Final report

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

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Co-ordinator:
Prof. Anders Omstedt
University of Gothenburg
Department of Earth Sciences
Sweden
Tel. +46317862881
Email: Anders.Omstedt@gvc.gu.se

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1. Summary

The overall objective of Baltic-C was to 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. This has been successfully achieved through a program design that closely linked new research vessel cruises and data mining to modelling developments.
The program has followed its original research and financial plan. The results have through an extensive dissemination (publications, summer schools, conferences, stakeholder meetings and education programs) been well distributed. Major results involve new field observations on the Baltic Sea CO_2-O_2 system including measurements from the atmosphere, the water body and from the marine sediments. For example data on surface water pCO_2 and O_2 observations from VOS "FINNMAID" (Helsinki – Gdynia – Rostock – Lübeck) were continuously collected during 2009 - 2011 yielding 3 - 4 pCO_2 and O_2 data sets each week. A new data base for river load to the Baltic Sea were collected including river flow, alkalinity, total inorganic carbon, total organic carbon, pH, temperature, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}. The river data were collected with one month resolution for the years 1990 – 2008. Acid atmospheric deposition data have also been collected and analyzed together with scenario data for the biogeochemical modeling of the Baltic Sea and its drainage basin.

The field data forms a most important source for increasing our understanding of the carbon cycle and for building new biogeochemical models in the sea and on land. The new integrated ecosystem model framework involves two land surface models (LPJ-GUESS and CSIM) and one Baltic Sea model (PROBE-Baltic). Meteorological forcing data and scenarios have been extracted from freely available sources. The terrestrial vegetation/biogeochemistry model LPJ-GUESS has been enhanced by incorporating a sub-model for C_{org} production in organic wetland soils. This model has been set up for application across the 50 × 50 km simulation grid on which climate atmospheric data were used. The Baltic Sea catchment model CSIM has been expanded by including base cations, anions, C_{org}, and C_T (taking into account the outputs of LPJ-GUESS), and can now calculate parameters such as river runoff, nutrient load, total alkalinity, pH, and pCO_2 for the Baltic Sea sub-basins. The Baltic Sea model PROBE-Baltic has been expanded by including *CO_2-O_2* dynamics during oxic and anoxic conditions, and present and past conditions have been studied extensively.

Climate scenario data have been extracted for the Baltic Sea drainage basin and for the various Baltic Sea sub-basins. Data from some emission scenarios (A1B, A2, and B1) and from three global climate models (ECHAM 5, HadCM3, and CCSM3) downscaled by one regional climate model (RCA3) have been derived for forcing the various model components of the Baltic-C project. Preliminary results have been presented during BONUS Forum stakeholder conferences and to the European community meeting arranged by BONUS. The final results are now in progress. One main message is that the Baltic Sea will most probably become more acid in the future implying a need for including managements tools that can address the combined effects of eutrophication, climate change and acidification. Our new Baltic-C integrated ecosystem model system forms a good base for building such managements tools.

2. Managements and gained scientific results

2.1 Work Package 1 – Management and Dissemination

Lead Partner: Anders Omstedt, University of Gothenburg

Researchers involved in the current work:
Anders Omstedt and David Rayner

2.1.1 Objective

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

2.1.2 Methodology and scientific achievements

Task 1.1; Programme management.

Baltic-C which was also a part in BALTEX has finished successfully and the programme managements have been run by Prof. Anders Omstedt and Dr. David Rayner at University of Gothenburg. A Scientific Steering Committee consisting of the project coordinator and principal scientists was formed with members linking to BALTEX and to CarboOcean and to the SOPRAN Project, the German contribution to the IGBP SOLAS Project. The program started up in January 2009 and a webpage was created through the BALTEX secretariat (http://www.baltex-research.eu/baltic-c/) where the development of the program can be followed including information about available data. The kick off meeting was held in Gothenburg in November 2008 then four Science Study Workshops on the Baltic Sea carbon cycle have been organized and several internal contacts have been performed. Members of Baltic-C have also been involved in organizing two larger Baltic Sea conferences with several scientific contributions from Baltic-C scientist and one summer school:

- 6th Study Conference on BALTEX: Changing Water, Energy and Biogeochemical Cycles in the Baltic Sea Basin. Międzyzdroje, Island of Wolin, Poland, 14 - 18 June 2010.
- 8th Baltic Sea Science Congress in St Petersburg, Russia, August, 2001.
- International Advanced PhD Course on Climate Impacts on the Baltic Sea: From Science to Policy, Nexø, Bornholm, Denmark July/August 2009.

The program management has developed a strong link between field activity, data mining and modelling. The modelling has centred on modelling past, present and future Baltic Sea conditions. For the future a number of available scenarios (Table 1) have been extracted and used by the different modelling groups.

