Baltic-C

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

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Table of contents

1. *Concept, objectives, and expected outcome*

Strategic objectives: Baltic-C will develop and apply a new integrated ecosystem model framework based on the cycling of organic carbon (C_{org}) and carbon dioxide (CO_2) in the Baltic Sea water and drainage basin, taking into account fluxes across the atmosphere and sediment interfaces; the aim is to provide a tool with which to support the management of the Baltic Sea. The objectives of the project are:

- to achieve significant progress in marine ecosystem modelling by aligning biomass production and oxygen depletion with CO_2 dynamics; and
- to provide the first comprehensive integrated assessment of the potential effects of climate change, eutrophication, increasing atmospheric CO_2 concentration, and acidic deposition on carbon cycling in the Baltic Sea and its catchment area.

Concept: Baltic-C will involve the developing, evaluating, and applying the first fully integrated model framework for the predictive analysis of the functioning and dynamics of the Baltic Sea organic/inorganic carbon and oxygen systems (Figure 1).

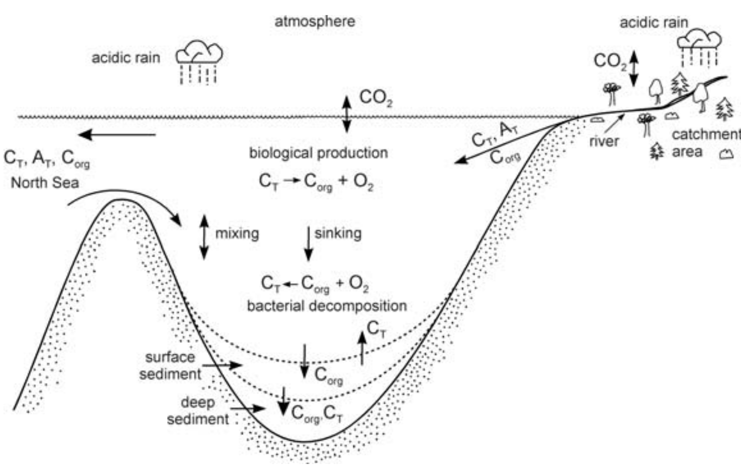

Figure 1. Basic problem addressed in Baltic-C (notations are explained in the text).

This framework will significantly improve our understanding of the relevant physical, chemical, and biological processes and will be supported by and validated against comprehensive observational data (Figure 2). The work plan includes the following steps:

- implementation of CO_2 chemistry as part of an existing and well-established Baltic Sea numerical model;
- linking models of the terrestrial carbon cycle and weathering regimes with a hydrological model to describe river carbon runoff to the Baltic Sea model;
- characterizing the Baltic CO_2 system and organic carbon inventories using existing data, data from dedicated research vessel cruises, and data gathered by new automated measurement systems on Voluntary Observation Ship (VOS);
- a river mouth programme (new and existing data) to quantify the inputs of alkalinity (A_T), total CO_2, organic carbon, and nutrients;
- measuring CO_2 air–sea fluxes at an existing field station to improve the parameterization of the gas exchange transfer velocity; and
- use data from the EMEP long-range atmospheric pollutant transport model to estimate the acid and nutrient deposition in the Baltic Sea and its drainage basin.

Expected outcomes: 1. A new integrated model framework that supports the water management of the Baltic Sea and its ecosystem, addressing the consequences of climate change, eutrophication, increasing atmospheric CO_2 concentration, and acid deposition. **2.** Demonstration applications of the new framework of direct value for management, i.e.:

- the first realistic quantification of the organic carbon (biomass) production and corresponding oxygen (O_2) depletion in different eutrophication scenarios;
- a far more precise quantification of acidification, in terms of pH changes, which may affect primary production and control the CO_3^{2-} concentrations that are essential for the survival of organisms forming calcium carbonate shells;
- the first quantification of the past, present, and future role of the Baltic Sea as a sink/source of atmospheric CO_2; and
- the first estimation of the potential costs of eutrophication related to the costs of the Baltic Sea as a sink/source of carbon.

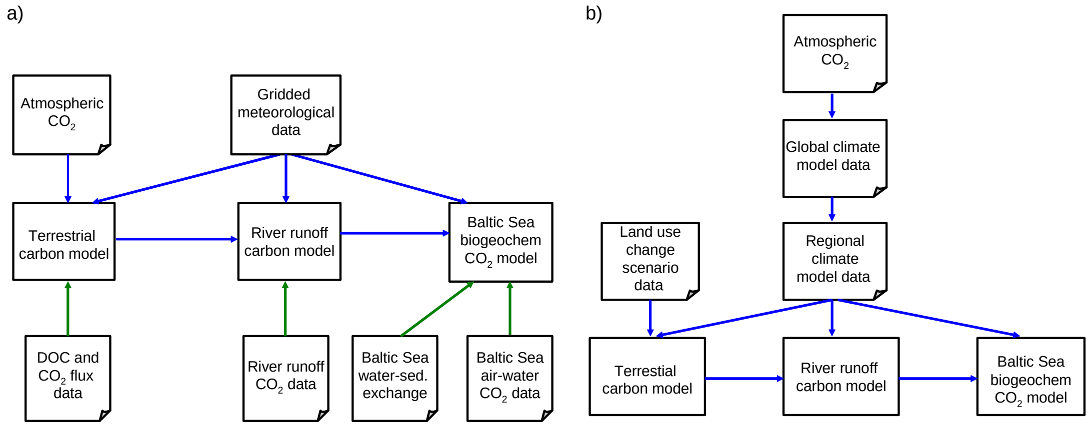

Figure 2. Baltic-C integrated model framework in the historical/validation phase (a) in which the 1960–2000 and 1500–2000 periods will be considered. The blue arrows indicate the model data flow and the green arrows indicate comparison of the model with observations. The scenario phase (b) will be based on several available transient scenario runs covering the 1960–2100 period.

