1 Project data

BONUS INTEGRAL

Integrated carbo**N** and Trac**E** **G**as monito**R**ing for the b**AL**tic sea

Final Report

Reporting Period: July 1st 2017 to Sept 30th 2020

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Swedish Meteorological and Hydrological Institute (SMHI),
University of Exeter (UNEXE)

2 Scientific and technological results achieved during the project

A.) INTRODUCTION

Several European nations are investing in the Integrated Carbon Observation System (ICOS). Finland, Sweden, and Germany are already partner of the ICOS ERIC 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, we 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 work plan of BONUS INTEGRAL was subdivided into 7 work packages, of which WP's 2-6 were related to the R&D program, WP1 to management of the project, and WP 7 to dissemination and outreach: WP1 Coordination and Management; WP2 Data mining, assimilation, integration; WP3 Infrastructure and observation amendments; WP4 Greenhouse gas data integration, WP5 Flux parameterization and estimates; WP6 Carbon-based ecosystem assessment; WP7 Dissemination and outreach. Within this final report, we report on the main output and advancements generated by the project (WPs2-7).

B.) DATA MINING, ASSIMILATION, INTEGRATION (WP2)

At the beginning of the project, as main objective of WP2, 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 were compiled, and as far as possible their quality was evaluated and controlled. Most of the existing data is stored in open databases like: MEMENTO, ICOS, COPERNICUS, SOCAT. Important data sources are also already ended BONUS projects like Baltic-C or Baltic Gas. Part of the data is available through the scientific literature, where the corresponding author is usually indicated. A common metadata base was produced and made available to the scientific community. This work early in the project helped to provide data for model verification (WP6), and to identify data gaps to be filled during the field work effort of the project (WP3). More detailed information can be found in Deliverable Reports 2.1, 2.3, and 2.3.

C.) INFRASTRUCTURE AND OBSERVATION AMENDMENTS (WP3)

In order to get vital additional information on surface greenhouse gas concentrations and fluxes as well as carbon system data, BONUS INTEGRAL provided 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, performed two field campaigns on research vessels, and installed a basic underway pCO_2 system on a coastal-near ferry line traversing the plume of the river Vistula. For individual platforms and locations, please refer to Figure 1. As an add-on to the project, a 3-months sailing expedition was embedded within BONUS INTEGRAL, providing essential information about the vertical integration of surface signals from ships of opportunity (SOOPs, also referred to as Voluntary Observing Ships, VOS).

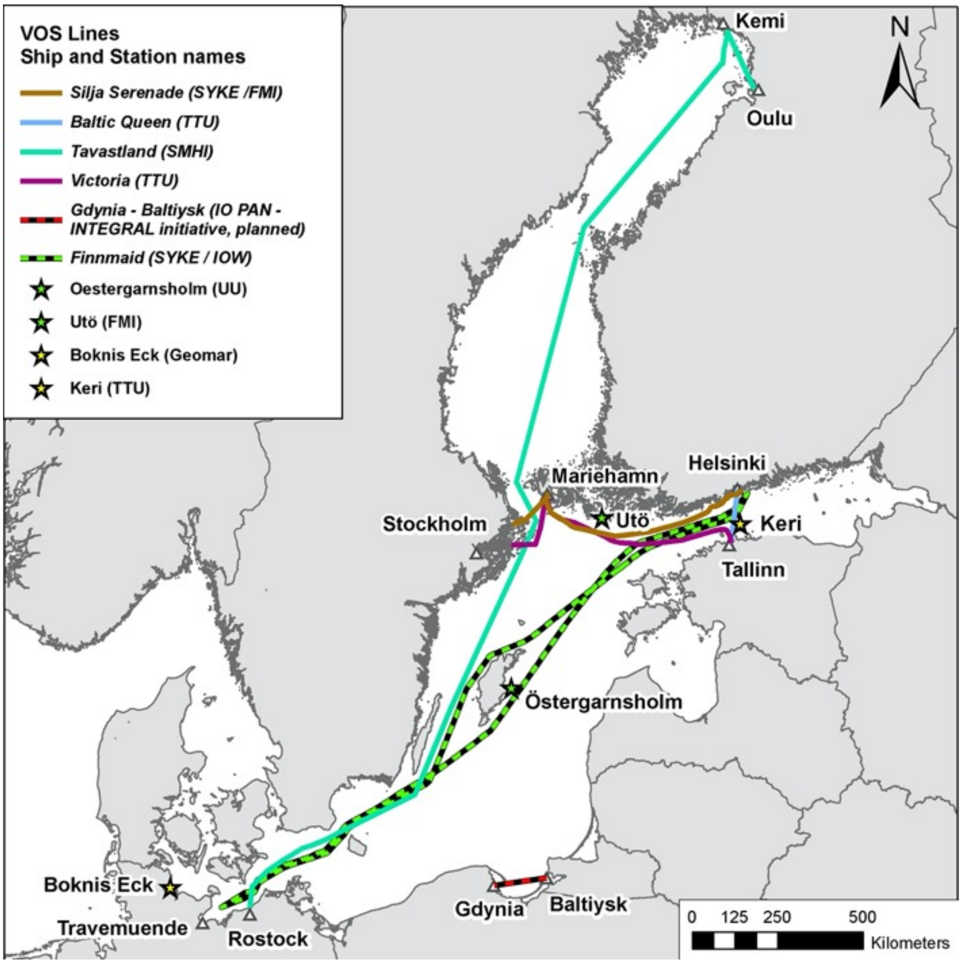

Figure 1: *Map of locations of infrastructure used within BONUS INTEGRAL. The stations Östergarnsholm, Utö, and SOOP Finnmaid are part of ICOS. The line Gdynia Baltiysk (SOOP Agat) is projected within BONUS INTEGRAL. All other infrastructure is established by other initiatives, but was partially amended.*

C1: Installation / operation of infrastructure amendments

At the beginning of the project, three infrastructures were officially integrated in the European ICOS RI, though very different in nature: The continuous surface water measurement system for pCO_2 (and pCH_4) on board SOOP Finnmaid commuting between Helsinki and Lübeck, run by partner IOW in a joint effort with the Finnish Environmental Institute (SYKE), the atmospheric station Utö providing atmospheric CO_2 and CH_4 partial pressure data and some additional, not ICOS-certified water side data on a small island in the south of the Archipelago Sea, run by partner FMI, and the flux tower station Östergarnsholm, which provides CO_2 flux data using direct eddy covariance measurements at the very small island of Östergarnsholm east of the Island of Gotland, run by partner UU. It was the strategy of the infrastructure implementation plan of BONUS INTEGRAL to extend these measurements as well as to equip other platforms run by the partners in order to extend the data coverage for CO_2 and other GHGs, with the aim to lobby for the sustainable use of these amendments after the end of the project. It has to be emphasized that the outcome of this endeavour was only possible through substantial contributions by the partner institutes as well as using synergies with other projects. In the following, the achievements of this effort is given station by station. Location or regular cruise tracks of the individual components of the “BONUS INTEGRAL observation network” are given in Figure 1.

SOOP Finnmaid - The SOOP Finnmaid has been operational and taking pCO_2 measurements since 2003, and pCH_4 measurements since 2010. The scientific effort is a joined effort between the Finnish Environmental Institute (SYKE) and Partner IOW. Unfortunately, the system stopped its GHG measurements in the time frame from October 2017 to April 2018, because of a severe blocking of the seawater inlet by biofouling, which had to be removed through a diver operation in Helsinki under ice-free conditions; a task that was impossible to complete before spring 2018. After that, the system was operational for most of the remaining time of the project. In November 2019, after several years of preparation by IOW, the new instrumentation (generation 3) was installed on board and delivered high quality data right after installation. Since that date, the worldwide unique system records data of pCO_2, pCH_4, O_2, pH, N_2O and CO from the surface waters with a time resolution of 1 min. Like in the original system, two independent water-air equilibration chambers measure, amongst the other parameters, the pCO_2 of seawater independently, and the consistency of both measurements within $<2\mu$atm is an important QC-criterion for both subsystems. The installation of the HydroFia pH system developed within BONUS PINBAL is the first long-term test on a SOOP line and provides an unprecedented data set of surface pH measurements across the Baltic Sea. An overview of the data from a single transect, which is produced usually within one day after finalization as basis for QC and trouble detection, is displayed in Figure 2.

All the pCO_2 data since 2003 have been evaluated in order to characterize underlying biogeochemical processes. This work started before the project and was finalized as a contribution to the project, and published in a scientific monograph (Schneider and Müller 2018, see Chapter 9). The assessment of the data is an important contribution to the dataset available for the goals of WP 4 and 5. Moreover, it clearly points to our current knowledge – and knowledge gaps – in connection to the controls on productivity, carbon uptake, and gas exchange, all of which is relevant for a state-of-the-art implementation of the carbon system in biogeochemical models (WP6). Similarly, the eight years of pCH_4 data are currently compiled and interpreted for spatiotemporal variability and underlying controlling parameters as part of the PhD-thesis of BONUS INTEGRAL scientist Erik Jacobs, with the first paper accepted for publication in the journal Biogeosciences (Jakobs et al., 2021 accepted). The data set acquired by SOOP Finnmaid is the backbone of several efforts within BONUS INTEGRAL WPs 4 to 6. The entire pCO_2 data set, which has been submitted to the SOCAT data base and is used in the annual Global Carbon Budget (Friedlingstein et al., 2019 & 2020), is displayed in Figure 3.

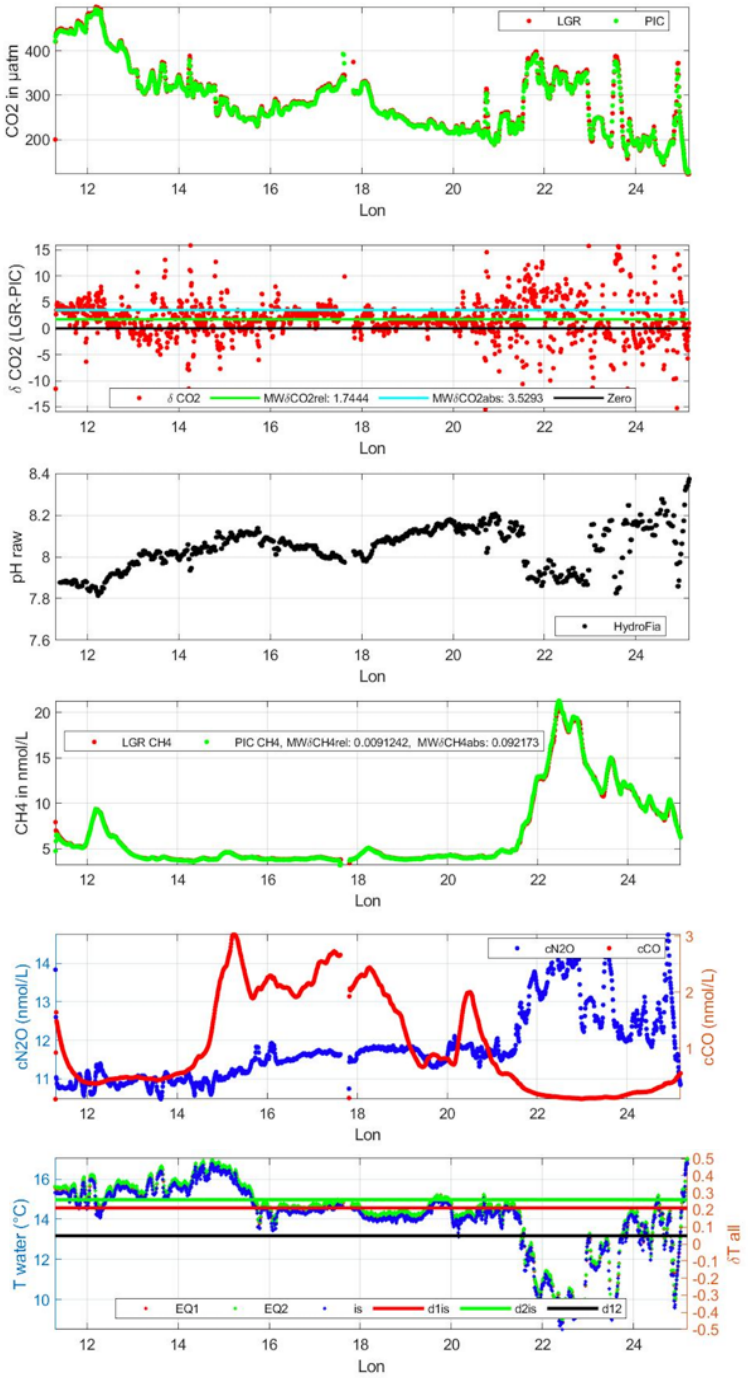

Figure 2: *Extract of the automated measurements of the new surface monitoring system on SOOP Finnmaid from June 21st to June 22nd between Lübeck (left) and Helsinki (right), for ship track see Figure 1. Panels from top to bottom: pCO_2 (from two sensors), difference in pCO_2 measurements with mean deviation, pH (uncalibrated), C_{CH4} (from two sensors), c_{N2O} and C_{CO}, water temperature from the equilibration systems and at the inlet (in situ), with indication of mean differences.*

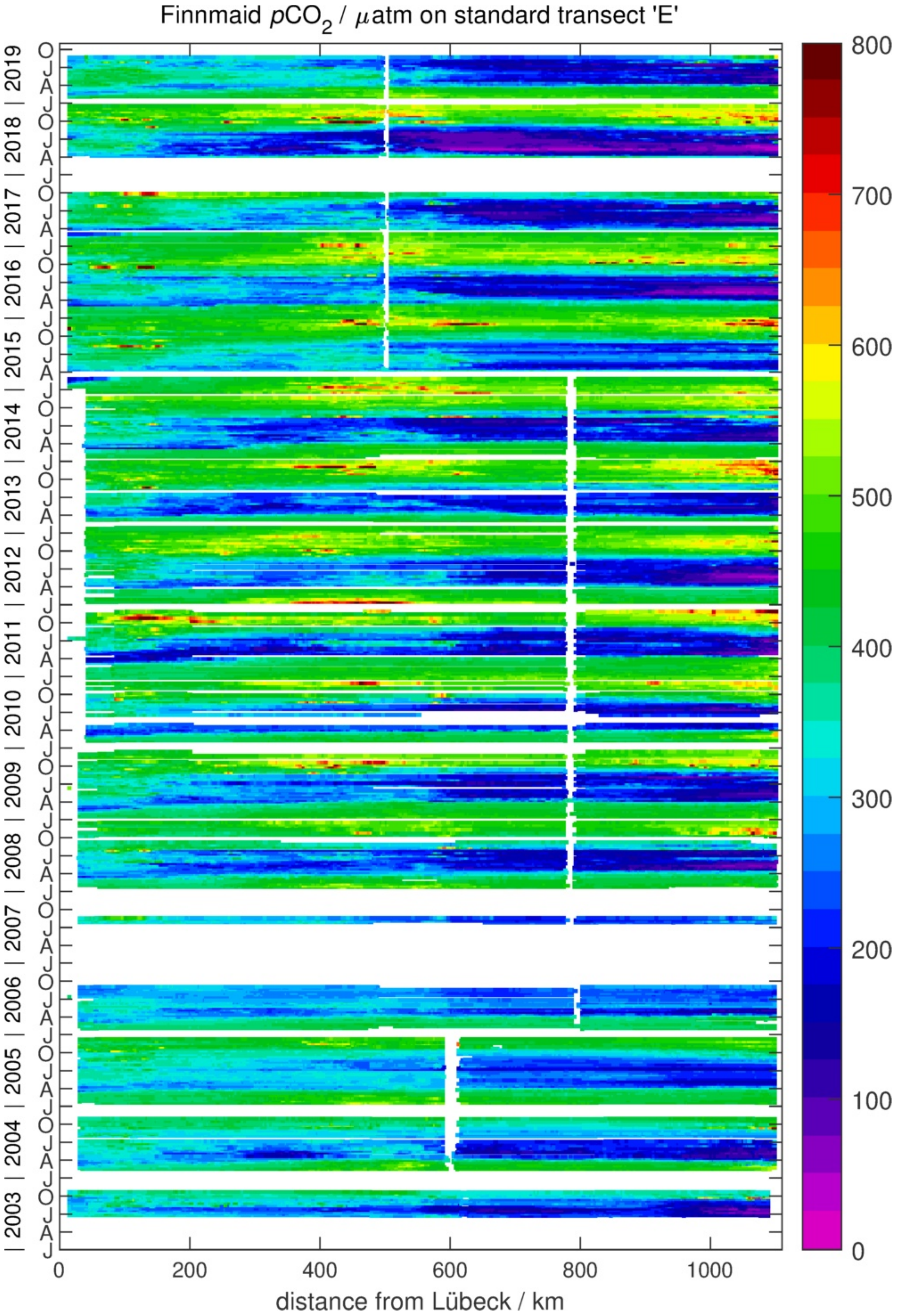

Figure 3: *Hovmöller diagram of the pCO₂ data recorded by SOOP Finnmaid from 2003 until the installation of the new system in November 2019. The data have been the backbone for spatio-seasonal data integration in Work Packages 4&5, and model validation in WP6. All data have been submitted to the SOCAT data base.*

