A European strategy plan with regard to the Argo extension in WBC and other boundary regions

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Version	Issue Date	Author	Comments
0.1	Oct. 14, 2020	Guillaume Maze	Document creation, first draft and layout of the plan to be discussed with partners (BSH, SOCIB, IPMA)
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0.3	Dec. 19, 2020	Guillaume Maze	Version submitted to the project coordination

EXECUTIVE SUMMARY

The task 2.3 of the WP2 EARISE package has an overarching goal to improve how Argo floats and data are used to study Ocean Boundary Currents (BC).

This deliverable is one component of the strategy toward this goal: to develop an Euro-Argo roadmap with regard to BCs. The other component of the task 2.3 strategy is related to using machine learning to improve Argo synergie with other observing systems in ocean state estimates.

The participants to task 2.3 identified boundary systems of interest and covered by this deliverable:

- the Gulf Stream (IFREMER),
- the West Spitsbergen Current and East Greenland Current (BSH, IOPAN),
- the BCs in the Western Mediterranean region (SOCIB, SU)
- and the Gulf of Cadiz Current (IPMA)

First we present the scientific rationales for observing these BC systems. Primarily because of their frontal intrinsic structure, BCs are associated with key scientific questions dealing with air-sea and open vs coastal interactions, with profound impact on other components of the climate system (the atmosphere or seaboard areas). This key ingredient, i.e. being a frontal structure, is also the origin of a large turbulent activity, which limits (i) the ability of Argo floats to remain in a BC regions and (ii) the representativity of Argo profiles in this realm of strong eddy field. Hence the need for a dedicated EA strategy with regard to BCs.

Second, a detailed analysis of the historical Argo sampling of these BCs is provided. This analysis is characterised by a very large range of Argo floats configuration parameters as well as very heterogeneous sampling density. Some regions like the Gulf Stream have been fairly well sampled (compared to the core Argo target), while others very poorly, like the Balearic Current and Gulf of Cadiz. It is noted that no specific configuration parameters are being used systematically to optimise observation of the frontal structure and its eddy field.

Last, we provide a first version for a European strategy plan with regard to the Argo extension in WBC and other boundary regions. This initial text lays out, for each BCs, the key European needs, existing capacities and current knowledge about what would be required, as well as the technological advances, to fulfill these needs. Among all these elements we highlight the need for a better informed strategy of numerical experiments based on a Virtual Fleet software to simulate Argo floats that will lead to determine the most appropriate sampling strategies (deployment plans and configuration parameters) in BCs. An initial version of this software has been released in June 2020. Partners are still developing experiments designs. The present strategy plan will thus be revisited in 2022 to take into account the results of these experiments.

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1 Context

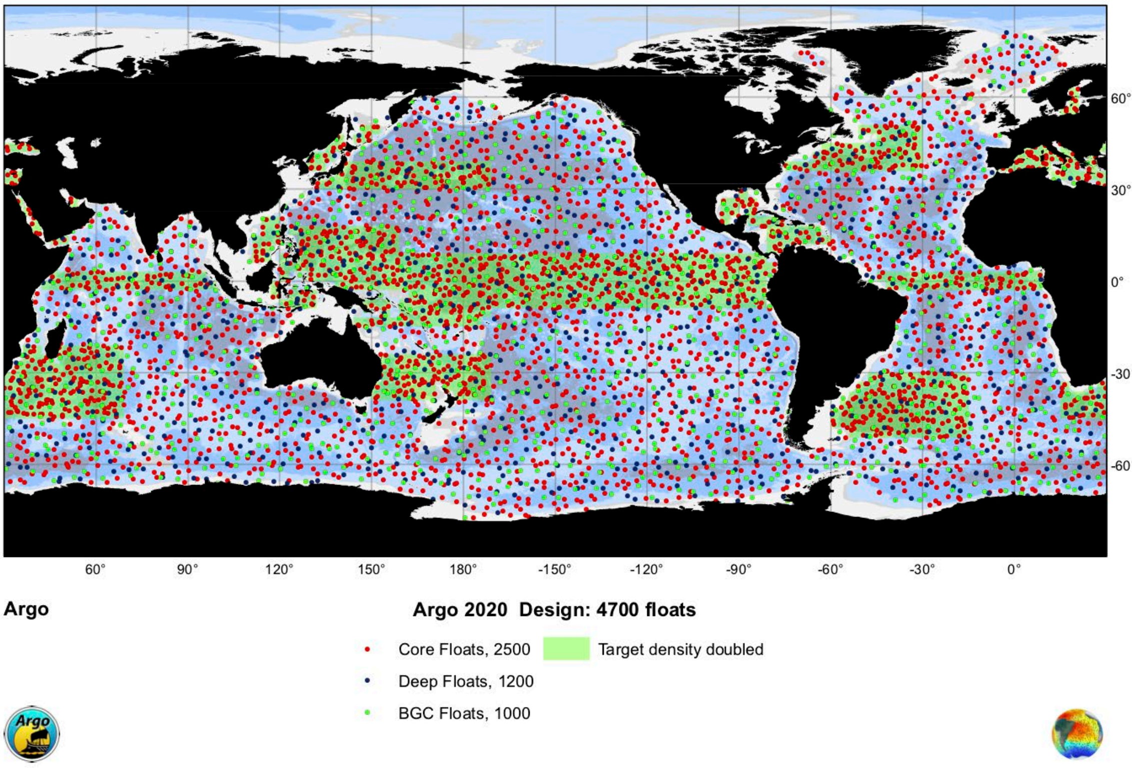

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Figure 1. Current target design of the international Argo observing array. Note the green areas showing regions where a doubled profil density is recommended.

Boundary current (BC) regions are hot spots of the ocean's variability because they host among the strongest currents of all and thus concentrate large signals (e.g. meridional heat transport) into a very turbulent region. At the international level, the Argo community has recognised for a long time the specific need for particular attention to BC. Therefore, the Argo Steering Team (AST) recommends in its design, a doubling of the profiles density in large BC systems, as it is shown in the figure 1 above.

Due to local process studies and strong regional interest by Japan, the Kuroshio/Oyashio system has been a historical pilot region for this coverage enhancement in BC. It has been reported that this increased coverage has a significant impact on ocean state estimates error reduction and is therefore a design to pursue (eg AST-17, AST-18, AST-19, Gasparin et al 2019).

At the European level, no clear interest in large BC systems was manifested before the Euro-Argo RISE project. So, the Euro-Argo (EA) roadmap (10.13155/48526) that addresses all interests of EA members is still missing a section on the EA strategy with regard to BC.

Within Euro-Argo RISE, the WP2 aims at improving the core Argo mission and in the context of task 2.3 to improve knowledge extracted from Argo to better inform on the ocean state in boundary currents. This document is thus a contribution to the elaboration of the EA strategy with regard to BC.

It will first be presented the scientific rationale and motivations for observing BC systems. The list of BC regions of interest to the EA member will be introduced. Then we will provide a detailed analysis of the historical sampling of these BC systems with Argo floats. In the last section of this deliverable we present the first version of the EA roadmap chapter on BC. It is based on the lessons learned from the historical sampling analysis and underlines the requirements for a better informed strategy that will be provided as an update to the EA roadmap at the end of the Euro-Argo RISE project (2022).

2 Scientific rationale

What is a boundary current system and why is it important ?

The ocean is a turbulent and chaotic dynamical system, therefore complex to understand and predict. This is particularly true in the western regions of the mid-latitude oceans, where very large currents narrow to intense fronts, meanders and numerous eddies about 100km wide. These regions are called "western boundary current extensions". Because they are turbulent, these regions are one of the main sources of uncertainty in the assessment of the ocean's role in climate and their behaviour under the influence of global climate change is still poorly known. This is illustrated in the figure 2 below showing the standard error of the 0-2000m ocean heat content time mean estimate from a standard ocean 3Dvar analysis of Argo data. These uncertainties can be reduced if we improve our ability to diagnose the temporal evolution of the three-dimensional structure of the extensions of the western boundary currents.

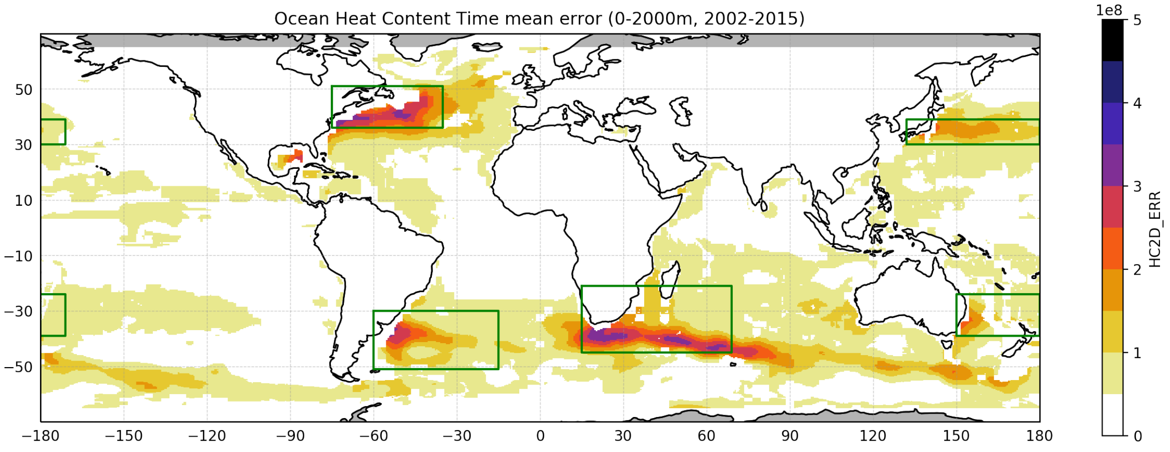


Figure 2. Standard error (J/m^2) on the 0-2000m ocean heat content EOV estimate for the 2002-2015 period, computed from a standard ocean 3Dvar analysis based on Argo data (ISAS15, Kolodziejczyk et al, 2017). All western boundary currents regions are highlighted in green boxes.

A straightforward answer to this high eddy activity driving a lower signal/noise ratio (especially for Argo's target space/time scales) is an enhanced resolution, as was recognised years ago by the AST (eg: AST-17, AST-18, AST-19). However, Argo, and in fact, none of the existing ocean observing systems is not able to provide an accurate time series of three-dimensional eddy scale thermal fields for these western boundary current extensions. For instance, satellite measurements have a high local frequency and precise horizontal resolution, but they capture only the surface signature of the ocean's interior structures. On the other hand, in situ measurements of the interior of the ocean collected by autonomous probes (such as Argo floats) provide a very accurate vertical thermal structure of the ocean, but they are rare and lack horizontal resolution. This is why it is important to recognise here that Argo alone cannot appropriately monitor ocean boundary currents and that the strategy and recommendations devised in this document will be one component of a more integrative approach to ocean observing systems in BC (cf OOPC Task Team on Western Boundary Current).

BC systems are not only located in the western flank of all major oceans. Eastern boundary currents (EBCs) are some of the most biologically productive regions in the world and respond dramatically to climate variability. The four major upwelling ecosystems are located in the EBCs systems of the oceans and include the Canary (SW Europe and NW Africa), the Benguela (SW Africa), the Humboldt (SW America), and the California (NW America) upwelling ecosystems. The main fisheries of the world occur in these regions and they account for more than 20-25% of the total worldwide catches of marine species, while representing only 3-5% of the ocean surface. Mesoscale, and more recently submesoscale activities, have been recognized as key factors for biological productivity. Due to the strong link between biological activity and wind, upwelling areas constitute relevant places to study the impact of global warming on first trophic levels. The Canary Current System (CCS) is separated into two distinct areas (the Iberian coast and the Northwest African coast) with apparently little continuity in the flow between them. This is caused by the split at the Gulf of Cadiz (Strait of Gibraltar), which allows the exchange of water between the Mediterranean Sea and the Atlantic Ocean. The CCS is perhaps the least studied or understood of these Eastern Boundary Upwelling Systems due to the paucity of information from coastal Northwest Africa, especially in the southern part of the Gulf of Cadiz (GoC) but also to the region’s complex topography and circulation.

Boundary systems of interest

Participants to this task identified in Figure 3 below their boundary systems of interest. These are:

- the Gulf Stream (IFREMER),
- the West Spitsbergen Current and East Greenland Current (BSH, IOPAN),
- the BC in the Western Mediterranean region (SOCIB)
- and the Gulf of Cadiz Current (IPMA)

In the following, each partner provides a scientific rationale and presentation of these BC regions.

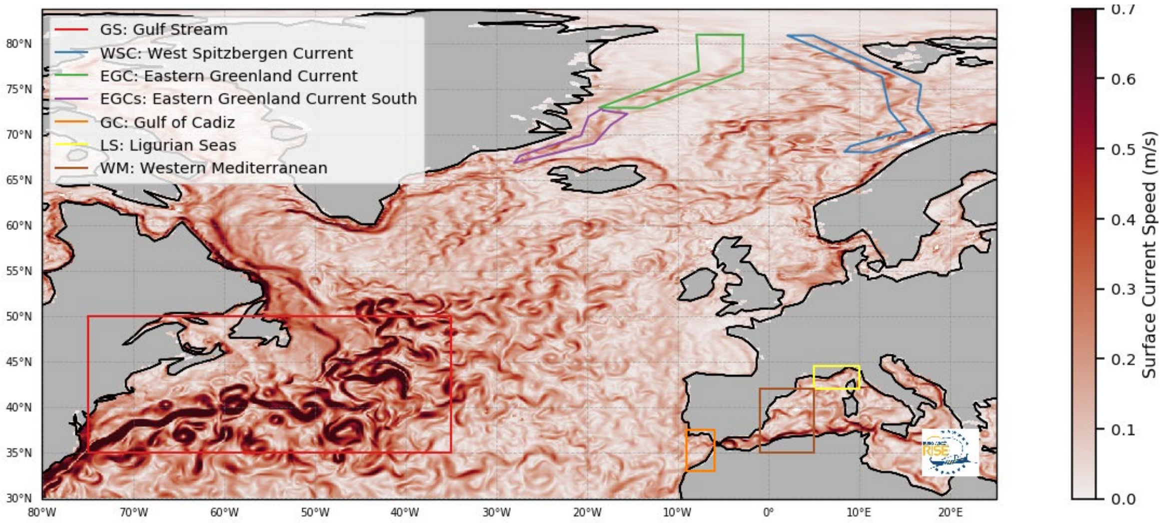


Figure 3. Synthetic map showing on top of the mean altimetry-derived currents all the Boundary Current systems of interest to Euro-Argo RISE WP2.3 partners.