2. *State of art, theory, and methods*

<u>Introduction</u>: The uptake of anthropogenic CO_2 by oceans has two basic aspects. The first refers to reducing the increase of atmospheric CO_2 and thus to mitigating greenhouse gas-induced climate change. Due to the high buffer capacity of ocean waters, only approximately 40% of past anthropogenic CO_2 emissions stayed in the atmosphere. It is assumed that the contribution of marginal seas and shelf areas to ocean CO_2 storage is disproportionately large, due to these areas' high biological productivity by which CO_2 is transformed to organic matter and eventually transported into deeper ocean water layers (shelf pump). The second relates to the changing of the CO_2 system by the uptake of excess anthropogenic CO_2; increased CO_2 partial pressures and decreases in pH and in carbonate ion concentrations are consequences that may adversely affect marine biogeochemistry and ecosystem functioning. The underlying processes are complex and include the response of the terrestrial biogeosphere to a changing environment, since coastal seas link the terrestrial, oceanic, and atmospheric carbon reservoirs (Gattuso et al., 1998). Baltic-C will address both aspects, which are interrelated by feedbacks, and account for other anthropogenic perturbations of the carbon cycle, such as eutrophication.

Measurements: Measurements of river input of biogeochemically relevant substances are mainly confined to nutrient concentrations and to biological oxygen demand (BOD) as a proxy for degradable organic substances. The data are regularly compiled and evaluated by HELCOM working groups. To identify regional differences and temporal trends in river water total alkalinity (A_T), Hjalmarsson et al. (2008) analyzed a large A_T dataset by extrapolating A_T/ Salinity (S) relationships for different Baltic Sea areas. Depending on limestone abundance in the corresponding catchment areas, they detected increasing and decreasing A_T trends in rivers originating from continental Europe and Scandinavia, respectively. The authors attributed these trends to increasing atmospheric CO_2, acid rain, and changes in land use.

A_T and pH are standard variables in some Baltic Sea monitoring programmes and are partly available in corresponding national databanks. These data were recently used to calculate CO_2 partial pressures (pCO_2) and to establish annual CO_2 air–sea exchange balances. For the 1994–2006 period, it was found that the Baltic Proper may be both a sink and source of atmospheric CO_2 (Wesslander and Omstedt, unpubl.).

Systematic studies of the Baltic Sea CO_2 system and its relationship to biogeochemistry started with the availability of new analytical techniques: Ohlson and Anderson (1990) hypothesized changes in the total dissolved inorganic carbon (C_T) due to acidic precipitation, while Thomas and Schneider (1999) used C_T and pCO_2 measurements to describe the seasonal CO_2 cycle in the surface water and to estimate the CO_2 air–sea exchange.

More comprehensive studies of the surface water CO_2 system were used to quantify net biomass production. Taking into account historical data (Buch, 1945), it has been shown that Baltic Sea productivity increased by a factor of 2–3 over the past century (Schneider and Kuss, 2004). The data also indicate that, unlike in oceanic waters, no calcite over-saturation occurs in the Baltic Sea at the onset of the growth period. Consequently, calcite-forming organisms in the Baltic are especially endangered by acidification.

Improved spatial and seasonal resolution of pCO_2 measurements was achieved by deploying a fully automated measurement system on a cargo ship cruising regularly between Lübeck and Helsinki; the data were used to identify and quantify plankton bloom events in different areas of the Baltic Proper (Schneider et al., 2006). Studies in deep water have so far concentrated on C_T accumulation during stagnation periods, to quantify the mineralization rates of organic matter (Schneider et al., 2001). Regarding particulate (POC) and dissolved (DOC) organic carbon, long-term observations have been compiled and evaluated by Nausch et al. (2008). The data indicate that high DOC concentrations in the Baltic Sea mainly derive from the terrestrial biosphere, but that a significant fraction is also produced by marine organisms.

Over the long term, sediments are the final POC sink. About half of the POC exported from the surface escapes remineralization in the water column and rains into the sediments while about 30% of the river POC inflow is deposited on the sediment surface (Algesten et al., 2006;

Thomas et al., 2003; Pempkowiak, 1985). However, much of the deposited POC is remineralized in the course of the early diagenesis (Carman and Rahm, 1997).

Modelling: Modelling the oceanic response to atmospheric carbon emission entails the consideration of various chemical, biological, and physical processes. Modelling design range from simple box models to process-oriented models and three-dimensional coupled atmosphere–ocean models. These models can be validated in various ways, and in the Ocean Carbon-Cycle Model Inter-comparison Project, 13 coarse-resolution global models were evaluated using CFC-11 distributions (Dutay et al., 2002) with quite large model variations.

Chuck et al. (2005) compared three different types of models and demonstrated important positive and negative feedback mechanisms. Interesting model-based tests of the possible future consequences of the role of the coastal ocean indicate that coastal oceans may have caused a decrease in CO_2 emissions since pre-industrial times, due to the rise of atmospheric CO_2 and the increase of net ecosystem production related to anthropogenic nutrient inputs (Andersson and Mackenzie, 2004). This matter is, however, still uncertain, and the interaction between eutrophication and climate is still poorly understood (BACC Author Team, 2008); new research and modelling efforts are therefore needed.

Review on important physical processes that need to be considered as well as active Baltic Sea models have been documented by e.g. Omstedt et al., (2004) and Meier et al, (2006) illustrating good progress and research needs. The core of the modelling in Baltic-C is based on a well-established Baltic Sea numerical model that has been extensively validated and tested in the BALTEX programme (e.g. Omstedt and Axell, 2003; Omstedt and Nohr, 2004; Omstedt and Hansson, 2006; Hansson and Omstedt, 2007). The model (PROBE-Baltic, Omstedt and Axell, 2003) is an advanced process-oriented coupled basin ocean model using the PROBE program (Svensson, 1998) to solve several equations, allowing for effective modelling of fully coupled physical–biogeochemical processes.

Various biogeochemical models have been developed to simulate aspects of the Baltic Sea ecosystem, in particular, Baltic Sea productivity and deep water oxygen depletion and hydrogen sulphide (H_2S) formation. Each of these ecosystem models is controlled by nutrients which are consumed by organic matter production and are released during the decomposition of this matter according to standard Redfield stoichiometry (e.g. Neumann, 2000).

