Project title: BaltRap - The Baltic Sea and its Southern Lowlands: Proxy-Environment interactions in times of rapid changes

Project number: K210/2016

Executive Summary

The BaltRap network was regrouping scientists from the Leibniz Institutes for Baltic Sea Research (IOW) and of Freshwater Ecology and Inland Fisheries (IGB), the Helmholz Centre German Research Centre for Geosciences (GFZ), and the University of Greifswald in Germany. The main goal of BaltRap was to combine sedimentary archives from the Baltic Sea with lake sediments and tree rings in order to comprehensively understand the impact of rapid climate change on the southern Baltic Sea region (SBSR) during the mid- to late Holocene (the last ca. 6000 years). The project could successfully address most of its objectives. First, the coupling of geochemical field data including water column and sediment analyses with instrumental time series from the Baltic Sea, lakes and trees allowed the development and understanding of existing and new environmental proxies, a key prerequisite for high quality paleoenvironmental reconstructions. Proxies to estimate changes in e.g. temperature, salinity, cyanobacterial biomass, redox conditions or human presence have been developed. Second, methods to synchronize archives from the marine and terrestrial environments have been developed and applied successfully, opening the possibility to understand the interactions between the Baltic Sea and its adjacent terrestrial systems. Such methods included the use of atmospheric lead ($^{206/207}$Pb), volcanic ashes, ^{10}Be, as well as persistent organic pollutants and pollen. And third, the proxy application on the different archives allowed reconstructing the variability of important climatic and anthropogenic parameters. For example, it was shown that cyanobacteria in lakes have never been as abundant as in the present day over the last 6000 years, but no such trend was found in the Baltic Sea. Periods of hypoxic conditions, most likely related to eutrophication, were mainly synchronous in the Baltic Sea and lakes, what suggest a common trigger. Ongoing trends of forest primary productivity in relation to human induced changes of atmospheric deposition and climate change could be identified and used to refine both, climate reconstructions as well as scenarios of future tree growth trends. The strength and innovative aspect of BaltRap was to compare and exchange analytical methods between the different partners. This exchange of knowledge, made possible over several BaltRap meetings as well as international conferences, brought a significant added value, especially for the young researchers. Due to changes in personnel and delays related to the COVID-19 pandemic, the BaltRap network has been extended by 22 months. The BaltRap project resulted in 31 publications in peer-reviewed journals, 10 theses, and 2 dissertations. Knowledge transfer has been made possible over press releases and a podcast. The BaltRap project achieved to open and strengthen collaboration between the different partners for still on-going and future works.

1. Achievement of objectives and milestones

Most of the milestones and related objectives could be achieved successfully. A first objective of BaltRap was the development and calibration of different proxies using recent sediments and observational data. Proxies to estimate e.g. water temperature, primary production and eutrophication of forests, lakes and the Baltic Sea, the presence of hypoxic conditions in the water column, or demographic growth and sewage pollution have been developed, thus enlarging the range of proxy application for high quality paleoenvironmental reconstruction. Two lakes with unique long-term monitoring data sets of over several decades were used to identify geochemical proxies and to correlate geochemical focusing with the altered redox conditions triggered by increased eutrophication. Within BaltRap new networks as for example a dense tree-ring data network for the SBSR have been developed and used inter alia for the first millennium long hydroclimate reconstruction of the region as well as for detailed analysis of ongoing forest growth trends. Synchronizing the marine, lake and tree rings archives was the second main objective of BaltRap. Different approaches were tested and applied allowing the determination of chronostratigraphic horizons fixing a main frame for a detailed, dynamical comparison between the different environments and proxies. Stable Pb isotopes ($^{206/207}$Pb), persistent organic pollutants (PAH_S and DDT), and pollens, as well as volcanic ashes and ^{10}Be represent promising excellent tools for establishing isochrones to synchronize archives. For example, years of massive pollen production of forests, so called mast years were used for the first time to synchronize pollen and tree-ring data, a promising approach for dating lake records or for refining tree-ring based climate reconstructions. The third and fourth main objectives consisted in producing and linking marine, lake and tree ring high resolution proxy records for the last 6000 years. While records of variability in e.g. dryness, temperature, vegetation, cyanobacterial production, or hypoxia have been produced, the work on synchronizing robustly the different records in order to estimate the response times of the different environments to rapid climate change is still on-going with promising results.

