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ORIGINAL RESEARCH ARTICLE

Argo floats in the southern Baltic Sea

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Summary This work aims to familiarize the reader with issues related to modern oceanographic measurement techniques performed by Argo autonomous profiling floats. The opportunity for this is the three years of innovative activity on the part of Argo-Poland in the Baltic Sea. Based on the experience and results acquired by the Institute of Oceanology of the Polish Academy of Sciences (IO PAN), we can say that a revolution in the Baltic Sea monitoring is underway. During three years of activity, the floats launched by IO PAN provided more than 1600 CTD profiles, including 600 O_2 profiles. Together with synoptic data from ships, data from moorings and surface buoys, the Argo float measurements are an important part of the southern Baltic monitoring system. Two Argo floats launched by IO PAN collected enough data to determine the dynamics of the oxygen content in various layers, the extent of hypoxic and anoxic zones, and to detect small baroclinic inflows to the Gotland and Gdańsk Deeps.
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1. Introduction

Rapidly progressing climate change has focused the interest of climatologists and weather services on the ocean. There was a need to create a system that, in place of thinly spaced oceanographic stations, would provide near-real-time information about the thermal state of the ocean from a global network of monitoring instruments. The assumption underlying the Argo Programme was that the use of autonomous, free-drifting profiling floats would meet this need. Following its implementation in 1999, Argo achieved global coverage of the upper 2000 m of the oceans in 2006. Nowadays, a global array of 4000 floats covers the oceans (Fig. 1). Argo floats provide the most important in situ ob-

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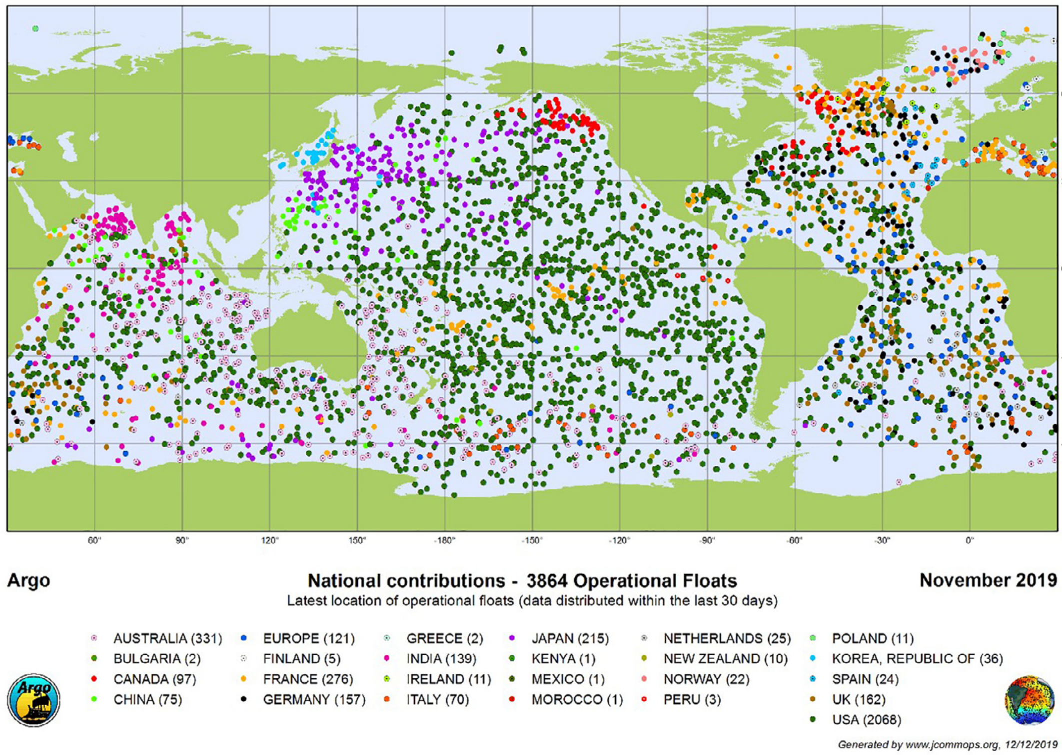


Figure 1 Location of operational floats and national contributions in November 2019.

servations for monitoring and understanding the influence of the ocean on Earth's climate and for operational oceanography (Le Traon, 2013). The Argo system is the main component of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS) (Roemmich et al., 2019). The freely available Argo data are used mainly in atmospheric, oceanographic and climate research. Since the programme's inception to October 2018, the floats have provided 2 000 000 profiles from the surface to 2000 m depth and a comparable amount of information on drift speed estimated at a depth of 1000 m. Floats deliver continuous observations of ocean temperature and salinity vs pressure. Data are transmitted by satellite to receiving centres and are available to users in near-real-time (NRT). The development and maintenance of a global array of profiling floats delivering NRT in situ data has been an outstanding achievement and revolution in oceanography. In fact, there have been three revolutions in world oceanography (Le Traon, 2013): 1) the development and introduction of high-resolution satellite altimetry; 2) the array of Argo floats; 3) the development of global operational oceanography, closely linked to the first two revolutions. In Baltic Sea research the second revolution — "Argo time" — has now begun.

The exchange of water between the North Sea and the Baltic through the narrow, shallow Danish Straits is very important for the entire Baltic Sea environment (Elken and Matthäus, 2008). This very limited exchange maintains brackish water conditions in the Baltic (HELCOM, 1986). Major Baltic Inflows (MBI) are the main source of deep-water ventilation in the central Baltic basins and govern environmental conditions below the halocline to a significant extent (Mohrholz, 2018). These inflows are barotropic, driven mainly by wind forcing and the water level difference between the Kattegat and western Baltic. MBIs occur mostly in the autumn and winter. Smaller, baroclinic inflows, occurring mostly in summer, are driven by the salinity gradient between the North and Baltic Seas. The importance of MBIs, smaller barotropic inflows and baroclinic inflows in Baltic Sea hydrography continue to be a matter of debate (Mohrholz, 2018).