SOOP Tavastland is operated by partner SMHI and started as a joined effort with SYKE in 2009. The ferrybox measures salinity, temperature, oxygen, turbidity, chlorophyll fluorescence, phycocyanin fluorescence, and CDOM-fluorescence. There are two automated water samplers that can be used to collect reference samples. A pCO_2 system from General Oceanics (GO) was installed next to the ferrybox one year later. After years of problems with the system and sporadic data collection, it was finally fully operational in the fall of 2019 due to supportive efforts by the BONUS INTEGRAL Partner GEOMAR, and has been measuring continuously since. With support of BONUS INTEGRAL, the station is now an official marine station within the ICOS RI. Figure 4 shows the seawater pCO_2 data from October 2019 onwards. The data gaps are mainly caused by problems with the seawater supply. The seawater supply will be completely renewed in fall 2020.

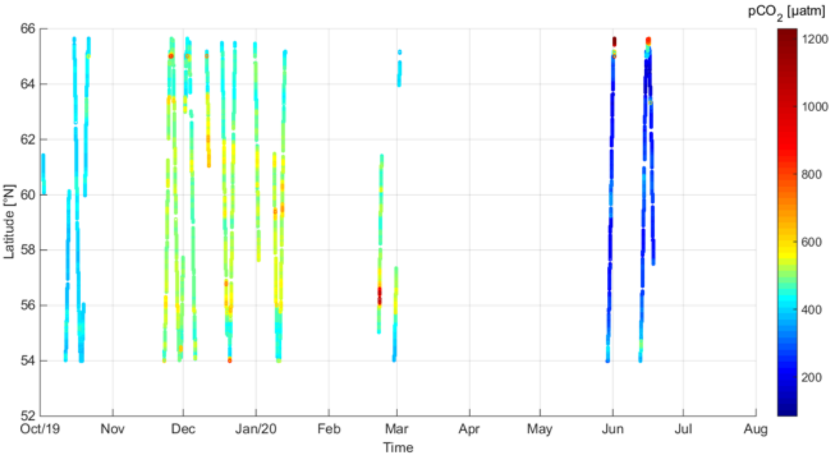

Figure4: Data of seawater pCO_2 from October 2019 until July 2020 recorded by the SOOP Tavastland. Data gaps are mainly due to pump problems. The huge gap in spring 2020 was caused by the Covid-19 pandemic as maintenance on board was not allowed. Data given against latitude. For cruise track information, see Fig. 1.

IOW and GEOMAR provided two optical CH_4/CO_2 and N_2O/CO sensors (Los Gatos Research, San Jose, CA) for the installation onboard SOOP Tavastland to expand the existing measurement setup by continuous high-frequency measurements of methane and nitrous oxide. For those parameters, the database in the northern basins is particularly scarce. Though problems with the seawater supply hampered the acquisition of high quality data, the street is paved for this approach once the ship's ferry box system will be renewed.

SOOP Silja Serenade: Partner FMI set up the pCO_2 observation on M/S Silja Serenade in November 2017, which was already equipped with T,S, and optical sensors as part of the Alg@line project. The pCO_2 observations were stopped for the ice season and started again in March 2018 and provided data over extended periods until March 2020. Since then, the ship route was changed to Helsinki-Riga. On this new route, the ship operated from June 26th until September 13th 2020, when the ship had so stop operation due to Covid-19 regulations.

SOOP Silja Europa (Line Tallinn-Helsinki) & **Baltic Queen** (Line Tallinn-Stockholm) are operated by TTU. A new ferrybox system was purchased and installed onboard Silja Europa (Tallinn-Helsinki), which would enable to add more sensors, including those measuring carbon system parameters. The ferry stopped operation in spring 2020 until June 12th 2020 due to travel restrictions. Installations of additional sensors cannot be realized before 2021, as operation was stopped again in September 2020 until at least March 31st 2021. However, through cooperation within BONUS INTEGRAL and also raising awareness of the need for carbon system parameter measurements by the Estonian government, it is likely that the ship's scientific equipment will be amended by carbon system instrumentation in the near future.

SOOP Agat. The Gulf of Gdansk is highly influenced by the Vistula River, which is the second largest river entering the Baltic Sea. The rivers, draining the continental part of the Baltic Sea catchment including the Vistula River, are known for very high total alkalinity (T_A), nutrient and organic matter loads. This drives high organic matter production and remineralization and may lead to high spatial and temporal variability of the marine CO_2 system, including changes in pH, CO_2 partial pressure (pCO_2) and levels of CO_2 exchange through the air-sea interface. Nevertheless, coastal regions of the southern Baltic Sea are still highly undersampled in terms of the CO_2 system, and pose a large question on the transformation and transport processes towards the open basins. This was the motivation for initiating surface observations of the CO_2 system across the Gulf of Gdansk within the BONUS INTEGRAL project to allow for improving the biogeochemical monitoring in one of the most dynamic land-sea exchange areas, the drainage of the Vistula River.

Figure 5: *Upper and Lower Left - SOOP Agat (source: www.naszbaltyk.com), Right - ferrybox installed in the engine room of the vessel.*

The ferrybox system, exclusively funded by the BONUS INTEGRAL project, was installed in December 2017 on MS Agat – a small passenger ferry operating regularly in the Gulf of Gdansk on the routes Gdynia-Hel and Gdynia-Baltijsk. The system comprises a thermosalinograph (Seabird) and a pCO_2 detector (Hydro-C, Kongsberg Maritime Contros GmbH, now 4H Jena Engineering). Additionally, the system has been adjusted to be compatible with a spectrophotometric system for pH measurements, HydroFIA pH, developed within the BONUS PINBAL project. In the first half of 2018, the ferrybox system was extensively tested for both its long-term mechanical stability as well as data quality. Small shortcomings were removed, and the system fully adjusted to the conditions on the ship. The quality of the

pCO_2 measurements was verified by cross-comparison of measured pCO_2 values with those calculated from DIC and pH in May 2018. Extensive further tests for long-term stability performed in the third year of the project revealed a series of technical problems on various components, which have been solved step by step until the end of 2019. After solving all technical problems, return to the fully operational mode was impeded by the Covid-19 pandemic. As a consequence of the mobility restrictions and the lock-down in Poland, the regular cruising to Baltiysk has been suspended and until now has not been revived.

The other route operated by MS Agat, between Gdynia and Hel (Polish inland waters) has been restored in late May 2020. Despite the lower interest of tourists in cruising, we were able to collect quite a number of pCO_2 measurements in the region. Figure 6 shows the mean daily values of salinity, temperature, pCO_2 and water flow in the system for the summer period 2020.

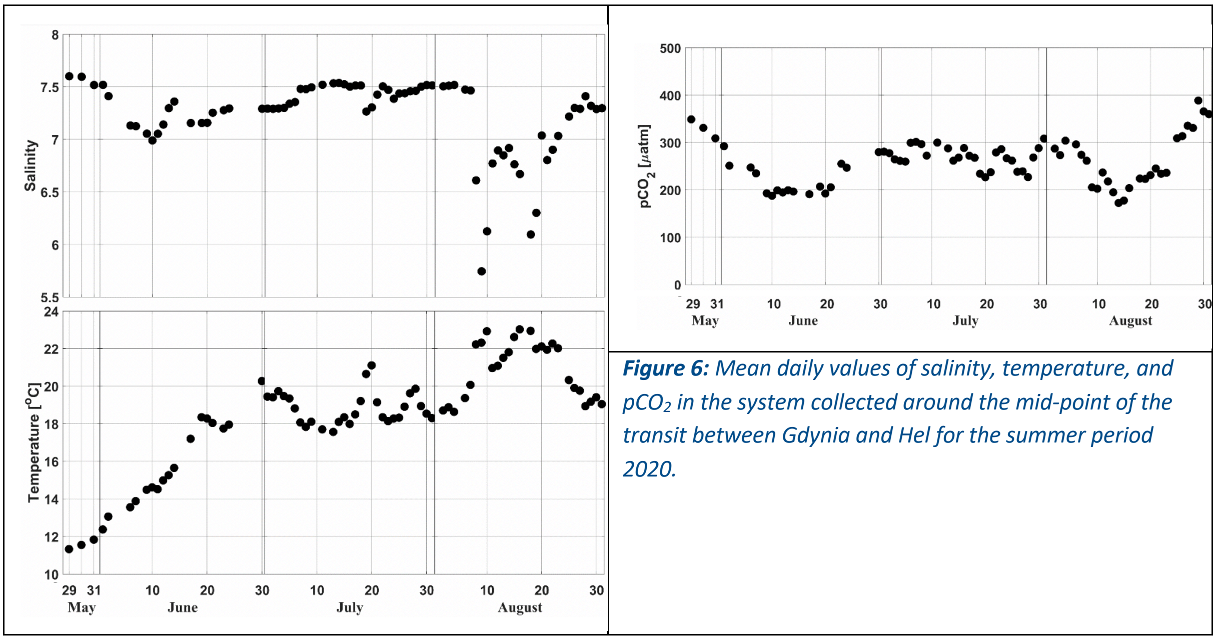

Figure 6: *Mean daily values of salinity, temperature, and pCO_2 in the system collected around the mid-point of the transit between Gdynia and Hel for the summer period 2020.*

This valuable data, although still sparse, demonstrates the potential to improve our understanding of the CO_2 system variability in the coastal zone of the southern Baltic Sea. Identification of the direct influence of the Vistula River in the region covered by the measurements suggests also that data generated from this newly established monitoring platform can help in the future to assess the CO_2 system transformations and ecosystem productivity in that highly dynamic region of freshwater and open Baltic Sea water mixing. The data therefore strongly support the case for including this part of the infrastructure developed within BONUS INTEGRAL into ICOS Poland.

Fixed Station Östergarnsholm, operated by partner UU, is a marine micrometeorological field station with continuous direct air-sea flux measurements of CO_2 exchange accompanied by other atmospheric parameters (heat flux, turbulence, radiation, precipitation). In the water, the station features continuous measurements of pCO_2, O_2, temperature profile, and salinity. The station is funded by the Swedish Research Council (VR) and Uppsala University. For the BONUS INTEGRAL project, direct flux measurements of methane (CH_4) were added in September 2017 and have been running continuously until the end of the project. The first year of CH_4 flux results has been published in a special issue (The Baltic Sea in transition) of

Frontiers in Earth Science (Gutierrez-Loza et al., 2019). Parts of the data are being submitted to SOCAT.

At the **fixed Station Utö**, run by FMI, atmospheric measurements of CO_2 and CH_4 are continuously operated as part of the ICOS atmospheric network. A variety of physical and chemical measurements on the water side are also maintained. The main amendment during the first year of BONUS INTEGRAL was the installation of a cabled profiling observatory at Utö in April 2018, which due to technological reasons did not provide data in the first year. The new system provides vertical information on biological and physical variables relevant to the biological carbon sink (Laakso et al., 2018).

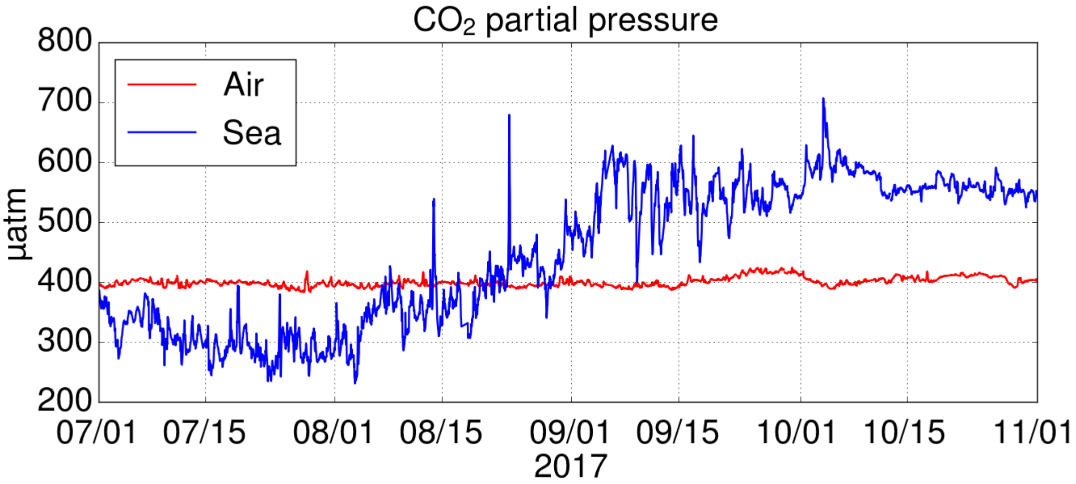

Figure 7: Atmospheric and sea water carbon dioxide partial pressures at Utö during the period of 1 July – 1 November 2017 (Honkanen et al., 2018). During the summer period, the sea water pCO_2-concentration is lower than the atmospheric concentration due to the biological carbon sink. Atmospheric CO_2-observations at Utö are part of ICOS.

The marine station is also equipped with a flow-through pumping system that transports surface water from 250m from the shore to the station, where seawater is analysed for pCO_2. The data (example shown in Figure 7) have been used within BONUS INTEGRAL for eddy covariance measurements of the sea-air flux (Honkanen et al., 2018), as well as for a study of the diurnal variation in surface pCO_2 and its main drivers (Honkanen et al., under review).

At the **Boknis Eck Time Series Station (BE)**, run by Partner GEOMAR, discrete water column sampling (at six standard sampling depths from 1 to 25 m) for N_2O, CH_4 and DIC/alkalinity is conducted on a monthly basis. Two manuscripts about the monthly N_2O/CH_4 data from BE have published in Biogeosciences by Xiao Ma (PhD Student, GEOMAR) partly supported by the project. The monthly N_2O/CH_4 and DIC/alkalinity measurements have been continued until the end of the project. An underwater observatory at Boknis Eck (with continuous measurements of dissolved pCO_2 and CH_4, which would have allowed to assess the dynamics of both gases with high temporal resolution) has been destroyed in August 2019, unfortunately. Partner GEOMAR is currently reconstructing the observatory and hope that measurements can be resumed in summer 2021.