2. Activities and obstacles

An expedition dedicated to BaltRap took place in the central Baltic Sea on board the research vessel Elisabeth Mann Borgese in December 2018. The different lakes studied in the frame of the network were sampled regularly. Water column suspended matter, sediment trap material, surface sediments and short sediment cores have been analysed for different organic and inorganic proxies. Intense tree-growth monitoring was conducted over the project runtime and a dense tree-ring network of the SBSR region was build up including field campaigns to obtain data for blank spots on the tree-ring map of the region. Archaeological wood was used to build more than 1000 year-long continuous chronologies with the aim of climate reconstructions. However, the incorporation and interpretation of data from former field campaigns dedicated to sunken forests in the SBSR turned out to be challenging. Three BaltRap meetings including all partners have been organized in Germany and Poland. Planned cooperation with additional partners

from Poland and Germany were successfully realized. While most of the objectives could be processed and mostly fulfilled, the milestones have been disturbed by both unexpected changes in the staff (young researchers), due to personal reasons like e.g. maternity leaves, and the COVID-19 pandemic. Personnel changes, contract extensions and modifications, as well as reclassification of travel and consumable expenses occurred for all project partners. Delays and additional costs in the project were partially offset by budgetary funds. As a consequence, the BALTRAP project was extended by 22 months without affecting costs.

3. Results and successes

In the frame of the BaltRap project 31 publications in peer-reviewed journals, 10 theses, and 2 dissertations were completed successfully. Building on her successful work within BaltRap, Jill Harvey from Greifswald University obtained a renowned Alexander von Humboldt International Research fellowship. In addition, Ebuka Nwosu from the GFZ obtained a PhD grant from the Deutsche Bundesstiftung Umwelt (DBU) for cyanobacterial analyses. Two BaltRap related PhD theses are still on-going. Two projects (TETRABAL and SyncBalt) thematically linked to BaltRap have been funded by the German Science Foundation (DFG). Some publications (Scharnweber et al., 2018; Kaiser et al.., 2020, 2022) have been relayed by different local and regional journals and magazines, and a podcast including topics connected to the BaltRap project has been realised ("Klimawandel und Meer – Der Fall Ostsee"; https://anchor.fm/ostseetag). The work between the BaltRap partners is still on-going, and recently produced data and results will likely be published in the near future. Further BaltRap-related projects have recently been funded by the DFG and the Leibniz Association (DFG Projektnummer 502442046, SAW - PHYTOARK).

4. Equal opportunities, career development and internationalization

In staff recruitment the equal gender rules from each institute were applied rigorously by 1) ensure gender equality in the staffing committee 2) including the participation of the Equal Opportunity Officer, and 3) where possible, inviting an equal number of female and male candidates. Job announcements were spread in international channels resulting in successful applications of researchers from abroad. In most of the cases, female candidates have been employed. The project frame allowed the young researchers to work in an interdisciplinary environment what fortified the development of their works and allowed them to open their abilities. Joint expeditions on sea and on land, as well as BaltRap meetings (in Germany and Poland) allowed an excellent exchange of knowledge to all BaltRap members. The young researchers could participate to different institutional workshops (soft skills, winter school) and international meetings, at least until the COVID-19 pandemic started.

5. Structures and collaboration

The collaboration during the BaltRap project occurred at two different levels. On the one hand, jointly collected samples from different lake and marine archives have been analyzed by different methods depending on the specialization of the different partners. This allowed not only to apply methods for the first time, but also to compare the archives of the different environments in terms of both timing and processes involved. On the other hand, formal and informal meetings as well as individual guest stays allowed an important knowledge exchange for interpreting the new results from the different interdisciplinary viewpoints of the BaltRap consortium. Scientists and students have been regularly visiting the different partner institutions for analyses and discussion. As some analyses could not be realized among the partner's institutions, new collaborations were established. For example, some organic proxies have been analyzed at Brown University (USA) and the Royal Netherlands Institute for Sea Research (NIOZ, NL). As well, specific inorganic proxies were measured at the Institute for Chemistry and Biology of the Marine Environment (ICBM, DE), the Institute of Geology and Geochemistry of Petroleum and Coal (RWTH Aachen University) or the University of Cologne (DE), and archaeological tree-ring data were provided by the German Archaeological Institute (DAI) in Berlin (DE).

