BONUS INTEGRAL

BONUS
SCIENCE FOR A BETTER FUTURE OF THE BALTIC SEA REGION

Integrated carboN and TracE Gas monitoRing for the bALtic sea

BONUS INTEGRAL project duration: July 1st 2017 - Sept. 30th 2020

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Project outline of goals and results envisaged at the beginning of the project cycle

Several European nations are investing in the European Integrated Carbon Observation System Research Infrastructure (ICOS RI). Finland, Sweden, and Germany are already partner of the ICOS RI with established infrastructure, while other countries like Poland and Estonia are currently in the process of developing their strategy. Although the overall aim of ICOS is to provide European-wide carbon dioxide and other greenhouse gas (GHG) concentration and flux data, an integration for the Baltic Sea region has not been pursued, and the added value of ICOS and related infrastructure for the Baltic Sea ecosystem monitoring and assessment had so far not been exploited at all.

Within BONUS INTEGRAL, the partners from eight institutions and five nations therefore aimed to:

- Integrate the different data streams of ICOS and related infrastructure in the pan-Baltic area,
- Provide better charts of seasonal carbon dioxide and GHG flux over the Baltic Sea, including advanced remote sensing approaches,

- Integrate the carbon system into a high-resolution 3D-model, which will contribute to a better description of the biogeochemical coupling of eutrophication and deoxygenation,
- Demonstrate the added value for a better biogeochemical ecosystem status description of the Baltic Sea,
- Advise the implementation of ICOS in the south-eastern countries of the Baltic, and actively promote components strengthening the value for Baltic Sea ecosystem status assessment,
- Develop, in close interaction with stakeholders, strategies for a better, cost-efficient monitoring approach for the Baltic Sea by integration of ICOS and related data.

The rationale for the work carried out in BONUS INTEGRAL is the conviction that for the Baltic Sea, cause-reaction relations between measures to combat eutrophication and the ecosystem response cannot properly be evaluated and predicted without a sound understanding of the carbon cycle. Moreover, monitoring carbon system parameters is a prerequisite for any attempt to trace acidification in the Baltic Sea. Lastly, in the era of greenhouse gas accounting, a budget of greenhouse gas fluxes between the Baltic Sea and the atmosphere and its human- and climate induced changes should be known as an indicator of ecosystem health.

Work performed in BONUS INTEGRAL

The work plan of BONUS INTEGRAL was subdivided into 7 work packages, of which WP1 was related to management, WP's 2-6 were related to the research program of the project, and WP 7 was dedicated to dissemination and outreach.

WP1 Coordination and Management included all activities related to management and reporting of the project, including annual meetings and acting as central contact point for the project.

WP2 Data mining, assimilation, and integration identified and evaluated existing data on greenhouse gases (CO_2, CH_4 and N_2O) as well as on the carbonate system (A_T, C_T, pH) in the Baltic Sea, and produced an easy accessible, unified meta-data information.

WP3 Infrastructure and observation amendments established several amendments to existing infrastructure, used its close relation/involvement in the HELCOM monitoring to effectively gain carbon system and trace gas data from selected monitoring stations, executed two field campaigns on research vessels, and installed a new underway pCO_2 system on a coastal-near ferry line traversing the plume of the river Vistula.

WP4 Greenhouse gas data integration merged historical data and the data gathered within the project and provided monthly surface pCO_2 concentration fields using machine-learning extrapolation schemes.