Apart from providing the data base for the spatiotemporal interpolation of GHG concentrations and fluxes (Work packages 4 and 5), and the verification of the 3D coupled hydrological-biogeochemical model (WP6), the development and amendment of infrastructure, all of which is operational still after the end of the project, plays a pivotal role towards the vision of BONUS

INTEGRAL, which is a sustained network of carbon dioxide (and GHG) measurements as a key for a better description of the ecological state of the Baltic Sea, in particular providing quantitative indicators for eutrophication and acidification. This is further highlighted in SEction 8 (Wider societal implications) of this report.

C2: Additional sampling for carbon system parameters and GHGs during regular monitoring cruises

Several partners of BONUS INTEGRAL are involved directly or through cooperation in the HELCOM biogeochemical monitoring of the Baltic Sea. As part of the data acquisition strategy of the project, additional samples of several carbon system and GHG parameters have been taken during the regular monitoring program. This allowed for a more complete carbon system description in combination to the HELCOM standard variables. The sampling strategy was guided by identified gaps in process understanding and need for extrapolation verification according to work within WPs 4 and 6. It was used to demonstrate the field-worthiness of the spectrophotometric pH method using instrumentation developed within BONUS PINBAL, to enhance information on the vertical distribution of carbon dioxide and trace gas parameters in some of the western and central basins, and to demonstrate the readiness for integration of both continuous and discrete sampling into the classical HELCOM monitoring program.

Proof of concept of spectrophotometric pH measurements during SMHI monitoring

During regular SMHI monitoring cruises, pH is analysed using a pH electrode calibrated with NBS buffers. This setup has been used since the early 1990s. A Contros HydroFIA pH system was tested during a cruise in March 2019. The pH-system was borrowed from University of Gothenburg and has been developed within the BONUS PINBAL project (Development of a spectrophotometric **p**H-measurement system for monitor**in**g in the **Bal**tic Sea).

Discrete samples from 11 different stations in the Swedish national monitoring program were analysed on both systems. The aim of this comparison was to change the monitoring set up for pH to a spectrophotometric method in order to improve the precision and long-term intercomparibility of measurements, and thereby the understanding of the carbonate system in the Baltic Sea. The results are promising, and the option to incorporate spectrophotometric pH measurements into regular monitoring schemes is now pursued in Sweden, Germany, and Estonia.

Carbon system and GHG measurements linked to the Estonian monitoring program

All six Estonian marine monitoring cruises on *RV Salme* in 2018 were joined by IOW in order to perform continuous surface water CO_2 and CH_4 measurements as well as to obtain discrete samples for carbon system parameters (pH, C_T, A_T) and the trace gases CH_4 and N_2O.

Discrete CO_2 and trace gas samples were taken at seven stations on a transect from the Northern Baltic Proper deep into the Gulf of Finland and on seven stations in the Gulf of Riga (five in January and April). The cruise track of the May/June cruise in 2018, with all stations where additional samples have been taken, is illustrated in Figure 8. Furthermore, the continuously measured partial pressure of CO_2 is displayed, indicating a strong spring bloom in both gulfs with pCO_2 values as low as 16 µatm in the central to south-eastern Gulf of Finland.

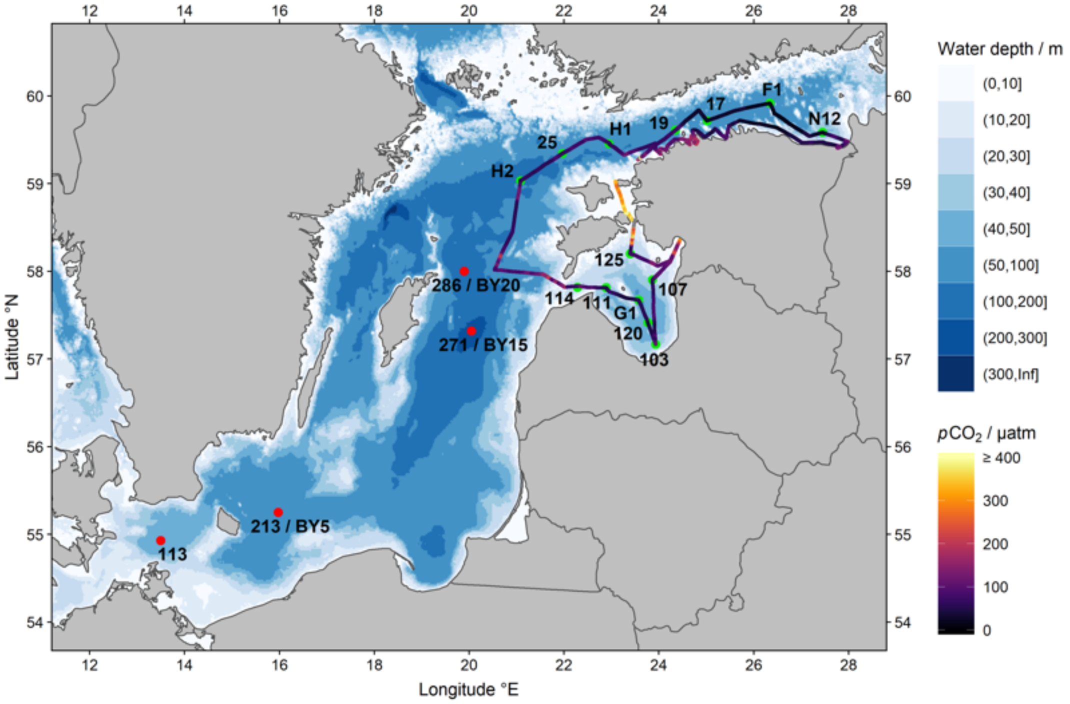

Figure 8: *Stations with additional CO_2 system and trace gas sampling performed on monitoring cruises aboard RV Elisabeth Mann Borgese (red) and RV Salme (green). Additionally, the cruise track of RV Salme from May 28th to June 2nd 2018 is shown with colours representing the partial pressure of CO_2 in the surface water as measured continuously with IOW's flow-through equilibrator system.*

Cruises RV Salme 2018	**No of samples $A_T/C_T/pH/CH_4/N_2O$**	**No of samples DOC/Metals**
January	62	
April	65	
May/June	80	
July	79	
August	83	27
October	77	27

Table 1: *Samples collected for the BONUS INTEGRAL project onboard RV Salme during 2018.*

There were multiple reasons for this extended joint effort: Firstly, it is to our knowledge the first seasonal trace gas study in the Gulf of Riga, and the measured parameters will allow a first assessment of the trace gas and carbon system dynamics in this region. Therefore, additional nutrient samples have been collected for a better biogeochemical assessment by Partner TTU, as well as samples for DOC and metal concentrations by Partner IO PAN (August and October cruise only, see Table 1). Secondly, the Gulf of Finland is a highly dynamic part of the Baltic Sea, which is also true with respect to the concentrations of dissolved gases as observed on the SOOP *Finnmaid* traversing the Baltic Sea between Lübeck-Travemünde (Germany) and Helsinki (Finland) (see also Fig. 1). In order to understand the underlying processes of those trace gas distributions, the analyses aboard Salme will certainly prove valuable since they add not only vertical profiles of trace gases, CO_2 system and other parameters, but also surface data that are both parallel and perpendicular to the track of SOOP Finnmaid. Therefore, the cruises provide detailed profiling with a wider parameter range to the superior spatial-temporal coverage of the SOOP line. In addition, comparison with the model-derived CO_2 distribution will provide valuable insight into the performance of the model for which hitherto the data for model validation were completely lacking. Lastly, this one-year long endeavour demonstrates a seamless integration of standard HELCOM monitoring and the amendments pursued within BONUS INTEGRAL, and fostered the collaboration between the institutions executing the biogeochemical monitoring in Estonia and Germany considerably. Workup of the data is currently ongoing as part of the PhD-thesis work of Sylvie Lainela (TTU) and Erik Jacobs (IOW).

Additional sampling at IOW: The CO_2 system and vertical GHG-dynamics in the major basins of the central Baltic Sea

The accumulation of total CO_2 in the deep water of the Gotland Basin (Figure 8, Station 271/BY15) has been measured since 2003 in conjunction with the IOW long-term observation program. The data provided insight into the dynamics of the organic matter mineralization, including the release and transformation of nitrogen and phosphorus compounds (Schneider and Otto, 2019). In the framework of BONUS INTEGRAL the measurements were considerably extended. Three additional stations (Figure 8) which represent the deep water in the Arkona Basin (Station 113), the Bornholm Basin (Station 213/BY5) and the Farö Deep (Station 286/BY20), were included in the measurement programme. At these stations the vertical profiles between the surface and the bottom water of total CO_2, alkalinity and pH are determined with a seasonal resolution of 2 – 3 months. The vertical resolution amounts to 5 m – 10 m in the surface layer and 25 m in deeper water layers. The work provides validation data for biogeochemical models and their modifications/amendments pursued within BONUS INTEGRAL.

Additional sampling for GHGs in the western Baltic Sea

Discrete samples for N_2O and CH_4 in the water column were also collected during two cruises to the southwestern Baltic Sea: (i) R/V Littorina cruise Lit-1914 from October 21st to October 25th 2019 and (ii) R/V Alkor cruise Alk-543 from August 21st to August 28th 2020. The data from both cruises significantly extended the data coverage of N_2O and CH_4 water column measurements in the southwestern Baltic Sea.

C3: Expeditions on research vessels dedicated to BONUS INTEGRAL

Two BONUS INTEGRAL field expeditions on RV Aranda and RV Elisabeth Mann Borgese took place from February 28th 2019 to March 11th 2019 (RV Aranda Cruise 04/19) and May 20th 2019 to June 5th 2019 (RV Elisabeth Mann Borgese Cruise 214). The scientific program of both cruises was tailored to serve the purposes of BONUS INTEGRAL. Several goals were pursued during both cruises:

- Extending the data set of surface data for the creation of maps of surface concentrations of CO_2, N_2O, and CH_4, and pH;
- Information on gradients of these parameters from the basins to the coastal-near regions;
- Simultaneous recording of data potentially useful for the interpretation of parameters retrievable through remote sensing, e.g. CDOM and Chl a;
- Insight into the vertical distribution of CH_4, N_2O, and inorganic carbon system parameters;

- Fostering the understanding of the poorly constrained biogeochemistry of the Gulf of Bothnia by recording a comparable data set in the pre-bloom and post-bloom period, to describe the nitrogen, phosphorus and carbon dynamics.

Both cruises really constituted highlights of cooperation within the project. Cruise Aranda 04/2019 hosted 13 scientists from 5 institutes, while Cruise EMB 214 was fully booked with its 12 places occupied, again representing 5 institutes. IOW; FMI, IO PAN, UU, TTU, SYKE, and UU were all involved in the campaigns, including almost all of the PhD students involved in the project. While the hosting institutes took care of the standard instrumentation and analysis (CTD, hydrographic data, nutrients (subcontracted to SYKE in the case of RV Aranda), various groups joined lab-forces to retrieve the most complete data sets.

- IOW and GEOMAR were responsible for underway trace gas measurements;
- IOW, with a lot of support from the other labs, was in charge of the carbon system parameters (C_T, pH, pCO_2)
- IO PAN sampled for the home-based analysis of POC and PON, including isotopic information;
- IOW and SYKE took samples for TN and in some cases TP;
- FMI took care of optical measurements (Chl a and CDOM), including some discrete sampling.

A total of 32 stations was sampled during Aranda 04/2019, while 33 stations were sampled during EMB 214, including 7 hydrographic transects using ScanFish.

The cruise tracks of both expeditions are shown in Figures 9ab. As an example of the data gathered, the on-board results for Station 24 of EMB 214 (TF 286 Faro Deep) is displayed in Figure 10.

The data have been used to fill gaps and extend the data base for surface trace gas measurements, and as control data for an EOF-based generation of pCO_2 maps (see Section 2F of this report). In particular, they substantially enhanced the data density for carbon parameters and other greenhouse gases in the Northern Basins (see Section 2E).

In particular, the data allow - for the first time - for a carbon-based budget of net carbon production in the Bothnian Sea over the spring bloom. The biological carbon uptake in the Gulf of Bothnia between late winter and late spring/early summer 2019 was assessed by using the data gathered from both BONUS INTEGRAL cruises. The uptake estimate is based on the differences in the dissolved inorganic carbon (DIC) between summer (R/V Elisabeth Mann Borgese) and winter (R/V Aranda) in the upper water column.

Because the dissolved inorganic carbon was analysed from water samples, its horizontal representativeness was not sufficient in order to make direct basin-wide conclusions on the biological uptake by spatial interpolation. To solve this problem, we constructed linear functions between DIC and salinity (S) for different depths by using the method of least squares. This way, we could interpolate DIC over the Gulf of Bothnia using the strong linear correlations between these parameters for both cruises. The least squares fit for the DIC-S relationships were generally good, as the lowest R^2 value of the fits was 0.997 and the mean squares errors were less than 9 µmol kg^{-1}, while the range of DIC covered almost 600 µmol kg^{-1}. In Fig. 11a, the dissolved inorganic carbon is shown as a function of salinity for the surface (sampling depth of less than or equal to 10 m).