Gulf Stream Extension

The Gulf Stream Extension is one of the strongest Western Boundary Currents in the global ocean. It is part of the wind driven and thermohaline circulations (Gnanadesikan, 1999) of the North Atlantic and plays a critical role in transporting heat poleward. Heat is taken up at low latitudes and released to the atmosphere (Kown et al, 2010) while being transported northward (Ferrari & Ferreira, 2011). In mid-latitudes, it acts as a heat buffer (Kown & Riser, 2004; Kelly & Dong, 2004). These impacts and roles of the Gulf Stream Extension into key climate processes, make this region an essential area to be observed and monitored.

The Gulf Stream Extension (GSE) is characterised by a large eddy activity and thus a strong eddy kinetic energy. Figure 4 below shows the GSE rectangular domain chosen to encompass the EKE maximum band. The box SouthWest corner is at 75W/33N, and NorthEast corner at 48W/45.5N. It extends to the west where the Gulf Stream Path deviates from the coast, to the east to the Mann eddy, which indicates the beginning of the GS northward path inflection toward the North West Corner and then North Atlantic Drift.

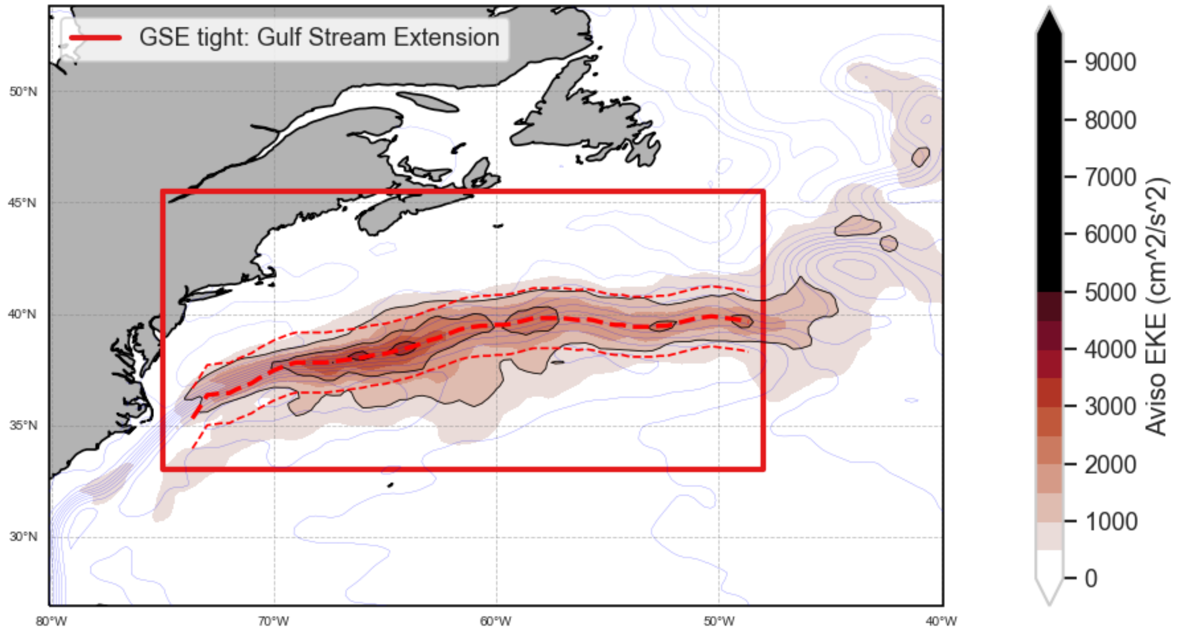


Figure 4. Mean altimetry-derived EKE distribution (red color shading) with mean dynamic topography contours (light blue). The red rectangular box (SW corner: 75W/33N, NE corner: 48W/45.5N) indicates the exact domain used for the historical sampling assessment of the region. The dashed thick red line indicates the mean Gulf Stream position (defined as the maximum mean EKE latitude), the light dashed red contours are the +/- 2 Rossby radius enveloppe (using a typical eddy scale of 75km radius). The total dashed red enveloppe is thus about 300 km wide in latitude.

Western Mediterranean BC

The circulation in the Western Mediterranean Sea (Figure 5) follows a generally cyclonic path around the continental slope (Millot, 1985). A number of distinct boundary currents (BC) are formed, the selection of the bounding box for these BCs takes into account the isobath lines (between 200 m and 1500 m, Figure 6).

The Algerian Current (AC) is formed from the inflow of Atlantic Waters (AWs) emerging from the Alboran Sea, and following the steeply sloping topography of North African coast. Some of this AW is transported northwards from the Algerian sub-basin via many different pathways, eventually joining the return flow coming from the Tyrrhenian Sea (Astraldi & Gasparini, 1992), creating the Northern Current (NC), which then flows along the continental slope in the Ligurian Sea, the Gulf of Lions and the Catalan Sea. Arriving at the Balearic sub-basin and the choke points of the Ibiza and Mallorca Channels, a branch of the NC returns to the north-east along the northern slope of the Balearic Islands forming the Balearic Current (BC) (García-Ladona et al, 1996; Salat, 1995).

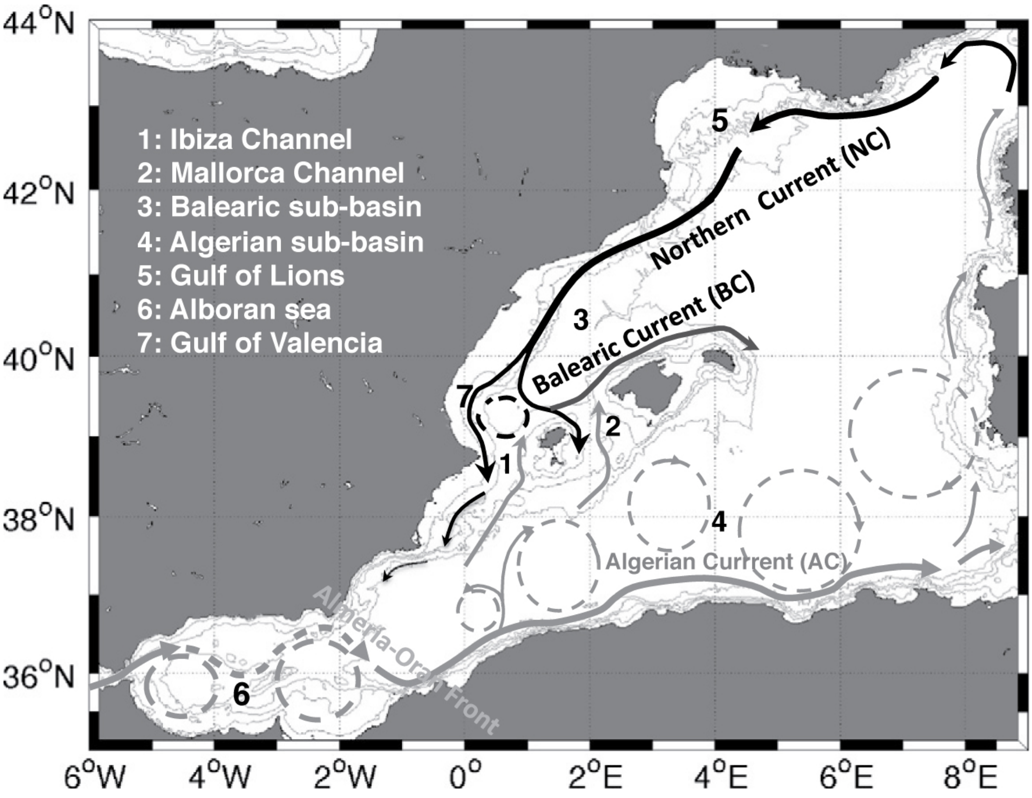


Figure 5. Western Mediterranean circulation (modified from: Balbín et al., 2014). The Mallorca and Ibiza channels are shown. The Northern and Balearic Currents are indicated by black and dark grey arrows (respectively) whilst the Algerian gyres and other variable pathways for recently entering Atlantic waters are indicated by light grey arrows.

The coastal currents display unstable features that evolve into mesoscale eddies. In order to include the meanders and eddy scales, extensions to the bounding boxes for the BCs to take account of the Rossby radius (R_0) are also needed. For the Balearic Sea, the sensible relevant depth scale (H) is approximately 400 m, therefore R_0 is around 15-20 km. For the Algerian current, H is more sensibly 1000-2000m and therefore R_0 is around 30-50 km (Figure 6).

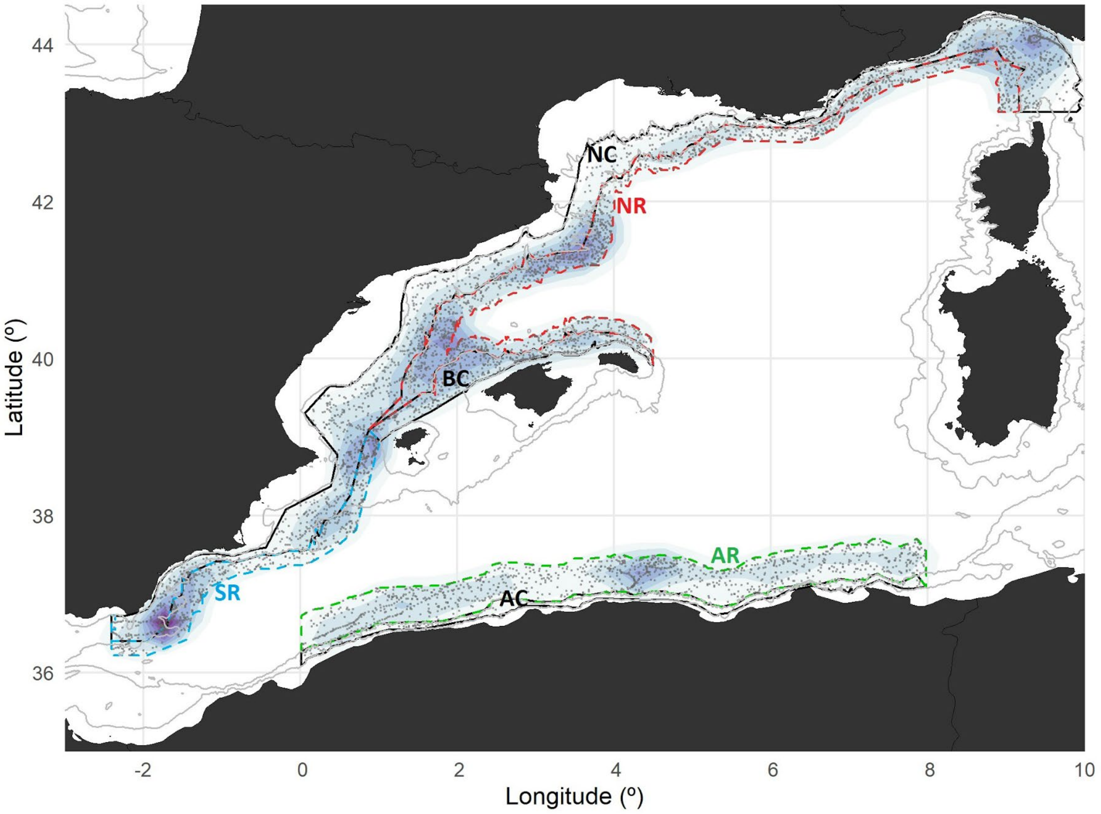


Figure 6. Boundary Currents (defined by solid lines) and associated rossby radius extensions (defined by dashed lines).

Nordic Seas BC

The circulation in the Nordic Seas consists of two distinct components: a boundary current circumnavigating the Nordic Seas (and the Arctic Ocean) (Rudels et al., 1999) and regional cyclonic circulation cells in the interior of the Nordic Seas. The boundary current (Figure 7) follows a cyclonic path around the sub-basins of the Nordic Seas (Latarius and Quadfasel, 2016), it's branches have been named West-Spitzbergen Current (WSC) on the eastern side of the Nordic Seas and East Greenland Current on the western side (EGC). The Fram Strait inbetween is the only deep connection between the Atlantic Ocean and Arctic Ocean and climatic importance of exchange through this gateway is significant. Changes of the Atlantic Water (AW) properties influence the local climate (Walczowski et al., 2012), and ice conditions north of Svalbard (Piechura, Walczowski, 2009). The stratified boundary current and the adjacent shelf areas make up about 20% of the area in the Nordic Seas. As the boundary current enters from the south across the Greenland-Iceland-Scotland Ridge the WSC current carries subtropical warm and saline Atlantic Water (AW) into the Nordic Seas where the AW is transformed through mixing with fresh water and negative buoyancy fluxes. Hydrographic fronts separate the Atlantic-origin waters from ambient waters in the WSC in the two branches (west and east) which are both important for the lateral transport of AW into the interior (Walczowski, 2013). The East Greenland Current (EGC) consists of three distinct components (Havik et al., 2017) . In addition to the well-known shelfbreak branch, there is an inshore branch on the continental shelf as well as a separate branch offshore of the shelfbreak. The inner branch contributes significantly to the overall freshwater transport of the rim current system, and the outer branch recirculates a substantial amount of Atlantic-origin Water equatorward in direct continuation of the western branch of the West Spitsbergen Current.