6. Quality assurance

International and/or in-house reference materials were analyzed next to the samples in the different laboratories in order to estimate and report on reproducibility and data uncertainties. Methods are carefully reported and measurement protocolls are kept accessible upon request. Some inter-calibration work between different laboratories has been realized in parallel to the BaltRap project. The University of Greifswald successfully participated in an international study aiming at creating a uniform and comparable standard for wood-density measurements (microdensitometry) of tree-ring samples. Young researchers were guided to perform along the good scientific practice and all published data are available either from the publications themselves, or from data publishers for earth and environmental sciences such as PANGAEA. Most publications are in open access (~70 %). No animal testing has been conducted.

7. Additional resources

Due to the early departure of the first project employee (PhD position) at the IOW, a shortened postdoc position has been opened, but led to delays and additional costs in the project, which were partially offset by budgetary funds. A further extension of 9-months of this postdoc positions has been funded by the IOW. The costs for the seagoing BaltRap expedition has been supported by the IOW. A internal competitive seed money project (consumable costs) funded by the IOW has been achieved successfully. In total, the value of in-kind resources of the IOW for BaltRap can be estimated to ~240 k€. The University of Greifswald supported the monitoring program within BaltRap with an estimated 30 k€ for instrumentation and maintenance of several forest sites of high resolution tree-

growth monitoring. The GFZ Potsdam and the Helmholtz Association funded lake monitoring and sediment sampling of Lake Tiefer See. The IGB provided technical staff for sediment sampling and the chemical lab analyses. The long-term monitoring program at Lake Arendsee and Lake Stechlin was used as an important data basis.

8. Outlook

The results of the BaltRap network have proven that different tools exist to synchronize and, thus, compare archives from different environments. These tools provide first robust tie points between records that will be further extended in ongoing and future work. For example, ^{10}Be may allow such a follow up approach. A recently granted DFG project will focus on this aspect. In lakes, geochemical focusing can favor the formation of vivianite and thus increase the permanent P fixation under anoxic conditions, which is important for lake management measures. The formation and stability of vivianite is subject of ongoing projects (e.g. EU-INT RecaP). The development of the stable tungsten isotopic composition as a new sedimentary paleo-redox proxy carried out in close collaboration with the University of Cologne opens a wide field of future applications. A DFG proposal and request for ship time have been submitted recently. Exploring decadal climate variability by increasing the temporal resolution of the proxy records may reveal important pattern concerning e.g. the evolution and impact of the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillations (AMO), two climate modes strongly influencing the southern Baltic Sea region. Tree-ring proxies have shown a great potential for the reconstruction of these atmospheric oscillation patterns, but the temporal coverage of the existing continuous chronologies in the region is rather short with ~ 1200 years. A prolongation of the existing records by for example incorporating the floating chronologies of the wood remains from the Baltic Sea bottom is therefore envisaged. Already established in-house cooperation at IOW with the regional climate modelers will shed light on this topic from transient Baltic Sea regional climate model simulations. Sediment DNA analyses has been successfully applied for lake sediments and proven that the history of cyanobacteria can be traced several millennia back in time. Together with biomarker analyses, ancient DNA represents a tool at hand for in-depth reconstruction of past natural variability and anthropogenic impact on marine and terrestrial environments. Extensive ancient DNA analyses on Baltic Sea Holocene sediments are now on-going in the frame of the SAW PHYTOARK project. Furthermore, BaltRap has laid the foundation to link pollen records from lake sediments with tree-ring data by using the massive pollen production in masting years which due to resource partitioning is also mirrored in tree-rings. Applying this method to longer time series and different study sites can help both disciplines by enhancing dating accuracy of sediment records and interpretation of past tree-growth patterns.