When using this approach to model surface water CO_2 partial pressure (pCO_2), large deviations from observed pCO_2 data were found, indicating fundamental deficiencies in the Redfield concept (Leinweber et al., 2005). This conclusion is supported by the carbon/phosphorus ratios of particulate organic matter measured in the central Baltic Sea, which exceeded the Redfield ratio by a factor of 3–4 (Larsson et al., 2001). It is thus necessary to reconsider the relationship between nutrient consumption and organic matter production in the Baltic Sea, and to validate the relationship by examining its consistency with the CO_2 budget. A first step in this direction is the recent coupling of a new biogeochemical model based on CO_2/O_2 dynamics (with fractional nutrient release in the photic zone) to the Baltic Sea numerical model to be used in Baltic-C.

Several approaches have been applied to study the weathering regimes of watersheds, ranging from studies of small rivers (White and Blum, 1995) to a more global perspective, studying the geochemistry of very large rivers (Gaillardet et al., 1997; Holland, 1978; Mortatti and Probst, 2003). These latter large scale approaches can implemented in the catchment simulation model CSIM (Mörth et al.2007) estimate watershed weathering rates of carbonates and silicates in the major 85 watersheds draining into the Baltic Sea. CSIM simulates simultaneously hydrology and nutrient land-sea fluxes from all major watersheds within the Baltic Sea drainage area.

In boreal watersheds of the Baltic Sea, C_{org} is mainly supplied from the upper soil layers and linked to the water draining as runoff, whereas weathering products like A_T, C_T, Ca are linked to deeper soil layers and to water draining from the system as groundwater (Smedberg et al. 2006). Moreover, C_{org} and A_T, C_T, Ca are linked to peat and forest cover, i.e., all river chemistry variables increase with increase cover of vegetation in the boreal forest dominated sub basins of the Baltic Sea (Humborg et al. 2004). C_{org} and A_T, C_T fluxes have been simulated for some characteristic boreal watersheds using the CSIM approach (Smedberg et al. 2006). Also in watersheds dominated by agriculture as found in the southeastern part of the Baltic Sea catchment a relationship between land class cover and A_T fluxes have been found.

Dissolved organic carbon (DOC) in runoff from the ecosystems of the Baltic Sea drainage basin is mainly related to land use (agriculture/forest), vegetation type and primary production (Humborg et al. 2004). Climate change will affect the structure and functioning of ecosystems, leading to potential changes in vegetation patterns, ecosystem exchange of CO_2 and dissolved organic matter (DOM) exports from ecosystems.

Dynamic vegetation models (DVMs) were developed in the 1990s to account for transient changes in vegetation structure and distribution and ecosystem biogeochemistry to climate and atmospheric change. LPJ-GUESS (Smith et al. 2001; Yurova & Lankreijer 2007) is a state-of-the-art regional DVM that distinguishes patch-scale heterogeneity, individual tree species and interactions among major soil organism groups in driving soil carbon dynamics. The model has been applied in a number of previous studies of boreal and temperate ecosystems and compared to observational data including tree species distributions, satellite observations, forest inventory data, soil carbon pools and ecosystem carbon and water fluxes (e.g. Morales et al. 2005).

Land use patterns will also change in response to climate but also socioeconomic forces. Methods for generating plausible scenarios of future land use change, consistent with greenhouse gas emissions, climate change and the underlying socioeconomic assumptions were developed in recent EU research programmes (Rounsevell et al. 2006). In order to generate scenario analyses on changes in weathering rates and C_{org} fluxes we use the model outputs on vegetation patterns and carbon cycling generated by the dynamic vegetation model (LPJ-GUESS) that will be directly linked to C_{org} and A_T, C_T, fluxes.

Future projections: Atmospheric global climate models (GCMs) give coarse information. To investigate smaller regions, such as the Baltic Sea, the simulation must be downscaled; accordingly, we will use data from dynamic downscaling with a regional climate model (RCM).

This project will use only one RCM as, when considering monthly mean variations, the different RCMs are relatively similar (Deque et al., 2007).

Baltic-C will use transient runs for the 1960–2100 period from the RCA3 model (Kjellström et al., 2005), which has been used in several different versions and forcings and the output of which can be obtained from the PRUDENCE and ENSEMBLES EU projects. The projections will be evaluated based on different measures, such as changes in pH, uptake/release of CO_2, oxygen concentration, biological production, temperature, ice, salinity, and estimated economic costs.

3. *Innovation and new approaches*

Baltic-C will for the first time constrain the organic and inorganic carbon budgets of the Baltic Sea, by addressing C fluxes from land, exchange fluxes between atmosphere and sediments, and internal C fluxes in the water bodies of the major basins. Only this holistic approach to quantifying and evaluating all C fluxes will give the ability for scenario analysis needed by policy makers. Increasing atmospheric CO_2 concentration will lower the seawater pH, carbonate concentration, and calcium carbonate saturation state and increase the dissolved CO_2 concentration; however, increased seawater alkalinity due to higher river runoff discharge might compensate for the lower carbonate saturation state. In turn, these changes will affect biogenic calcification, phytoplankton production, and species composition in the Baltic Sea.

The acid–base balance will also be influenced by eutrophication that may counteract increasing atmospheric CO_2 concentrations. Our ability to reliably predict the future state of the Baltic Sea ecosystem relies on properly quantifying all these major C fluxes. Scientists participating in Baltic-C will numerically simulate the C assimilation by phytoplankton using parameterizations that are based on data of the decrease in dissolved CO_2 inventories obtained from continuous pCO_2 measurements on a cargo ship. This is especially germane in the Baltic Sea, in view of the occurrence of massive cyanobacteria blooms that do not follow regular Redfield stoichiometry.

4. *Themes and key research issues of BONUS Science Plan*

Theme 1: A new model framework for water management will be the outcome of the project (Baltic-C); it will be used as a scientific basis for environmental scenarios for investigating future developments and implications of policy actions.

Theme 2: Interaction between climate change and the Baltic Sea ecosystem will be addressed. Baltic-C will use ecosystem modelling with more accurate organic matter production rates consistent with observations of the surface water CO_2 system. Innovative techniques will be used to compile the database for the surface water CO_2 system.

Theme 3: The effects of eutrophication on biomass production will be estimated using the carbon/oxygen-based Baltic Sea numerical model. Integrating a Baltic Sea numerical model with a terrestrial ecosystem model and a hydrological model of the catchments provides the model framework. For the atmospheric deposition of nutrients, Baltic-C will refer to data from the European Monitoring and Evaluation Programme (EMEP).