The heat budget of the upper water column requires lateral input, which balances the net annual heat loss of 80 W/m2. The role of eddies shed by the warm-water boundary currents has emerged as a key factor for the lateral heat flux. Within the Nordic Seas, the role played by the Lofoten basin in the transformation of Atlantic Water (AW) has increasingly been recognized. From an analysis of current meter data in the WSC at Fram Strait Appen et al. (2016) have found an e-folding growth period for baroclinic instabilities of about half a day in winter, indicating that the current has the ability to rapidly grow unstable and form eddies. In summer, the WSC is significantly less unstable with an e-folding growth period of 2 days. Observations of the eddy kinetic energy (EKE) in the areas adjacent to the boundary current (Figure 8) show a peak in eddy kinetic energy in January–February when it is most unstable. Since 1987 annual summer cruises to the Nordic Seas and Fram Strait have been conducted by the IOPAN research vessel Oceania under the long-term monitoring program AREX in the same area (Walczowski et al. 2017) and have shown a steady increase of Atlantic water salinity south of Svalbard (76.5 °N).

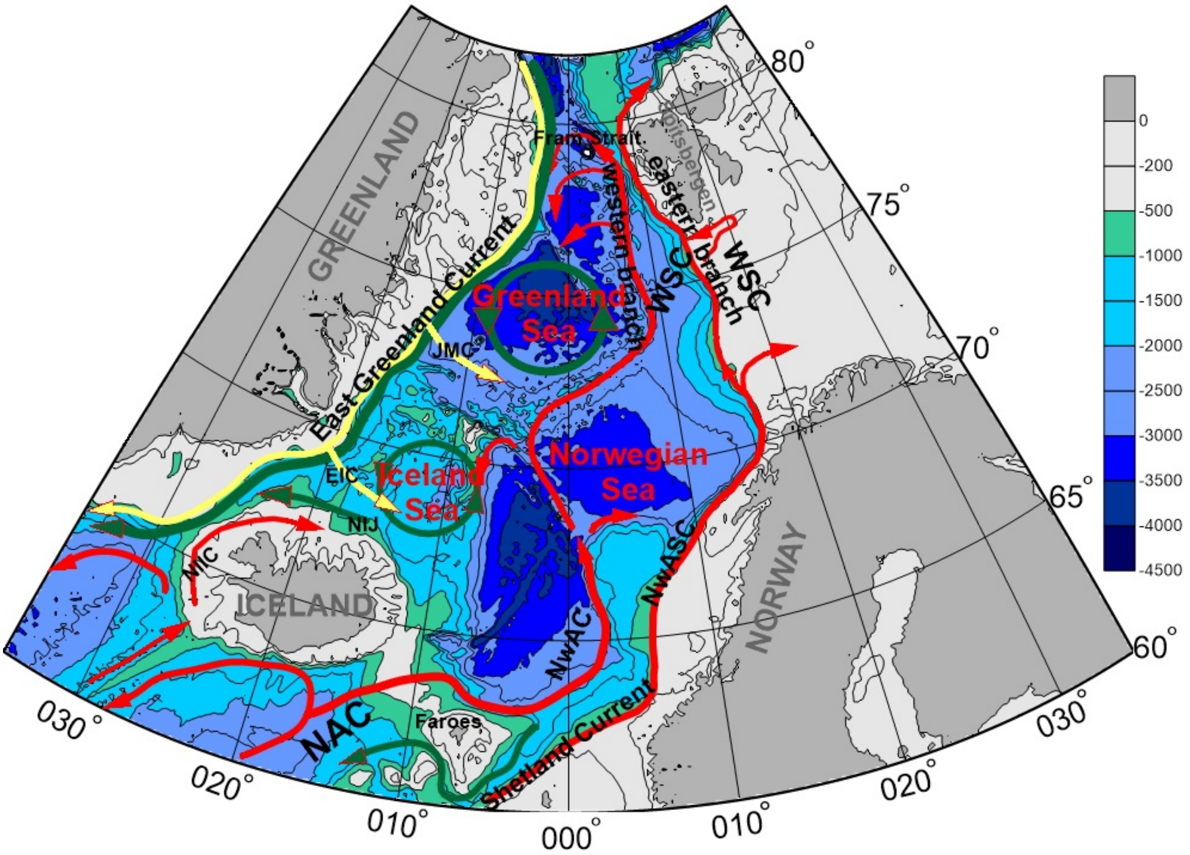


Figure 7. Map of the Nordic Seas with bathymetry and circulation patterns. Red and yellow arrows indicate warm Atlantic Water inflow and cold and fresher outflow, respectively. Green arrows

indicate cold, dense water circulation. The acronyms are the East Icelandic Current (EIC), the Jan Mayen Current (JMC), the North Atlantic Current (NAC), the North Icelandic Irminger Current (NIIC), the North Icelandic Jet (NIJ), the Norwegian Atlantic Current (NwAC), the Norwegian-Atlantic Slope Current (NwASC), and the West Spitsbergen Current (WSC). Circulation scheme in the Nordic Seas from Latarius and Quadfasel (2016).

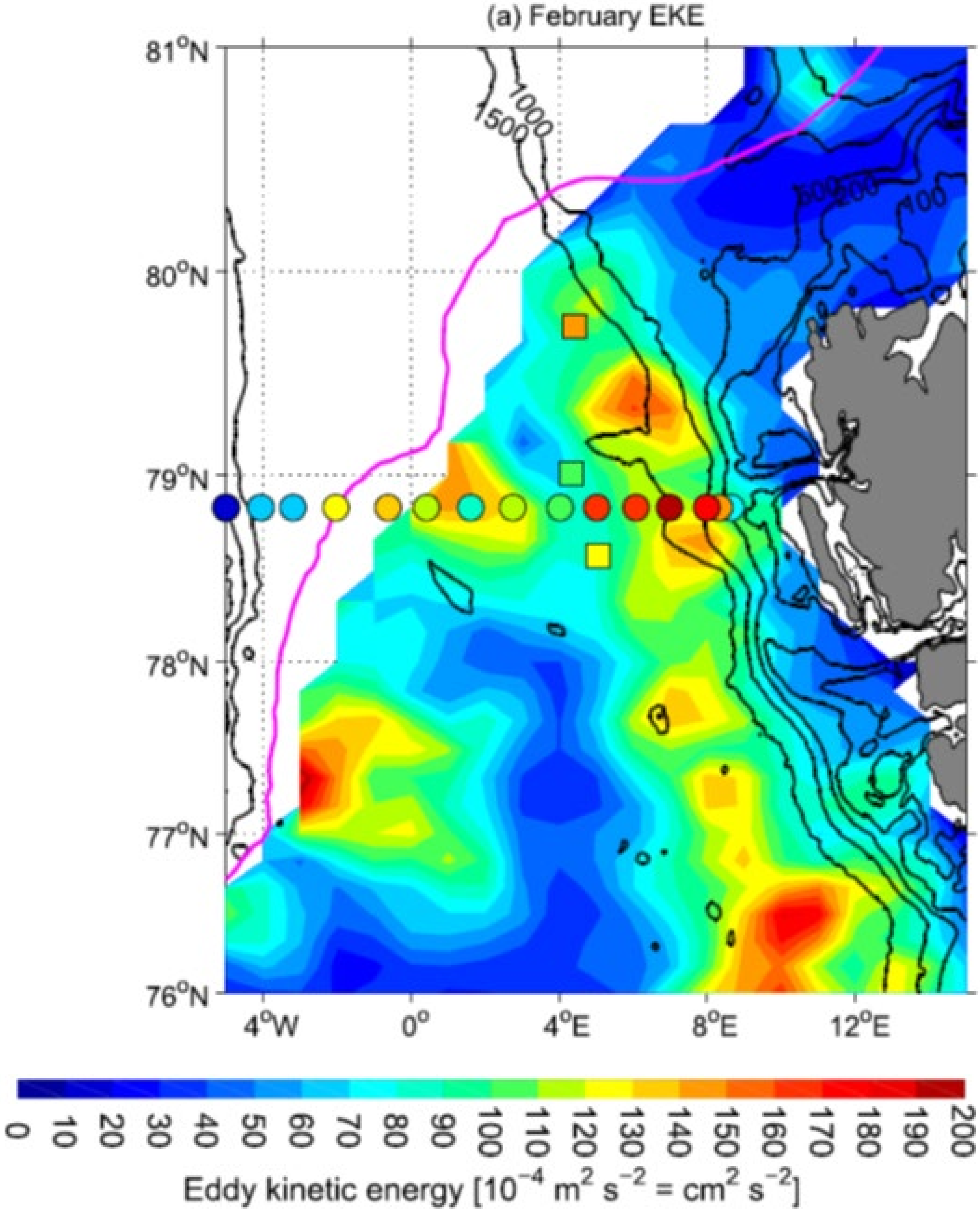


Figure 8. EKE in February from Appen et al. (2016) see their Fig.9. The mean ice edge from AMSR-E/AMSR-2 microwave sensor is shown in magenta.

Nurser and Bacon (2014) have estimated the first baroclinic deformation (or Rossby) radii for the area 60 °N from climatological ocean data. Values are generally low (1–7 km), reflecting weak density stratification, shallow water, or both. Seasonality strongly impacts the Rossby radius in shallower parts, where winter homogenization of the water column can reduce it to below 1 km. In the Norwegian Sea and the Atlantic-dominated inflows $R_1 \sim 7$ km. The Iceland and Greenland Sea with the polar-dominated outflows have even smaller $R_1 \sim 3$ km.

Based on the information from literature the bounding boxes have been selected to encompass the boundary current over the shelf and the adjacent areas over the shelf break monitor the lateral heat from the boundary current into the deep basins.

Gulf of Cadiz

The GoC is a region poorly sampled by Argo and surface floats. However, it is not clear if this is only due to the scarce number of deployments or by processes that are not favourable for their retention in the region. In fact, the GoC is a very dynamic system with inflow of Atlantic Water to the Mediterranean Sea and outflow of Mediterranean Water (MW) flowing into the North Atlantic (Figure 9) and along European west coasts. This poses interesting challenges to keep a sustainable observing system in GoC based on Argo and other floats. The MW outflow spreads in the northeastern part of the GoC as a bottom-gravity current but at the western part of the gulf the flow stabilizes and continues flowing against the slope between the depths of 400 to 2000 m along the Atlantic coast of the Iberian Peninsula and reaching latitudes of up to 55° N. The MW is characterized by temperature and salinity maxima at the depths of the main cores (400 m, 800 m and 1200 m), low-nutrient and oxygen contents, and relatively high abundance of particles. Along its path, the current at times separates from the slope forming eddies (called meddies). The MW is an important salt and heat source to the North Atlantic Ocean, and its variability could have also important consequences for the thermohaline circulation of the Atlantic Ocean. However, since the 2000s the observation effort of the MW is very scarce. Therefore, the GoC is a good place to test/validate Argo floats measurements of different ocean properties (e.g., biogeochemical) and for testing sustainable sampling schemes under dynamic environments. It will be also an important contribution to the monitoring of MW and its influence in the Atlantic Ocean.

In 2020, Argo-France has offered IPMA 2 Argo floats, who equipped them with oxygen sensors. These floats were deployed on Oct. 7 and 10th 2020 from a France SHOM campaign in the Gulf of Cadiz, under the scientific supervision of IPMA (see figure below). These floats will be used to determine how the GoC can be better monitored with Argo floats, especially in terms of configuration parameters.

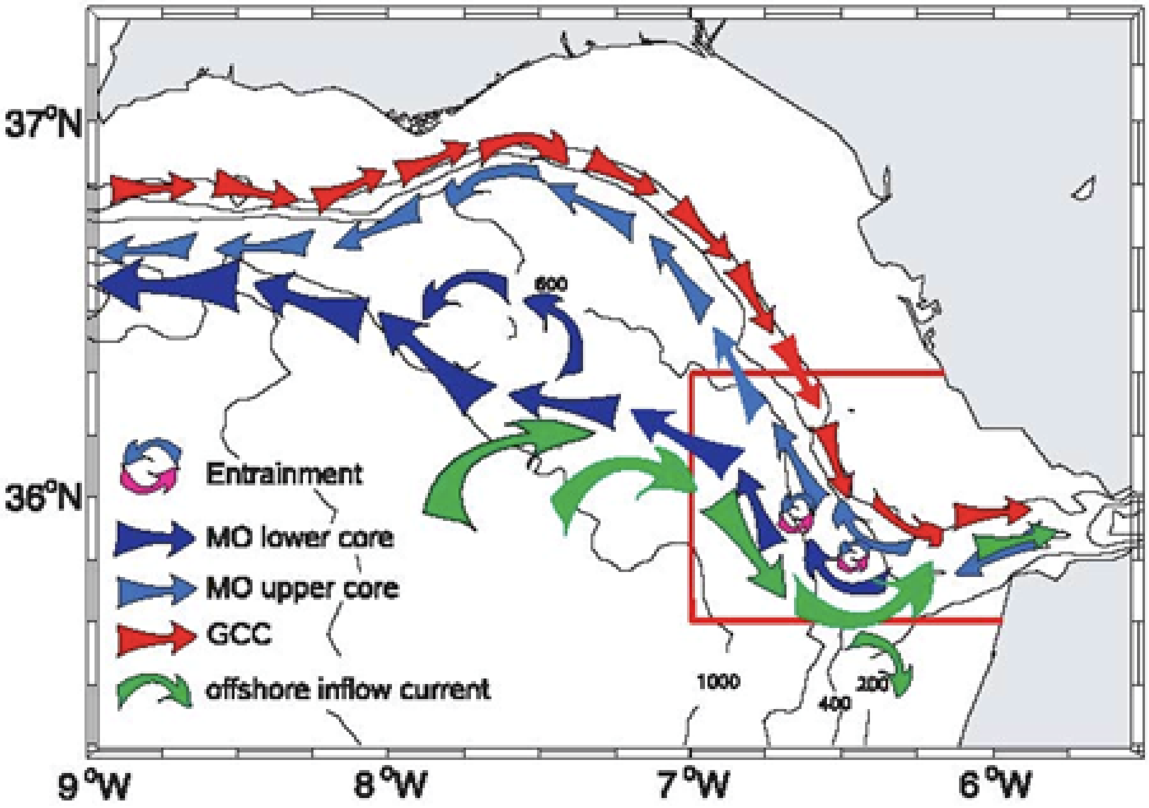


Figure 9. Schematic representation of the mean Gulf of Cadiz slope current system. The blue arrows represent the Mediterranean outflow upper and lower cores. Bright red arrows represent the mean path of the inshore inflow (the Gulf of Cadiz slope current-GCC), and green arrows stand for the offshore Atlantic inflow (From Peliz et al., 2009).