The Polish Exclusive Economic Zone (Polish EEZ) includes part of the Bornholm Basin, the Słupsk Furrow, part of the Eastern Gotland Basin and the Gdańsk Basin. The Słupsk Furrow is the only deep connection between the Bornholm and Gotland basins (Fig. 2) and the only pathway for eastward deep-water advection. The dynamics of eastward water transport is governed by the interaction of bottom topography and external forcing: currents can be interrupted, and mesoscale processes play an important role (Piechura et al., 1997). Therefore, regular observations and a coherent system utilizing observational data and modelling are needed in order to thoroughly understand inflow processes and how they affect the Baltic Sea. The inclusion of Argo floats in the southern Baltic Observing System was proposed by Walczowski et al. (2017). They suggested using various data sources, including hydrographic sections from synoptic surveys, Eulerian data from a moored buoy and Lagrangian data provided by Argo floats to monitor the properties and dynamics of deep inflows of saline, oxygenated water from the North Sea. After three years of work, all the signs are that these ideas are feasible.

The aim of this paper is to briefly describe the Argo float technology, network organization and data potential

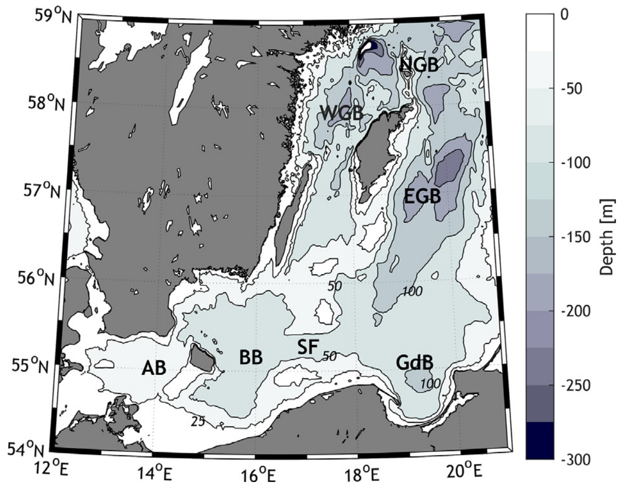


Figure 2 Main basins of the Baltic Proper: Arkona Basin (AB), Bornholm Basin (BB), Gdańsk Basin (GdB), Eastern Gotland Basin (EGB), Western Gotland Basin (WGB), Northern Gotland Basin (NGB) and Słupsk Furrow (SF).

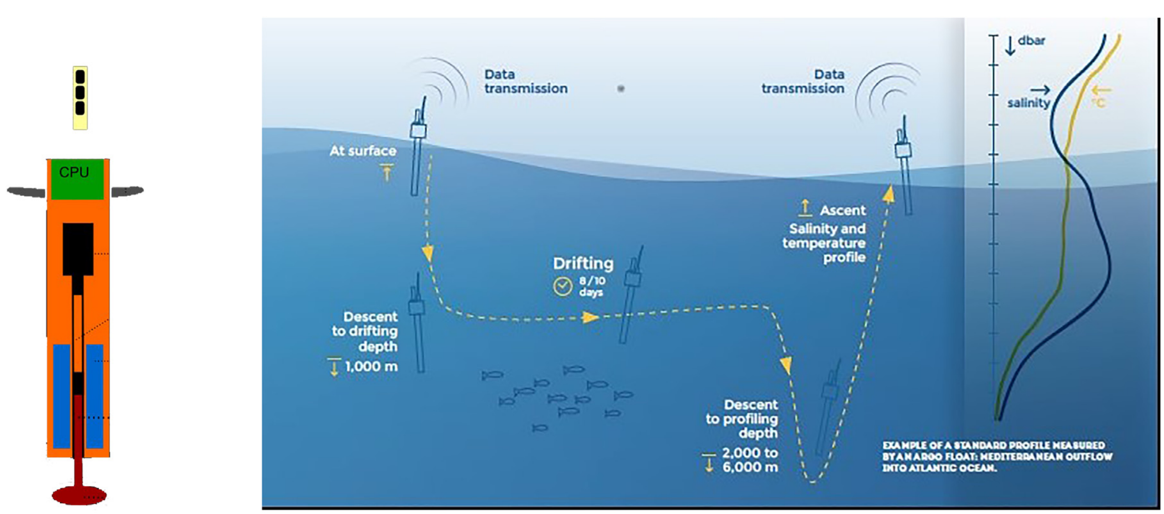
because we are going through a second, Argo revolution in the Baltic Sea. Just a few years ago, the thinking was that this deep-ocean technology was unsuitable for use in the small, shallow Baltic Sea. But in fact, Argo floats work well here and provide valuable data that should be used in Baltic Sea monitoring and forecasting systems, as well as in comprehensive analyses of the state of the Baltic Sea. Finnish oceanographers have shown that Argo data are very useful for monitoring and hydrographic analyses in the Bothnian Sea (Haavisto et al., 2018; Roiha et al., 2018) and Gotland Basin (Siiriä et al., 2019). Data obtained by the Institute of Oceanology Polish Academy of Sciences during the three years of Argo Poland activity in the Baltic Sea are presented. Our intention is not to carry out a thorough analysis of all the data, rather familiarize the reader with the operation of the Argo system, to describe southern Baltic Argo data, to highlight their value, usefulness and potential, and to encourage their utilization. Looking for and collaborating with end-user communities in order to improve the utilization of Argo data is an important aspect of the Argo programme.

2. Argo technology and data

Argo floats were developed for oceanic measurements. The most commonly-used Argo float type (Core Argo) is a small, autonomous underwater platform that measures the temperature and conductivity of seawater vs pressure. The maximum profiling depth is 2000 m. The float is about 1.60 m tall, weighs 20 kg, and has neutral buoyancy in the water. The sensors and antenna of the satellite data transmission system are located in the upper part of the float (Fig. 3 a). It does not have its own propulsion but drifts freely in the sea. Depth changes are enforced by altering the float's buoyancy: this is done by pumping the oil from the inside of the float into the outer rubber bladder or sucking it back inside.

The typical deep-ocean work cycle of such a float is shown in Fig. 3 b. Floats are programmed to dive to a 'parking depth' of 1000 m and to drift for approximately nine days. They then descend to the profiling depth of 2000 m for Core Argo and 6000 m for Deep Argo. Temperature, conductivity, pressure and other water properties are recorded during the drift and ascent (six to sixteen hours). Once back at the surface, the float transmits data via satellite in near-real-time. The rapid transmission of observational data to data centres enhances the usefulness of Argo floats for numerical ocean forecasts. The large amount of data collected and good ocean coverage has made Argo floats an invaluable source of information about changes in ocean heat content, and the surfacing positions provide information on ocean dynamics.