Theme 6: The removal of many trace metals by deposition into sediment is controlled by the abundance of particulate organic carbon and by pH-dependent adsorption on them. Hence, both acidification and biomass production affect the budgets of trace metals.

Theme 7: Social science information regarding the environmental externality costs of Baltic Sea change will support the ecosystem approach to management.

5. Contribution in producing BONUS deliverables

Baltic-C will promote high-profile Baltic Sea research at the European and international levels and will substantially enhance scientific knowledge, understanding, and capability by including training and education. These contributions will be reflected in teaching and in the publication of papers in leading peer-reviewed journals. Beyond increasing scientific knowledge, Baltic-C will develop a model system that addresses several issues important to Baltic Sea water management. This integrated model framework will provide the scientific basis for improved water management and regulation. New innovative observations will be organized and offered to the research and water management communities. Baltic-C will contribute in several ways to producing the deliverables described in the BONUS-196 Science Plan. These deliverables are outlined in the Bonus Science Plan (Table 1, page 11): under the heading "Linking sciences and policy", Baltic-C will contribute to all BONUS deliverables; under "Large-scale ecosystem threats and changes responses and migration", Baltic-C will contribute mainly to deliverables 1–4; while under "Strengthen collaboration and use of common resources", Baltic-C contributes mainly to deliverables 3–6 and 8.

6. Dissemination plan

Direct contacts/workshops with BONUS, HELCOM, and the Swedish Water District Authority will ensure that interim and final results contribute directly to the development of new water management strategies and policy measures. Results dissemination and information exchange will be organized by the University of Gothenburg (proposed host of the future Swedish Marine Institute), the International BALTEX Secretariat, and the Baltic Nest Institute. The proposal was developed in cooperation with the research groups active in the Baltic Sea Experiment (BALTEX; www.baltex-research.eu); the scope of the proposal was discussed in the BALTEX Science Steering Group.

Through cooperation between Baltic-C, BALTEX, and EUR-OCEANS (http://www.eur-oceans.eu/), an interdisciplinary graduate summer school is planned for summer 2009 in which members of the Baltic-C group lecture on Baltic Sea carbon systems, climate systems, and modelling.

7. Participants and management of Baltic-C

Coordination will be done by University of Gothenburg, Sweden, which will provide solid administrative support. The management design and responsibilities of the involved institutions are presented in Figure 3 and the subsequent text.

1. Programme management, synthesis and assessment, and dissemination

- WP1. Programme management (Anders Omstedt, University of Gothenburg, Sweden; participant code 1). Synthesis and assessing the Baltic Sea CO_2 carbon cycle: past and present state, and possible future changes. Disseminating results (University of Gothenburg, Sweden, BALTEX Secretariat, Baltic Nest Institute, and PhD courses).

2. Observational data and experimental work

- WP2. Measuring the Baltic Sea CO_2 system and carbon inventories (Bernd Schneider, Baltic Sea Research Institute, Germany; participant code 2).

- WP3. Inventory of river runoff data (Matti Pertillä, Finnish Institute of Marine Research, Finland; participant code 3).
- WP4. Mineralization of organic material, deepwater–sediment interaction (Janusz Pempkowiak, Institute of Oceanology, Polish Academy of Sciences, Poland; participant code 4).
- WP5. Atmospheric forcing including air–sea CO_2 interaction, atmospheric deposition of acidic components (H_2SO_4 and HNO_3) over whole catchments, and climate scenario outputs available from other EU programs (Anna Rutgersson, Uppsala University, Sweden; participant code 5).

3. Modelling, integration, and scenarios

- WP6. Modelling the organic matter input from terrestrial vegetation and soils (Benjamin Smith, Lund University, Sweden; participant code 6).
- WP7. Modelling the input of A_T, C_T, Ca, and C_{org} from all rivers entering the Baltic Sea (Christoph Humborg, Stockholm University, Sweden; participant code 7).
- WP8. Modelling the Baltic Sea physical–biogeochemical system based on CO_2/O_2 dynamics and climate change (Anders Omstedt, Göteborg University, Sweden; participant code 1).

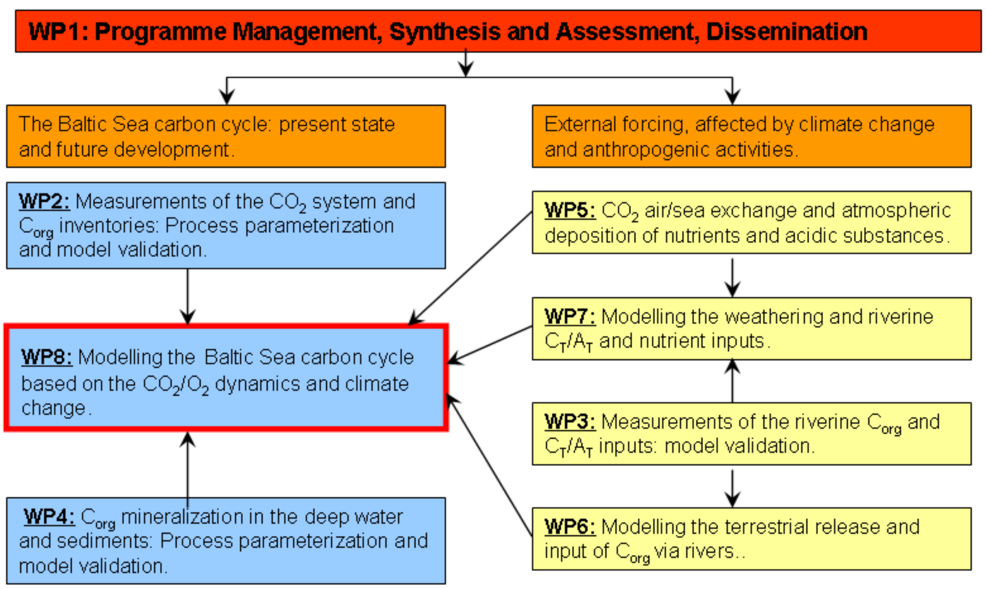

Figure 3. Baltic-C programme structure.