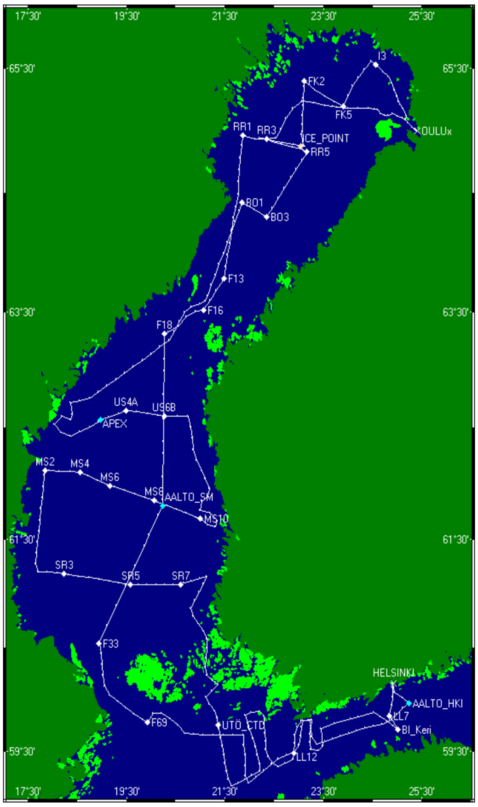

***Figure 9a:** Track and stations of the BONUS INTEGRAL WINTER cruise February 28th to March 11th 2019.*

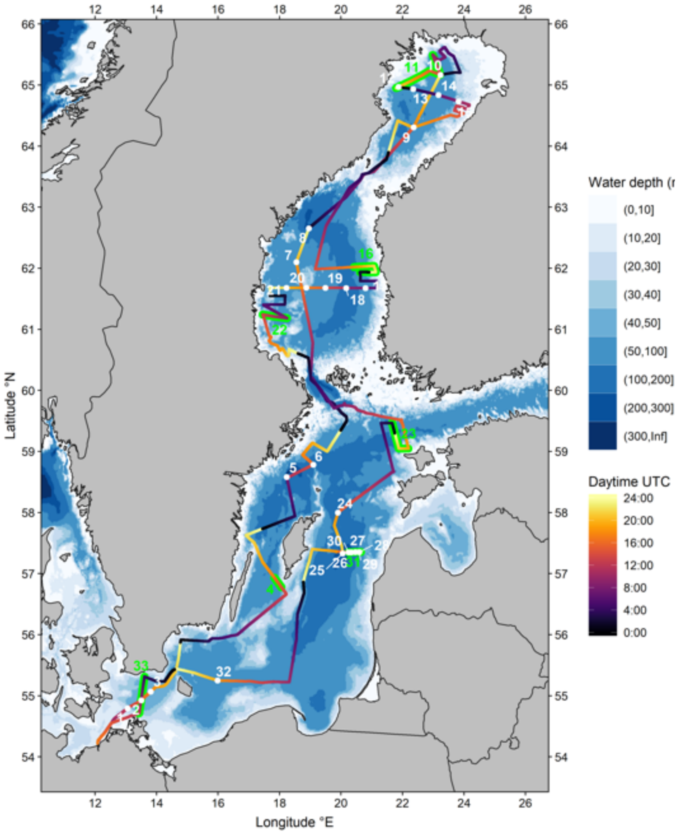

***Figure 9b:** Cruise Track for the BONUS INTEGRAL summer cruise, May 21st to June 5th 2019 with underlaying bathymetry. The colour code of the track indicates the time of day (UTC). CTD sampling stations are indicated as white dots, ScanFish Transects as green lines.*

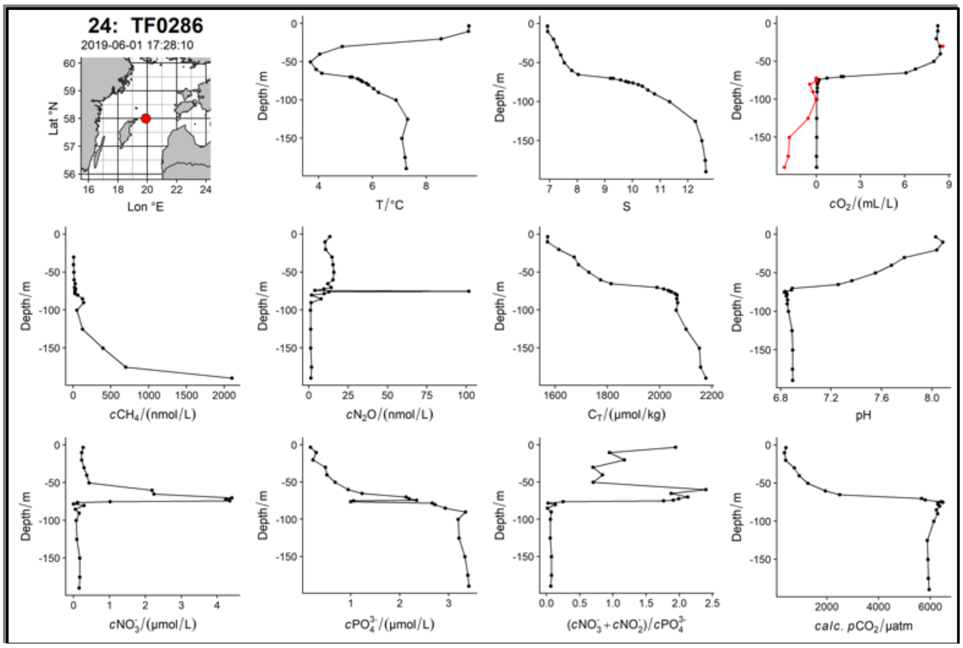

***Figure 10:** Preliminary results from Station 24 of EMB 214 (TF 286), including Temperature, Salinity, Oxygen (and H_2S), dissolved CH_4 and N_2O, CT, pH, dissolved nitrate and phosphate, and derived C/P ratio and calculated pCO_2.*

In this surface layer, the DIC in summer was lower than in winter for the same salinity, i.e. the summer slope of the best fit is lower than the winter slope. For all depths, the slope of the winter DIC was closely the same, but the slope of summer DIC increased as depth increases, and at the depth of approximately 40 m, the slopes of winter and summer DIC were equivalent. Thus, the removal of DIC due to primary production in the Gulf of Bothnia was limited to the surface waters, down to a maximum depth of 40 m. With our approach, we can estimate the net carbon uptake due to biological production. As the summer cruise took place shortly after the spring bloom, the counteracting invasion of atmospheric CO_2 should be almost negligible. Still, we can consider our approach as a conservative estimate.

By using the sea surface salinity measured with the flow-through system and the derived DIC-S relationships, we interpolated DIC in the Gulf of Bothnia for both in summer and winter. The DIC change between winter and summer in the first 10 m is shown in Fig. 11b. In the centre of the Bothnian Sea, the biological carbon uptake in the first 10 m was ~ 50 µmol kg^{-1}, $^{-}$whereas in the Bothnian Bay, the carbon uptake was barely evident, confirming that the summer bloom had not yet effectively started in this basin. This work emphasises the applicability of smart interpolation methods when dealing with limited number of sampling stations.

In summary, the BONUS INTEGRAL expeditions in winter and early summer 2019 considerably extended the project-relevant data base, which was important towards the goals of WPS 4, 5, and 6. Moreover, it allows for detailed studies in the scope of the project, such as the assessment of the integrated net carbon uptake in the Northern Basins during spring. Lastly, and not completely planned beforehand, it turned out to be a hands on training for carbon and greenhouse data retrieval at sea for the young scientists involved in the project, and fostered the networking and knowledge transfer between the different groups very effectively.

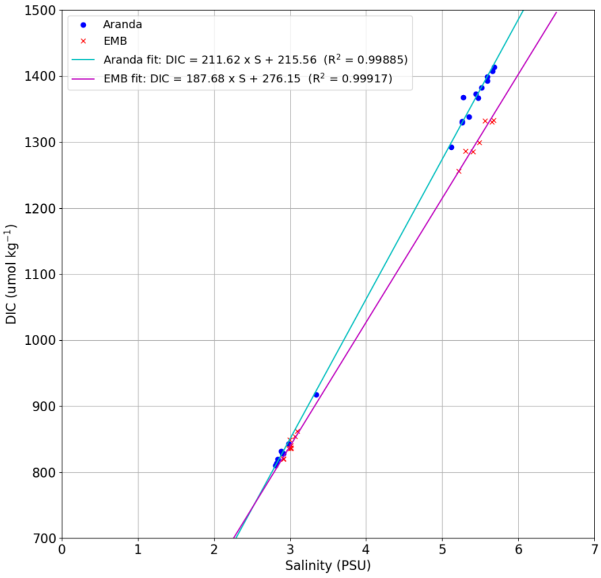

Figure 11a: *The dissolved inorganic carbon concentration (DIC) as a function of salinity: winter measurements as blue dots and summer measurements as red crosses.*

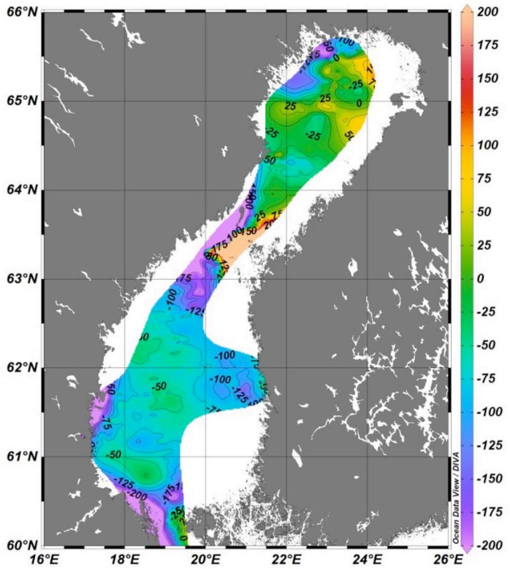

Figure 11b: *The change in dissolved inorganic carbon (µmol kg^{-1}) between June and February 2019.*

C4: The BloomSail project

The Bloom Sail expedition took in spring-summer of 2018, with the “hot phase” between June and August. It was lucky coincidence that the experiment took place within the summer 2018, which ended with the warmest surface temperatures ever recorded in some areas of the Central Baltic Sea.

The central scientific finding of the expedition is a tight coupling between the vertical distribution of net community production of organic matter and warming of surface waters over the course of a cyanobacteria bloom. Lacking depth-resolved observations with high spatio-temporal resolution and coverage, this coupling was not known before. The value of this finding lies in its application to combined SOOP and hydrographical model data: With the newly gained understanding, it is possible to calculate the depth-integrated net community production (tightly coupled to eutrophication) based on surface CO_2 observations (SOOP) and changes in the vertical distribution of seawater temperature over time (model). Taking SOOP Finnmaid and GETM model data as an example, both required data sets are available for almost two decades and – taking into account the new findings – will allow to estimate net community production and therefore the potentially available organic matter for export with enhanced confidence.

A manuscript summarizing the findings has been submitted to Biogeosciences and is currently under discussion.

D.) GREENHOUSE GAS DATA INTEGRATION (WP4)

A major objective of BONUS INTEGRAL was to provide GHG (CO_2, N_2O and CH_4) concentration fields for the Baltic Sea and make them available to WP5, other scientists, and the public / stakeholders. To do so, we merged historical data provided by WP2 (Data mining) as well as actual data from the Baltic Sea GHG monitoring network under BONUS INTEGRAL (WP3), performed quality checks based on the available data and metadata, and harmonized the data. Based on this work, BONUS INTEGRAL aimed at computing CO_2 and GHG concentrations fields as the base for seasonalized flux mapping (in WP5).

pCO_2 fields

Earth observation satellites have revolutionized the study of the ocean. They now provide detailed repetitive measurements over remote areas of the globe, which were previously monitored by instruments mounted on ships and buoys and with a limited number of (isolated) observations. To date, however, no generally valid remote sensing algorithm available for deriving the surface partial pressure of carbon dioxide (pCO_2) in all ocean basins exists. It is generally agreed that the sea surface pCO_2 is determined by biological processes, physical mixing in vertical and horizontal directions, and bacterial respiration, which converts organic carbon into CO_2. We use remotely sensed data of SST, chlorophyll-a, CDOM (from MODIS and MERIS) together with modelled data of sea surface salinity and mixed layer depth.

We produced improved pCO_2 fields from high quality oceanic variables with algorithms of improved performance compared to earlier studies. The monthly maps of sea surface pCO_2 were derived for the period of 2002 to 2011, from February to October (see Figure 12 below, also Zhang et al., 2021). As the Baltic Seas is situated at high latitudes frequent cloud coverage and poor illumination during the winter hamper the availability of the satellite images and sea surface variables of adequate quality during these months. As a result, the pCO_2 maps based on remote sensing data were generated for the months from February to October. For the months from November to January, we adopted an interpolation method to derive the pCO_2 field based on only in-situ data.

A completely different approach to derive monthly pCO_2 fields was pursued with WP6, using observational data in combination to model-derived patterns for spatial interpolation. While direct observations of pCO_2 provide accurate samples of the spatio-temporal distribution, sampling by necessity is limited in space and time. Biogeochemical models, in contrast, provide filled spatio-temporal fields of the distribution without gaps. However, they only approximate reality and their accuracy and representation of processes may be questionable. Using either observations or models alone to reconstruct the “true” pCO_2 field falls short of both approaches' combined potential.

With our method, data errors and temporal spread in the data can be accounted for to yield synoptic mapped fields without gaps or discontinuities. It has been used to establish a monthly surface pCO_2 climatology for the Central Baltic Sea based on SOOP Finnmaid pCO_2 data from 2003 to 2019, as an alternative approach to the Earth Observation based Random Forrest approach (Section F, Figure 17). More detailed information can be found in BONUS Deliverable Reports D4.3 and D6.4.

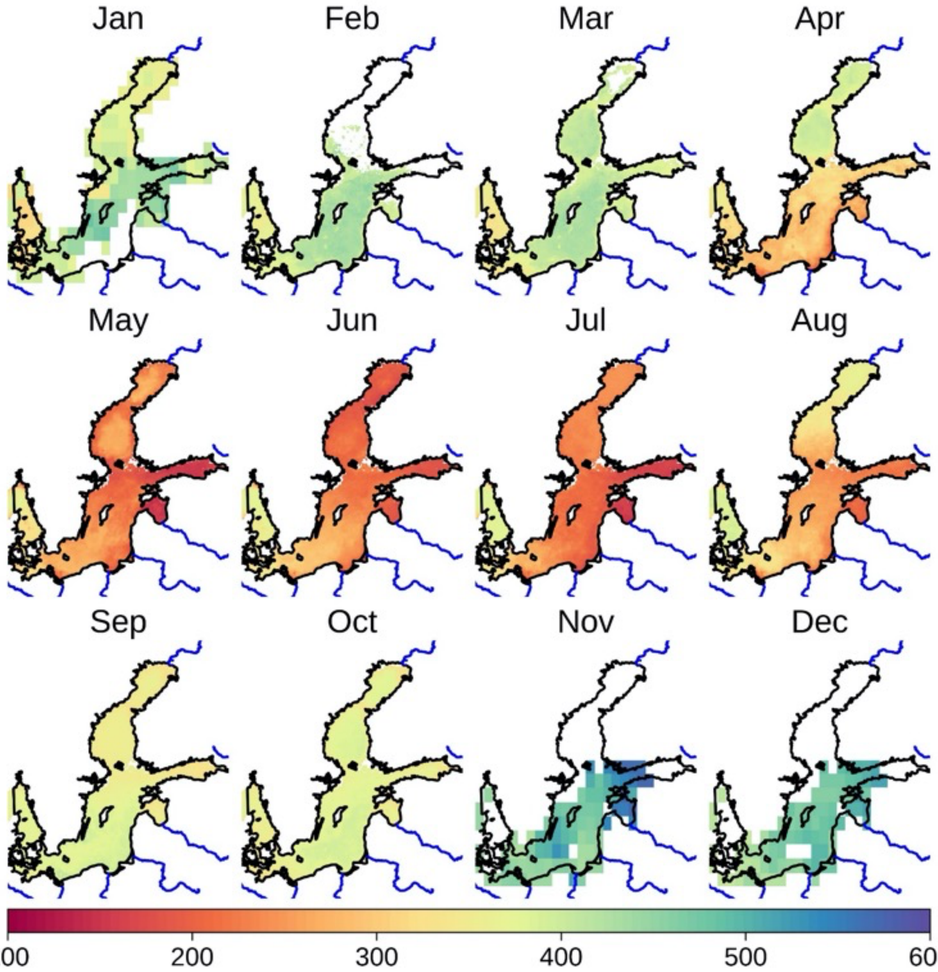

***Figure 12**: Monthly average pCO_2 concentrations for the period 2002 to 2011; for the months February to October Random Forest with remote sensing products are used and for November to January interpolation of in-situ data are used.*

Methane and nitrous oxide fields

Since N_2O and CH_4 emissions from the ocean could offset the CO_2 sink, we aim at the quantification of the N_2O and CH_4 emissions from the Baltic Sea to estimate the potential offset of these gases on the Baltic Sea carbon sink within the BONUS INTEGRAL project.

BONUS INTEGRAL greatly enhanced the data coverage for surface N_2O and CH_4 measurements from the Baltic Sea (Figure 13). The collection of historic data from the Baltic Sea revealed a very limited data coverage for N_2O, while the availability of surface CH_4 data was strongly dominated by data from the ship of opportunity SOOP Finnmaid, which mainly covered the central part of the Baltic Sea. Hardly any data were available from the Gulf of Bothnia, Gdansk Bay and the Gulf of Riga. During BONUS INTEGRAL, additional surface CH_4 and N_2O data were collected from the BONUS INTEGRAL cruises (R/V Aranda cruise 04/2019, February/March 2019, R/V Elisabeth Mann Borghese cruise EMB 214, May/June 2019), from the SOOP Finnmaid (CH_4 data only), from the Boknis Eck Time Series Station and from the SOOP Tavastland (start of CH_4 and N_2O measurements in March 2019).