Older devices used the Argos one-way satellite transmission system. The progress that has taken place in the construction of Argo profilers over the past 20 years is best demonstrated by the fact that with the first Argo, 12 hours were needed to transmit the data set from one cycle; now



a) b)

Figure 3 Argo float scheme (left) and deep ocean cycle (right).

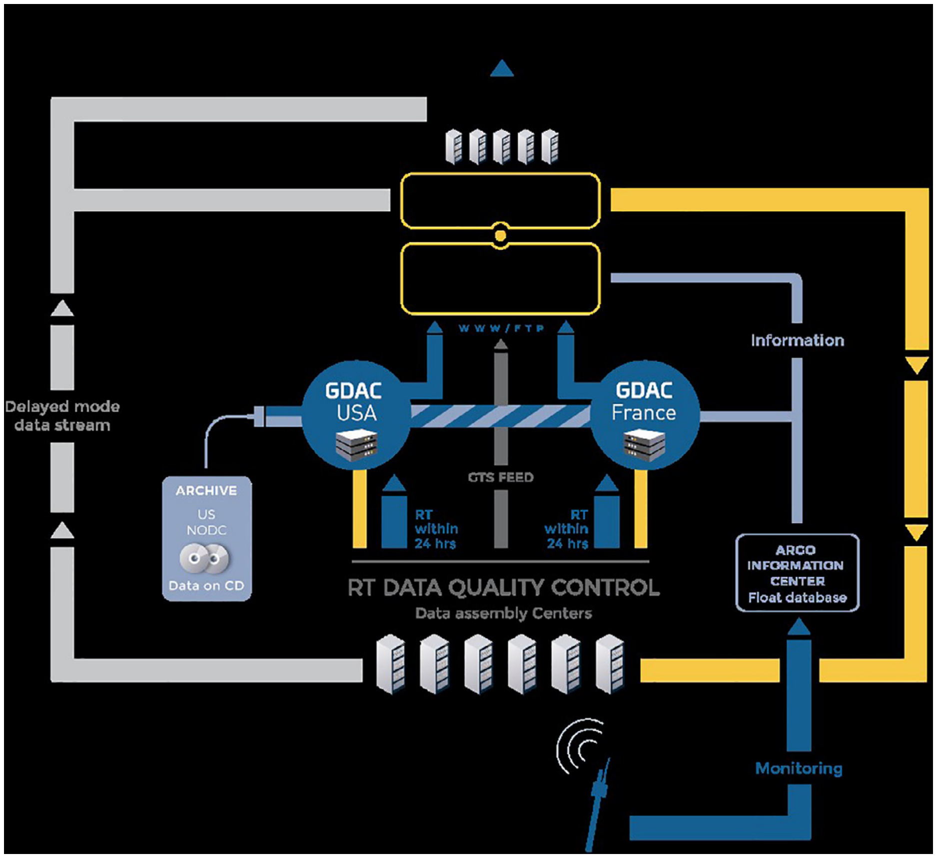


Figure 4 Argo data management system. The pathways of Argo near-real-time and delayed-mode data are illustrated. (Copyright: by courtesy of Euro-Argo ERIC).

this can be done in 20 minutes. The majority of modern floats use the two-way transmission Iridium or Argos system; such floats can work up to 4 years with 10-day cycles. The bidirectional transmission allows float settings to be altered during the mission. A float's operating time depends on its battery capacity and the stability of its sensors; once the battery runs out, the float sinks. This sometimes raises doubts and questions about the environmental legitimacy of such a procedure. Unfortunately, the recovery of spent floats from the ocean is still unprofitable and at present environmentally unjustified. The amounts of fuel consumed and CO_2 emitted by the vessel recovering the float would be incomparably greater than the economic and environmental gains resulting from its recovery.

Each Argo float has a unique World Meteorological Organization (WMO) number, such as are allocated to ocean platforms reporting in the Global Telecommunications System (GTS). When float surfaces, data are transmitted within 12 hours to Data Assembly Centres (DACs), where they are submitted to preliminary control using an agreed set of real-time quality control tests, where uncorrected data are flagged. The data are then transmitted to the Global Data Assembly Centres (GDACs) in Brest, France and Monterey, California (Fig. 4), where the freely available data can be obtained from the Internet within 24 hours of transmission. Within one year of data being collected, these are subjected to delayed-mode quality control via GDACs. All this work is coordinated by the Argo Data Management Team (ADMT).

3. Argo-Poland project

The Institute of Oceanology of the Polish Academy of Sciences, being the only scientific institution in Poland carrying out systematic research in the deep ocean, was designated by the Ministry of Sciences and Higher Education (MNiSW) to be the national representative in the European Argo programme. IO PAN has been participating in this programme since 2009. In 2014, the Euro-Argo European Research Infrastructure Consortium (ERIC) was established with the aim of maintaining one-quarter of the international Argo network. Poland joined the consortium as an observer. Initially, Euro-Argo interests were focused mainly on the Atlantic Ocean, the Nordic Seas and the Mediterranean Sea. Also, the initial deployments by IO PAN were made in the Nordic Seas during Arctic expeditions of its research vessel r/v *Oceania*, organized within the framework of the long-term AREX research program. However, the experience of Finnish oceanographers has shown that it is possible to operate Argo floats even in the shallow Baltic Sea; they began their activity on the Baltic Sea in 2011. That is why Polish and Finnish oceanographers have jointly expanded Euro-Argo's interests to include marginal seas such as the Baltic and the Black Sea (Euro-Argo ERIC, 2017). The recommendation for the Baltic Sea is to keep seven floats active at all times, deployed within its several basins. Float recovery is planned, with redeployment after maintenance and calibration.

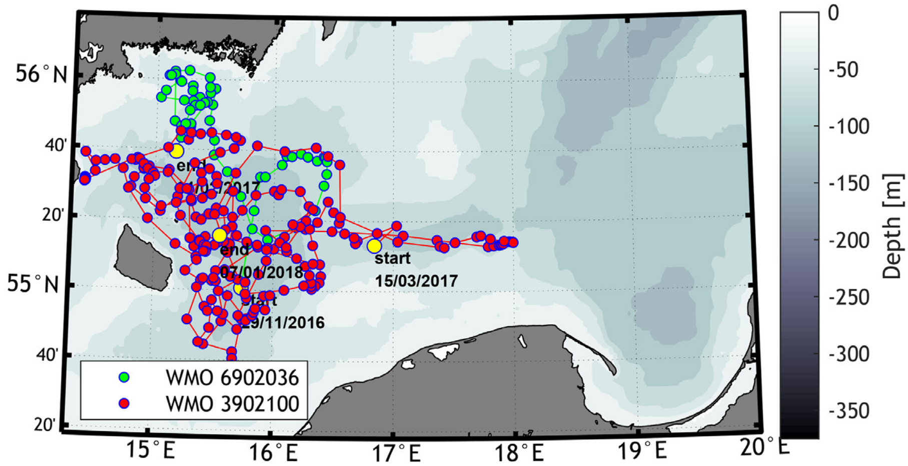


Figure 5 Pathways of the first Polish Argo float in the Baltic Sea during two deployments, as WMO 6902036 and WMO 6902100.