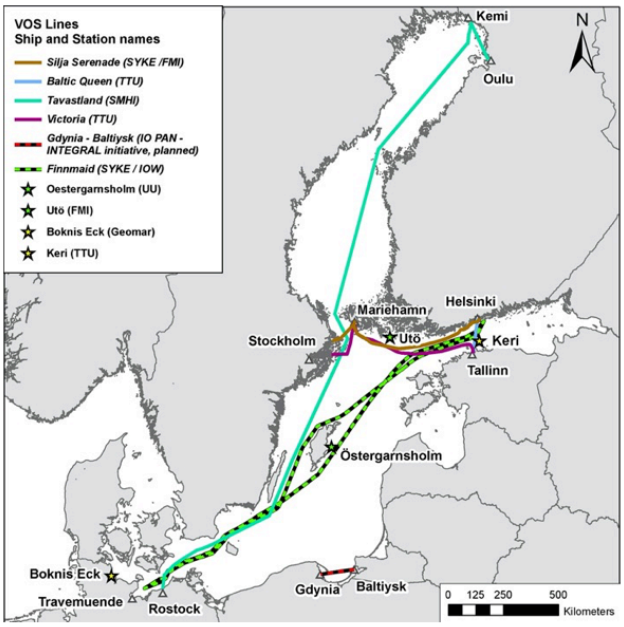

Figure 1: Map of the BONUS INTEGRAL observational network.

WP4 also compiled and analysed all available data on the non-CO_2 GHGs (N_2O and CH_4) for the Baltic Sea and mapped these data, which were found not to allow (yet) for the construction of seasonal maps.

WP5 Flux parameterization and estimates provided Baltic-wide CO_2 flux estimates by using the seasonal concentration fields developed within the project, and applying various air-sea parameterizations, including a turbulence-based parameterization implemented into a state-of-the-art wave model, which was developed within the project. This was compared to a classical wind-speed parameterization, with several additional processes added by using enhanced features of the FluxEngine toolbox in order to analyse the effect of the uncertainties in current flux parameterizations on the CO_2 gas exchange of the Baltic Sea.

WP6 Carbon-based ecosystem assessment improved the carbon cycle representation in a coupled 3D-hydrological-biogeochemical model by implementing an improved process understanding from measurements performed within the BONUS INTEGRAL project. The continuously optimized model was used to calculate the carbon budget and its changes in time for the Baltic Sea and, together with observations, to derive pCO_2 fields in an approach using the measured data in combination with model-derived patterns. The model was also used to develop strategies for optimized carbon monitoring taking temporal and spatial variability of the system with as little as possible data into account.

WP7 Dissemination and outreach was a major component of BONUS INTEGRAL, including knowledge transfer between partners and countries, teaching principles of modern carbon and greenhouse gas analytics and sensors for the next generation of enthusiastic scientists in the framework of a summer school, and promoting the use of SOOP-lines (Ship of Opportunity) and carbon data for a cost-effective monitoring of the Baltic Sea through continuous stakeholder dialogue. BONUS INTEGRAL also provided a Policy Brief demonstrating and road-mapping the better integration of SOOP-based sampling strategies and ICOS-related infrastructure for the ecosystem monitoring of the Baltic Sea

Main results achieved during the project

Scientific and Technological Highlights

The project, in synergy to related activities by the partners, was able to considerably enhance the infrastructure for carbon dioxide- and GHG-measurements in the Baltic Sea in a sustainable way (Figure 1). On the SOOP line Finnmaid, running between Helsinki and Lübeck, a new generation of underway instrumentation was installed, now continuously recording pCO_2, N_2O, and CH_4 data as well as spectrophotometric pH measurements (an application of technology developed within the Innovation Project BONUS PINBAL and a big step towards a future monitoring of acidification in the Baltic Sea). The instrumentation is part of ICOS and currently worldwide unique. The pCO_2-measurements on SOOP Tavastland, which have discontinued several years ago, were revived within the project. This is invaluable to close the data gap in the Northern Basins, and measurements are secured for the next years by the admittance of the ship to the Swedish ICOS network. A small SOOP line in the Gulf of Gdansk was realized by the project, providing invaluable data from one of the largest riverine estuaries in the Baltic Sea.

Two scientific cruises in winter and early summer have been executed by the project, providing hitherto missing knowledge on the near-shore gradients of GHG-distributions, and allowing for a data-based assessment of the uptake of carbon during the spring bloom in the Bothnian Bay. Augmenting the activities during an entire year of the Estonian monitoring on RV Salme allowed a first carbon and trace gas inventory in the Gulf of Riga, and proved the seamless integration of high resolution surface

measurements and discrete sampling for carbon and trace gases into regular monitoring activities (Figure 2).