The main goal in this study case is to investigate what could be the better sampling strategy for the monitoring of the circulation, hydrography and biogeochemical components of the GoC based on Argo floats but also the monitoring of the variability of the MW and its properties (e.g., biogeochemical). It was decided that the region of interest will include all the GoC defined by the coordinates latitude 33-37° N and longitude 6-9° W.

3 Detailed historical sampling assessment

We conducted a detailed analysis of the historical sampling with Argo floats of the BC regions (each partner working on its BC of interest) in order to set the reference level (e.g. observation density, most frequent vertical resolution, cycling frequency, parking depth) from which a new strategy can be developed.

1. Gulf Stream Extension

Spatial sampling characteristics

The historical analysis of the Gulf Stream Extension region covers the June 2002 to June 2020 period. A total of 23.531 profiles have been sampled in the area during this period. Figure 10 below shows the spatial density of these profiles. Density is on a 1x1 degree cell grid and scaled by the expected number of profiles following the Argo target of 1 profile per month per 3x3 cell (for the 18 years period, we thus expect about 24 profiles per 1x1 cells). **This figure shows that, without any consideration of the quality of the data, the GSE is fairly well sampled in space, typically 3 to 4 times the Argo target.**

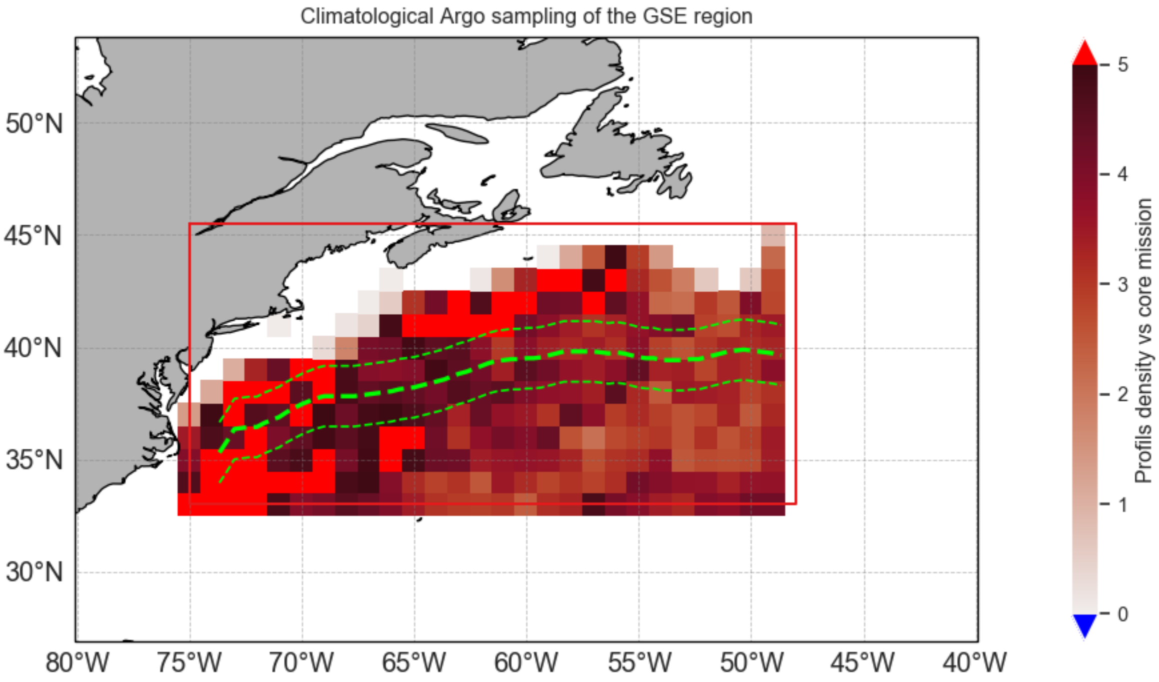


Figure 10. Distribution in space of the 23.531 profiles sampled from 2002 to 2019. Density binned on a 1x1 cell grid and scaled by the expected 24 profiles of the core Argo mission target. Thus, a map value of 3 means they are 3 more profiles than expected. The thick green line indicates the mean Gulf Stream position (defined as the maximum mean EKE latitude, derived from AVISO altimetry dataset), the light green contours are the +/- 2 Rossby radius enveloppe (typical eddy scales of 75km radius). The total green enveloppe is thus about 300 km wide.

Deployments of floats and profiles over time

These 23.531 profiles were sampled from 368 floats, among which only 102 (28%) were deployed in the area. So, more than ⅔ of the floats entering the area were deployed outside of it. The table 1 below, provides the annual distribution of profiles and floats deployments (inside and outside of the domain).

Table 1. Deployments and profiles annual census in the Gulf Stream area

Time Period 2002-2019		Number of deployments		Number of profiles
		Inside	Outside	
Total		**102**	**266**	**23.531**
Per Year	*2002*	1		379
	2003	0		729
	2004	0		1033
	2005	6		768
	2006	7		750
	2007	0		1097
	2008	0		1017
	2009	0		1069
	2010	3		1060
	2011	4		831
	2012	7		1233
	2013	16		1742
	2014	10		1525
	2015	10		1634
	2016	15		2103
	2017	9		2145
	2018	13		2234
	2019	1		2191
Per season	*Winter*	4		5923
	Spring	45		5685
	Summer	13		5812
	Autumn	40		6111

Given the highly turbulent ocean dynamic in the area, we further computed the typical residence time of a float entering the area. The histogram of values is given in the figure below. It is striking to note that ⅓ of the floats entering the area do stay for more than 10 days and that 80% of the floats stay for less than 6 months.

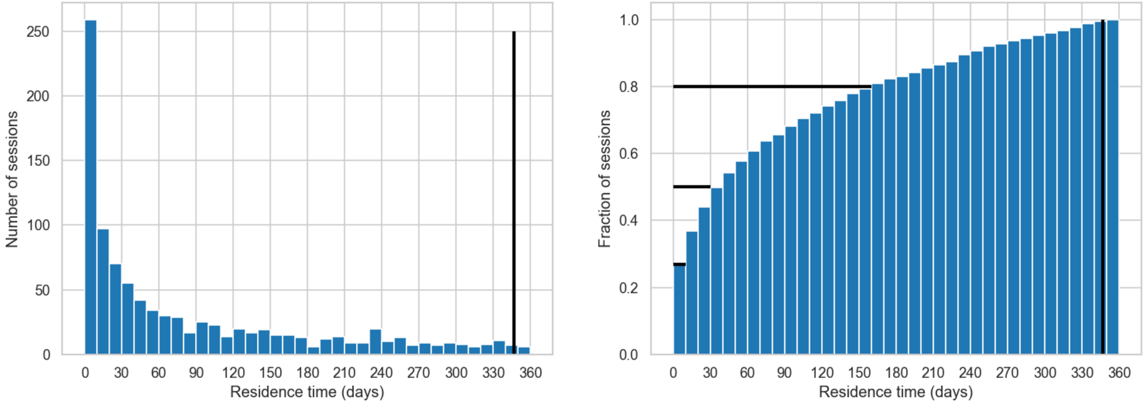


Figure 11. Left: Residence time (in days) of a float entering the Gulf Stream area. The typical time that a float would take to cross from West to East the entire box at 1000m depth would be 347 days (vertical black line). **Bottom**: Cumulative pdf of the residence time. This can be read as follows: *27% of the floats stay less than 10 days in the area; 50% of the floats stay less than 30 days, 80% of the floats stay less than 6 months in the area, nearly none of the floats take the shortest path to cross the area from West to East.*

Float characteristics and frequent configuration

Table 2: Number of profiles sampled by each profiler type

Profiler type	Nb of profiles
Webb Research, Seabird sensor	9745
S2A float	4020
Solo, Seabird conductivity sensor	3662
Nova float	2453
Solo, FSI conductivity sensor	2296
Arvor, Seabird conductivity sensor	661
Provor, Seabird conductivity sensor	597
Provor, FSI conductivity sensor	52
Unknown	45

From the census of table 2, we note that the most frequent float model sampling the Gulf Stream area is the APEX from Webb Research, and then the Solo2.

If we count the number of profiles managed by each DAC, we have 13 741 profiles managed by AOML (USA), 6 514 by MEDS (Canada) and 3 276 by (Ifremer, France).

- Cycling frequency, parking depth, vertical sampling

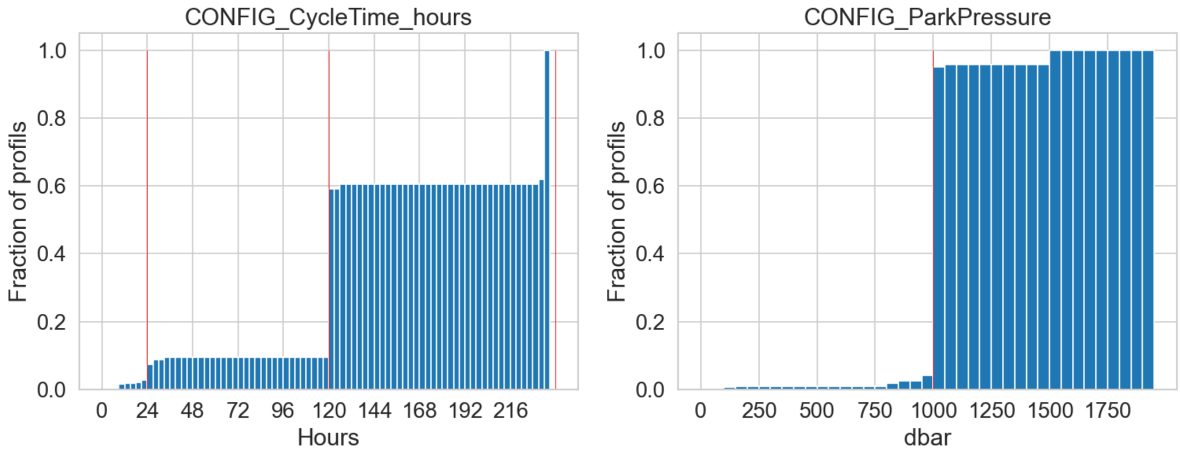


Figure 12. Cumulative pdf of cycles period and parking depth of profiles sampled in the GSE.

Figure 12 shows that the vast majority of floats have the mission configuration parameters:

- 50% of the floats cycle at 5 days (10% at 1 day and 40% at 10 days)
- 95% of the floats drift at 1000db

Last, we determined that 60% of the profils have less than 150 points, 20% between 400 and 600 and 20% between 800 and 1000 points.

2. Western Mediterranean BC

Spatial sampling characteristics

Figure 6 showed the density map in the boundary currents (NC, BC, AC) and their Rossby associated areas (NR: North East Region, SR: South West Region, AR: Algerian Region) selected. Figure 13 shows the distribution of profiles along the Western Mediterranean Sea. The darker colors in the density maps, represent a high value of profiles associated with the recurrent mesoscale structures. The time period included for the historical sampling and configuration is from 2003 to June 2020.