Table 1. Scenarios adopted for simulations of vegetation cover and composition, and DOC production by terrestrial ecosystems Baltic-C.

	GCM	*SRES narrative*	*Ensemble member*	*Land cover*	*Nutrient loads*	*GCM bias correction*	**Factor addressed**
1	ECHAM	A1B	#1	present-day	present-day	none	(baseline scenario)
2	ECHAM	A1B	#2	present-day	present-day	none	natural variability
3	ECHAM	A1B	#3	present-day	present-day	none	natural variability
4	HadCM	A1B		present-day	present-day	none	climate system
5	CCSM	A1B		present-day	present-day	none	climate system
6	ECHAM	A2		present-day	present-day	none	emissions (higher)
7	ECHAM	B1		present-day	present-day	none	emissions (lower)
8	ECHAM	A1B	#1	GRAS	present-day	none	land cover change
9	ECHAM	A1B	#1	present-day	"medium"	none	nutrient loads change
10	ECHAM	A2		BAMBU	"business as usual"	none	multi-factor, "business as usual"
11	ECHAM	A1B	#1	GRAS	"medium"	none	multi-factor,

12	ECHAM	B1		SEDG	Baltic Sea action plan	none	"balanced policy" multi-factor, "environmental"
13	ECHAM	A2		BAMBU	"business as usual"	yes	bias-corrected version of Scenario 10
14	ECHAM	A1B	#1	GRAS	"medium"	yes	bias-corrected version of Scenario 11
15	ECHAM	B1		SEDG	Baltic Sea action plan	yes	bias-corrected version of Scenario 12

Baltic-C have published 32 articles in reviewed scientific journals, 13 work in progress, 9 works classified as books, book chapters or master thesis, 17 reports and popular articles, 24 conference and workshops abstract, see reference list at the end of the report.

Nine pH D student programs have contributed to the Baltic-C. Christin Eriksson (University of Gothenburg), Daniel Hansson (University of Gothenburg) and Karol Kulinski (Institute of Oceanology, Poland) defended their PhDs 2009, Erik Gustafsson (University of Gothenburg) defended his PhD 2010, Karin Wesslander (University of Gothenburg) in 2011, Aleksandra Szczepańska (Institute of Oceanology, Poland), Anna Maciejewska (Institute of Oceanology, Poland) and Maria Norman (University of Uppsala)will defend their PhD in 2012 and Moa Edman (University of Gothenburg) in 2013.To strengthen the cooperation around Baltic Sea carbon cycle, Bernd Schneider was appointed as visiting professor at University of Gothenburg**.**

Thirteen research vessel cruises (Table 2) oriented towards the Baltic Sea carbon cycle has been performed, and in addition data have been collected from the field station Östergarnsholm during the project.

Table 2. Research vessel cruises during included in the Baltic –C program.

Research Vessel	Institute	Time	Expedition code
MERIAN	IOW	18.06. – 14.07.2008	MSM 08/03
ARANDA	FMI	12.01. – 06.02.2009	Baltic C
ARANDA	FMI	26.03. – 08.04.2009	CO2/ALKA/WAVE
OCEANIA	IOPAS	22.04. – 29.04.2009	Baltic-C/ZCHIBM/09
ARANDA	FMI	03.08. – 10.08.2009	FYTO 09/COMBINE 3
MERIAN	IOW	28.08. – 08.09.2009	MSM 12/04a
OCEANIA	IOPAS	19.10. – 31.10.2009	ZDM/Baltic-C/ZCHIBM/09
ARANDA	FMI	11.01. – 04.02.2010	Baltic C
OCEANIA	IOPAS	18.03. – 22.03.2010	Baltic-C/ZCHIBM/ZFM/10
OCEANIA	IOPAS	17.04. – 30.04.2010	Baltic-C/ZCHIBM/10
ARANDA	FMI	09.08. – 27.08.2010	COMBINE3/Trofia

ALKOR	IOW	30.06. – 12.07.2010	AL356
OCEANIA	IOPAS	06.05. – 16.05.2011	Baltic-C/ZCHIBM/11

Task 1.2: Workshop and estimated environmental economic aspect.
Initiatives have been taken to have a joint BONUS meeting together with HELCOM and other end users. The coordinating university has offered the possibility to host this conference within the university of Gothenburg facilities but decision was taken to organize this meeting in Gdansk, Poland. In the early stage a workshop on environmental economics responses to the different projections were planned. Due to budget cuts this workshop was not organized by the Baltic-C program.

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 task was organized within the BACC II program (http://www.baltex-research.eu/BACC2/index.html). BACC II (Second BALTEX Assessment of Climate Change for the Baltic Sea basin) is in close cooperation with HELCOM and chaired by Hans von Storch and Anders Omstedt. Several Baltic-C scientists are involved in this work as members of BACC II Science Steering Committee, as lead authors and authors. The book will be published 2014.