8. *Significant facilities and major equipment available*

The Östergarnsholm field station:

This station is located (57º 27'N, 18º 59'E) in the centre of the Baltic Proper. The measuring site at Östergarnsholm has been running since 1995, and atmospheric carbon dioxide and carbon dioxide fluxes (using the eddy correlation method) have been measured since 2001. The tower is instrumented to measure wind and temperature at five levels and humidity, radiation, and carbon dioxide concentration at one level. Turbulence is measured at three levels, and rapid humidity and carbon dioxide fluctuations are measured, giving direct fluxes at two levels. In May 2005, we deployed a SAMI buoy for continuously measurements of the surface water CO_2 partial pressure.

Research Vessels and databases:
Baltic-C involves three participating institutions (IOW, IOPAS, and FIMR) with access to research vessels with well-equipped laboratories. These ships are instrumented for on-board analysis of carbon, total alkalinity, oxygen, pH, and nutrients, and for continuous-flow CO_2 partial pressure measurement. The participants have developed extensive databases, most data in which have been submitted to the International Council for the Exploration of the Sea (ICES) and the Baltic Sea Commission, HELCOM. The contents of these and the national institution databases will be explored, harmonised and utilized as much as possible.

Database and modelling facilities:
Baltic-C involves four participating institutions (UG, UU, UL, and US) with significant large available datasets of importance for modelling developments and advanced modelling environments related to the Baltic Sea oceanography, biogeochemical processes, Baltic Basin river runoff, terrestrial processes, and climate change.

9. Research exchange and training

The Baltic-C will establish an interdisciplinary exchange program for involved scientists with research visits of one to two weeks per year. This program will intensify the exchange of knowledge between involved research institutions. The focus will be on bridging the gaps between observational and modelling activities. Baltic-C will also be directly involved in creating an interdisciplinary marine graduate summer school of the highest international standard in cooperation with BONUS, BALTEX, and EUR-OCEANS. Scientists involved in the Baltic-C programme are actively involved in organizing this summer school and will directly contribute by giving lectures related to climate change and possible threats to the Baltic Sea, the Baltic Sea CO_2/carbon cycle, and ocean acidification. Baltic-C will involve training of additional pH D students financed from other sources.

10. Detailed workplan/research plan

WP1. Programme management, synthesis and assessment, and dissemination (Anders Omstedt, University of Gothenburg, Sweden; participant code 1).

Objectives: To implement the effective programme management, synthesis, assessment, and dissemination of the results of Baltic-C.

Task 1.1: *Programme management.* The programme will be managed via the University of Gothenburg, Sweden; Prof. Anders Omstedt will be the coordinator with administrative support from the university. A **Scientific Steering Committee** consisting of the project coordinator and principal scientistsBaltic-C is also linked to CarboOcean and the SOPRAN Project, the German contribution to the IGBP SOLAS Project.

Task 1.2: *Workshop and estimated environmental economics aspects.* A joint workshop with scientists from the University of Gothenburg, BONUS, HELCOM, and the Swedish Water District Authority will be organized in which Baltic-C developments are discussed in an EAM framework. Environmental economics responses to the different modelled future projections will be defined based on changes in nutrient load and in the Baltic Sea CO_2 carbon cycle. Due to budget cuts this workshop will be organized outside the Baltic-C program and at a later phase.

Task 1.3: Synthesis and assessment of Baltic Sea CO_2 system. The Baltic-C assessment will provide the scientific community and water management authorities with an assessment of ongoing climate change in the Baltic Sea. An important component is the comparison between pre-industrial conditions, industrial conditions, and possible future projections. Changes in relevant environmental systems due to climate change will be assessed, such as changes in the sink/source function for atmospheric CO_2, acid–base balance (pH), nutrient load and oxygen content (eutrophication), heat balance (temperature), and water balance (salinity). This will produce results/new data that will be of importance in the development of new water management strategies and policies (D2, D3).

Task 1.4: *Dissemination.* Results will be disseminated in cooperation with the BONUS programme, BALTEX Secretariat, Baltic Nest Institute, HELCOM, and Swedish Water District Authority. To develop interdisciplinary training for involved scientists, a one–two-week exchange program will be held each year. The Baltic-C program will also be involved in creating an interdisciplinary marine graduate summer school of the highest international calibre in cooperation with BONUS, BALTEX, and EUR-OCEANS (D4).

WP2. Measurements of the Baltic Sea CO_2 system and carbon inventories (Bernd Schneider, Baltic Sea Research Institute, Germany; participant code 2).

Objectives: To provide validation data for the biogeochemical modelling of the Baltic Sea carbon cycle and to derive process parameterizations for biomass production and nitrogen fixation.

Task 2.1: *Recording surface water pCO_2 and O_2 using a fully automated measurement system deployed on VOS "FINNMAID".* Data with high resolution in space (about 1 nautical mile) and time (2–4 days) will be available for the area between the Mecklenburg Bight and the Gulf of Finland. Surface pCO_2 and O_2 in the Gulfs of Bothnia, Riga and Finland and in the Belt Sea/Kattegat area will be measured during two research cruises (*Task 2.2*). As well as providing model validation data, the measurements will be used to establish CO_2/O_2 mass balances. These will be used to reconstruct the chronology of biomass production, including nitrogen fixation, and to improve the corresponding parameterizations now used in biogeochemical models. Finally, a CO_2 gas exchange balance will be established based on the pCO_2 data, to identify the Baltic Sea as a sink or source of atmospheric CO_2 (D5, D6, D7, and D8).

Task 2.2: *Determining the organic/inorganic carbon and oxygen pools in different Baltic Sea sub-regions.* To obtain a synoptic view of the inorganic/organic carbon and O_2 pools in different areas of the Baltic Sea, there will be two research cruises. To capture seasonal variability, the cruises will take place in winter (February–March 2009) and at the end of the productive period (June–July 2009). The concentrations of C_T, A_T, POC, DOC, and O_2 will be determined in the major sub-basins representing the horizontal resolution of the model. As well as the carbon measurements, standard hydrochemical variables (nitrate, ammonia, phosphate, silicate, and hydrogen sulphide) will be analyzed (D9).

Task 2.3: *Compiling and evaluating CO_2/carbon data collected by previous research and monitoring programmes.* Some National Institutions have made their monitoring databanks accessible through the Internet. As well as standard nutrient and O_2/H_2S data, variables related to the Baltic Sea carbon cycle (A_T, pH, POC, and DOC) are also reported for selected stations and periods. These data will be compiled and aggregated to be used for model validation. Similarly, the results of prior CO_2/carbon research, generally performed by the Baltic-C consortium, will be considered. If appropriate, we will try to identify long-term trends for specific variables (D10, D11).