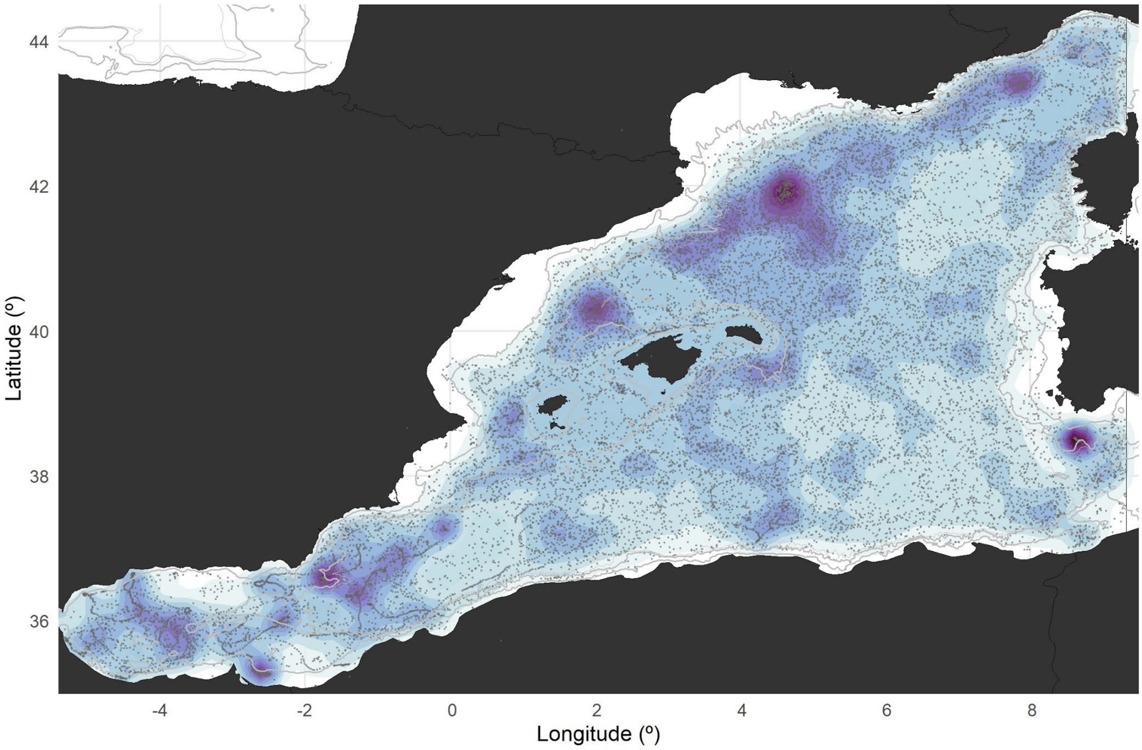


Figure 13. Density map of profiles in the Western Mediterranean Sea.

Deployments of floats and profiles over time

Table 3 shows the number of deployments and profiles per boundary current on a yearly basis and per season. The Rossby associated areas are in table 4. In these tables, *inside* means deployments done in the areas defined. On the contrary, *outside* means that the deployments were done out of the area defined but the floats did some profiles in the boundary currents and Rossby associated areas.

Figure 14 shows the statistics in percentage for the data in Tables 1 and 2. Figure 15 shows the number of profiles per month.

As it is shown in table 3, nine floats have been deployed inside the BCs and the total number of profiles is 1805. In the associated Rossby areas the number of profiles is 2961.

Autumn is the season with more profiles registered, and October is the month with a higher value of profiles, this is mostly due to the Northern Current.

Table 3. Deployments and profiles in the Mediterranean boundary currents.

Time Period 2003-06/2020		Northern Current (NC)			Balearic Current (BC)			Algerian Current (AC)		
		Number of deployments		**Number of profiles**	**Number of deployments**		**Number of profiles**	**Number of deployments**		**Number of profiles**
		Inside	Outside		Inside	Outside		Inside	Outside	
Total		**8**	**58**	**1258**	**1**	**29**	**414**	**0**	**17**	**133**
Per Year	*2003*	0	2	1	0	0	0	0	0	0
	2004	0	4	18	0	2	0	0	1	0
	2005	1	1	56	0	0	2	0	0	1
	2006	0	1	39	0	1	4	0	1	0
	2007	0	2	50	0	1	4	0	0	0
	2008	0	5	48	0	4	8	0	2	12
	2009	0	2	42	0	1	25	0	2	17
	2010	0	2	1	0	1	17	0	0	13
	2011	0	3	23	0	1	12	0	1	6
	2012	0	5	8	1	2	9	0	2	2
	2013	0	5	112	0	1	35	0	1	5
	2014	0	7	109	0	3	0	0	2	20
	2015	2	3	245	0	3	53	0	1	28
	2016	1	4	179	0	1	65	0	0	0
	2017	2	4	48	0	3	61	0	3	10
	2018	1	3	138	0	2	47	0	1	0
	2019	1	5	97	0	2	12	0	0	7
	2020	0	0	34	0	1	60	0	0	12
Per season	*Winter*	1	12	255	0	12	106	0	5	37
	Spring	2	23	301	0	7	127	0	6	21
	Summer	3	18	277	1	9	100	0	6	26
	Autumn	2	5	425	0	1	81	0	0	49

Table 4. Deployments and profiles within the Rossby radius delimited BC areas

Time Period 2003-06/2020		**Northeast region (NR)**			**Southwestern region (SR)**			**Algerian region (AR)**		
		Number of deployments		**Number of profiles**	**Number of deployments**		**Number of profiles**	**Number of deployments**		**Number of profiles**
		Inside	Outside		Inside	Outside		Inside	Outside	
Total		**13**	**59**	**1360**	**3**	**34**	**547**	**3**	**47**	**1054**
Per Year	*2003*	3	1	30	0	0	0	0	0	0
	2004	2	4	38	1	1	1	0	3	3
	2005	0	0	24	0	1	15	0	1	4
	2006	0	1	51	0	1	19	0	1	3
	2007	0	2	34	0	0	39	0	0	0
	2008	3	3	76	0	3	2	0	2	15
	2009	0	2	96	0	0	6	0	2	41
	2010	0	1	20	0	0	7	0	1	28
	2011	0	1	54	0	3	8	1	1	33
	2012	1	7	25	0	4	6	0	5	10
	2013	0	4	140	1	1	29	0	2	73
	2014	2	10	74	0	2	43	0	9	97
	2015	1	4	175	1	5	44	0	5	102
	2016	0	5	110	0	0	156	0	3	268
	2017	0	6	119	0	6	53	2	4	165
	2018	0	3	98	0	4	62	0	5	94
	2019	1	5	124	0	3	56	0	3	61
	2020	0	0	72	0	0	1	0	0	57
Per season	*Winter*	3	9	345	0	11	111	2	9	268
	Spring	2	17	377	1	7	174	0	19	295
	Summer	2	25	281	0	12	132	0	16	222
	Autumn	6	8	357	2	4	130	1	3	269

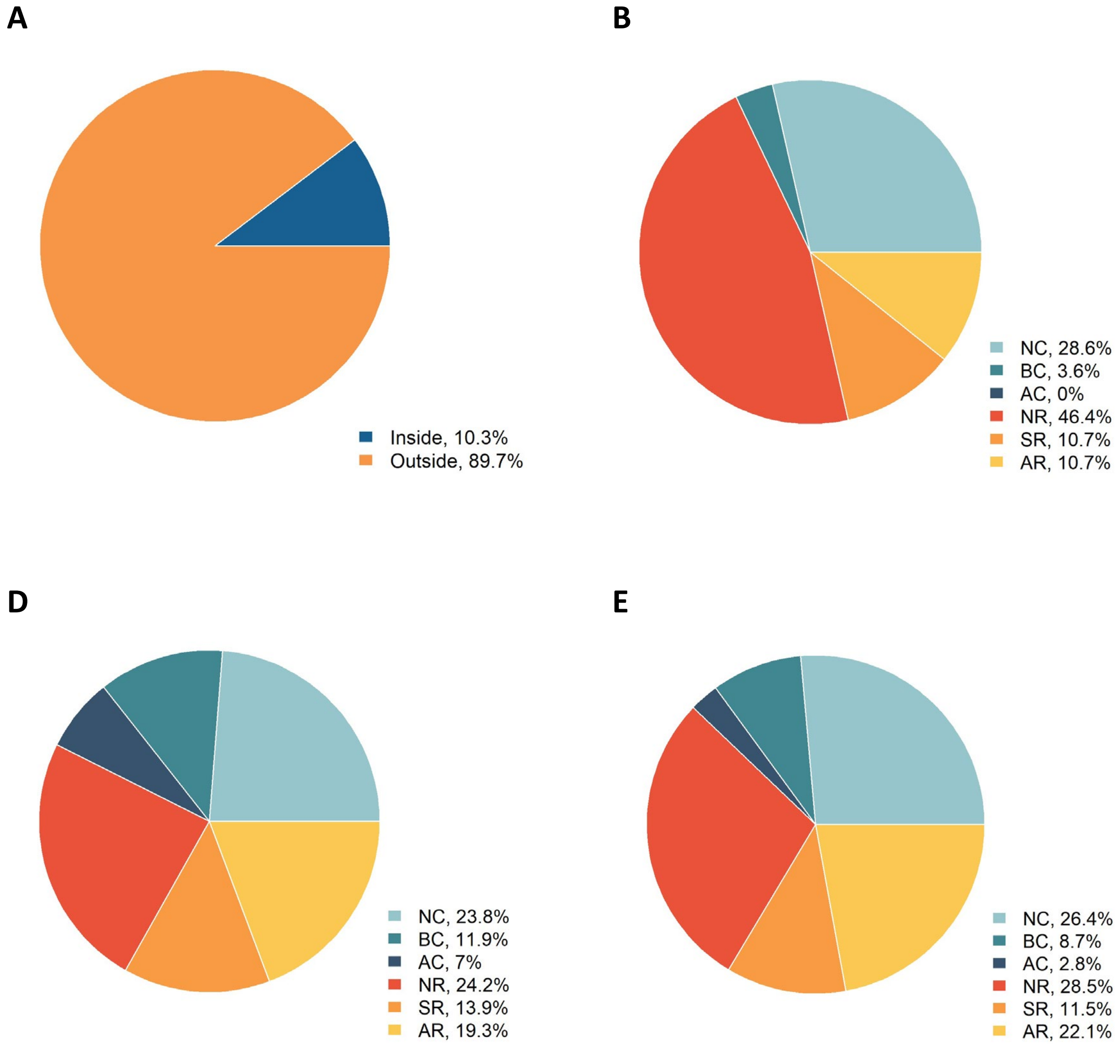


Figure 14. Percentage of floats deployed inside and outside of the boundary currents and Rossby associated areas. General deployments (**A**), deployments inside per area (**B**), deployments outside per area (**C**) and profiles done per area (**D**).

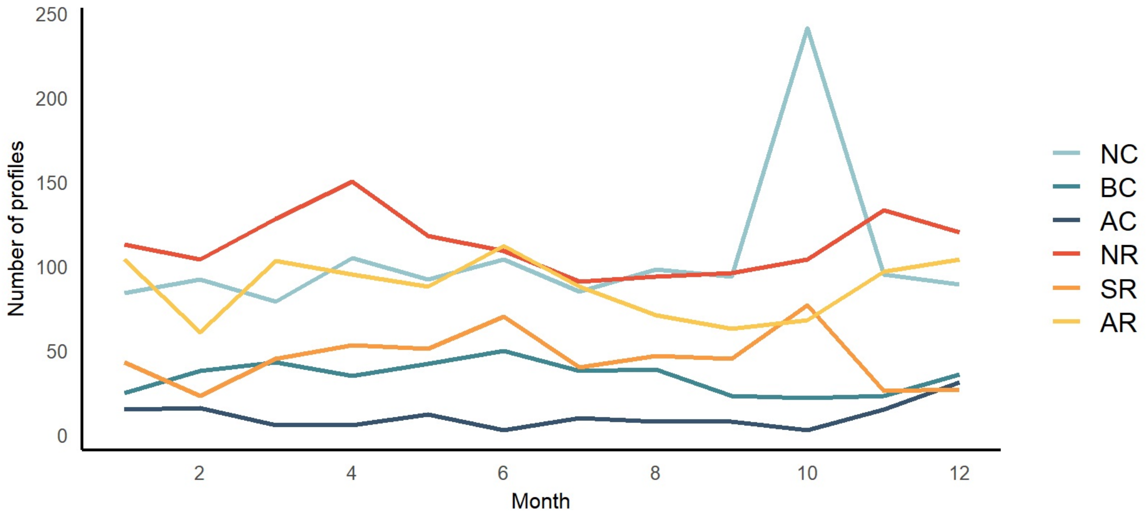


Figure 15. Number of profiles per BC regions of the Western Medditteranean Sea on a monthly basis (period: 2003-06/2020).