The data compilation shows that N_2O in the Baltic Sea is comparably uniform, as large gradients between the coastal and the open waters could not be identified. N_2O saturation ranged between ~90 and 120%. The annual distribution seemed to show noticeable seasonality with N_2O supersaturation in late spring/early summer, and undersaturation in autumn/winter.

The CH_4 distribution showed strongly enhanced concentrations towards the coastal margins, particularly in regions with large riverine inputs, such as the Oder river, the Neva river and the Bay of Bothnia. In these regions, the CH_4 measurements also showed the highest variability between different sampling campaigns.

The temporal data coverage currently does not allow for the calculation of monthly maps of CH_4 and N_2O based on spatial interpolation Annual and seasonal distribution maps of ΔCH_4 could reproduce the original fields to a high level of convergence (Fig. 13). However, since the data coverage particularly in the south eastern part of the Baltic Sea and across gradients between the near-coastal area and the „open“ Baltic Sea is comparably sparse, the distribution field may underestimate CH_4 gradients in the near-coastal range. Due to the data sparsity in large parts of the Baltic, the derived ΔN_2O and ΔCH_4 fields furthermore have a high risk of bias towards selected sampling periods on one hand, and towards measurement bias between the different campaigns on the other hand.

This is particularly evident for the N_2O distribution fields: since the N_2O seasonality revealed phases of N_2O oversaturation as well as N_2O undersaturation without any obvious spatial pattern, the role of the entire Baltic as an overall source or sink of N_2O remains unclear.

Overall, we therefore found that, despite our efforts and the significant extension of the data base achieved by the project, the N_2O and CH_4 data basis is not yet sufficient for a scientifically sound publication of basin-wide N_2O and CH_4 distribution fields.

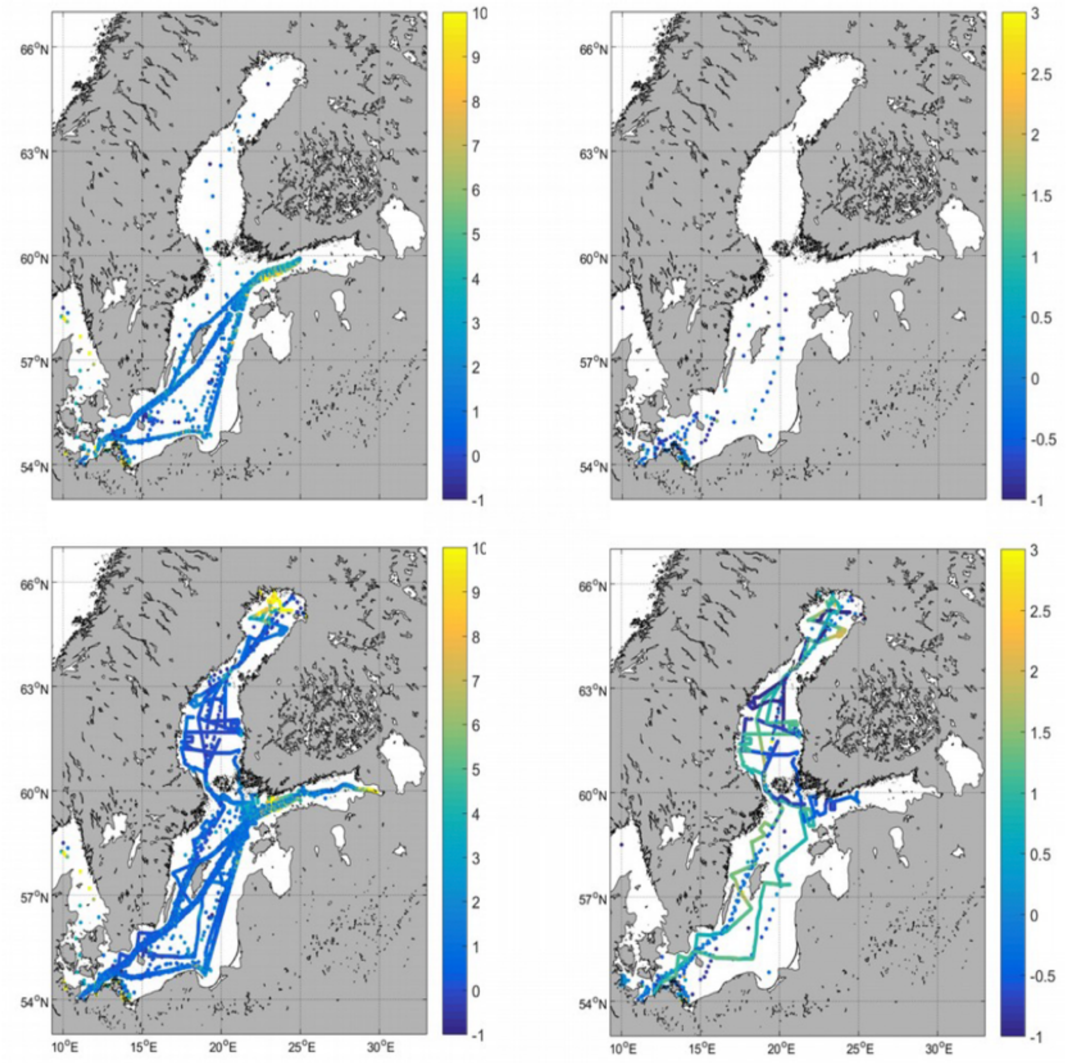

Figure 13: *ΔCH_4 [nmol L^{-1}] (left) and ΔN_2O [nmol L^{-1}] (right) from surface measurements before (top) and after the BONUS INTEGRAL project.*

E.) FLUX PARAMETERIZATION AND ESTIMATES (WP5)

Baltic Sea wide sea-atmosphere gas fluxes were calculated using new, state-of-the art methods and the concentration fields compiled and provided by WP4. The work comprised a new Baltic-specific, air-sea parameterization based on turbulence, wave, and air-sea flux data. The parameterization was introduced into a third-generation numerical wave model and implemented in the FluxEngine toolbox to allow for a comparison of different air-sea exchange models for Baltic Sea flux estimates.

E1: Turbulence-based air-sea exchange coefficients

Air–sea gas fluxes are commonly estimated using wind-based parameterizations. The subsurface turbulence is regarded as a dominant factor in air-sea gas exchange, but the relative importance of different sources of turbulence is still not known. In order to model the gas transfer accurately, at least the most important sources should be solved. Since wind-generated waves are an important, if not dominant, source of subsurface turbulence via breaking, both microscale and whitecapping, kinetic energy dissipation (TKE) due to wave breaking is a good candidate for the parameterisation of the transfer velocity, and can be superior to parameterisations "just" based on wind speed.

Fluxes of CO_2, humidity, temperature, momentum in combination with high-frequency wave measurements from several cruises on RV Aranda were used to study the role of turbulence caused by wave breaking in the gas exchange. The experimental set-up for measuring the wind and wave data on board RV *Aranda* has been verified and documented in (Björkqvist et al., 2019). The high-frequency wave data, important for the air-sea interaction processes, was used to quantify the dissipated wave energy. It was found that the dissipation of TKE was a better predictor of the observed CO_2 fluxes than the parameterisation based solely on shear-induced turbulence (water side friction velocity) or mean wind speed. The scatter in the observations was quite large, suggesting that there are other factors involved in certain environmental conditions. The dissipation of TKE was calculated using the same formulation than in the wave model WAM, and the new developed parametrisation of transfer velocity based on TKE dissipation can be directly used with the wave model WAM (more details in Deliverable Report 5.1).

E2: Flux calculations with the new wave model-based parameterization and other parameterizations using the FluxEngine Toolbox

At regional scales, neglecting other gas exchange forcing mechanisms and focussing entirely on wind speed as governing variable may lead to large uncertainties in the flux estimates and the carbon budgets, in particular in heterogeneous environments such as marginal seas and coastal areas. The methodology towards evaluation of different air-sea flux parameterizations within WP5 of BONUS INTEGRAL was two-fold. On one hand, a numerical wave model to calculate Baltic Sea wide estimates of the transfer velocity from the wave-based parameterizations mentioned above was used (Figure 14, more details in Deliverable Report 5.2). On the other hand, we used an existing wind speed-based parameterization, but accounted for a range of other factors, namely convection, precipitation, and surfactants. The FluxEngine Toolbox was used to calculate CO_2 fluxes, applying different parameterizations for the transfer velocity, resulting in estimates for the mean annual flux in the Baltic Sea (for more details, see Deliverable Report 5.3).

The results of the wave-dependent parameterizations captured more variability than traditional wind-speed based models in sheltered and near shore areas. For this reason, including wave effects explicitly (as opposed to using the wind speed as a proxy) seems like a promising approach for smaller semi-enclosed basins, as well as for coastal applications globally. The amount of wave breaking is calculated in all third-generation numerical wave models, but in the case of WAM, the model code was modified to offer this variable as an output to the user; this model set-up is now ready to be used in upcoming studies for the Baltic Sea.

In addition to the actual amount of wave breaking, one key assumption is the profile of the sub-surface turbulence. For the purpose of modelling the transfer velocities, the results that did not assume a constant turbulence layer near the surface – combined with a varying exponent for the Schmidt number – were found to be most applicable. With a fixed exponent for the Schmidt number, the parameterization was consistent with published results that describe the transfer velocity based on general measurements of the sub-surface turbulence. However, additional well-designed experimental studies are clearly needed to further increase our understanding of the connection between wave breaking, the sub-surface turbulence it creates, and the role that turbulence has in increasing gas-fluxes.

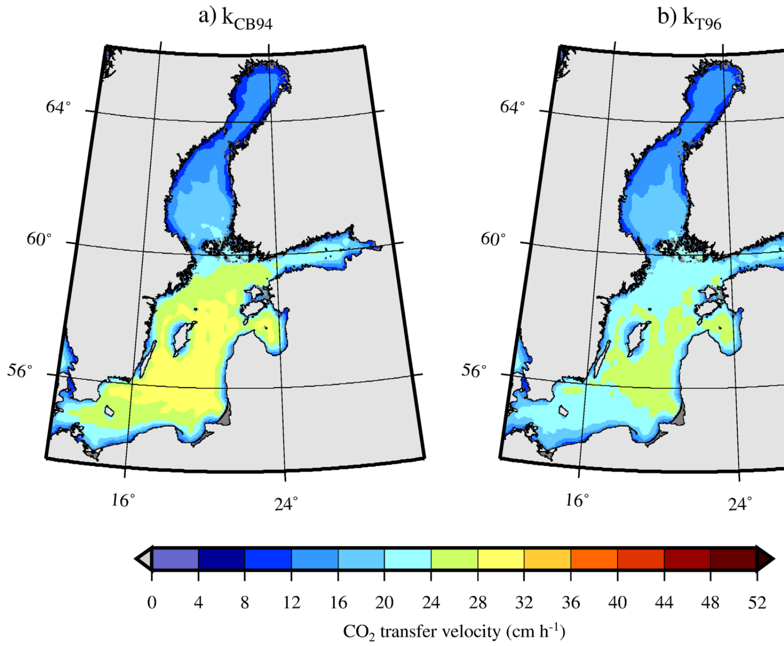

Figure 14: *Mean transfer velocities (k660) for October 2016 using the wave breaking based parameterizations (from Deliverable 5.1). Here,* k_{T96} *(panel b) assumes a constant turbulence layer below the surface that depends on the significant wave height, while* k_{CB94} *(panel a) does not.*

We further investigated the impact of relevant parameters—other than wind speed—on air–sea CO_2 exchange in the Baltic Sea. We used six parameterizations of the gas transfer velocity to evaluate the effect of precipitation, oceanic convection, and surfactants on the net CO_2 flux at regional and sub-basin scales.

The difference in the CO_2 mean flux is small with values ranging between 0.0 and −0.02 g C $m^{-2}d^{-1}$ among the different cases. However, the implications on the seasonal variability are shown to be significant. The inter-annual and spatial variability are also found to be associated with the forcing mechanisms evaluated in the study. Oceanic convection is the most relevant parameter modulating the air–sea gas exchange by enhancing upward fluxes in our study. Convective processes have a major effect in the Gulf of Bothnia and Central Basin due to the strong cooling of the surface during the winter months. During summer, surfactants and convection act as competing mechanisms. Convective processes slightly enhance the downward fluxes, while surfactants tend to suppress it. Precipitation is the only parameter that results in an overall increase of the downward net flux. This work has been submitted for publication in the Journal of Marine Systems (Gutierrez-Loza et al., submitted).

In addition, a new parameterization based on wave information from the WAM-model and the friction velocity are introduced following the methodology presented for FluxEngine and WAM. The transfer velocity is clearly higher throughout the year (in particular during fall). This also influences the seasonal cycle of the flux. The impact of using the wave-based parameterization is less for the annual flux, as the enhanced downward flux during summer is partly compensated with an enhanced upward flux during winter (Figure 15).

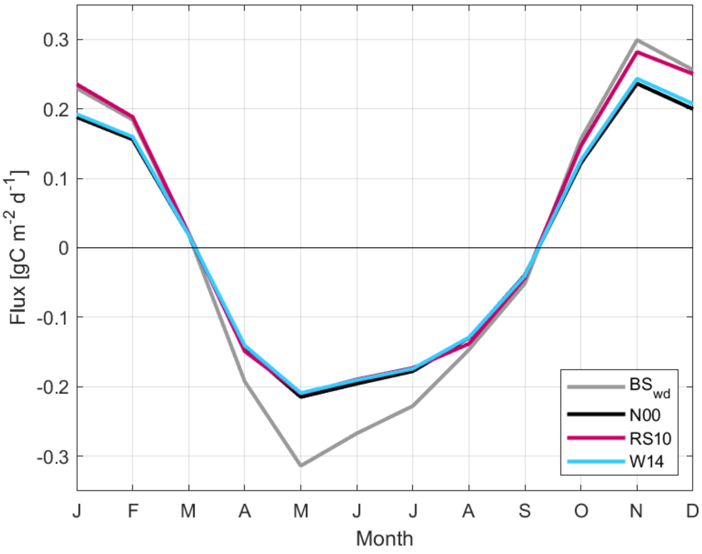

Figure 15: Monthly means of the air–sea CO_2 flux in the Baltic Sea using different parameterizations as specified in Deliverable reports 5.2-5.3, in addition to the wave-based parameterization (BS_{wd}).

F: CARBON-BASED ECOSYSTEM ASSESSMENT (WP6)

BONUS INTEGRAL aimed to improve carbon cycle models by using the improved process understanding from measurements compiled in WP 2 and 3, and implement carbon as central variable for the assessment of the Baltic Sea eutrophication. We aimed for calculating the carbon budget and its changes in time for the entire Baltic Sea, for the coastal zone, and the Baltic Sea sub-basins separately, using a high-resolution carbon system model and BONUS INTEGRAL observations. The model was also used to develop strategies for optimized carbon monitoring with as little as possible sampling effort, taking into account temporal and spatial variability of the system. A detailed "final status" report summarizing the performance of the model with respect to the scope of the project is given in Deliverable Report 6.4.