WP3. Inventory of river runoff data (Matti Pertillä, Finnish Institute of Marine Research, Finland; participant code 3).

Objectives: Combining existing and new data to provide a reliable dataset of parameters for the river input evaluations of the carbon components and for validating the river runoff models.

Task 3.1: *Evaluating the river input concentrations from existing monitoring and research data.* The HELCOM input database includes river loads calculated by submitting organizations, based on concentration and flux measurements in national databases. River runoff monitoring does not usually capture inorganic carbon components, except in a few cases (a one year EUR-OCEANS study of the Rivers Vistula and Odra with monthly resolution). In some cases, river monitoring captures both alkalinity and pH, which can be used to calculate C_T (D12).

Task 3.2: *Evaluating river concentrations from marine data.* In the absence of river monitoring data, the alkalinity concentration can partly be assessed using river runoff estimates and by extrapolating regional marine property vs. salinity graphs to zero salinity. The C_T concentration in incoming rivers is estimated by evaluating a salinity–A_T plot, when possible, and computing freshwater C_T, assuming CO_2 equilibrium with the atmosphere. C_{org} concentrations will be evaluated using salinity–C_{org} properties, when possible. Data collected during the project cruises will also be used to evaluate input values via extrapolation (D13).

Task 3.3: *Measuring input concentrations.* In some areas, the marine data do not allow for reliable extrapolation. To fill in the gaps, the river input data will be completed by studying the main rivers running into the Baltic Sea for A_T, C_T , C_{org}, and pH (D13).

WP4. Mineralization of organic material, deepwater–sediment interaction (Janusz Pempkowiak, Institute of Oceanology, Polish Academy of Sciences, Poland; participant code 4).

Objectives: The work package aims to: 1. quantify organic matter remineralization rates based on organic matter concentration profiles and labile vs. resistant fractions of organic matter in bottom sediments; 2. quantify the organic matter remineralization rates at the sediment–water interface based on CO_2 concentration time series in the above-bottom water layers; 3. quantify the carbon species (both organic and inorganic) fluxes across the sediment–water interface; and 4. quantify the carbon burial in bottom sediments as the proportion of carbon originally deposited in sediments.

Task 4.1: *Establishing remineralization rate constants for organic matter based on existing data.* Methods based on organic/inorganic carbon profiles in cores, sedimentation rates based on 210Pb/137Cs activity concentration profiles, and labile/resistant fractions based on TG/ir traces will be used (D14).

Task 4.2: *Collecting new experimental data to improve and extend the rates provided in task 4.1*. New cores will be taken in deep areas not covered so far and that have both oxic/anoxic redox conditions (WP3 and 4, D15, D16, and D18, D17 deleted due to overlap).

Task 4.3: *Establishing loads of carbon species passing across the sediment–water interface over the entire Baltic.* The load estimates will be based on a budget approach, i.e., the proportions of the sea bottom covered with different sediment types, organic/inorganic carbon concentrations, and sedimentation rates (D19).

Task 4.4: *Determining remineralization rate constants at the sediment surface and in the water column, based on CO_2 concentrations in Gotland Sea deep water*. Since 2003, C_T depth profiles have been measured in the central Gotland Sea 2–3 times per month. The data will be used to determine the remineralization rates at the sediment surface and in the water column based on C_T accumulation in periods of stagnation and to infer remineralization rate constants for different redox conditions (WP 2 and 4, D20, D21 D22, and D23).

WP5. Atmospheric forcing (air–sea interaction, scenarios) (Anna Rutgersson, Uppsala University, Sweden; participant code 5).

Objectives: To provide acid deposition data and scenario data for the biogeochemical modelling of the Baltic Sea carbon cycle and to improve the parameterizations of the air–sea exchange of CO_2.

Task 5.1: *Air–sea interaction.* Takahashi et al. (2002) demonstrated that the calculated total annual ocean uptake of CO_2 increased by 70% when the formulation of the gas transfer velocity was changed. By simultaneously measuring the difference in the partial pressure and vertical flux of CO_2 together with other meteorological data, we will improve the formulation of the gas transfer velocity (Rutgersson et al., 2008). This will mainly be done using data from the Östergarnsholm field station. Measurements will be analysed to develop the new parameterizations and to generate data for validating the Baltic Sea model (D24, D25).

Task 5.2: *Acid deposition.* Besides CO_2, the main acid-forming pollutants are sulphur dioxide and nitrogen oxides. We will extract the acidification data for the Baltic Sea drainage basin and for the Baltic Sea water surface and estimate the total deposition from EMEP data in combination with the SMHI environmental monitoring system (D26).

Task 5.3: *Climate scenarios and land-use data.* This study uses emission scenarios A2, A1B, and B2; B2 represents relatively low emissions, A2 relatively high emissions, and A1B slightly lower emissions than those of A2. These scenarios are used in two different global climate models (GCMs) covering extended periods. Most of the simulations use the ECHAM4

(Roeckner et al., 1999) and ECHAM5 models, but we will investigate the impact of a completely different GCM using the CCM3.0. The GCMs give quite coarse information, so to investigate smaller areas, such as the Baltic Sea, the simulation must be downscaled using a regional climate model (RCM). We will use transient scenarios covering the 1961–2100 period at a 25-km horizontal resolution.

Historical land use data are required to describe vegetation/land use patterns as input to historical simulations using the vegetation model. High-resolution gridded land cover data for recent decades are available from the statistics-based CORINE 2000 database (EEA, 2002), and from PELCOM, which combines satellite observations with extensive ground truthing and ancillary data, such as forest inventory information (Mücher et al., 2000). To account for the effects of centennial-scale land use changes, data from the $0.5 \times 0.5°$ gridded HYDE database extending back to 1700 (Klein Goldewijk, 2001) will be used. The future scenario simulations will use European land use scenarios from the EU-FP6 project ALARM, consistent with the emissions trajectories forcing the corresponding climate simulations (D27).