Task 1.4: Dissemination.
Several Baltic-C results have been disseminated in cooperation with the BONUS, BALTEX Secretariat, Baltic Nest Institute, HELCOM, and Swedish Institute for the Marine Environment. To develop interdisciplinary training for involved scientists four Science Study Workshops on the Baltic Sea carbon cycle have been organized. The Baltic-C program was also involved in creating an interdisciplinary marine graduate summer school of the highest international caliber in cooperation with BONUS, Ecosupport, BALTEX, and EUR-OCEANS. During the BONUS Forum stakeholder conferences Baltic-C has informed about its activities and also been actively involved when during 2001 presenting the results to the European community. Baltic-C scientists have also supported HELCOM in summarizing knowledge about acidification and flux of CO_2 and working on the BACC II assessment.

All publications are given in the reference list at the end of the final report.

2.2 Work Package 2 – Measuring the Baltic Sea CO_2 system and carbon inventories.

Lead Partner: Bernd Schneider, Baltic Sea Research Institute (IOW), Germany
Researchers involved in the current work:
Dr. Anne Loeffler

2.2.1 Objective

To provide validation data for the biogeochemical modeling of the Baltic Sea carbon cycle and to derive process parameterizations for biomass production and organic matter mineralization.

2.2.2 Methodology and scientific achievements

The contributions to Baltic-C are based on a comprehensive measurement program. Records of the surface water pCO_2 and O_2 are performed with a fully automated measurement system on a cargo ship. Additionally, research cruises and participation in regular monitoring activities are used to describe the regional and vertical distribution of the variables of the marine CO_2 system. The data are used to characterize the present state of the CO_2 system, to improve the process parameterizations in biogeochemical models and to validate the model simulations.

Task 2.1: Recording surface water pCO_2 and O_2 using a fully automated measurement system deployed on VOS "FINNMAID".

Surface water pCO_2 and O_2 measurements on VOS "FINNMAID" (Helsinki – Gdynia – Rostock – Lübeck) were continuously performed during 2009 - 2011 yielding 3 - 4 pCO_2 and O_2 data sets each week. The data from previous years (since 2003) were re-analyzed and after submission to SOCAT they are now publically available at the Carbon Dioxide Information and Analysis Center (CDIAC, ORNL, US). The data were used to estimate the annual CO_2 air/sea balances for the central Baltic, the western Gulf of Finland and the Arkona Sea. On an average these three regions acted as a distinct sink for atmospheric CO_2 . Furthermore, the data facilitated the quantification of the net biomass production in different regions and years. Combining the biomass production with a nitrogen budget yielded the mid-summer nitrogen fixation. The calculations also showed that a nitrogen source must exist in late spring to maintain the production. This opened up the discussion of an early "cold" nitrogen fixation.

Task 2.2: Determining the organic/inorganic carbon and oxygen pools in different Baltic Sea sub-regions.

After a cruise with r/v Maria S. Merian in August/September 2009, the major Baltic-C research cruise with r/v Alkor took place in June/July 2010. Water samples were taken at about 60 stations in the major basins of the Baltic Sea except the Kattegat and the Gulf of Finland. Chemical analysis was performed for total CO_2, alkalinity, O_2/H_2S and nutrients. The surface water CO_2 partial pressure was recorded continuously during the entire cruise. Together with pCO_2 data from previous cruises an air/sea gas exchange was established for the Gulf of Bothnia. It was shown that the Bothnian Sea is a distinct sink for atmospheric CO_2 whereas the Bothnian Bay is approximately at equilibrium with the atmosphere on an annual basis.

Task 2.3: Compiling and evaluating CO_2/carbon data collected by previous research and monitoring programmes.

The vertical distribution of total CO_2 in the deep water of the Gotland Sea was determined with a temporal resolution about 3 months since 2003. A period of deep water stagnation was identified for 2004 – 2006 and was used to establish mass balances for total CO_2 and dissolved inorganic nitrogen. Taking into account vertical mixing, mineralization and denitrification rates were calculated for sub-layers at depths below 150 m.

Past changes in the marine CO_2 system were derived from data for alkalinity, pH, total CO_2 and the CO_2 partial pressure in the northern Baltic Sea reported by Kurt Buch for the period 1927 – 1938. The data indicated an increase in alkalinity in the central Baltic and the Gulf of

Finland that has partly compensated the acidification caused by the increasing atmospheric CO_2. Based on the surface CO_2 partial pressure it was estimated that the net spring production was by a factor of 4 – 5 lower at the beginning of the last century.