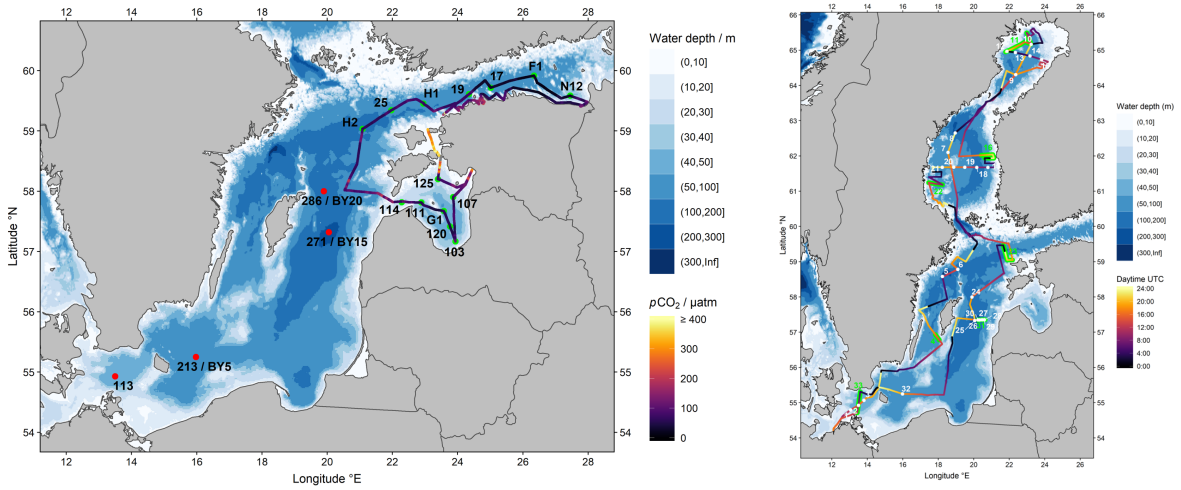

Figure 2: Left: *Cruise track of RV Salme from May 28th to June 2nd 2018 with colours representing the partial pressure of CO_2 in the surface, and stations of trace gas and carbon system sampling indicated by the red and green dots.* ***Right:*** *Cruise Track for the BONUS INTEGRAL summer cruise. The colour code of the track indicates the time of day (UTC). CTD sampling stations are indicated as white dots, hydrographic ScanFish transects as green lines. Both maps with underlaying bathymetry.*

The project provided a new and improved calculation of a monthly climatology of pCO_2 fields, the driver for the exchange with the atmosphere. These maps are based on a compilation of the available data in combination with satellite- and model-derived data (Figure 3).

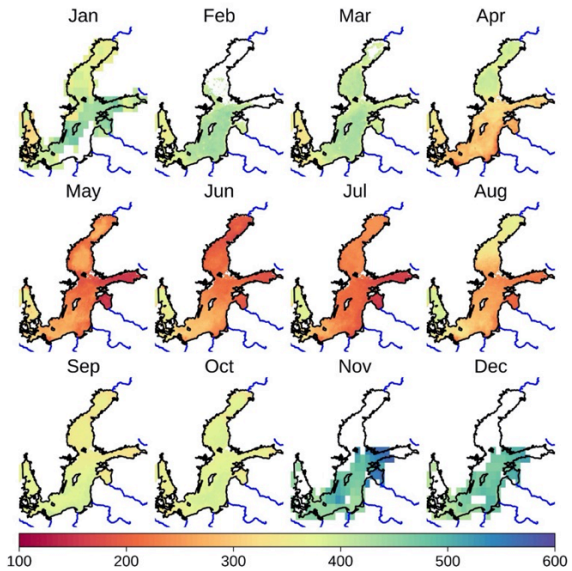

Figure 3*: Monthly average pCO_2 concentrations for the period 2002 to 2011; for the months February to October Random Forest with remote sensing products, and for November to January interpolation of in-situ data are used.*