WP6. Modelling the organic matter input from terrestrial vegetation and soils (Benjamin Smith, Lund University, Sweden; participant code 6).

Objectives: The work package will develop and validate the modelling of the organic matter input from terrestrial vegetation and soils and explore the coupling to the river runoff carbon model.

Task 6.1: *Terrestrial carbon model setup, validation, and coupling to the river runoff carbon model (WP7).* We will use a well-established dynamic vegetation model, LPJ-GUESS (Smith et al., 2001; Yurova & Lankreijer 2007), to simulate the vegetation structure and composition as well as ecosystem carbon cycling and its components (i.e., net primary production and heterotrophic respiration) on a watershed basis throughout the Baltic Sea Basin. The model will be set up for each of the 85 watersheds of the Baltic Sea Basin. A parameterisation of DOC production (Yurova et al. 2007) will be implemented within the model. DOC production will be estimated for each vegetation type (D28).

Task 6.2: *Modelling present and past changes in vegetation structure and functioning and in dissolved organic carbon export.* The vegetation and DOC production model *Task 6.1* will be applied on a catchment basis throughout the Baltic Sea basin, driven by observed climate data (CRU TS 2.1, 1901–2002) and atmospheric CO_2 concentrations from the pre-industrial period to the present day. Output data (vegetation fractions and DOC exports) for the 1993–2002 period will be transferred to the river runoff carbon model in WP7 in order to estimate TOC fluxes to the Baltic Sea (D29).

Task 6.3: *Modelling possible future changes in vegetation structure and functioning and in dissolved organic carbon export.* In this task, the model will be used to estimate transient changes in DOC exports under scenarios of change in climate and land use to 2100, as described in WP5. The predicted fluxes will be transferred to the river runoff carbon model in WP7 for the estimation of TOC discharges to the Baltic Sea (D30).

WP. 7. Modelling the input A_T, C_T, Ca, and C_{org} from all rivers to the Baltic Sea (Christoph Humborg, Stockholm University, Sweden; participant code 7).

Objectives: The work package will model the river inflow of dissolved inorganic and organic carbon species, Ca, N and P from 83 major watersheds forming the Baltic Sea catchments. Also to make scenario analyses on impacts of climate change and changes in land usage patterns on A_T, C_T, Ca, and C_{org} , N and P land-sea fluxes from the Baltic Sea catchments.

Task 7: *Compilation of river chemistry and hydro-meteorological forcing data*. Data will be compiled from official sources stored in a common database (MySQL) and will be done in close collaboration with WP3. Hydro-meteorological data will be compiled on a catchment level from WP5 (D31).

Task 7.2: *Model calibration and validation of A_T, C_T, Ca and Corg inputs.* The basic model used in this study is the CSIM model which uses type concentrations for simulating nutrients (N, P). The model will be expanded to include A_T, C_T, Ca and Corg. Variations are basically a result of changes in the landscape, i.e. giving new mixing relations between landscape components, but dynamic changes are included from changes in the TOC/DOC through relations with Si and other stochiometric relations (D32).

Task 7.3: *Scenario analyses of A_T, C_T, Ca and C_{org} inputs as a function of land cover change and changes in river discharge as an effect of regional climate change.* This will be accomplished by first modelling the runoff from the 83 major rivers entering the Baltic Sea until the year 2100. Land cover changes will then be the forcing function for changes in the load of A_T, C_T, Ca and C_{org} according to the model assumptions in Task 7.2 (D33).

Task 7.4: *Scenario analyses on effects of regional climate change on N and P fluxes from 83 major watersheds forming the Baltic Sea catchment*. Assuming a steady state situation for land cover and land use patterns makes it possible to study the influence of climate change alone. The task will use the Task 7.3 simulated runoff data to estimate changes in the load of N and P until 2100 restricted under the above steady state assumptions (D34).

Task 7.5: *Scenario analyses on changes in land cover types (agricultural vs. forest vs. wetlands) and land use patterns (changes in fertilizer use and livestock density) on N and P fluxes from 83 major watersheds forming the Baltic Sea catchments.* Changes in nutrient loads are heavily dependent on the livestock density and fertilizer use. Data on the possible increase/decrease in livestock density will be made from a prognosis of the relations of protein intake per capita and population increase until the year 2100. Land cover changes will be taken from WP6. Possible reduction in the load of N and P will be based on ‘ecological’ farming (D35).

WP8. Modelling the Baltic Sea physical–biogeochemical system based on the CO_2/O_2 dynamics and climate change (Anders Omstedt, University of Gothenburg, Sweden; participant code 1).

Objectives: The work package will develop, validate, and explore a new Baltic Sea physical–biogeochemical model system based on CO_2/O_2 dynamics and applied to past, present, and possible future climate change studies.

Task 8.1: *Modelling present and past changes of the Baltic Sea CO_2 system*. This will use a well-established Baltic Sea numerical model extensively validated and tested in the BALTEX programme (PROBE-Baltic, Omstedt and Axell, 2003). The forcing functions and response characteristics of the Baltic Sea with regard to pre-industrial (AD 1500–1800) and industrial era (AD 1800–2000) climatic conditions have recently been developed and analyzed (Hansson and Omstedt, 2007; Eriksson et al., 2007) and are available for the project. The chemical part includes six equations covering oxygen, phosphate, nitrate, and ammonia and two equations for calculating total alkalinity and total inorganic carbon. The biological part of the model includes at least two equations for calculating primary production (D36, Table 2).

Task 8.2: *Modelling possible future changes in the Baltic Sea CO_2 system*. Based on transient scenario runs covering the 1960–2100 period, we will first examine the statistics from the climate model forcing by evaluating the 1960–2000 period using the Baltic-C integrated framework. The climate change will be determined by comparing the statistics for "scenario simulations" (using anthropogenic greenhouse gas emissions) with the statistics for "control runs" supposedly representing contemporary conditions. At least 12 transient climate runs will be considered. They will be based on two GCMs assuming two different emission scenarios down-scaled by one RCM and on three different assumptions regarding land-use changes (D37).

Table 2. Baltic-C deliverable list for the different work packages. Note due to budget cuts D1 will be done outside Baltic-C and D17 deleted due to overlap .