IO PAN, the Polish representative in the Euro-Argo ERIC and Global Argo organizations, provides data from Polish floats to GDACs and participates in the data validation. All the data are available on the webpages of GDACs and the IO PAN Argo-Poland project.

4. Float deployments in the Baltic Sea

Because of its specific properties, the Baltic Sea sets somewhat different requirements for Argo floats than the deep ocean. The Baltic is a small, shallow, semi-enclosed body of water. The structure of the water column is characterized by a strong permanent pycnocline, a separation zone between local, brackish surface waters and more saline waters originating from the North Sea. The vertical density gradient between the surface and deep waters is much larger in the Baltic Sea than the typical gradient for oceanic waters. This applies mainly to the deeps of the southern and central Baltic, and to a lesser extent to the Gulfs of Bothnia and Finland. In addition, ship traffic in the Baltic Sea is heavy and its waters are intensively exploited for fish.

In 2011, the first floats in the Baltic Sea were deployed by Finnish oceanographers (Purokoski et al., 2013). They used the most popular APEX floats produced by Webb (USA). The first Polish float was deployed in the Baltic Sea on 21 November 2016. This was also an APEX float, ballasted in accordance with the southern Baltic Sea water density. It was an experimental mission, aimed at testing the float in southern Baltic Sea conditions and training the issuing of commands for remotely controlling the float settings. In addition, the possibilities of indirectly controlling float drift were tested by altering the 'parking depth' or forcing the float to stay at the surface. The course of this first mission (WMO 6902036) was dramatic, coinciding as it did with the passage of hurricane 'Barbara' across the Baltic Sea region. The wind strength reached 11° B. During this time the float got very close to the Swedish coast (Fig. 5), entering shallow waters. Ongoing weather forecasts and the results from a numerical model working in real-time at IO PAN were used to adjust the float's settings, enabling it to drift away from the shore. The float survived, transmitting data on a daily basis and was recovered during a cruise of r/v *Oceania* in January 2017.

This first mission yielded 56 CTD profiles and provided valuable experience regarding the behaviour of Argo floats in the Baltic Sea in general and the APEX float in particular. But even so, the mission met with limited success: the strong pycnocline prevented the float from reaching the sea bed, 'false grounding' occurred during every descent, the float stopped at a maximum depth of 60 m, and the float's small bladder capacity made it incapable of adjusting its buoyancy to the southern Baltic deep's steep vertical density gradients.

The procedure to recover the float was also a valuable experience. Following the practice of our Finnish colleagues, we decided to re-use Baltic Argo floats many times. Unlike the deep ocean, the small dimensions of the Baltic Sea make float recovery cost-effective. Additional advantages for IO PAN are the numerous cruises of r/v *Oceania*, during which floats can be recovered and re-launched. Only the weather can hamper this practice. Strong winds and high waves make it hard to pick out the float: as it drifts across the water surface, only its antenna and a small part of the sensors protrude from the water surface.

The recovered float from the first mission (WMO 6902036) was redeployed as WMO 3902100 during the *r/v Oceania* cruise in March 2017. It worked for almost a year until January 2018, data transmission ceasing a week before its planned recovery. In both missions, this APEX float produced 280 profiles, providing valuable data on the hydrography of the upper layer and the pycnocline of the Bornholm Basin. Interestingly, this float was trawled by an Estonian fishing boat near Władysławowo in the summer of 2019.

In 2017, in cooperation with Euro-Argo ERIC, two floats belonging to the Monitoring the Ocean Climate Change with Argo (MOCCA) project were tested in the Polish EEZ. They were ARVOR-type floats made by the French company NKE. In comparison with APEX, this kind of float has a larger hydraulic bladder capacity (800 ml), which offers a wider range of float buoyancy changes and better chances of crossing the pycnocline. The floats were adapted to the Baltic Sea's water density by removing 250 g of ballast from the hull. The first ARVOR float was launched in the Gdańsk

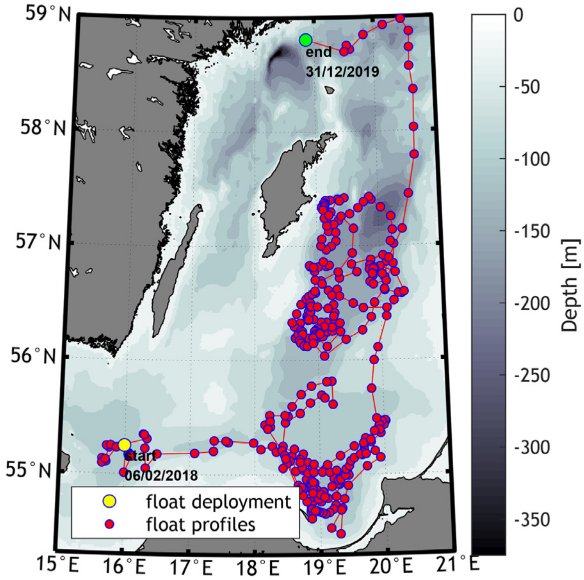


Figure 6 Pathways of the first Polish Argo Arvor float in the Baltic Sea, WMO 3902101.

Deep in September 2017, but after a few days, because it was approaching dangerously close to the shore, float WMO 3901940 was recovered by r/v *Oceania*. It was redeployed in November 2017 as WMO 3902133. The second MOCCA project float was deployed in September 2017 with the WMO number 3901941. This one was recovered by r/v *Oceania* in summer 2019 after having performed the impressive number of 382 profiles. It was subsequently sent to the manufacturer for maintenance, sensor calibration and battery exchange. This opened a new era of re-usable ARVOR floats.