Considerable progress has been achieved with regard to carbon dioxide and methane flux calculations in the Baltic Sea. This includes direct flux studies of carbon dioxide and, for the first time in the Baltic Sea area, of methane, by using so called eddy covariance measurements. Additionally, a new air-sea parameterization was derived, relying on the analysis of turbulence induced by waves. Implementation into a state-of-the-art wave model allowed to develop regional gridded data the air-sea exchange coefficient, taking into account the true wave spectrum of the Baltic Sea, including effects produced by shallow waters, limiting wave development near coasts. Moreover, by testing the sensitivity of air-sea flux calculations to individual added processes like convection, precipitation or exchange suppression by surfactants, major insights into the uncertainties of these estimates was possible.

The implementation of new possibilities into the FluxEngine toolbox enables the execution of these sensitivity studies not only for BONUS INTEGRAL ,but also for the wide scientific community.

Modifications and improvements of the carbon-transforming processes in the 3D hydrographic-biogeochemical model considerably improved the capacity of the model to quantitatively describe the surface pCO_2 seasonal cycle, governed by net primary production and mineralization, which is tightly linked to eutrophication. Using the measurements from surface observations in combination with the model-derived pattern provides a novel approach to derive seasonal pCO_2 maps. Maybe most importantly for the scope of BONUS INTEGRAL, considerations of the uncertainty of the output of this combined approach allows to evaluate the increased accuracy caused by additional observational data (Figure 4). This approach paves the way for model-derived optimization of environmental sampling strategies, which is applicable not only for surface pCO_2 data.

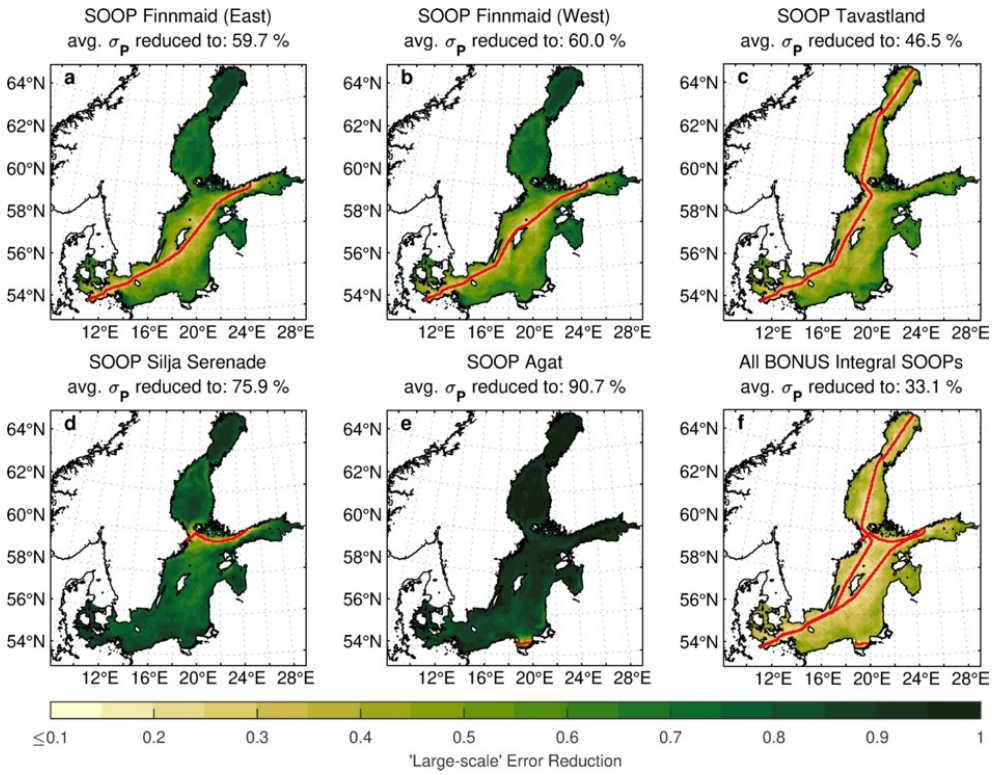

Figure 4: *Reduction in large-scale error by SOOP line surface pCO_2 sampling for (a) Finnmaid on Eastern route, (b) Finnmaid on Western route, (c) Tavastland, (d) Silja Serenade, (e) Agat, and (f) all SOOP lines of BONUS INTEGRAL combined (with an assumed common 5 µatm observation error).*