Deliverables List

Del. No.	Deliverable Name	WP no.	Delivery date (month)
D1	Estimating environmental costs of change in the acid-base balance (pH).	1	12
D2	Assessment of Baltic Sea CO_2 system.	1	36
D3	The Baltic-C data base.	1	36
D4	Lecture and notes on the Baltic Sea CO_2 system under climate change.	1	12
D5	Seasonally resolved pCO_2 fields for the entire Baltic Sea.	2	12
D6	Seasonally resolved pCO_2 fields for the entire Baltic Sea: Update.	2	24
D7	Improved process parameterizations (biomass production, nitrogen fixation).	2	12
D8	CO_2 gas exchange balance.	2	24
D9	Concentrations of inorganic/organic carbon species in the major model sub-basins.	2	12
D10	Compilation of existing CO_2/carbon data.	2	6
D11	Trend analysis for CO_2/carbon variables.	2	12
D12	River inflow of: alkalinity, pH, total organic carbon, total inorganic carbon, and calcium: Initial database.	3	6
D13	River inflow of: alkalinity, pH, total organic carbon, total inorganic carbon, and calcium: Updated database.	3	18
D14	Calculate remineralisation rates of organic matter based on existing data.	4	6
D15	New stratified sediment samples collected covering Arkona Deep, Bornholm Deep, Gotland Deep, Coastal areas.	4	12
D16	Mineralization rates at the sediment water interface and in the deep water.	4	12
D17	Mineralization rate at different redox conditions.	4	12
D18	Collected cores analyzed.	4	18
D19	Mineralization rates established for a range of environmental conditions.	4	18
D20	Loads of carbon deposited to sediments and return flux of carbon from sediments for the entire Baltic Sea established.	4	24
D21	Carbon burial rates in the Baltic sediments established.	4	30
D22	Data base consisting of C_T depth profiles measured in the central Gotland Sea.	4	36
D23	Report concerning mechanisms of carbon flux to the Baltic sediments.	4	36
D24	Improved parameterisation of the gas exchange transfer velocity.	5	18
D25	Measurements from the first 12 month of the project taken at the Östergarnsholm station.	5	18
D26	Acidic deposition for the Baltic Sea drainage basin.	5	8
D27	Compiled present and future scenario land use data for the Baltic Sea drainage basin.	5	12
D28	Set up and validation of the vegetation model with implementation of DOC export algorithm and coupling to river runoff model.	6	18
D29	Modelling present and past changes in vegetation, CO_2 exchange and DOC production on watershed basis for the Baltic Sea drainage basins.	6	18
D30	Modelling future changes in vegetation, CO_2 exchange and DOC production on watershed basis for the Baltic Sea drainage basis	6	24
D31	Data set on A_T, C_T, Ca and C_{org} inputs to the Baltic Sea.	7	6
D32	Model describing A_T, C_T, Ca and C_{org} inputs from 83 major watersheds for the period 1990-2000.	7	12
D33	Model runs and data set A_T, C_T, Ca and C_{org} fluxes from 83 watersheds as a function of land cover changes.	7	24
D34	Model runs and data set on N and P fluxes from 83 watersheds as a function of land cover changes.	7	24
D35	Model runs and data on N and P fluxes from 83 watersheds as a function land use changes.	7	24
D36	Modelling present and past changes of Baltic Sea CO_2 system.	8	18
D37	Modelling possible future changes in the Baltic Sea CO_2 system.	8	24

11. Project timing

The Baltic-C will run for three years and here are some of the major milestones:-

Mile stone	Title	Mth
M1	Integrated data will be available for past, present and future model runs	12
M2	Baltic Sea Summer School	12
M3	Model setups are ready and validated	18
M4	Model runs on present and past changes of Baltic Sea CO_2 system completed	18
M5	Model runs on possible future changes in the Baltic Sea CO_2 system completed	24
M6	The assessment of Baltic Sea CO_2 system will be presented	36
M7	The Baltic-C data base will be delivered	36

Further details are illustrated in the Gantt chart below, where D1 will not be included within Baltic-C and D17 deleted due to overlap.

Time Schedule of Baltic-C Work Packages, Deliverables per Work Package and Milestones (Month 1 - Month 36)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
WP 1																																					
Deliverables												D1																								D2	
Deliverables												D4																								D3	
WP 2																																					
Deliverables						D10						D5												D6													
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Deliverables												D9												D8													
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WP 3																																					
Deliverables						D12												D13																			
WP 4																																					
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WP 8																																					
Deliverables																		D36						D37													
Milestones												M1						M3						M5												M6	
Milestones												M2						M4																		M7	
Baltic-C Mt	x											x												x						x							Baltic-C meetings
Baltic-C Ws												x																									Baltic-C workshop on calculating environm
Baltic-C Ss									x																												Baltic-C summer school (in cooperation wi
Baltic-C Fm						x				x																											Baltic-C field measurements

12. Data submission plan

The Baltic-C project will collect and generate data at several levels, for which a clear strategy is planned. Baltic-C data management will handle the following:

1. Primary data collected in the project, such as pCO_2, A_T, and pH
2. Primary data for model validation representing new and collected data from different shared databases, such as T, S, O_2, PO_4, and NO_3
3. Derived data for model validation based on primary data, such as pCO_2
4. Baltic Sea atmosphere forcing data and scenarios
5. Baltic Sea terrestrial data for river runoff calculations
6. Baltic Sea river runoff data, such as Q_f, A_T, C_T, Ca, and C_{org}
7. Baltic Sea model output data, such as T, S, O_2, biological production, pH, and fluxes.

The feature most characteristic of science is its reproducibility. If scientists from different research groups cannot duplicate new results, they must conclude that they are invalid. This is a great strength of science: it generates a system for self-correction. Earlier Baltic Sea research efforts have had problems in this area, for example, models were developed based on data from single institutions. With shared databases this restriction is no more acceptable. In climate research, methods have recently been developed to address reproducibility, and appendices are added to publications including complete information about methods and data sources. Baltic-C will take this approach, making all necessary data for Baltic Sea modelling easily available by appending it to the assessment report. The primary data generated in Baltic-C will be submitted to HELCOM and ICES.

13. Ethical issues

Baltic-C does not involve research that requires any ethical approvals, but it will be carried out in a robust way to the highest possible research standards in this field. Training on research ethics will be provided during the Summer schools and other Baltic-C events.

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