2.3 Work Package 3 – Inventory of river runoff data

Lead Partner: Matti Perttilä, Finnish Meteorological Institute , Finland.
Researchers involved in the current work:
Laura Joensuu

2.3.1 Objective

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.

2.3.2 Methodology and scientific achievements

Task 3.1: Evaluating the river input concentrations from existing monitoring and research data.

River input concentrations were collected for the following parameters: river flow, alkalinity, total inorganic carbon, total organic carbon, pH, temperature, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}. Data were collected at one month resolution for the years 1990 – 2008. Appropriate data for Finnish and Swedish rivers was obtained from the HELCOM data system (www.ymparisto.fi). The HELCOM monitoring system for river input is designed for eutrophication and pollution monitoring, not for studying the effects of the climate change. Of the above parameters, only TOC (total organic carbon) is included (as a voluntary parameter). Thus there was very little other data in the HELCOM data files, except from Finland and Sweden. Data for other rivers was obtained either through personal contacts or with the help of national information centers. The sources are listed in the readme file with the data compilation. For most river inputs, the available data is incomplete with respect to the aim (years 1990 – 2008 at monthly resolution), but can nevertheless be used for modelling the changes (see WP 7). The only major river for which data was not obtained is the Neva, in spite of several approaches to Russian authorities at different organizational levels. Because of the importance of Neva, the lack of data cannot probably be ignored, and thus for this river, other means of evaluation will be attempted. The data compilation is available at ftp://ftp.fmi.fi (deliverable 12) as an Access file.

Task 3.2: Evaluating river concentrations from marine data.

The work to complete the monitoring data was done. Two approaches were used. Both of them, the extrapolation of marine data to zero salinity, and a box-model approach yield input approximations as annual averages.

Task 3.3: Measuring input concentrations.

Input concentrations of the major Finnish and Swedish rivers running into the Gulf of Bothnia have been measured once, in order to obtain a comparison check of the sampling/analysis methodology. Possibility of creating a temporary monitoring system for the Neva River is under consideration.

2.4 Work Package 4 – Mineralization of organic material, deep water–sediment interaction

Lead Partner: Janusz Pempkowiak, Institute of Oceanology, Polish Academy of Sciences, Poland.

Researchers involved in the current work:

Ph D student Anna Maciejewska, Ph D student Aleksandra Szczepańska, Dr Karol Kuliński.

2.4.1 Objective

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.

2.4.2 Methodology and scientific achievements

Task 4.1: Establishing remineralization rate constants for organic matter based on existing data (Regarding D16).

Results of organic matter concentrations in surface and stratified sediment samples (cores) were reanalyzed. Surface sediment samples were collected at various locations of the Baltic Sea (28 sediment samples).The mineralization rates of organic matter in sediments ranged from 1.7 $gm^{-2}y^{-1}$ to 2.2 $gm^{-2}y^{-1}$. Larger rates were found in sediments collected from more shallow oxic areas of the Baltic bottom.

Task 4.2: Collecting new experimental data to improve and extend the rates provided in task 4.1 (Regarding D18).

Collecting new stratified sediment samples

Sediment cores were collected in 2009 at the following locations**:** Arkona Deep, Gotland Deep, Bornholm Deep, Gdansk Deep, Gulf of Bothnia, southern coast of the Baltic Sea. The cores were cut into slices 10mm thick and stored in a deep freezer for further analysis in laboratory

Collected sediment cores analysed

The obtained samples (243 sediment samples) were analyzed for the following properties: Corg, DOC, DIC, ^{210}Pb, ^{137}Cs, moisture, loss on ignition, porosity, pCO2, pH, A_T. The meta data base information's are available on Baltic-C homepage.

*Task 4.3: Establishing loads of carbon species passing across the sediment–water interface over the entire Baltic (*Regarding D19)

Mineralization rates established for a range of environmental condition

Based on the DIC and DOC profiles in the water samples obtained from sediment samples (see D18),and the age of the samples derived from ^{210}Pb profiles (validated with ^{137}Cs profiles) mineralization rates of organic matter in the sediments column were calculated. These ranged from 2.4 to 5.7 $gm^{-2}y^{-1}$. Larger rated were found in the deeper, anoxic, bottom sediments. The feature is tentatively attributed to faster sedimentation rates, and higher organic matter content in such sediments.

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 (Regarding D20)

Mineralization rates at the sediment water interface and in the deep water
Measurements of the concentrations of total CO(2) (Cr), O(2), H(2)S, NO(2)(-), NO(3)(-), and NH(4)(+) were performed for several years at intervals of 2-3 months in the deep water of the Gotland Basin (Baltic Sea). The data were used to determine mineralization and denitrification rates in four sub layers below 150 m during a period of stagnation. To account for the vertical mixing at the boundaries of the sub layers, mixing coefficients were determined based on the temporal changes of the salinity profiles. Mass balances were established for each measured variable and yielded the sink/source rates in the individual sub layers for each time interval. The seasonality of mineralization rates was confined to water layers that were in close contact with the sediment surface, indicating that the mineralization took place mainly at the sediment surface.