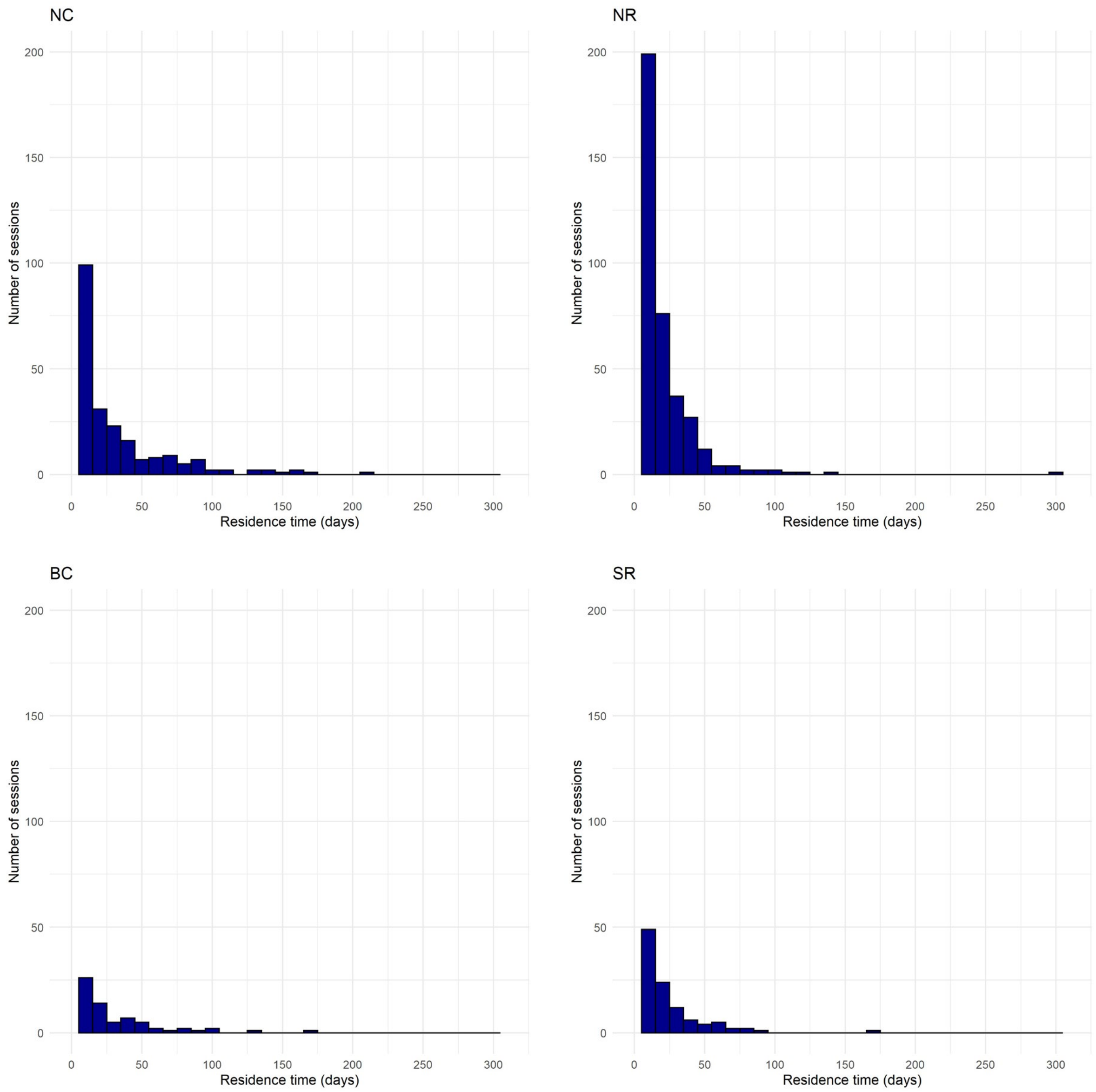
Float characteristics and frequent configuration

Table 5 represents the most frequent float configuration parameters in the BC Western Mediterranean areas. The majority of floats show a cycle length of 5 days but with different parking depths; 350, 700, 1000 and 1200 depending on the area. The most representative vertical sampling scheme is the same for all areas defined (surface: 1 dbar; intermediate: 10 dbar; bottom: 25 dbar) except for Northern Current. The majority of float types are ARVOR, APEX and PROVOR.

Table 5. Frequent configuration parameters and float characteristics per area (NC: Northern Current, BC: Balearic Current, AC: Algerian Current, NR: North East Region, SR: South West Region, AR: Algerian Region)

Configuration parameters		**Area**					
		NC	**BC**	**AC**	**NR**	**SR**	**AR**
Cycling frequency (hours)		120	120	120	120	120	120
Parking depth (dbar)		350	700	1200	1000	350	1200
Vertical sampling scheme (dbar)	*Surface*	2	1	1	1	1	1
	Intermediate	10	10	10	10	10	10
	Bottom	25	25	25	25	25	25
Residence time, mean (Cycles)		7.14	6.18	3.17	3.81	5.16	6.51

Floats models	ARVOR	ARVOR	APEX	ARVOR/ PROVOR	ARVOR	APEX/ARVOR
Transmission system	37 Iridium, 29 Argos	14 Iridium, 16 Argos	6 Iridium, 11 Argos	40 Iridium, 32 Argos	20 Iridium, 17 Argos	24 Iridium, 26 Argos



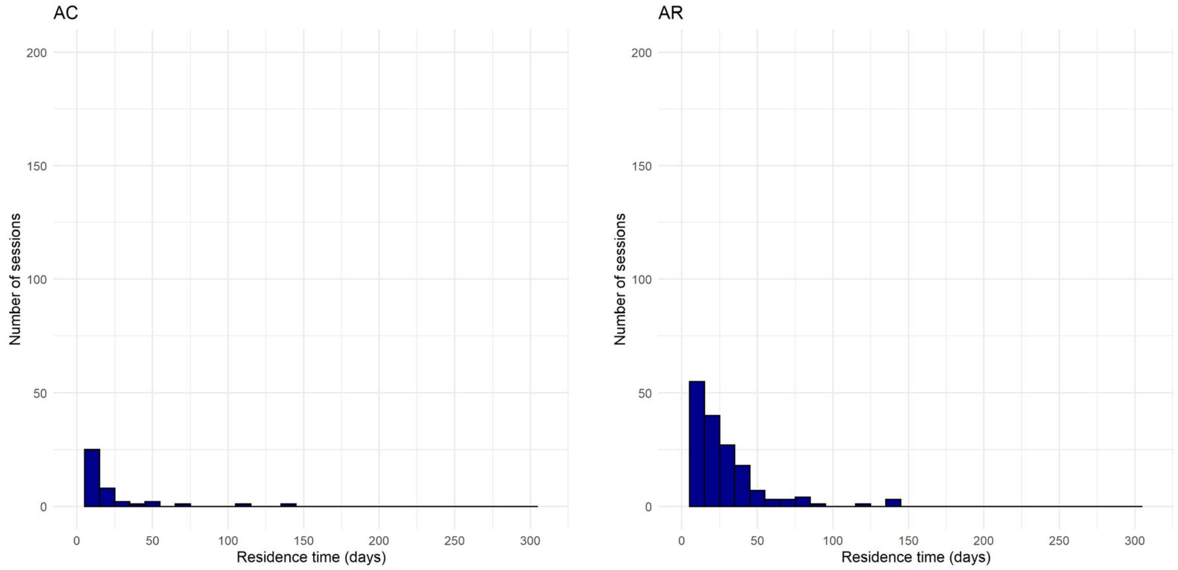
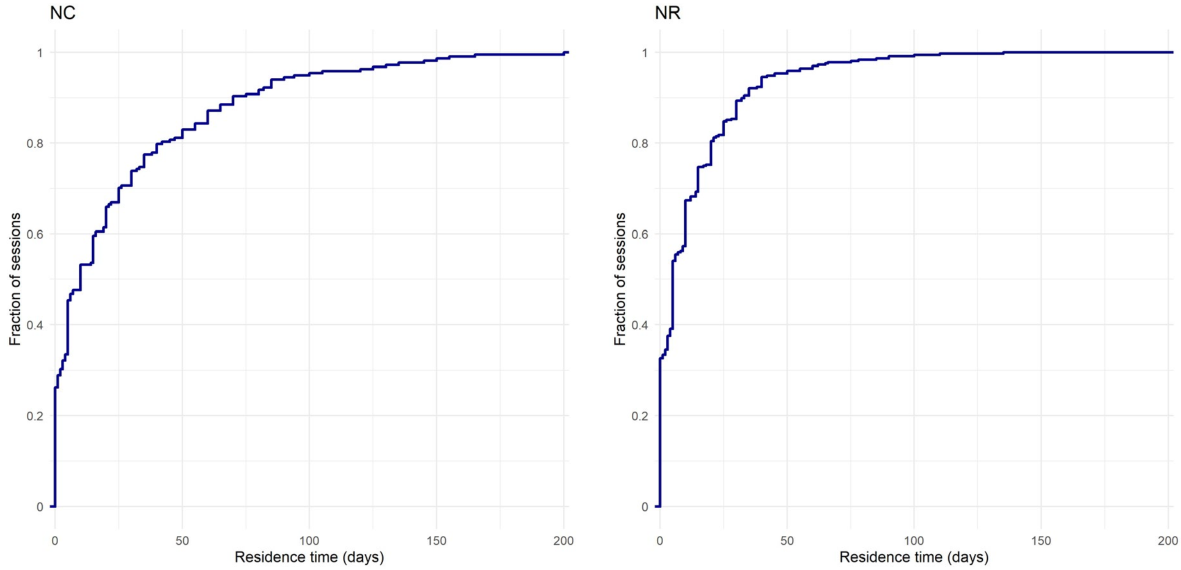


Figure 16. Residence time (in days) of a float entering the Western Mediterranean boundary currents (**left**) and their associated Rossby areas (**right**).



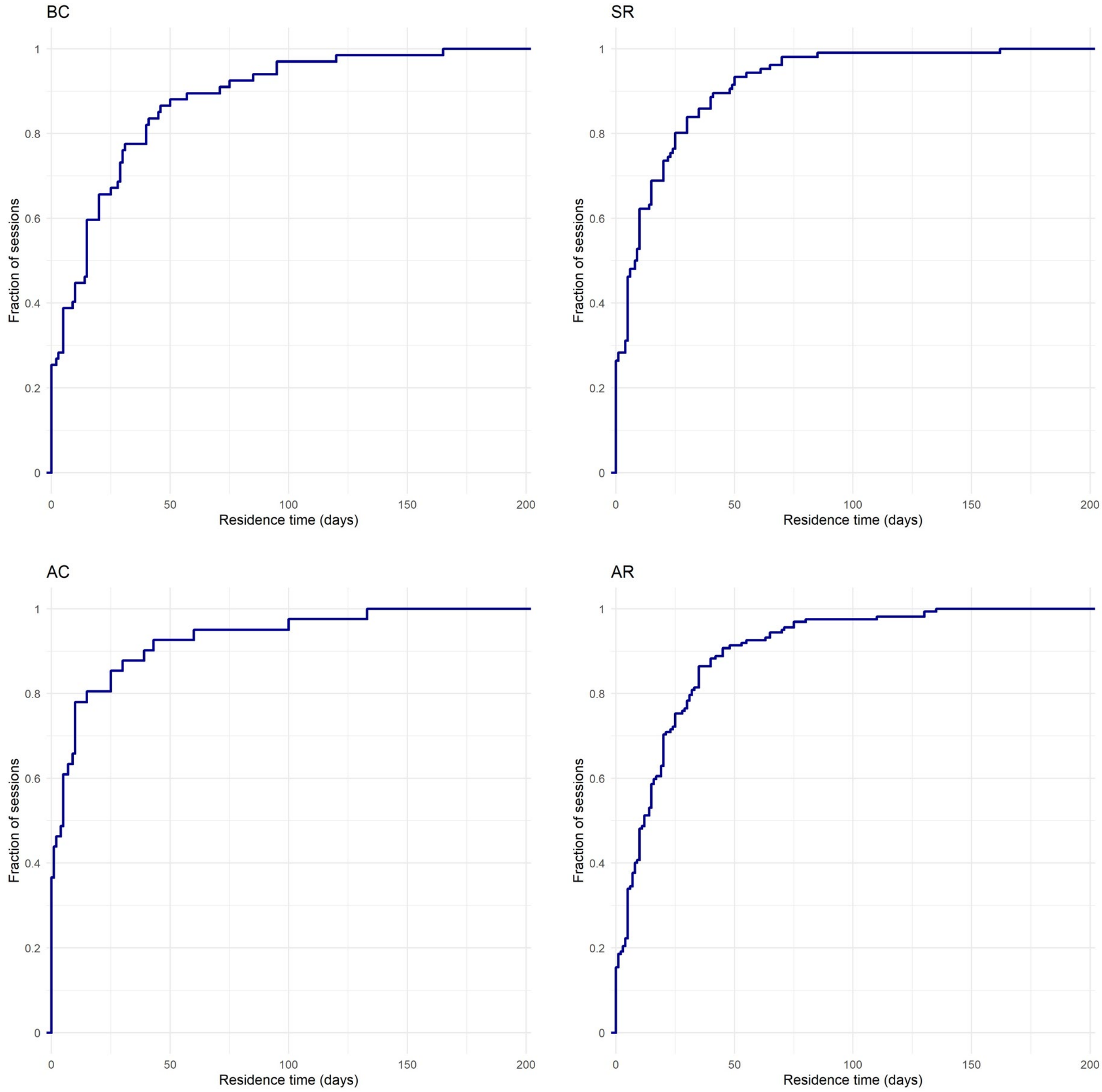


Figure 17. Cumulative pdf of the residence time for the Western Mediterranean boundary currents (**left**) and their associated Rossby areas (**right**).

3. Nordic Seas BC

Spatial sampling characteristics

Figure 18 shows the density of floats in the selected boundary currents (WSC, EGC and EGCsouth) as a function of measurement date. Figure 19 shows the distribution of profiles in the entire Nordic Seas. The time period included for the historical sampling and configuration is from 2001 to November 2020.