F1: Model assessment and improvement, and an EOF approach based on observations and the dominant patterns of the model output

The carbon cycling model components were scrutinized based on comparison to available field data. A major focus was the improvement of the surface representation of the pCO_2, for which different non-Redfieldish (non-fixed C/N/P-stoichiometry) parameterizations for DOC and DON were introduced in the description of primary production. At a later stage, two different parameterizations were tested, one with only one additional DOM / POM component that modifies only the C-content ("TEP"-version) and one with three additional DOM / POM components that modify the C-, N- and P-content ("pocNP"-version). Both approaches considerably improved the "climatology" of the surface pCO_2 cycle, yet still underestimated interannual variability (Figure 16).

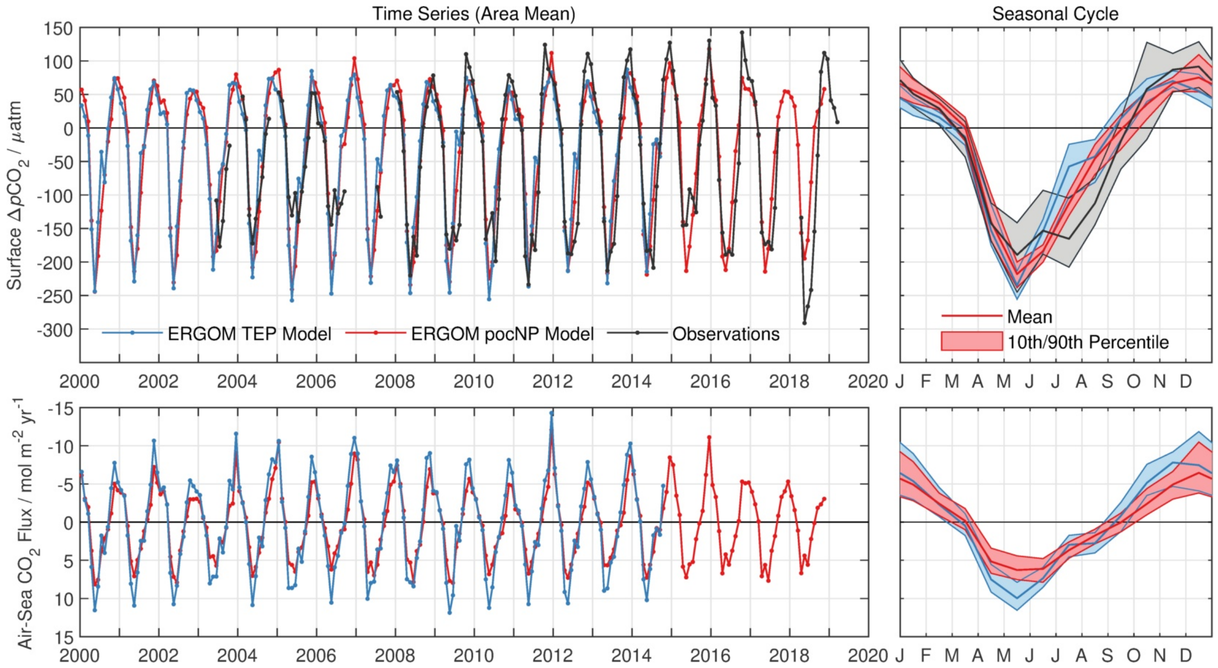

Figure 16:: *Surface air-sea pCO_2 difference (top; positive being supersaturated) and air-sea CO_2 flux (bottom; positive being ingassing) for the two ERGOM versions (blue and red, TEP and pocNP, respectively) and from observations (black; pCO_2 difference only). Left panels give the entire available time series and right panels the monthly mean seasonal cycle (bold line) with 10th/90th percentiles (shading / thin lines).*

Considering both model and observational data, both come with certain shortcomings: (A) Models are only a model of reality, and (B) observations are limited in their spatiotemporal coverage. We therefore use a combined approach (C) to minimize these shortcomings. For this, we extracted the patterns of variability from the model using a DINEOF and then subsequently reconstructed the surface pCO_2 ($spCO_2$) field using the Finnmaid observations to determine which patterns of variability are actually dominating at a given time. As the underlying processes for both spring and summer bloom, remineralization, entrainment, and air sea gas exchange are well included in the ERGOM model, we infer that the combined approach (C) scales the model's information according to the available observational data. The DINEOF analysis was done both with the TEP and the pocNP model versions. The combined approach between model and observations, merging model patterns with scattered observations, allowed to produce data-supported, realistic surface pCO_2 distribution maps (Figure 17, for details see Deliverable Report 6.2).

Comparison of pCO_2 derived from field observations, model, and the combined-approach reveal some shortcomings of the carbon-cycle representation of the model, like an overestimation of the spring bloom in the central and in particular in the western basins, an underestimation of the N-fxing summer bloom, and an overestimation of mineralization in the Bay of Mecklenburg.

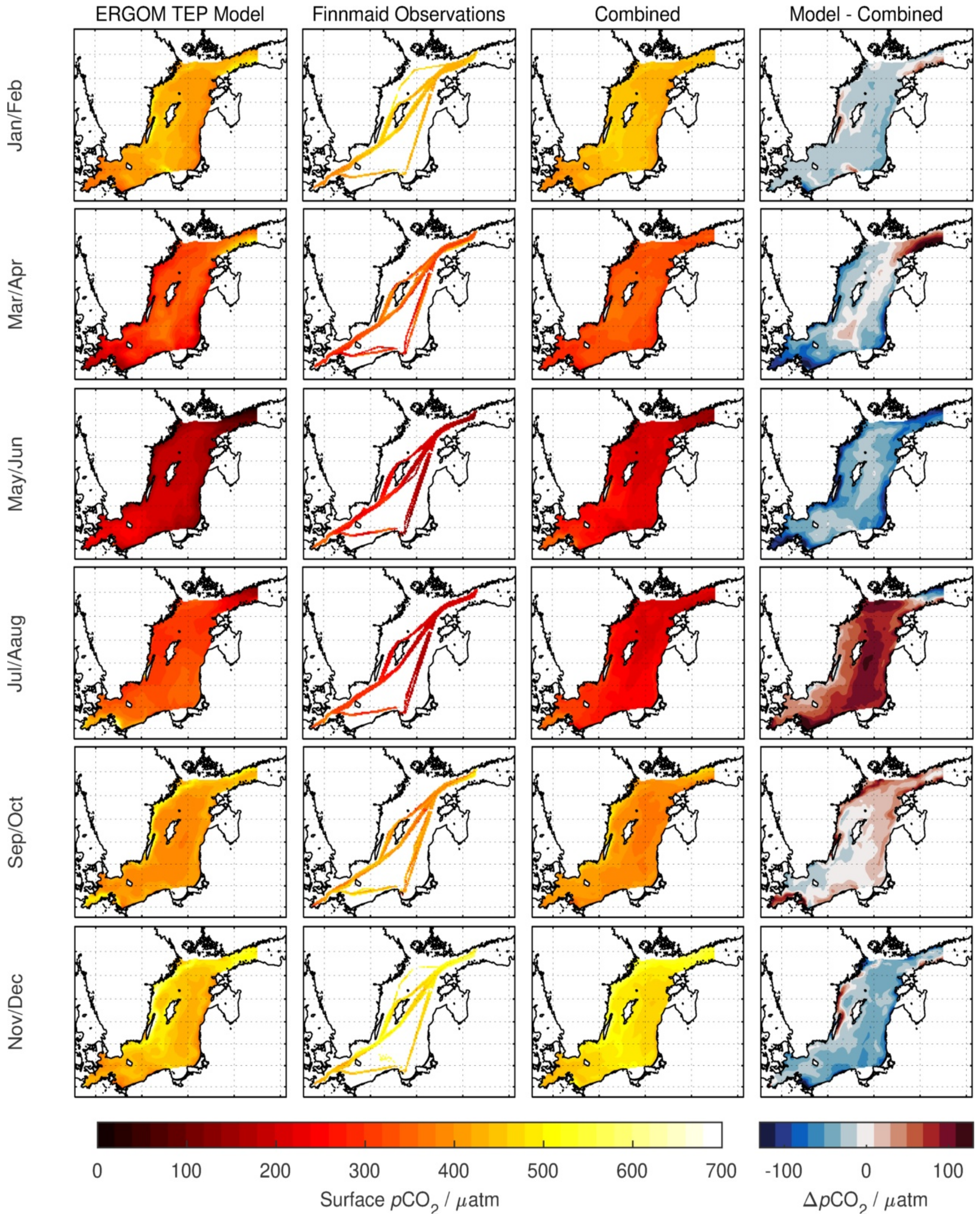

Figure 17: *Seasonal evolution of surface pCO_2 based on the TEP ERGOM model results (left column), Finnmaid observations (2nd from left), and the combined approach (2nd from right). Data are averaged for January/February, March/April, May/June, July/August, September/October, and November/December (top to bottom), respectively, on the 3 nm model grid using all available data from 2003 to 2014. Contour intervals are at 20 µatm. The right column gives the difference between the ERGOM model and the Finnmaid/EOF-combined approach.*

F2: Optimized monitoring strategies for the carbonate system

The pCO_2 maps derived by the combined approach come with uncertainties of their pCO_2 estimates, which can be used to evaluate the impact of individual or a network of observations to reduce the uncertainties. This way, different observation network designs or monitoring strategies were compared with a quantifiable metric (for details see Delivery Report D6.3).

To observe surface CO_2 variations, spatial coverage of continuous surface observations on Ships of Opportunity (SOOPs) is unmatched (Figure 18). This is particular true when considering a network of sustained (e.g., Finnmaid) and reinforced or newly established SOOPs (e.g., Tavastland, Agat) as part of BONUS INTEGRAL (Figure 18f). Typically, limitation to specific shipping routes is a drawback of SOOP lines, however, due to the extent of the Baltic Sea, this is less of an issue. Nonetheless, highly dynamic and more secluded areas such as the Gulf of Finland East of Helsinki, the Gulf of Riga, or the wider Gdansk basin would benefit from additional SOOP surface observations with their characteristic high temporal repetition rate as additional asset.

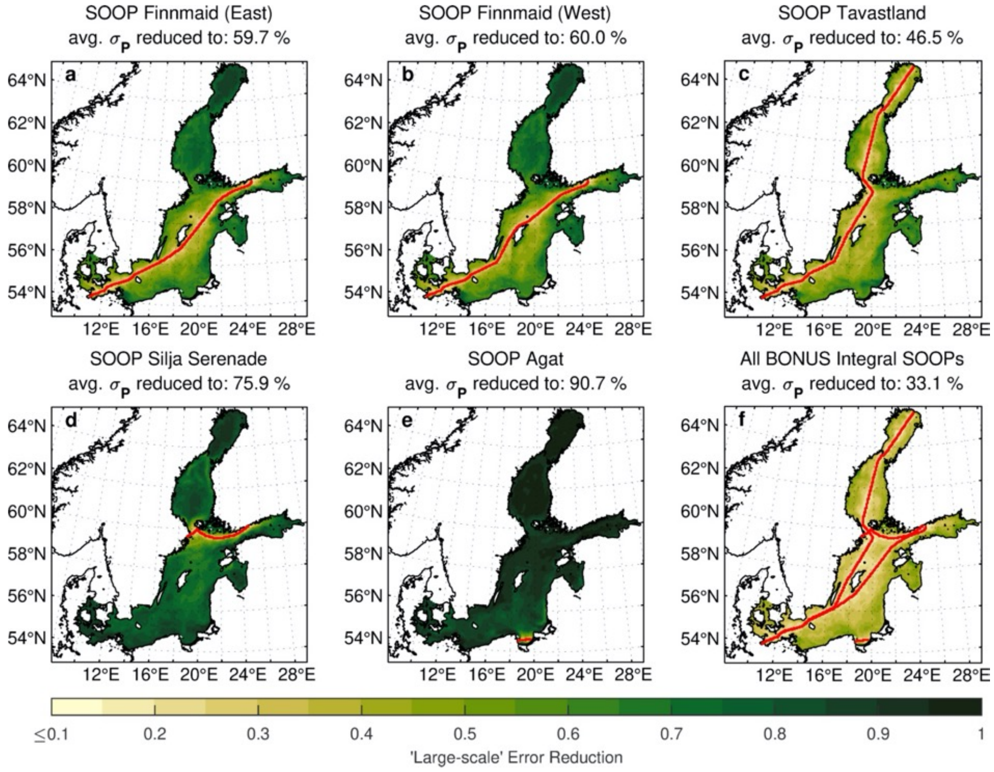

Figure 18: *Reduction in large-scale error by SOOP line surface pCO_2 sampling for (a) Finnmaid on Eastern route, (b) Finnmaid on Western route, (c) Tavastland, (d) Silja Serenade, (e) Agat, and (f) all SOOP lines of BONUS INTEGRAL combined (with an assumed common 5 µatm observation error).*

F3: Budgets, Fluxes, Trend Analysis, and Monitoring Strategies

Delivery Report D6.4 provides a concise summary of the results obtained in WP6, with up to date numbers and figures of the state of knowledge at the end of BONUS INTEGRAL. It addresses a model and observation-based description of the seasonal carbon cycle both at the surface (surface pCO_2) and in the upper water column (total inorganic carbon, C_T), as well as surface, profile, and boundary fluxes. The last ones are assessed with respect to their impact on the overall budget as well as potential temporal trends. The analysis of the mean seasonal cycle of air-sea CO_2 fluxes reveals the Baltic Sea to be a net sink of atmospheric CO_2 on the order of 1.2 mol C m^{-2} yr^{-1}. While the surface water layer exhibits a similar biologically-driven seasonal amplitude, the profile fluxes, however, indicate that this net carbon uptake does not persist in the upper water column. Instead, it is buried in the sediments eventually (60–70 %) or exported through the open boundary to the North Sea together with the freshwater excess of the Baltic Sea.

G.) DISSEMINATION AND OUTREACH (WP7)

Dissemination of knowledge from BONUS INTEGRAL at various levels was an essential part of the project's concept. This includes knowledge transfer within the group and among countries, training about modern carbon and greenhouse gas analytics, flux assessment and modelling for the next generation of enthusiastic scientists in the framework of a summer school and training workshops, the promotion of the use of SOOP lines and carbon data for a cost effective monitoring of the Baltic Sea via workshops and a stakeholder dialogue, and a brochure demonstrating and road-mapping a better integration of SOOP-based sampling strategies and ICOS-related infrastructure for the ecosystem monitoring of the Baltic Sea.

G1: Knowledge and technology transfer amongst scientists

The transfer of knowledge was especially important for countries that just began regular monitoring of pCO_2. In case of Poland, the small SOOP line in the Gulf of Gdansk established within BONUS INTEGRAL is the first SOOP line running in Poland, not only by the IO PAN but also in general. This initiative required, aside from funding, repeated transfer of know-how about pCO_2 measurements and the underlying technology. Thus, the first plans for this installation were developed in a close collaboration between IO PAN and IOW (in particular by Dr. Bernd Schneider), using the experience from more than 15 years of pCO_2 monitoring in the Baltic Sea on the SOOP Finnmaid. For reviving the pCO_2 system on SOOP Tavastland and the attempt to amend the system by CH_4 and N_2O measurements, SMHI could benefit from the long-lasting experience of running SOOP-lines based on a GO-system by GEOMAR. The joint venture between TTU and IOW in connection to the GHG- and carbon system measurements as amendment to the Estonian monitoring in 2018 was a mutual knowledge transfer concerning carbon system and greenhouse gas measurements at the one side and the physical-hydrographical setting in the Gulfs of Riga and Finland at the other side. Lastly, a workshop on technology and quality control of carbon system data was organized between IOCCP, BONUS INTEGRAL and ICOS, hosted in Sopot, Poland by Partner IOPAN, with special (but not exclusive) focus on Estonia and Poland.