The total mineralization rate in the basin was found to be 2.0 mol $m^{-2}yr^{-1}$, thereby implying that about 80% of the particulate organic carbon input occurred by lateral transport. A redox balance indicated that manganese dioxide and possibly iron oxides contributed to the oxidation of organic matter by about 13%.

Loads of carbon deposited to sediments and return flux of carbon from sediments for the entire Baltic Sea established
The bottom sediments are crucial carbon sink in the Baltic Sea. Basing on sediment properties derived from the analyzed sediment samples (see D18, D16), and sediment deposition rates derived from ^{210}Pband ^{137}Cs profiles it is established that the load of organic matter deposited to sediments in the entire Baltic is 0.37×10^8mol (+/- 0.05×10^8mol). Thus the annual flux of carbon to sediments amounts to−3.87 Tg of organic carbon, while inorganic carbon flux can be neglected. This amount needs to be corrected by the return carbon flux (1.14 Tg yr^{-1}) originating from the long-term mineralization and hydrolysis of the organic matter deposited in the sediments. The bulk of the carbon returning to the water column (91 %) is dissolved inorganic carbon (DIC), indicating that the rate of mineralization exceeds that of hydrolysis of organic carbon in the sediments. Of the deposited carbon load 31% is mineralized and returned in the overlaying water as DIC. At the same time 2.9% of the deposited carbon is returned to water as DOC.

2.5 Work Package 5 – Atmospheric forcing (air–sea interaction, scenarios)

Lead Partner: Anna Rutgersson, Uppsala University, Sweden
Researchers involved in the work:
Dr. Björn Carlsson Claremar, PhD Student Maria Norman, Master Student Ida Sjöström

2.5.1 Objective

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

2.5.2 Methodology and scientific achievements

The contributions to Baltic-C is based on new data from the Östergarnsholm site for improved parameterization of air-sea gas exchange as well as development of gridded data of atmospheric forcing of the Baltic Sea drainage basin for past, present and future conditions. Scientific achievements includes that the lead Partner (Anna Rutgersson) is one of the lead authors of the BACCII book focusing the climate of the Baltic Sea region.

Task 5.1: Air–sea interaction.

Using direct flux measurements from the Östergarnsholm field station a new process was identified altering traditional descriptions of air-sea exchange of CO_2 (and other gases). For a deep mixed layer and convection in the water (generated by cooling at the water surface) the transfer velocity was shown to be significantly enhanced (Rutgersson and Smedman, 2010; Rutgersson et al., 2011). The new process is introduced in the Baltic Sea model (Norman et al., 2012; Deliverable 24). The water-side convection is then expresses relating the characteristic velocity of transfer to the buoyancy at the surface and mixed layer depth. The direct flux measurements as well as additional measurements have been taken at the Östergarnsholm site during the project and generated a data-base for 12 months of data (Deliverable 25). Method development of the eddy-covariance method gave an alternative method to directly estimate fluxes also using ship data (Norman et al. 2011).

Task 5.2: Acid deposition.

A data base for the acid deposition to the different Baltic Sea basins as well as to the Baltic Sea drainage basin was generated for the period 1960 to 2006. The acid deposition is taken from the EMEP chemical transport model (for 1990 to 2006) (http://www.emep.int/OpenSource/index.html). For the years 1960–1989, the trends in emissions of SO_2, NO_x and NH_3 were scaled by the deposition in 1990 and seasonal variations were based on the 1990–2006 mean variation. The emissions were taken from the gridded (1°x1°) EDGAR-HYDE data set (http://www.mnp.nl/edgar/model/). It contains global anthropogenic emissions of NO_x, SO_2, NH_3 among others species. Also a data base for deposition of base cations and chloride ions was generated over the drainage basin by interpolating measurements in the EMEP network. Data base of acid deposition, base cations deposition as well as CO_2 concentration (derived according to Rutgersson et al., 2009) is reported as Deliverable 26 (D26) to the BONUS system and in Claremar et al. (2012).

Task 5.3: Climate scenarios and land-use data.