In the initial phase of the floats' activity, experiments were performed to improve their operation. Various grounding algorithms, drifting depths and communication procedures were tested. Increasing parking depth accuracy improved float behaviour during the drifting phase, changing the grounding strategy and allowing touching bottom eliminated the 'false bottom' effect. Optimization of float settings meant that the devices were now able to reach the sea bed, where water with salinity higher than 17 was observed; previously tested APEX floats were able to reach depth occupied by water with salinity up to 12. Such profiling is particularly important for investigating water inflows from the North Sea and deep-water properties. The profiling period was also changed during float missions. Initially, profiling was daily, but ultimately we settled on a two-day profiling period in most missions. The usual parking (drifting) depth was 50 m.

As a result of the invaluable experience gained with ARVOR in the Baltic Sea, IO PAN decided to purchase such devices for the needs of the Argo-Poland project. With funds from the Ministry of Science and Higher Education, we acquired two floats with additional dissolved oxygen (DO) concentration sensors, as monitoring dissolved oxygen dynamics is very important from the point of view of Baltic Sea ecology. Floats with DO sensors belong to the Biogeochemical (BGC) float class. The first Polish ARVOR BGC float (WMO 3902101) was deployed in the Bornholm Basin in February 2018 (Fig. 6), operating in a two-day cycle. During two months, it drifted from the Bornholm Basin to the Gdańsk Deep. The transit through the Słupsk Furrow, the main pathway of eastward deep-water advection, took 20 days. On the fastest section between profiles 29 and 30, the mean drift speed was higher than 20 cm s^{-1}, which was much faster than mean drift speed in the Bornholm Basin. The float remained in the Gdańsk Deep until January 2019, performing 130 dives, after which it drifted away to the Gotland Deep. In this case, too, the transit between deeps was fast, with mean velocities between profiles of up to 18 cm s^{-1}. In December 2019 the float was still operational, having performed 350 dives up to that moment.

The second Polish ARVOR BGC float (WMO 3902104) was deployed in the Bornholm Basin in May 2018. For three months it drifted eastwards (Fig. 7). In September 2018 it was recovered and redeployed back in the Bornholm Basin. As before, this operation required a change of WMO number, so that after redeployment the float was renumbered WMO 3902106. Most of the time, it remained in the Bornholm Basin, but in June 2019 it began drifting eastwards (Fig. 7).

During a three-year period (November 2016—December 2019), the Argo floats deployed by IO PAN in the southern

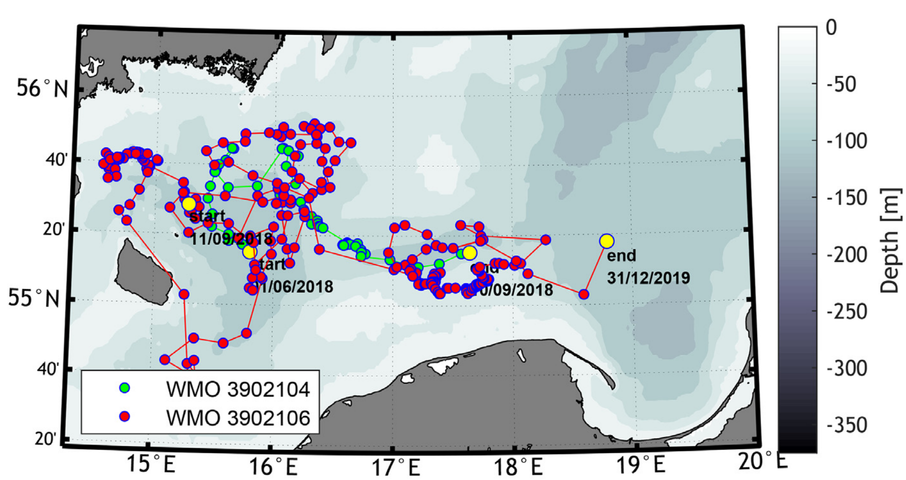


Figure 7 Pathways of the ARVOR float WMO 3902104, and after redeployment WMO 3902106.

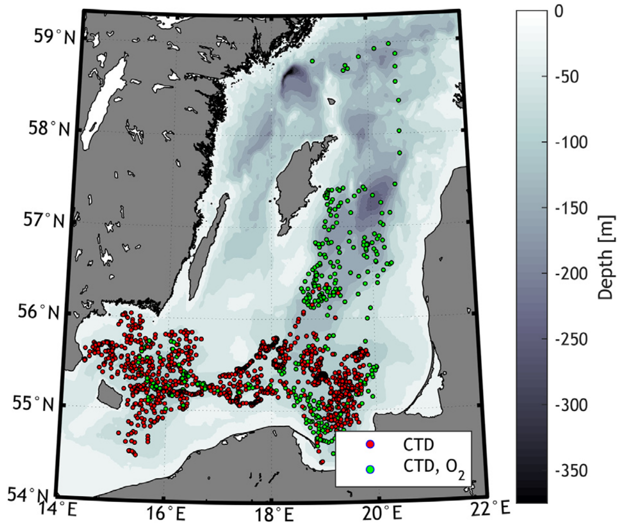


Figure 8 Positions of IOPAN Argo float profiles in the Baltic Sea between November 2016 and December 2019.

Baltic performed 1600 CTD profiles (including 600 of DO). The measurements covered the Bornholm Basin, Słupsk Furrow, Gdańsk Deep and Gotland Basin (Fig. 8). Most of the time, the floats remained in deep regions, only occasionally drifting into shallow water or coming dangerously close to the shore. The mean drift speed did not exceed 8 cm s^{-1}, but during the transition between deeps, maximum speeds, calculated as the mean speed along a straight line between profiles, were in excess of 20 cm s^{-1}. Although eastward movements were prevalent, some westward drift was observed even in the Słupsk Furrow. As they drifted, the floats moved in loops: the radius of the smallest of these loops was of the order of 4 km, which is close to the baroclinic Rossby deformation radius for the Baltic Sea basins in question (5—7 km) (Osiński et al., 2010). The direction of circulation was both cyclonic and anticyclonic.

5. Importance of Argo data

The balance of oxygen dissolved in the Baltic seawater column is different for the surface and deep layers. Mixing of these two water masses is restricted by the halocline/pycnocline barrier. The primary source of oxygen in the upper layer is the atmosphere, whereas in the deep layer it is oxygen-rich water flowing in through the Danish Straits. The west-to-east advection of North Sea water provides this life-giving element to Baltic deep waters, which suffer from hypoxia ($O_2 < 2$ ml l^{-1} or ~90 μmol kg^{-1}) and even anoxia (no oxygen at all). Owing to the strong stratification of the water column, the layers below the permanent pycnocline cannot be efficiently ventilated by convection, so the oxygen dynamics depends mainly on lateral advection.