Dissemination Highlights

Amongst Scientists, exchange of expertise played a major role for the construction of the SOOP line Agat, the joint venture which allowed the collection of the unique enhanced data set from the Estonian monitoring, and the resumption of the pCO_2 measurements on SOOP Tavastland. In all cases, the exchange of expertise was essential, and assured a homogenization of technology and data processing right from the beginning,

For the new generation of young scientists, the IOCCP – BONUS INTEGRAL Summer School-"Instrumenting our ocean for better observation: a training course on a suite of biogeochemical sensors" was surely the most important dissemination event co-organized and -funded by the project. The course, held at the Sven Lovén Center for Marine Sciences, Sweden, was attended by 27 outstanding early career scientists, including 18 females, invited from over 135 applicants worldwide, including two PhD students from BONUS INTEGRAL. A group of highly renowned instructors shared

their time and expertise to provide basic training for those just embarking on their adventure with the biogeochemical sensors, including oxygen optodes, biooptics, pH-instrumentation, and pCO_2-sensors. The school was a highlight in the international visibility of the project and also BONUS, recognized far beyond the European boundaries, and also featured in the AGU EOS journal (https://eos.org/science-updates/training-the-next-generation-of-marine-biogeochemists).

Promoting a strong component of the ocean (marine) theme of ICOS in the pan-Baltic area with added value for the environmental monitoring of the Baltic Sea turned out extremely successful. Partners IO PAN (Poland) and TTU (Estonia) are now designated members of their national ICOS consortia, likely including the SOOP Agat that was established through BONUS INTEGRAL. Moreover, the SOOP Tavastland is now official component of ICOS Sweden, maintained by BONUS INTEGRAL partner SMHI. BONUS INTEGRAL definitely strengthened the position of the partners on their way into ICOS.

The implementation of inorganic carbon monitoring in the Baltic Sea has been advanced considerably. A project for the development of a carbon-based acidification monitoring has been granted to TTU by the Estonian Ministry of the Environment. In Germany, the agency in charge of the HELCOM monitoring (BSH) granted a project to establish monitoring of pH by spectrophotometry in the Baltic Sea. SMHI started an intercomparison of this method with formerly applied methods to switch to this advanced technology. This considerable progress towards the implementation of carbon system parameters for a better monitoring of eutrophication and acidification in the Baltic Sea is surely related to the stakeholder work of BONUS INTEGRAL at HELCOM and national agencies.

The continuity plan of the project

Most of the infrastructure developed or used within the project is secured for the next years. For further homogenization of measurements and operations, various of the partners work together in the Horizon 2020 project JerichoS3, which selected the Gulf of Finland as a “Pilot Supersite”. The development in Sweden, Estonia and Germany appears promising towards the establishment or resumption of the monitoring of carbon parameters, and might form a nucleus for a HELCOM-wide effort, as the lack of a suitable indicator for acidification has been widely recognized. The indicator development for acidification is currently pursued further in the project OMAI (Operational Marine Acidification Indicator) funded by the Nordic Research Council, with partners from Sweden, Germany, Denmark and Finland, under the auspice of the IN Eutrophication.

More of BONUS INTEGRAL

A Policy Brief with the vision and recommendations of BONUS INTEGRAL towards an improved Baltic Sea monitoring of acidification and eutrophication can be accessed via the BONUS website at: https://www.bonusportal.org/files/6964/BONUS_INTEGRAL_Policy_Brief.pdf. For more detailed information about the project’s outcome, including a list of publications (23 published at the time of this summary), please be referred to our website: https://www.io-warnemuende.de/integral-home.html.

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