studies are needed also in this topic.

INFLOW Project partners have presented, and will present, their results in national and international conferences and stakeholder events. Besides academic dissertations the results will be (and some have been) published in peer-reviewed national and international scientific journals of the highest caliber, in popular forum journals, as well as in media via journalists. Project data and the main conclusions will be presented in continually updated INFLOW webpage and multinational databases, like PANGAEA® Publishing Network for Geoscientific & Environmental Data database. (http://www.pangaea.de/about/). In addition selected model simulations will be made available from IOWs' Live Access Server (http://www.io-warnemuende.de/phy/las/de_las.html).

Appendices

Appendix I. Institutes, persons and persons months of INFLOW Project during 2009-2011. PS = Principal Scientist.

Institute	Person	Acronym	Person month	
GTK				
	Aarno Kotilainen	ALE	10	Coordinator
	Joonas Virtasalo	JVV	22	Post-doc
	Jyrki Hämäläinen	JRH	0.3	Scientist
	Anu Kaskela	AMK	0.2	Scientist
IOW				
	Karoline Kabel	KKA	33 (6 in kind)	PhD student
	Thomas Leipe	TLE	4	Senior scientist
	Matthias Moros	MMO	17	Senior scientist
	Thomas Neumann	TNE	6	PS
	Christian Porsche	CPO	27 (6 in kind)	PhD student
GEUS				
	Antoon Kuijpers	AKU	7	PS
	Niels E. Poulsen	NEP	4	Senior scientist
	Jens Peter Rasmussen	JPR	1.5	Senior scientist
	Kaarina Weckström	KW	0.5	Post-doc
	Sofia Ribeiro	SOR	8	Post-doc
	Francisca Staines-Urias	FSU	6	Post-doc
Lund				
	Bryan Lougheed	BLO	36	PhD student
	Ian Snowball	ISO	3	PS
SMHI				
	Helen Andersson		0.5	Senior scientist
	Kari Eilola	KEI	1.6	Senior scientist
	Robinson Hordoir	RHO	6.9	Senior scientist
	Markus Meier	MME	4.5	PS
	Gustav Strandberg	GST	6.9	Senior scientist
	Semjon Schimanke	SSC	7	Post-doc
	Erik Kjellström	EKJ	1	Senior scientist
	Zohreh Ranjbar	ZRA	5.3	
	Ivan Kuznetsov	IKU	1.9	
	Karin Borenäs	KBO	<0.1	
Szczecin				
	Andrzej Witkowski	AWI	5	PS
	Slawomir Dobosz	SDO	36	PhD student
BCCR				
	Eystein Jansen	EJA	2.5	PS
	Björg Risebrobakken	BRI	7	Post-doc
	Dagfinn Bøe	DAB	4.8	
	Jørund Strømsø	JST	In kind ca 0.5	
VSEGEI				
	Timofev Bodryakov	TBO	13	PhD student
	Andrey Grigoriev	AGR	12.5	Senior scientist
	Juriy Kropatchev	JKR	0.5	
	Elene Nesterova	ENE	0.5	
	Daria Ryabchuk	DRY	10	Senior scientist
	AlexanderSergeev	ASE	8	Student
	Mikhail Spiridonov	MSP	13.5	PS

	Vladimir Zhamoida	VFH	12.5	Senior scientist
Helsinki				
	Laura Arppe	LAR	27	Post-doc
	Mia Kotilainen	MKO	2.5	Senior scientist
	Juha Karhu	JKA	1.5	PS
	Malviina Hallamaa	MHA	1	Student
Total person months used			**391.4**	