The significant reduction in Major Baltic Inflows recorded in the early 1980s led to a decline in deep-water renewal (Fischer and Matthäus, 1996). In recent decades, too, the frequency of these large, barotropic inflows has dropped. On the other hand, Mohrholz (2018) showed that MBI frequency does not display a consistent trend. Other studies indicate that smaller baroclinic inflows may be playing a greater role than previously thought in the oxygenation of the southern Baltic deeps (Meier et al., 2006). Even so, the Baltic Sea is one of the largest dead zones in the world (Conley et al., 2009; Diaz and Rosenberg, 2008). Worse still, the zones of hypoxia and anoxia are expanding in all parts of the Baltic Sea. Despite the MBI in 2014, approximately 16% of the bottom area was affected by anoxia and 29% by hypoxia in 2015 (Hansson and Andersson, 2015). Oxygen in deep waters is consumed mostly during the decomposition of organic matter sinking from the surface layer, where it

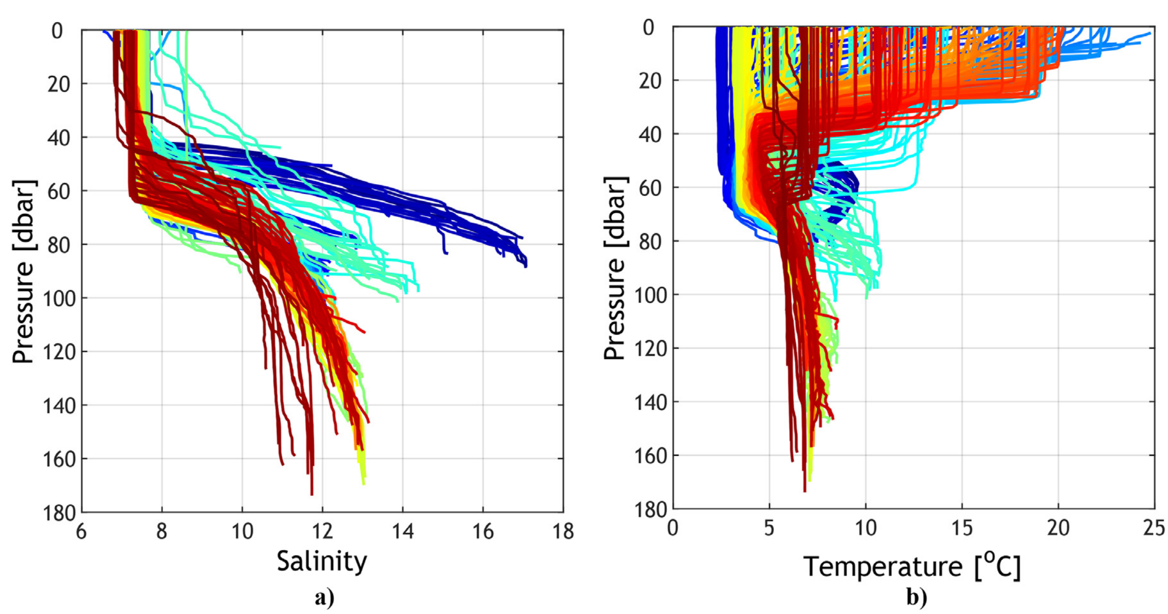


Figure 9 Salinity and temperature profiles recorded by float WMO 9202101 (February 2018—December 2019). The colour scale indicates the time of measurements, as in Fig. 10.

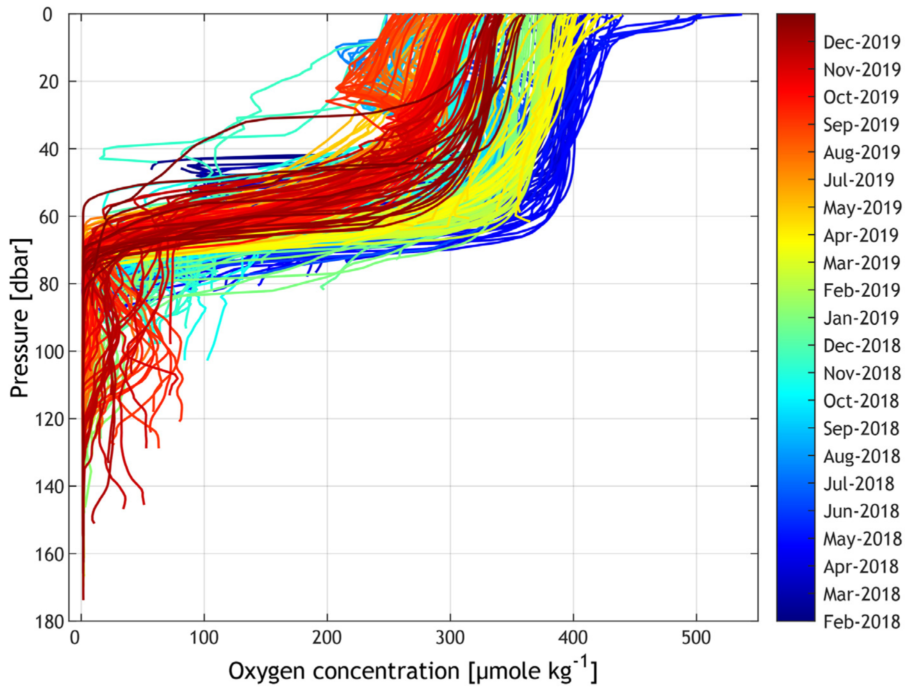


Figure 10 Dissolved oxygen concentration profiles recorded by float WMO 9202101 (February 2018—December 2019).

is produced (Stigebrandt, 2017). In the long term, the consumption of oxygen is greater than its supply, so it becomes depleted and is replaced by toxic hydrogen sulphide in the near-bottom layer (Stigebrandt et al., 2015).