Global Climate scenarios regionally downscaled by the regional climate model RCA are available from the Swedish Meteorological and Hydrological Institute through the EU projects PRUDENCE and ENSEMBLES. Transient climate scenario data are here extracted for the Baltic Sea drainage basin as well as for the Baltic Sea basins for a period representing the climate change between 1960 and 2100. Data from several emission scenarios (A1B, A2 and B1) as well as several global climate models (ECHAM 5, HadCM3 and CCSM3) are derived to be used to force the different model components within the Baltic-C project. The data base of atmospheric forcing during past, present and future climate in the Baltic Sea region is reported as Deliverable 27 (D27) in the project. The data from the GCM:s were by Carlsson et al (2010) and Sjöström et al (2010) shown to well represent some features of present day climate, some major biases of the parameters from the GCM:s were, however, identified. The scenarios of the Baltic-C project have been derived using both the output from the GCM: s directly as well as using the “delta-change methodology”.

Land use change was included as an additional dimension of change in scenario ensemble adopted for Baltic-C (Table 1). Land use change scenarios for the 21st century consistent with the global narratives underlying the emissions scenarios of the IPCC were adopted from the EU-FP7 project ALARM. These scenarios are modelled using the methodology of Rounsevell et al. (2005, 2006) refined by coupling the European land use model with a global econometric model that allows estimation of parameters that affect the global population, global gross domestic product (GDP) distribution, global trade and markets for land-based commodities (food, wood products), and with an ecosystem model that computes agricultural yields, accounting for the effects of climate change on crop production. The ALARM scenarios GRAS, SEDG and BAMBU (Spangenberg et al. 2012) were adopted in combination with climate scenarios forced by the A1B, B1 and A2 emissions scenarios, respectively.

References:

Rounsevell, M.D.A., Ewert, F., Reginster, I. et al. 2005. Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. *Agriculture, Ecosystems & Environment* 107: 117-135.

Rounsevell, M.D.A., Reginster, I., Araújo, M.B. et al. 2006. A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems & Environment* 114: 57-68.

Spangenberg, J.H., Bondeau, A., Carter, T.R., et al. 2012. Scenarios for investigating risks to biodiversity. *Global Ecology & Biogeography* 21: 5–18.

2.6 Work Package 6 – Modelling the organic matter input from terrestrial vegetation and soils

Lead Partner: Benjamin Smith, Lund University, Sweden

Researchers involved in the current work:

LU: Ben Smith, Peter Frodin, Guy Schurgers, Paul Miller

External collaborator (not funded by Baltic-C): Alla Yurova, Institution for Numerical Mathematics, University of Moscow.

2.6.1 Objective

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.

2.6.2 Methodology and scientific achievements

Task 6.1: Terrestrial carbon model setup, validation, and coupling to the river runoff carbon model (WP7).

The terrestrial vegetation/biogeochemistry model LPJ-GUESS (Smith et al. 2001) has been enhanced by incorporation of a sub-model for DOC production and sorption dynamics in organic wetland soils based on the model of Yurova et al. 2008. The model has been set up for application across the 50 x 50 km simulation grid on which climate driver data from WP5 are provided. Wetland area fractions provided by WP7 are used to scale the model-generated DOC concentrations to the grid cell scale. For forests and open (mainly cultivated) land, a more simplified, empirical approach was adopted, assuming constant DOC concentrations of 40 mg l^{-1} (forest) and 8 mg l^{-1} (open land) in runoff from these ecosystems, based on typical average values reported in the literature (Michailzik et al. 2001). For coupling to river runoff, monthly grid cell average DOC fluxes are provided as forcing fields for the CSIM hydrochemistry model in WP7.

LPJ-GUESS has been extensively validated, for example in relation to observations or independent estimations of ecosystem productivity (Smith et al. 2008, 2011; Tang et al. 2010), CO_2 exchange (Morales et al. 2005; Wramneby et al. 2008) and vegetation composition and structure (Smith et al. 2001, 2011; Hickler et al. 2012). These factors reflect driving mechanisms for the DOC fluxes simulated. The DOC production itself was parameterised for and successfully validated against (independent) measured DOC

concentrations and respiration fluxes for a wetland catchment in northern Sweden (Yurova et al. 2008).
Evaluation of the *regional* DOC fluxes simulated in this project, however, presents a greater challenge, as the available data are confined to monitoring data on river mouth concentrations of DOC and this means that transport and chemical transformations of DOC in the watershed, and augmentation by non-terrestrial sources, must be taken into account. Preliminary results from the CSIM hydrochemistry model (WP7) when forced by ecosystem DOC fluxes from LPJ-GUESS show satisfactory agreement between observed and modelled DOC concentrations for the recent past.