G2: The IOCCP – BONUS INTEGRAL Summer School- "Instrumenting our ocean for better observation: a training course on a suite of biogeochemical sensors"

Early in the lifetime of the BONUS INTEGRAL it became clear that several international efforts towards a summer school on carbon system and GHG were discussed, but individually not outfitted with the required resources. After several planning rounds of M. Telszewski, Director of IOCCP, and Gregor Rehder, coordinator of BONUS INTEGRAL, we came to the conclusion that a joined IOCCP / BONUS INTEGRAL summer school would be an ideal solution and a true win-win situation for both sides. It would lead to an outstanding summer school, increase the international visibility of BONUS INTEGRAL and BONUS as a whole, and would ideally be suited to train the next generation of bright students in the use of technology and data handling for autonomous high resolution environmental observation, which is exactly the strategy pursued by BONUS INTEGRAL. At a later stage, the ICOS OTC was encouraged and also committed to the training workshop.

To help train the new generation of marine biogeochemists in the proper use of a suite of biogeochemical sensors and to assure the best possible quality of the data produced, the IOCCP and BONUS INTEGRAL held a 10-day training workshop on “Instrumenting our ocean for better observation: a training course on a suite of biogeochemical sensors”. 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. Two PhD students from BONUS INTEGRAL were accepted as participants based on their qualifications. 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, pCO_2-sensors, and a state-of-the-art General Oceanics pCO_2 underway system. 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).

Recognizing the need to broaden the impact and to leave a legacy of this course, IOCCP and BONUS INTEGRAL decided to share the training materials, including video recorded lectures, with the broad ocean community via the course website: www.ioccp.org/2019-training-course. On this website, additional information is also available, including the program and session description, and short vitas of the instructors. More information can be found in Deliverable Report 7.3.

G3: Stakeholder dialogue and information, and promoting the marine (ocean) branch of ICOS in the pan-Balic area

While the launch of two BONUS Synthesis projects (SEAM and FUMARI) and the Covid 19 pandemia required some deviations from the original dissemination plan (see Deliverable Report 7.4), BONUS INTEGRAL did its best to make best use of resources with respect to stakeholder communication, lobbying for high resolution carbon system measurements, and changing the political landscape. In several aspects, the situation at the end of the project is far beyond our original expectations. HELCOM, identified early as our primary stakeholder entity and hub towards decision makers, was addressed in several ways, in some cases by interaction with other initiatives. Using the visibility of the project and some of the project partners in the European Integrated Carbon Observation System Research Infrastructure (ICOS RI) was also pivotal for some of the achievements towards the main overarching goal of BONUS INTEGRAL, i.e. development and improvement of the scientific-technological basis for monitoring programs.

Lobbying for a strong component of the ocean (marine) theme of ICOS in the pan-Baltic area

Over the course of the project, BONUS INTEGRAL played a pivotal role in strengthening the pan-Baltic ocean component of ICOS, emphasizing the co-benefit for the assessment of the ecological status in the Baltic Sea, addressing in particular eutrophication and acidification. Continuous effort let to – or at least played an important role - in the following achievements:

- IO PAN as the only marine partner in the ICOS consortium of Poland, with a long-term plan to include the installation running on MS Agat established within BONUS INTEGRAL, is foreseen as part of ICOS-PL;

- TTU will be partner for the ocean component of ICOS in Estonia, though the joining of ICOS by Estonia has recently been postponed;
- The pCO_2 instrumentation on SOOP Tavastland is now official component of ICOS Sweden, with BONUS INTEGRAL partner Anna Willstrand Wranne as PI. The line, once fully operational, will have a tremendous importance for the ecological assessment of the northern basins.

Implementation of inorganic carbon monitoring in the Baltic Sea

Apart from the additional surface pCO_2 measurements mentioned above, considerable progress has been made towards the implementation of carbon system parameters for a better monitoring of eutrophication and acidification in the Baltic Sea.

- The development of the monitoring program for carbon system parameters in the Estonian marine areas was suggested, based on the data and knowledge gained during the BONUS INTEGRAL project. The proposal was accepted by the Estonian Ministry of the Environment and the program is under development.
- SMHI, executing the biogeochemical open water monitoring in the Baltic Sea for Sweden, performed an intercomparison between formerly used measurement methods for pH and the newly developed method within BONUS PINBAL, now commercially available, which has been further scrutinized by BONUS INTEGRAL. This is the first step towards a long-term traceable monitoring of pH in the Baltic Sea.
- In Germany, based on BONUS INTEGRAL results, the national authority responsible for the HELCOM monitoring in the Baltic Sea (Bundesamt für Seeschifffahrt und Hydrographie, BSH) granted a project to establish monitoring of pH by spectrophotometry in the Baltic Sea. This might result in the resumption of the monitoring of carbon parameters which was discontinued decades ago. The recognition of this need is strongly related to the stakeholder work of BONUS INTEGRAL at the German national authorities.
- The interplay of the different components run by Finland, Estonia and Germany are supposed to be integrated further in the Gulf of Finland pilot supersite in the framework of the Horizon 2020 project JerichoS3. BONUS INTEGRAL played a pivotal role in establishing the network and harmonization of the infrastructure.

Supporting monitoring development through HELCOM-related work

Based on presentations given at the 7th and 8th meeting of HELCOM State & Conservation (the latter given by the coordinator of BONUS INTEGRAL), Sweden and Germany offered to co-lead work on an acidification indicator, which is under the auspice of the IN Eutrophication. In the following, Gregor Rehder as Coordinator of BONUS INTEGRAL participated free of charge in the project OMAI (Operational Marine Acidification Indicator) funded by the Nordic Research Council, with partners from Sweden, Germany, Denmark and Finland, including current IN Eutrophication chair Vivi Flehming-Lehtinen.

Several members of BONUS INTEGRAL were involved in producing the HELCOM Climate fact sheets, partly in leading positions. In particular, Karol Kuliński, Gregor Rehder, and Anna Rutgersson, all PIs within BONUS INTEGRAL (and involved in Baltic Earth) drafted the part on “Changes in carbonate chemistry (including air-sea exchange of CO_2 and acidification). In addition Anna Rutgersson was leading the section on Energy Cycles.

Direct stakeholder dialogue

BONUS SEAM, FUMARI and INTEGRAL organized a stakeholder event on “Revising monitoring in the Baltic Sea: a workshop on recommendations to and from three BONUS-projects” held at the Swedish Agency for Marine and Water management, Gothenburg, with various stakeholder from foremost Swedish environmental agencies.

Due to the Covid-19-caused cancellation of a stakeholder conference as a side event to the 12th Meeting of HELCOM State & Conservation, BONUS INTEGRAL (as BONUS SEAM and FUMARI) got time to present their key messages and recommendations at the HELCOM meeting itself in form of online presentations. This event was scheduled on May 14th, 2020.

Print dissemination products

In the BONUS INTEGRAL DoW, it was envisaged to provide a brochure and whitepaper reporting the “added value of carbon dioxide and greenhouse gas measurements on SOOP lines and the use of SOOP lines within the HELCOM Monitoring strategy..” The brochure was created in the last month of the project with assistance of a graphic design bureau, published as a BONUS Policy Brief (https://www.bonusportal.org/files/6964/BONUS_INTEGRAL_Policy_Brief.pdf), and posted on the BONUS webpage. The printed version will be distributed at larger conferences and workshops once these will take place again. For the white paper, it was decided to merge the work with a very related effort by the project BONUS SEAM (BONUS SEAM Deliverable 3.2 on “High-frequency automated observing systems to meet the monitoring and assessment needs in the Baltic Sea”). This appears appropriate, as one of the added values in the technological approach promoted within BONUS INTEGRAL is in fact the high-resolution data acquisition ability that has been optimized and demonstrated in the project. This paper is slightly delayed and will be submitted in the first quarter of 2021.

3 Summary of the produced scientific and technological foreground capable of industrial or commercial application, plan for the use and dissemination of this foreground and measures taken for its protection

Summary of the produced scientific foreground:

BONUS INTEGRAL has produced exclusively scientific foreground (i.e., no technological foreground), none of which is suitable for industrial or commercial application. Infrastructure amendments and implementation by individual partners stay by this partner, and currently all developed infrastructure is in further use for the monitoring of the environmental state of the Baltic Sea. Data gathered by the project, which were positively evaluated within the project’s QC measures, was shared amongst the partners, and transferred to publicly accessible data bases at the end of the project (see Deliverable Report 1.4). Scientific foreground (i.e. knowledge) has been published or disseminated otherwise, targeting the scientific community, stakeholders in environmental conservation and policy branches, and the general public.

Protection of the foreground:

No foreground capable of industrial or commercial application was produced, and thus no measures (e.g., patents) were taken to protect this foreground (e.g., no patents, copyrights requested). Feedback between the company now producing the Contros HydroFia-pH instrument (4HJena) and BONUS INTEGRAL staff lead to further improvements of the instrument in a mutual benefit situation. In the case of publications or manuscripts in preparation or in review, the underlying data have been made and will be made publicly available. Data gathered by individual partners have been shared for the purpose of the project, but remain under the ownership of the data-producing partner when it comes to data publishing or DOI-assignment.

Dissemination of foreground:

As mentioned, all QC-ed environmental data gathered during the project will become available through public data bases. Scientific knowledge (foreground) was and will be disseminated by publications (see Section 9 of this report). Major information has been distributed by a policy brief and information to the main stakeholders, i.e. national agencies in charge of the environmental monitoring of the Baltic Sea and HELCOM (see section 2G). For the dissemination of scientific knowledge through publications, open access formats were chosen in almost all cases.

4 Further research and actions needed in the field

The overarching goal of BONUS INTEGRAL was to develop and promote new monitoring strategies for the Baltic Sea, focussing on the implementation of sustained carbon system parameters and – to a lesser extend – the greenhouse gases methane and nitrous oxide, using synergies with efforts of the European Integrated Carbon Observation System Research Infrastructure (ICOS RI). By doing so, the project also addressed questions regarding the carbon and GHG-cycling in the Baltic Sea. We address future needs of these strategic and scientific goals separately, starting with the latter.

Despite the considerably increased data base for CH_4 and N_2O measurements (Figure 13), it was not possible yet to provide seasonal or even monthly maps of these gases for the entire Baltic. This would require a longer record on some of the SOOP lines in the Baltic Sea(so far only the SOOP Finnmaid is regularly featuring theses measurements), in combination with a few more RV-based campaigns addressing the gradients from the coasts to the open basins. As changes in anthropogenic use, deep water redox state, and key biota all can affect the source strength of the Baltic Sea to the atmosphere for these greenhouse gases, closing this gap is recommended.

Work on the carbon system will always have future research needs, as it is addressing the main biogeochemical cycling of the Baltic Sea and thus, proper description of eutrophication and acidification. Major gaps identified is the data shortage of vertical profiles other than alkalinity, and in particular a lack of observations in the Northern Basins (though BONUS INTEGRAL largely improved this situation. These data are required, also in biogeochemical modelling, to better predict the cause-and react chain between Baltic Sea restoration measures (e.g. nutrient reduction) and ecosystem response (e.g. oxygen debt or integrated algal biomass).

Strategically, homogenization and joined planning of technologies and data between the countries need to be continued. The admission of the pCO_2 measurements on SOOP Tavastland as contribution to ICOS Sweden is a major step forward in this direction. Monitoring entities in Sweden, Germany and Estonia are joining forces to establish a method for the consistent monitoring of pH to track acidification. As pointed out also by the Synergy project BONUS FUMARI, future work is needed to formulate a clear procedure with regard to implementing new indicators and methods into the HELCOM monitoring. Moreover, the ecosystem monitoring would benefit and safe resources by a harmonization of the individual national activities under a joint organizational body.

5 Promoting an effective science-policy interface to ensure optimal take up of research results (corresponding with the reported performance statistics 1-4)

The Members of BONUS INTEGRAL actively promoted the overarching goals of BONUS INTEGRAL to stakeholders and related science organizations, and continue to do so after the end of the project. This is facilitated by the active role several PIs play in the key organizations (HELCOM, IPCC, SOLAS, ICOS, National Authorities, Baltic Earth).

Towards fit for purpose regulations and policies, BONUS INTEGRAL coordinator Gregor Rehder together with Jakob Carstensen from the University of Aarhus, Denmark, successfully proposed (on behalf of Sweden) the adoption of carbon system parameters as "candidate indicator" for acidification at the 7th and 8th HELCOM State and Conservation meetings. Together with partners from University Stockholm, SYKE, and the University of Aarhus, further steps are taken towards developing an acidification indicator, as reaction to the adoption of the candidate indicator on acidification. This work is under the auspices of HELCOM IN Eutrophication. On request of the BSH, responsible for the ecological monitoring of the Baltic Sea open waters in Germany, IOW assesses the technology of spectrophotometric pH measurements, developed within BONUS PINBAL and further within BONUS INTEGRAL, for future operational monitoring in Germany. Similar work towards implementation of a monitoring program to trace acidification in Estonian waters is in progress in Estonia by partner TTU. Gregor Rehder presented the INTEGRAL recommendations for an enhanced biogeochemical monitoring of the Baltic Sea at the 12th Meeting of HELCOM State and Conservation in May 2020 on behalf of the entire BONUS INTEGRAL consortium.

Several members of BONUS INTEGRAL, including Anna Rutgersson, Karol Kulinski, Gregor Rehder and Markus Meier, have been working actively in the newly formed EN Clime of HELCOM, which is led by BONUS INTEGRAL PI Markus Meier, and contributed to the drafting of the climate fact sheet. This work is almost finalized.

Various of the PIs of BONUS INTEGRAL have been active in a variety of Stakeholder committees and science organization bodies, including the HELCOM EN Clime and IN Eutrophication, the Baltic Earth Steering Group, the International SOLAS Scientific Steering Committee, the Finnish National Scientific Committee on Oceanic Research, IAPSO, BOOS, and the ICES Marine Chemistry working group. In total, one hundred entries have been registered in this category, and some might have been forgotten.

Throughout the entire project duration, BONUS INTEGRAL and its members were engaged in stakeholder information, ranging from co-organization of conferences like the 2nd Baltic Earth conference in Helsingør in 2018 or the stakeholder workshop on “Revising monitoring in the Baltic Sea: a workshop on recommendations to and from three BONUS-projects” held at the Swedish Agency for Marine and Water management, to smaller and more individually tailored events, the most memorable of which surely being the visit of the President of Finland, Mr. Sauli Niinistö (Figure 19).

***Figure 19:** Presentation of Station Utö to the President of Finland, Sauli Niinistö, by BONUS INTEGRAL PI Lauri Laakso in Helsinki.*

6 Collaboration with relevant research programs and the science communities in the other European sea basins and on international level (corresponding with the reported performance statistic 5)

BONUS INTEGRAL and its PIs used the international network for collaboration with multiple international programs and activities. The summer school (IOCCP & BONUS INTEGRAL Training course on “Instrumenting our oceans for better observation) as well as a technological workshop particularly designed for members potentially joining the ICOS network were organized in collaboration with the International Ocean Carbon Coordination Project (IOCCP). BONUS INTEGRAL exchanged strategic ideas with the ICOS head office, and was highlighted by an invited talk at the 3rd ICOS International Conference focussing on the added value produced by ICOS infrastructure demonstrated by BONUS INTEGRAL. Strong collaboration was also established with the activities of the European Project Jericho Next, with special emphasis on the homogenization of carbon system measurements, which is further pursued in the Horizon 2020 project JerichoS3. Recently, exchange was also intensified with the European BGC-Argo network, fostering the vision of the integrated data analysis of these two large European RIs (ICOS and Euro-Argo).