In light of these facts, the monitoring of inflows is clearly a matter of urgency. Deep-water dynamics and variability of dissolved oxygen concentrations are crucial phenomena in the Baltic Sea and heavily dependent on the advection of water from the North Sea. In the western Baltic, data on inflows are gathered by permanent MARNET stations, moored in the Danish Straits (Darss Sill) and the Arkona Basin (Mohrholz et al., 2015). Data from these stations are transmitted in real-time. Unfortunately, there are no real-time data from the Polish EEZ. The measurements currently being made by IO PAN are sufficient for investigating the seasonal and long-term variability of southern Baltic water masses (Rak and Wieczorek, 2012) and for monitoring MBIs (Piechura and Beszczyńska-Möller, 2004; Rak, 2016), but not for analysing or even detecting baroclinic inflows. Also, low-resolution models are incapable of analysing these phenomena (Meier et al., 2006). To improve inflow monitoring, more measurements are needed, especially since a large proportion of the water exchange takes place during smaller barotropic and baroclinic inflows, which are more difficult to detect. That is why extensive and frequent measurements of dissolved oxygen concentrations in parallel with temperature and salinity are particularly important in the Baltic Sea.

Argo floats make such measurements possible. Unlike the 10-day measurement period of deep-ocean Argo floats, the IO PAN Baltic Sea floats usually operate in one- or two-day measurement cycles. The water is shallow, so profiling times are short, with a better spatial resolution of measurements. Within a relatively short time, CTD/O_2 floats collected data showing a range of hypoxic/anoxic zones in the Bornholm Basin, Gdańsk and Gotland Deeps, baroclinic inflows of better-oxygenated water in winter 2018 and summer—autumn 2019, the seasonal cycle of oxygen in the upper layer of the water column, and the oxycline dynamics. All the data were made available online in NRT. This provides an additional opportunity to send research vessels to certain regions, where process-oriented studies can then be carried out.

6. Selected results

The study below demonstrates the opportunities offered by Argo observations for diagnosing the dynamics of dissolved oxygen in the southern Baltic.

The profiles of properties from the whole measurement period (Fig. 9) show a seasonal variability of temperature in the upper layer as well as spatial variability of salinity in the deeper layers in various regions of the southern Baltic. Near-bottom salinity was the highest (up to 17) in the Bornholm Basin (blue lines), lower in the Gdańsk Deep, and the lowest in the Gotland Deep (red lines). The DO profiles (Fig. 10) show well-oxygenated surface waters, a strong oxycline and anoxic waters in the Gdańsk and Gotland Deeps. The temporal increase of DO in August—September at the 100 m level indicates a weak baroclinic inflow to the Gdańsk and Gotland Deeps.

The time series constructed from the raw data demonstrate the considerable seasonality of temperature (Fig. 11a) and DO concentration (Fig. 11b) in the upper layer (0—40 m) and the lack of seasonality in the deep layer (Fig. 11d). In upper layer DO is negatively correlated with water temperature. Both patterns of temperature

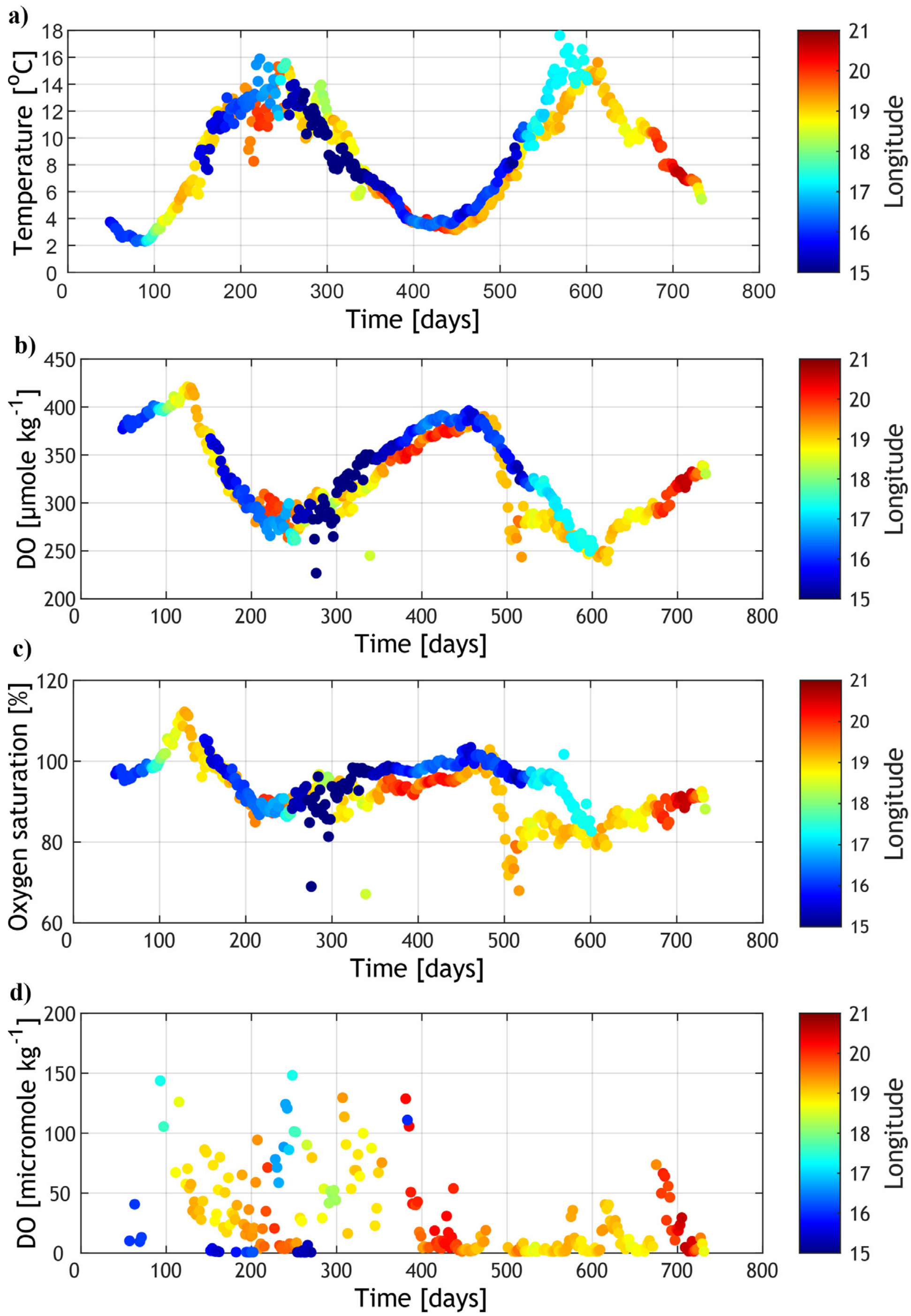


Figure 11 Time series of mean temperature for the 0—40 m layer (a), dissolved oxygen concentration for the 0—40 m layer (b), oxygen saturation [%] for the 0—40 m layer (c) and dissolved oxygen concentration for the 70—90 m layer (d) recorded by floats WMO 9202101, WMO9202104 and WMO9202106 from February 2018 to December 2019. The colour scale indicates the longitudes of the measurements. The time axes begin on 1 January 2018.

and DO are similar in the western and eastern parts of the investigated area. The time series of oxygen saturation O_{2sat} (Fig. 11c) reveal supersaturation of the Gdańsk Basin surface waters in mid-May 2018 and in May—June 2019 and region of low surface waters saturation east of Gotland. Seasonality of surface waters layer saturation is not so pronounced as in the case of DO. Pronounced shift between minimum temperature and maximum saturation and high level of saturation in spring 2018 show that oxygen delivery related to primary production in photosynthetic zone plays an important role in the surface waters oxygen budget.