Task 6.2: Modelling present and past changes in vegetation structure and functioning and in dissolved organic carbon export.
DOC concentrations in runoff from wetlands simulated by LPJ-GUESS in a hindcast simulation averaged 128 mgC l^{-1} across the Baltic Sea catchment area for the period 1961-1990. As expected, this is appreciably higher than the prescribed constants of 40 and 8 mgC l^{-1} assumed respectively for forests and cultivated land (see Section 2.3). DOC export by ecosystems, taking account of the amount of simulated runoff and the concentration of DOC in the flushed soil, is estimated to amount to 9.0 gC m^{-2} yr^{-1} averaged over the Baltic Sea catchment area as a whole. Taking into account variation in runoff among land cover classes, and the differential cover of forests, wetlands and open land, this total may be partitioned into a net contribution of around 1.5 gC m^{-2} yr^{-1} from both wetlands and cultivated lands, while forests contribute around two thirds of the total with an average efflux of 6.1 gC m^{-2} yr^{-1}. The explanation for the dominant contribution of forests is their large areal coverage combined with an intermediate DOC production compared to the other land cover classes.

Results have been provided to WP7 for use in forcing the CSIM model.

Task 6.3: Modelling possible future changes in vegetation structure and functioning and in dissolved organic carbon export
Scenarios of possible future changes in greenhouse forcing, climate and human land use are needed to provide a basis for the analysis of interactions and feedbacks in the Baltic Sea CO_2/O_2 system accounting for land-sea biogeochemical coupling. It was previously decided to adopt a selection of the IPCC-SRES narratives, and climate model simulations based on these, as the basic scenario framework of Baltic-C. A refined suite of 15 scenarios encompassing uncertainty in the true nature of the global climate system (represented by three different GCMs), natural climate variability (represented by three ensemble members for the ECHAM5 GCM) and the future course of socio-economic development (represented by three GHG emissions scenarios) was adopted for use in the whole project (Table 1). Scenarios of land use change consistent with the underlying socio-economic assumptions of the SRES-based GCM scenarios were chosen from the EU project ALARM (WP 5). The main criteria for the choice of scenarios to explore are that they cover the scope of possible future changes in a comprehensive way, maintaining realistic relationships between different driving variables, and accommodating major aspects of uncertainty. It is not realistic or intended to provide predictions or projections of any “accuracy”.

Within the uncertainty in future climate forcing represented by the suite of climate models, initial forcing conditions and GHG emissions adopted (scenarios 1-7 in Table 1), an overall increase in DOC production compared with present-day levels, is predicted in all scenarios, varying from +30 to +43% by the late 21st century. In general, temperature, precipitation and atmospheric CO_2 concentrations (the latter positively influencing photosynthesis and water use efficiency in many plants) all behave as positive drivers of plant growth and litter production within the climate domain of the Baltic Sea area, while warmer temperatures and increased soil flushing associated with increased rainfall will tend to amplify decomposition processes. In general this points to the likelyhood of higher DOC exports from terrestrial ecosystems of the Baltic Sea under the warmer, potentially moister, high-CO_2 future climate projected by the climate scenarios.

In terms of the influence of land cover, forests were estimated to account for the majority of a potential future increase in ecosystem DOC exports, averaging +2 gC m^{-2} yr^{-1} (+42%) among scenarios, compared to modern baseline levels. This is explained by the high coverage of forests relative to wetlands, and by the higher runoff DOC concentration constant assumed, relative to open land. For cultivated land and wetlands, the estimated increase averaged 0.3 gC m^{-2} yr^{-1} (28%) and 0.2 gC m^{-2} yr^{-1} (18%) respectively. However, the results for forests and cultivated lands must be interpreted with caution, and are likely to be overestimates; rises averaging around 30% in simulated runoff are assumed to lead to increased soil flushing, runoff DOC concentrations being conserved at the levels prescribed from literature. In reality, DOC fluxes must be limited by DOC production, with the degree of flushing having only a limited positive impact on the proportional export of DOC, and this implies that the actual change in DOC export may still be positive, but smaller.

For the land use change scenarios, overlaying the relevant ALARM land cover scenario with the common baseline land cover data adopted in WP6-8 has proved problematic. Consequently, the results are still being finalised. They will be included in a scenarios paper being prepared together with the other WPs with expected submission during 2012.

2.7 Work Package 7 – Modelling the input A_T, C_T, Ca, and Corg from all rivers to the Baltic Sea

Lead Partner: Christoph Humborg, Stockholm University, Sweden
Researchers involved in the current work:
Magnus Mörth, Christoph Humborg, Teresia Wällstedt and Erik Smedberg

2.7.1 Objective

The work package has modelled the river inflow of dissolved inorganic and organic carbon species, Ca, N and P from 83 major watersheds forming the Baltic Sea catchments. Further scenario analyses on impacts of climate change and changes in land usage patterns on A_T, C_T, Ca, and Corg, N and P land-sea fluxes from the Baltic Sea catchments are performed.