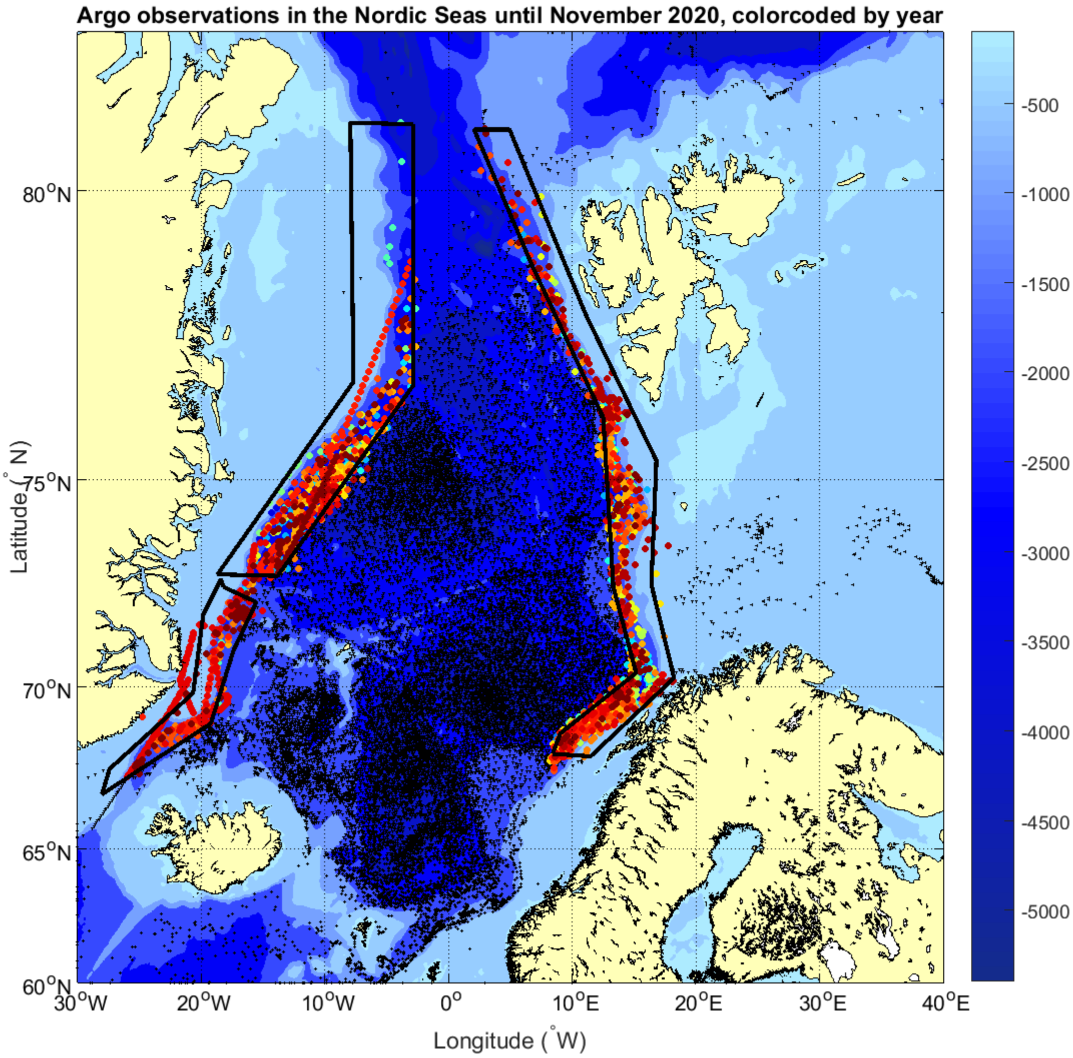


Figure 18. Float observations in the boundary currents (black polygons).

Observations in the Nordic Seas have increased over time and have reached high and stable levels around 2012 (see Table 6). After the later period there have been more than 60 active floats operating in the Nordic Seas, mostly in the deep basins, but also with more frequent observations in the boundary currents. The spatial coverage in all boundary currents is varying and the northern part of the EGC is very poorly sampled.

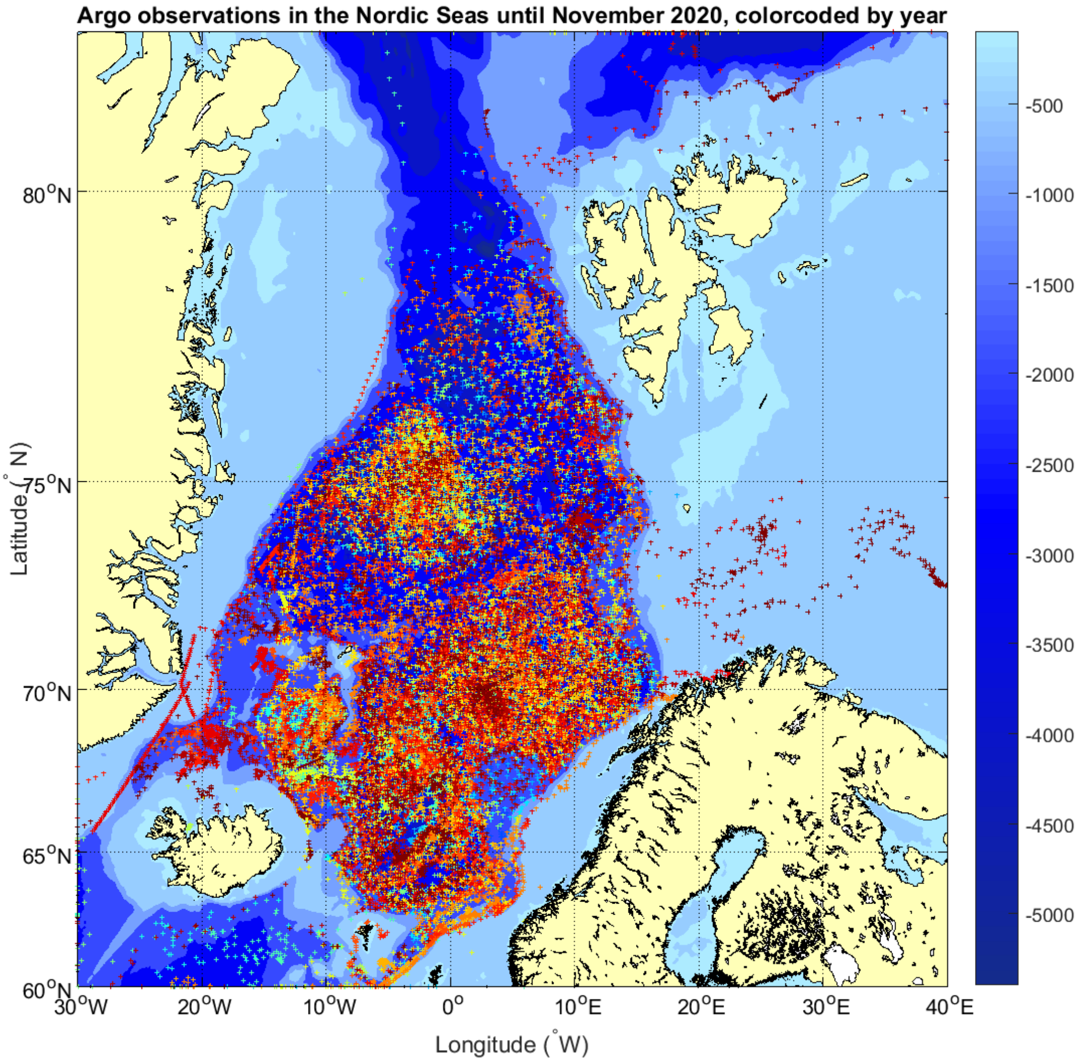


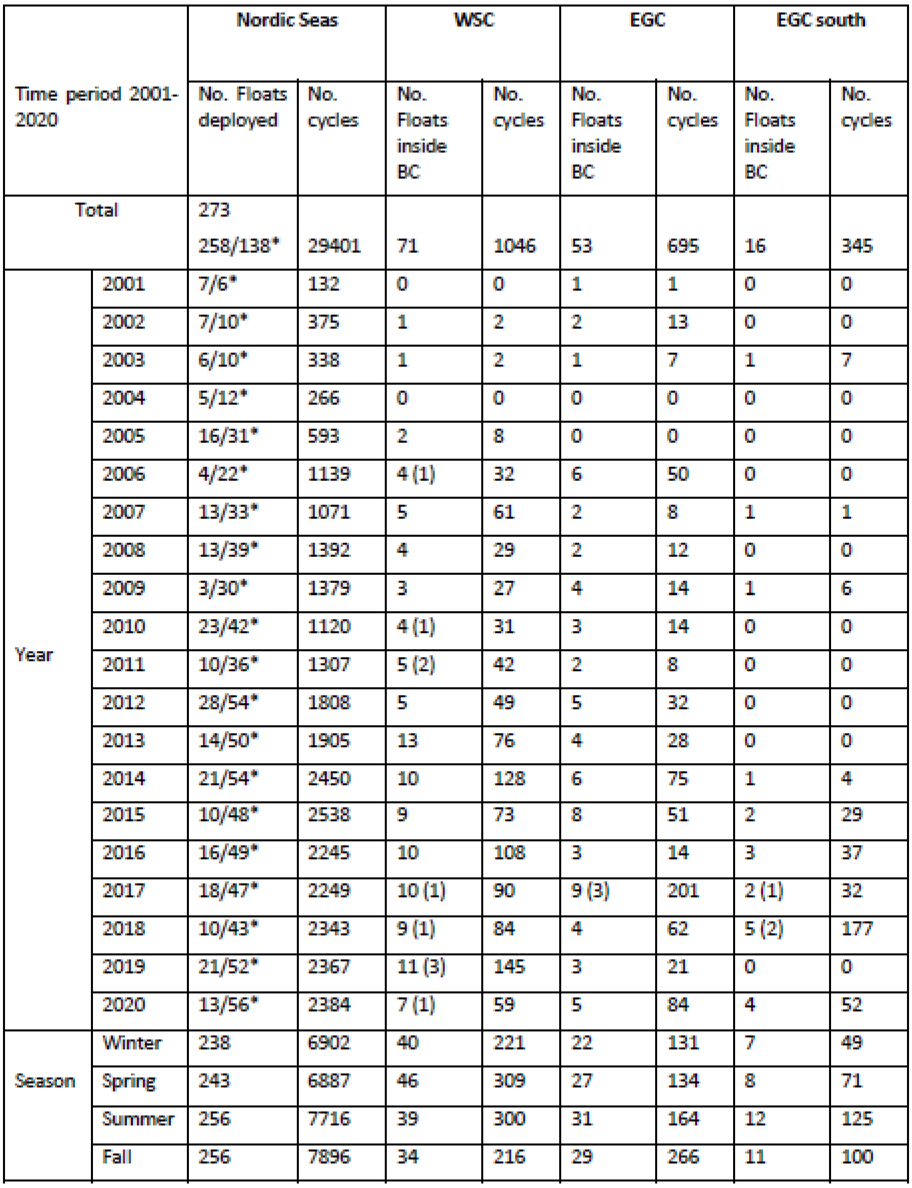
Figure 19. All float observations in the entire Nordic Seas.

Deployments of floats and profiles over time

Table 6 shows the number of deployments and profiles per boundary current on a yearly basis and per season. In addition to the number of new deployments in a particular year the numbers of active floats in the deep basins are given in order to contrast the sampling in the boundary currents from the sampling in the interior basin.

Table 6. Deployments and profiles annual census for the high latitudes BC regions. Please note, that at the AIC, 274 floats are listed with deployments in the Nordic Seas, but only 258 have delivered data. In the total count * is the number of floats which never reported cycles in any of the boundary currents, at yearly level * gives the number of active floats in that particular year, that never drifted into the boundary current. Seasons have been

defined as follows, Winter: January-March, Spring: April-June, Summer: July-September, and Fall: October-December.



		Nordic Seas		WSC		EGC		EGC south	
Time period 2001-2020		No. Floats deployed	No. cycles	No. Floats inside BC	No. cycles	No. Floats inside BC	No. cycles	No. Floats inside BC	No. cycles
Total		273 258/138*	29401	71	1046	53	695	16	345
Year	2001	7/6*	132	0	0	1	1	0	0
	2002	7/10*	375	1	2	2	13	0	0
	2003	6/10*	338	1	2	1	7	1	7
	2004	5/12*	266	0	0	0	0	0	0
	2005	16/31*	593	2	8	0	0	0	0
	2006	4/22*	1139	4 (1)	32	6	50	0	0
	2007	13/33*	1071	5	61	2	8	1	1
	2008	13/39*	1392	4	29	2	12	0	0
	2009	3/30*	1379	3	27	4	14	1	6
	2010	23/42*	1120	4 (1)	31	3	14	0	0
	2011	10/36*	1307	5 (2)	42	2	8	0	0
	2012	28/54*	1808	5	49	5	32	0	0
	2013	14/50*	1905	13	76	4	28	0	0
	2014	21/54*	2450	10	128	6	75	1	4
	2015	10/48*	2538	9	73	8	51	2	29
	2016	16/49*	2245	10	108	3	14	3	37
	2017	18/47*	2249	10 (1)	90	9 (3)	201	2 (1)	32
	2018	10/43*	2343	9 (1)	84	4	62	5 (2)	177
	2019	21/52*	2367	11 (3)	145	3	21	0	0
	2020	13/56*	2384	7 (1)	59	5	84	4	52
Season	Winter	238	6902	40	221	22	131	7	49
	Spring	243	6887	46	309	27	134	8	71
	Summer	256	7716	39	300	31	164	12	125
	Fall	256	7896	34	216	29	266	11	100

The number of floats active in the boundary currents and in the deep basins is shown in Figure 20 (left) and also the number of cycles performed in each area. Based on the number of floats the distribution appears more favourable for the boundary current. But since the floats only remain in the boundary currents for short periods of time, the percentages are much reduced in terms of cycles (Figure 20, right). But 8 % (2086 cycles) of the total cycles (290401) are sampled in the three boundary currents and with increasing number of cycles due to changes in the mission parameters.