Calculated seasonal distribution of the oxygen concentration in the upper layer shows the highest DO concentration in April and the lowest in the August—September period

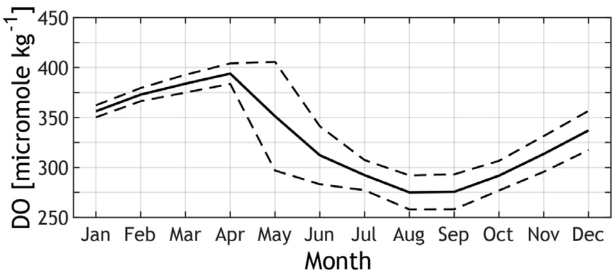


Figure 12 Seasonal distributions of mean dissolved oxygen concentration in the 0—40 m layer as recorded by floats WMO 9202101, WMO9202104 and WMO9202106 from February 2018 to December 2019. The standard deviation of the data is indicated.

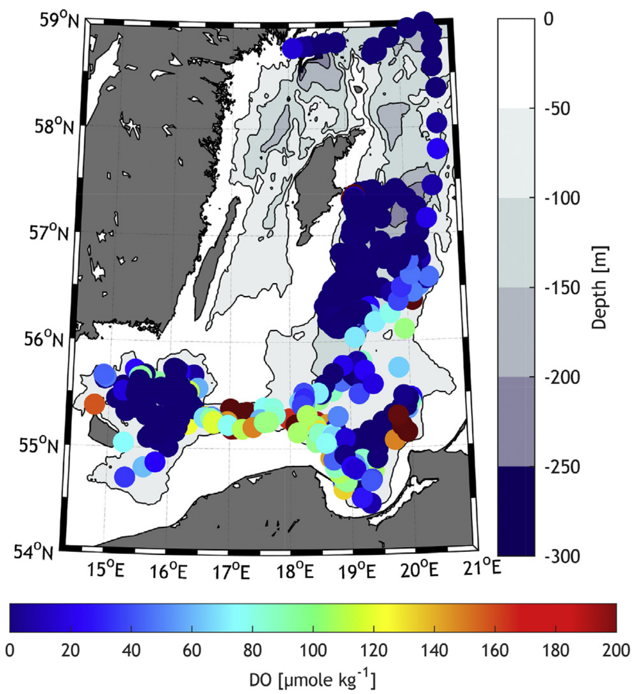


Figure 13 Near-bottom dissolved oxygen concentration. Data for regions deeper than 60 m.

(Fig. 12). High standard deviation in May arise from various dynamics of processes in springs 2018 and 2019 and the occurrence of low DO region east of Gotland in May 2019.

The absence of seasonal variability in DO in the deeper layers means that all the data can be used for investigating the bottom-layer oxygen content (Fig. 13). The deeper parts of the Bornholm Basin, Gdańsk and Gotland Deeps are mostly affected by hypoxia and anoxia. Other phenomena are discernible, like the previously mentioned small inflow reaching the Gotland Basin, and the advection pathways of oxygen-rich water. The sequence of salinity and DO rising was observed in summer—autumn 2019: at the end of June 2019 the water with extraordinary high salinity (12.8—13.9) and DO concentration (85—135 μmole kg^{-1}) in near-bottom layer (80 m depth) was observed in the central part of Słupsk Furrow at longitude 17.2°—17.4°N by float 3902106, at the beginning of September 2019 increasing of dissolved oxygen concentration in level 80—120 m was observed in the eastern Gotland Basin by the float 3902101. At 100 m depth DO concentration raised from 1 to 80 μmole kg^{-1} (Fig. 10). Another increasing of DO level and salinity (100 μmole kg^{-1} at 100 m) was noticed in Gdańsk Deep in November—December 2018.

7. Conclusions

In open-ocean oceanography, the importance of autonomous devices in measurements is increasing. Argo floats are a reliable and cheap source of oceanographic real-time data, and the global Argo array is well-organized and maintained. As a result of the coordinated work of the countries involved in global Argo, the data are freely available in the Coriolis Service. The Euro-Argo ERIC is an important part of this system, and a big advantage of Euro-Argo is that it covers the shelf seas.

The possibility of using Argo floats as part of a comprehensive southern Baltic monitoring system was postulated by Walczowski et al. (2017). Various sources of data, such as Argo floats, cruises and moorings can provide extensive, complementary data for the better monitoring of the Baltic Sea, the improvement of numerical models and validation of satellite observations.

Our three-years' experience with Argo floats in the Baltic Sea, in conjunction with the even longer work of Finnish oceanographers, shows that shallow shelf seas can also be explored with these floats. Contact with the sea bed (grounding), proximity to the shore and collisions with ships are not as dangerous for the float as had seemed earlier. In small seas like the Baltic, floats — mostly the sophisticated and expensive BGC floats — can be profitably recovered, refurbished and redeployed. The numbers and importance of BGC floats in the Baltic Sea are set to increase. Even the use of the simplest BGC float, equipped with just an oxygen sensor, significantly enhances the opportunities for recording important processes and data interpretation. According to Euro-Argo's preliminary estimates, seven continuously working floats should be adequate for the basic monitoring of Baltic deep waters, although their recovery, redeployment and relocation may be necessary. Additional sensors and the implementation of full BGC floats raises the value of the data. The competent, meaningful use of all the data requires the cooperation of multidisciplinary teams of scientists and technicians on the one hand and countries on the other. Despite some initial teething troubles, there is no doubt that the second, Argo revolution in oceanography has arrived in the Baltic Sea.

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