2.7.2 Methodology and scientific achievements

Task 7.3: Scenario analyses of A_T, C_T, Ca and Corg inputs as a function of land cover change and changes in river discharge as an effect of regional climate change.
Much work has been dedicated to filling the gaps in the dataset for calibration and validation. The datasets for Odra, Vistula and Neva have been complemented with data from the Gems database (http://www.gemstat.org/). Much data for calibration and validation data is still missing, especially for Estonian and Latvian rivers. These gaps have been filled by applying different multivariate correlation functions. The scenario runs need input data from WP 6, especially data on DOC from forests and agricultural areas as well as data on land-cover

change. We have not received these data yet. However, the model has been calibrated and validated for hydrology, SBC, SAA, DOC and DIC for present day conditions and as soon as the scenario input data are delivered, work can be initiated to find retention factors for DOC. Thereafter we can do the scenario runs that we foresee will take about one month work.

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.
We have received the climate change scenarios for the 8 original scenarios from WP5. During the workshop in Lund in November, it was decided to also run scenarios with delta-change on three different scenarios; we have yet not received data for these additional scenarios. However, we have calculated the effect of changes in temperature and precipitation on N and P fluxes for all 83 watersheds using the strong correlation functions between load and runoff for the catchments of the various Baltic Sea basins (n=7).

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.
We have not calculated the land cover scenarios because we realized during the project that agricultural practices that we calculated with the NANI tool (Net anthropogenic nutrient inputs) are much more significant for N and P fluxes than relatively moderate changes in agricultural areas. We calculated therefore 4 lifestyle scenarios: i) the effects of 20% increase in fertilizer use, human consumption, animal consumption, animal production, crop production to humans and animals; ii) effect of adjustment of agricultural practices to EU-15 level on nutrient fluxes from transitional countries (Poland, Baltic States and Russia); iii) effect of 20% decrease in atmospheric deposition following the NEC directive and iv) business as usual, increase in human consumption of animal proteins by 3% annually with using the relationships of the various NANI components (animal and crop production and finally fertilizer use).

2.8 Work Package 8 – Modelling the Baltic Sea physical–biogeochemical system based on the CO_2/O_2 dynamics and climate change

Lead Partner: Anders Omstedt, University of Gothenburg, Sweden
Researchers involved in the work:
Dr. Erik Gustafsson, Dr. Karin Wesslander, PhD Student Moa Edman

2.8.1 Objective

The work package have 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.

2.8.2 Methodology and scientific achievements

Task 8.1: Modelling present and past changes of the Baltic Sea CO_2 system.
The Baltic Sea CO_2 has now been introduced into a well established process-oriented Baltic Sea model and the present and past changes have been studied (Omstedt et al., 2009). The model has been further developed and designed for the scenarios runs and predictive capability has been improved by includes CO_2 dynamics for oxic and anoxic conditions as well as improved biochemical modeling (Edman and Omstedt, 2012, and Gustafsson, 2011).

The observational data have also been analyzed in detail with regard to the carbon system (Wesslander et al., 2010, Hjalmarsson et al., 2008). Also a reconstruction of past 100-500 years river runoff to the Baltic Sea and hypoxia conditions have been studied (Gustafsson and Omstedt, 2009, Hansson et al., 2010, Hansson and Gustafsson, 2011). This data forms a base for further studies about past marine conditions in the Baltic Sea and the model reconstructions have been delivered to other BONUS programs. A new book (Omstedt, 2011) that gives a guide to Baltic Sea modeling including the CO_2 system is published including extra material that makes the model code freely available.

T*ask 8.2: Modelling possible future changes in the Baltic Sea CO_2 system.*
Before running scenarios we have analyzed factors influencing the acid-base (pH) balance of the Baltic Sea. Using calculations based on the marine carbon system and on Baltic Sea modeling, the sensitivity of surface pH has been examined (Omstedt, Edman, Anderson and Laudon, 2010). The results from this sensitivity study indicate that fossil fuel burning is likely to have both a direct and indirect effect through increased CO_2 levels, altering seawater pH as well as changing the river chemistry. The influences from eutrophication, marine acidification, climate change and land-sea interaction have been analyzed. A large number of sscenario simulations have been collected and forcing fields have been analysed (Carlsson and Rutgersson, 2010, Carlsson et al., 2010, Claremar et al., 2011, 2012). These forcing fields have then been applied to the Baltic-C land surface models generating scenarios on river inflows of nutrients and carbon to the Baltic Sea. These forcing fields have then been for the Baltic Sea modelling. Preliminary results have been presented during 2011 (Omstedt and the Baltic-C team, 2011), during BONUS Forum stakeholder conferences and to the European community meeting arranged by BONUS. The final results are now in preparation (Omstedt et al., 2012). The main message is that the Baltic Sea will most probably become more acid in the future.

3. Publications:

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