7 Progress in comparison with the original research and the schedule of deliverables

Progress in comparison with the original research plan

Some of the work planned in the project was fulfilled slightly delayed for various reasons. This included delayed installation of some of the instrumentation due to technical difficulties, rescheduling due to changes in personnel, and in the last period, also some restrictions caused by the Covid 9 pandemic (like maintenance or technological changes on the measurement platforms, in person travel etc.). Therefore, an extension of the project for three months was requested and granted by BONUS EEIG and all national funding agencies, and a new schedule of deliverables was agreed upon. The new schedule of deliverables also reflected that one single deliverable could not be met, which was the organization of a final stakeholder conference. Though initial steps had been taken, the anticipated date was after the occurrence of the Covid-19 pandemic, and it was impossible to realize a larger event in the remaining time of the project. This was accepted by all funding parties, and consequently this deliverable was removed from the list of deliverables.

However, due to the activity towards engagement of stakeholders over the entire course of the project, the main scope and goals of stakeholder liaison could even be exceeded. The SOOP Tavastland is now part of ICOS Sweden and operation secured for at least five years, Partner IO PAN and the developed SOOP Agat are on the national roadmap for ICOS Poland, and Partner TTU is envisaged to maintain oceanic ICOS infrastructure in the Baltic Sea once Estonia joins the ICOS RI. Moreover, the agencies responsible for the HELCOM monitoring in Germany, Estonia and Sweden are actively preparing to extend their carbon system monitoring efforts, and the work towards a carbon system based indicator has been adopted by HELCOM State and Conservation.

So it can be stated that all deliverables have been met.

8 Wider societal implications

BONUS INTEGRAL is not directly leading to economic value or jobs. However, it supports the governance of the Baltic Sea, and marginal seas in general, by showing the way to monitor and make use of a so far underrepresented key variable of ecosystem functioning, i.e. the carbon system. The Marine Strategy Framework Directive, setting a framework for the European community with respect to the protection and governance of marine waters, reflects the appreciation and value the EU – and its citizens - place on the marine ecosystem. The integrity and good environmental status (or well-being) of the Baltic Sea ecosystem is a major asset of the pan-Baltic coastal society, affecting trade and transport, human wellbeing, fisheries, and tourism.

By defining the success of the implementation of the MSFD and the BSAP through targeting a good environmental status, rather than "just" defining emission scenarios, the assessment of measures to protect the Baltic Sea ecosystem requires a sound understanding of the response of these measures by the ecosystem. For measures regarding eutrophication, linking the indicators addressing primary production (i.e. nutrient inventory and loads, Secci depths, Chl-a, etc.) and its consequences on deep water oxygen conditions (i.e. oxygen debt, hypoxic area, and benthic habitats) requires an understanding of the involved carbon cycling. BONUS INTEGRAL advanced this understanding through strengthening the observational as well as modelling capacities in the Baltic Sea region.

Marine acidification is a major concern for coastal ecosystems for which, recognized by HELCOM and the EU, a suitable indicator is currently missing. The development of suitable monitoring strategies and technology for brackish water pH and carbon system parameters, as pushed forward by BONUS INTEGRAL, is prerequisite for the drafting of an acidification indicator for the Baltic Sea, a process which could be started during the course of - and strongly supported by - BONUS INTEGRAL.

In an era of tight financial budgets, optimal use of resources is a justified requirement for all measures financed by the European or national entities through its citizens (i.e. tax payers). Here, BONUS INTEGRAL demonstrated the added value of the ICOS RI for the environmental monitoring of the Baltic Sea, and fostered and promoted the use of autonomous technology on volunteering free of cost platforms.

Through the BONUS INTEGRAL policy brief, the information at the level of stakeholders like HELCOM and the national authorities in control of the Baltic Sea monitoring, the successful promotion of a stronger marine Baltic component of the European ICOS RI, and through its role in the development of an acidification indicator, BONUS INTEGRAL helped to enable stakeholders, including policy makers and governmental bodies, to make informed decisions supporting the maintenance of ecosystem integrity and governance of the Baltic Sea. Through information of the public and the next generation of scientists (i.e. IOCCP and BONUS INTEGRAL summer training course), BONUS INTEGRAL also fostered "(coastal)ocean literacy", an important prerequisite for a balanced and healthy relationship between the population and the sea, and consequently defined as one of the main goals in the upcoming UN Decade of Ocean Science for Sustainable Development.

9 Publications and academic degrees

Given the fact that the peer-reviewed output of research projects is known to proceed further after the official end of the project, BONUS INTEGRAL has an extremely successful record of peer-reviewed publications completely or partly deriving from the project already. Also, the project was the base of funding and science content for a number of PhD thesis, some of them already completed, even more expected to be finalized within the next year.

Publications arising from the project

A: currently submitted or under review:

Gutierrez-Loza, L., Wallin, M.B., Sahlée, E., Holding, T., Shutler, J., Rehder, G., Rutgersson, A. "Air-sea CO_2 exchange in the Baltic Sea—a sensitivity analysis of the gas transfer velocity" (submitted to J. Mar Sys).

Martti Honkanen, M. , Müller J.D., Jukka Seppälä, J., Rehder, G., Kielosto S., Ylöstalo, P., Mäkelä. T., Hatakka, J., and Laakso, L.: Diurnal cycle of the CO_2 system in the coastal region of the BalticSea (submitted to Ocean Sciences).

Müller, J. D., B. Schneider, U. Gräwe, P. Fietzek, M. B. Wallin, A. Rutgersson, N. Wasmund, S. Krüger, and G. Rehder. Cyanobacteria net community production in the Baltic Sea as inferred from profiling pCO_2 measurements (submitted to Biogeosciences)

B: Accepted and in press

Jacobs, E., Bittig, H. C., Gräwe, U., Graves, C. A., Glockzin, M., Müller, J. D., Schneider, B., and Rehder, G.: Upwelling-induced trace gas dynamics in the Baltic Sea inferred from 8 years of autonomous measurements on a ship of opportunity, Biogeosciences Discuss., https://doi.org/10.5194/bg-2020-365, in press, 2021.

Sanders, T., J. Thomsen, J. D. Müller, G. Rehder, and F. Melzner: Decoupling salinity and carbonate chemistry: Low calcium ion concentration rather than salinity limits calcification in BalticSea mussels, Biogeosciences Discuss., https://doi.org/10.5194/bg-2020-382, in press, 2021.

B: published

Bange, H. W., Arévalo-Martínez, D. L., de la Paz, M., Farías, L., Kaiser, J., Kock, A., Law, C. S., Rees, A. P., Rehder, G., Tortell, P. D., Upstill-Goddard, R. C. and Wilson, S. T., (2019). A harmonized nitrous oxide (N_2O) ocean observation network for the 21st century. Frontiers in Marine Science, 6; doi: 10.3389/fmars.2019.00157.

Björkqvist, J.-V., Pettersson, H., Drennan, W. M., and Kahma, K. K., (2019). A new inverse phase-speed spectrum of non-linear gravity wind waves. Journal of Geophysical Research: Oceans, doi: 10.1029/2018JC014904.

Friedlingstein, P., et al. (2020), Global Carbon Budget 2020, Earth System Science Data, 12(4) 3269-3340.

Friedlingstein, P., et al. (2019), Global Carbon Budget 2019, Earth System Science Data, 11(4), 1783-1838.

Holding, T., Ashton, I. G., Shutler, J. D., Land, P. E., Nightingale, P. D., Rees, A. P., Brown, I., Piolle, J. F., Kock, A., Bange, H. W., Woolf, D. K., Goddijn-Murphy, L., Pereira, R., Paul, F., Girard-Ardhuin, F., Chapron, B., Rehder, G., Ardhuin, F., and Donlon, C. J., (2019). The FluxEngine air–sea gas flux toolbox: simplified interface and extensions for in situ analyses and multiple sparingly soluble gases, Ocean Sci., 15, 1707-1728; doi: 10.5194/os-15-1707-2019.

Honkanen, M., Tuovinen, J.-P., Laurila, T., Mäkelä, T., Hatakka, J., Kielosto, S. and Laakso, L., (2018). Measuring turbulent CO_2 fluxes with a closed-path gas analyzer in a marine environment. Atmos. Meas. Tech., 11, 5335-5350, https://doi.org/10.5194/amt-11-5335-2018.

Gutiérrez-Loza, L., Wallin, M. B., Sahlée, E., Nilsson, E., Bange, H. W., Kock, A. and Rutgersson, A., (2019). Measurement of air-sea methane fluxes in the Baltic Sea using the Eddy covariance method. Frontiers Earth Sci, 7.

Kuliński, K., Szymczycha, B., Koziorowska, K., Hammer, K. and Schneider, B., (2018). Anomaly of total boron concentration in the brackish waters of the Baltic Sea and its consequence for the CO_2 system calculations. Marine Chemistry 204, 11-19.

Laakso, L., Mikkonen, S., Drebs, A., Karjalainen, A., Pirinen, P. and Alenius, P., (2018). 100 years of atmospheric and marine observations at the Finnish Utö Island in the Baltic Sea. Ocean Sci., 14, 617-632, https://doi.org/10.5194/os-14-617-2018.

Ma, X., Sun M., Lennartz S.T., Bange, H.W.., 2020: A decade of methane measurements at the Boknis Eck Time Series Station in Eckernförde Bay (southwestern Baltic Sea). Biogeosciences 17:3427-3438. doi.org/10.5194/bg-17-3427-2020, July 2020.

Ma, X., Lennartz, S. T., and Bange, H. W., (2019). A multi-year observation of nitrous oxide at the Boknis Eck Time Series Station in the Eckernförde Bay (southwestern Baltic Sea), Biogeosciences, 16, 4097-4111; doi: 10.5194/bg-16-4097-2019.

Müller, J. D., Bastkowski, F., Sander, B., Seitz, S., Turner, D. R., Dickson, A. G. and Rehder, G., (2018). Metrology for pH Measurements in Brackish Waters—Part 1: Extending Electrochemical pH_T Measurements of TRIS Buffers to Salinities 5–20. Frontiers in Marine Science, 5(July), 1–12. https://doi.org/10.3389/fmars.2018.00176.

Müller, J. D. and Rehder, G., (2018). Metrology of pH Measurements in Brackish Waters—Part 2: Experimental Characterization of Purified meta-Cresol Purple for Spectrophotometric pH_T Measurements. Frontiers in Marine Science, 5(July), 1–9. https://doi.org/10.3389/fmars.2018.00177.

Nilsson, E., H. Bergström, A. Rutgersson, E. Podgrajsek, M.B. Wallin, G. Bergström, E. Dellwik, S. Landwehr and Ward, B., (2018). Evaluating Humidity and Sea Salt Disturbances on CO_2 Flux Measurements. J. Atmos. Oceanic Technol., 35, 859–875, https://doi.org/10.1175/JTECH-D-17-0072.1.

Rutgersson, A., Heidi Pettersson, Erik Nilsson, Hans Bergström, Marcus B.E. Wallin, E. Douglas Nilsson, Erik Sahlée, Lichuan E. Wu & E. Monica Mårtensson (2020) Using land-based stations for air–sea interaction studies, Tellus A: Dynamic Meteorology and Oceanography, 72:1, 1-23, doi: 10.1080/16000870.2019.1697601.

Schneider, B. and Müller, J. D., (2018). Biogeochemical Transformations in the Baltic Sea - Observations Through Carbon Dioxide Glasses. Springer Oceanography. Springer Scientific, Berlin (116 pp).

Schneider, B. and Otto, S., (2019). Organic matter mineralization in the deep water of the Gotland Basin (Baltic Sea): Rates and oxidant demand. Journal of Marine Systems 195, 20-29.

Steinhoff, T. et al. Constraining the Oceanic Uptake and Fluxes of Greenhouse Gases by Building an Ocean Network of Certified Stations: The Ocean Component of the Integrated Carbon Observation System, ICOS-Oceans (2019), Frontiers in Mar. Sci, 6: 400. doi 10.3389/fmars.2019.004400.

Stokowski M., Schneider B., Rehder G., Kuliński K., (2020). The characteristics of the CO_2 system of the Oder River estuary (Baltic Sea). Journal of Marine Systems 211, 103418.

Stokowski, M., P. Makuch, K. Rutkowski, M. Wichorowski, and K. Kuliński (2021). A system for the determination of surface water pCO_2 in a highly variable environment, exemplified in the southern Baltic Sea, *Oceanologia*, *63*(2), 276-282.

Wanninkhof, R., P. A. Pickers, A. M. Omar, A. Sutton, A. Murata, A. Olsen, B. B. Stephens, B. Tilbrook, D. Munro, D. Pierrot, G. Rehder, J. M. Santana-Casiano, J. D. Müller, J. Trinanes, K. Tedesco, K. O'Brien, K. Currie, L. Barbero, M. Telszewski, M. Hoppema, M. Ishii, M. González-Dávila, N. R. Bates, N. Metzl, P. Suntharalingam, R. A. Feely, S.-i. Nakaoka, S. K. Lauvset, T. Takahashi, T. Steinhoff and U. Schuster. A Surface Ocean CO_2 Reference Network, SOCONET and Associated Marine Boundary Layer CO_2 Measurements (2019). Frontiers in Mar. Sci., 6: 400. doi 10.3389/fmars.2019.00400.

Watson A.J., Schuster U., Shutler J.D., Holding T., Ashton I.G.C., Landschützer P., Woolf D.K., Goddijn-Murphy L. (2020). Revised estimates of ocean-atmosphere CO_2 flux are consistent with ocean carbon inventory. Nature Communications, 11(1), 4422, doi:10.1038/s41467-020-18203-3.

Zhang, S.; Rutgersson, A.; Philipson, P.; Wallin, M.B. Remote Sensing Supported Sea Surface pCO_2 (2021). Estimation and Variable Analysis in the Baltic Sea. Remote Sens., 13, 259. https://doi.org/10.3390/ rs13020259

PhD-thesis arising from the project

A: Defended

Björkqvist, J.V.: "Waves in Archipelagos", PhD thesis, University of Helsiki, Finland, 2020 (FMI).

Ma, X.: From coastal waters to the open ocean: the variability and emissions of methane and nitrous oxide, PhD thesis, University of Kiel, Kiel, Germany, 2020 (GEOMAR).

Müller, J. D.: Ocean Acidification in the Baltic Sea: Involved Processes, Metrology of pH in Brackish Waters, and Calcification under Fluctuating Conditions, University of Rostock, Germany, 2018 (IOW).

Gutierrez-Loza, L.: Mechanisms controlling air-sea gas exchange in the Baltic Sea. (Licentiate thesis), Uppsala University, Sweden, 2020(UU).

B: in progress (Short description of content is given rather than tentative title)

Gutierrez-Loza, L. (UU): Marine methane and carbon dioxide fluxes, methods and measurements (Doctoral thesis).

Honkanen, M. (FMI): Carbon cycle studies at Utö station and in the Northern Baltic Sea

Jakobs, E.: Longterm observations of methane and carbon dioxide in the Baltic Sea

Lainela, S.: Carbon system investigations in Estonian Waters (TTU)

Stokowski, M.: Carbon system investigations along River-Baltic Sea transition zones in the southern Baltic Sea (IOPAN)

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