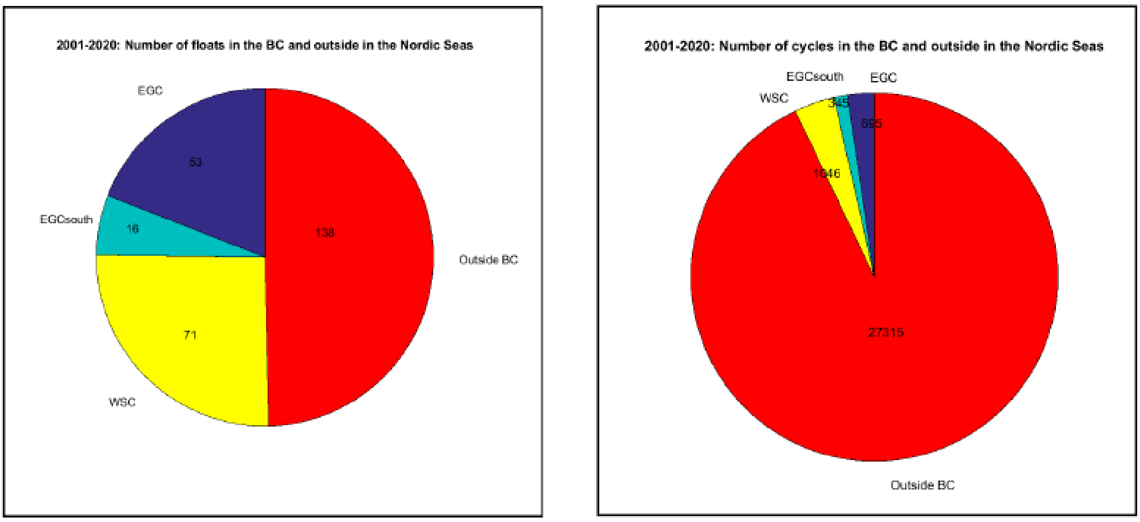


Figure 20. Number of floats operating in the Nordic Seas and the boundary currents (left) and number of cycles obtained (right) for the period 2001-2020.

The seasonal cycle (Figure 21) is well covered in all months. Data density for the seasonal cycle is best in the WSC and lowest in EGCsouth. The observations in the EGC shows a higher number of profiles in the year from October-November.

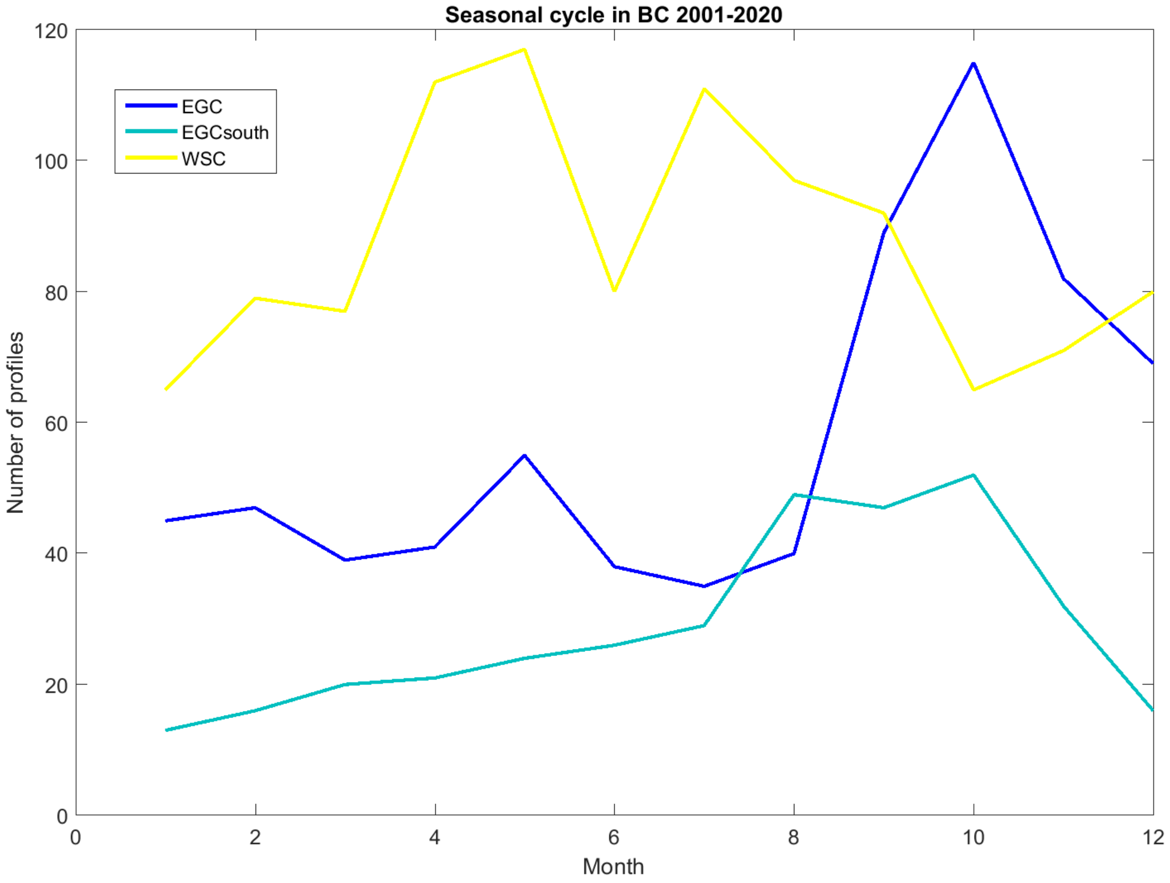


Figure 21. Seasonal cycle observed by the floats in the boundary current.

Floats deployed in the eastern part of the WSC usually drift to the north, pass Fram Strait into the Arctic proper, drift eastward along the Nansen Basin shelf and die under the ice. The maximal eastward extension reached float WMO 3902105 (Figure 22): 81.24° N, 43.70° E. Trajectories of floats cached by the boundary current are similar to each other. Most settings applied to the ARVOR floats were the same as in the core Argo: 10 days period, 1000 m parking depth, 2000 m maximal diving depth. In the region north of Svalbard the period of measurements, as well as the parking depth usually were changed since it made no sense to spare batteries with the expected early death of the floats in the rapidly expanding seasonal ice cover. Additionally data from the Marginal Ice Zone (MIZ) are important and valuable, also for the development of ice avoidance methods for the area.

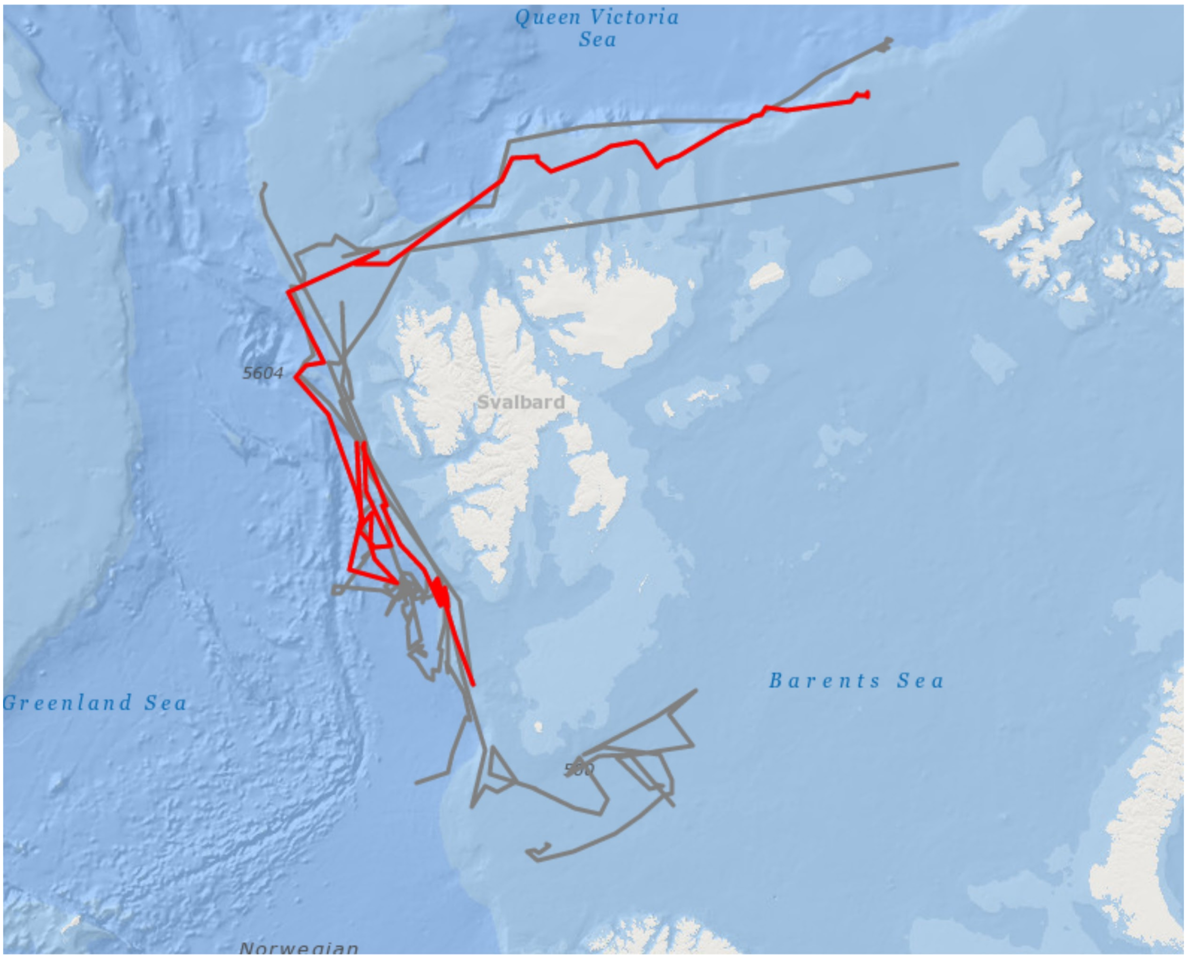


Figure 22. Trajectories of IOPAN floats deployed in the WSC core. In red - still active float 3902107.

Float characteristics and frequent configuration

The historical sampling boundary currents in the Nordic Seas (Figure 23) follows the standard Argo mission settings for the majority of floats (10 day cycle length, 1000 m park depth and 2000 m profile depth). The float types are in the majority TWR floats (APEX) or NKE floats (ARVOR, ARVOR-L, PROVOR). After 2017 multiple mission settings for a single float have been observed due to the possibilities of the two-way communication. Shallower park depth of 300-500 m and shorter cycle length of 1-3 days seem to be more appropriate to sample the BCs properly. These were particularly applied in the most recent deployments by Poland and France in the WSC and EGC.

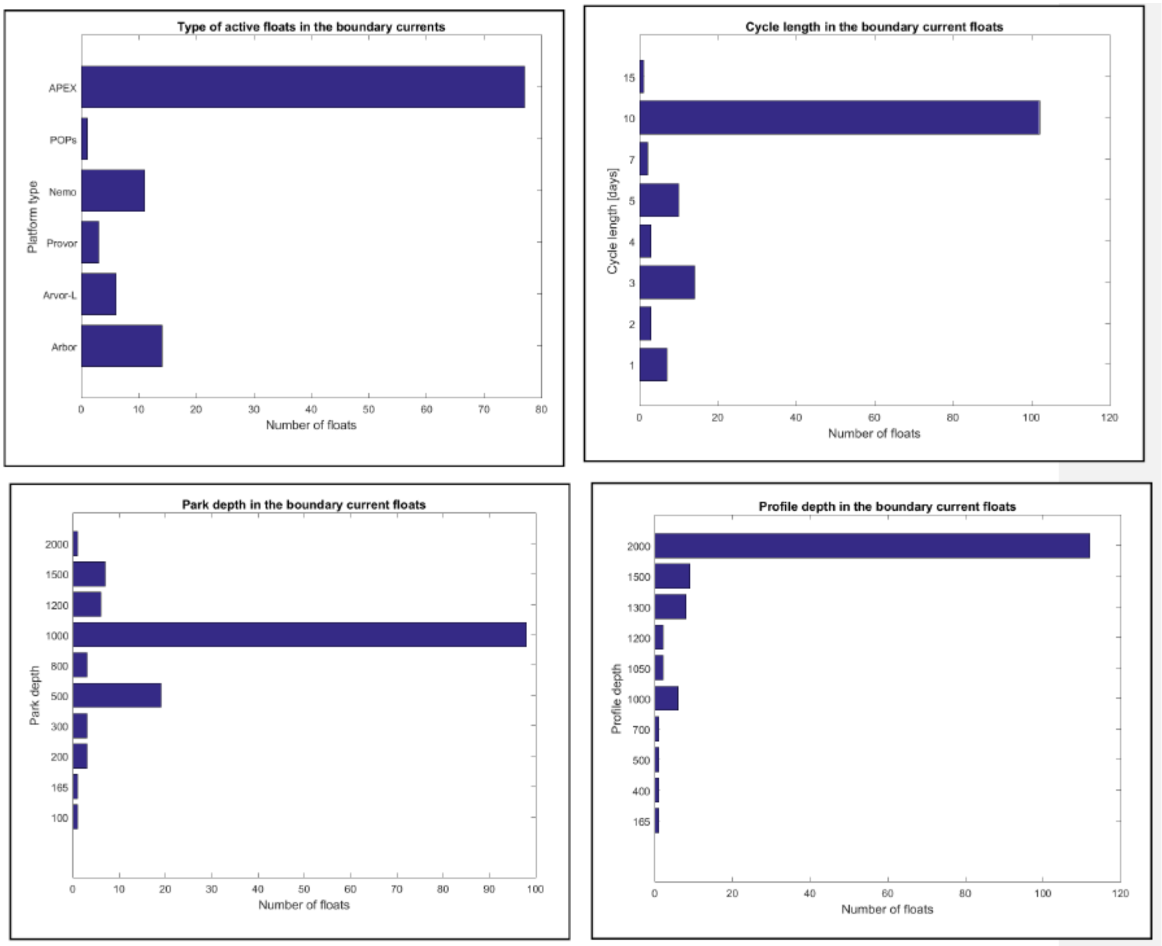


Figure 23. Mission configurations for the floats in the BC in the period 2001-2020.

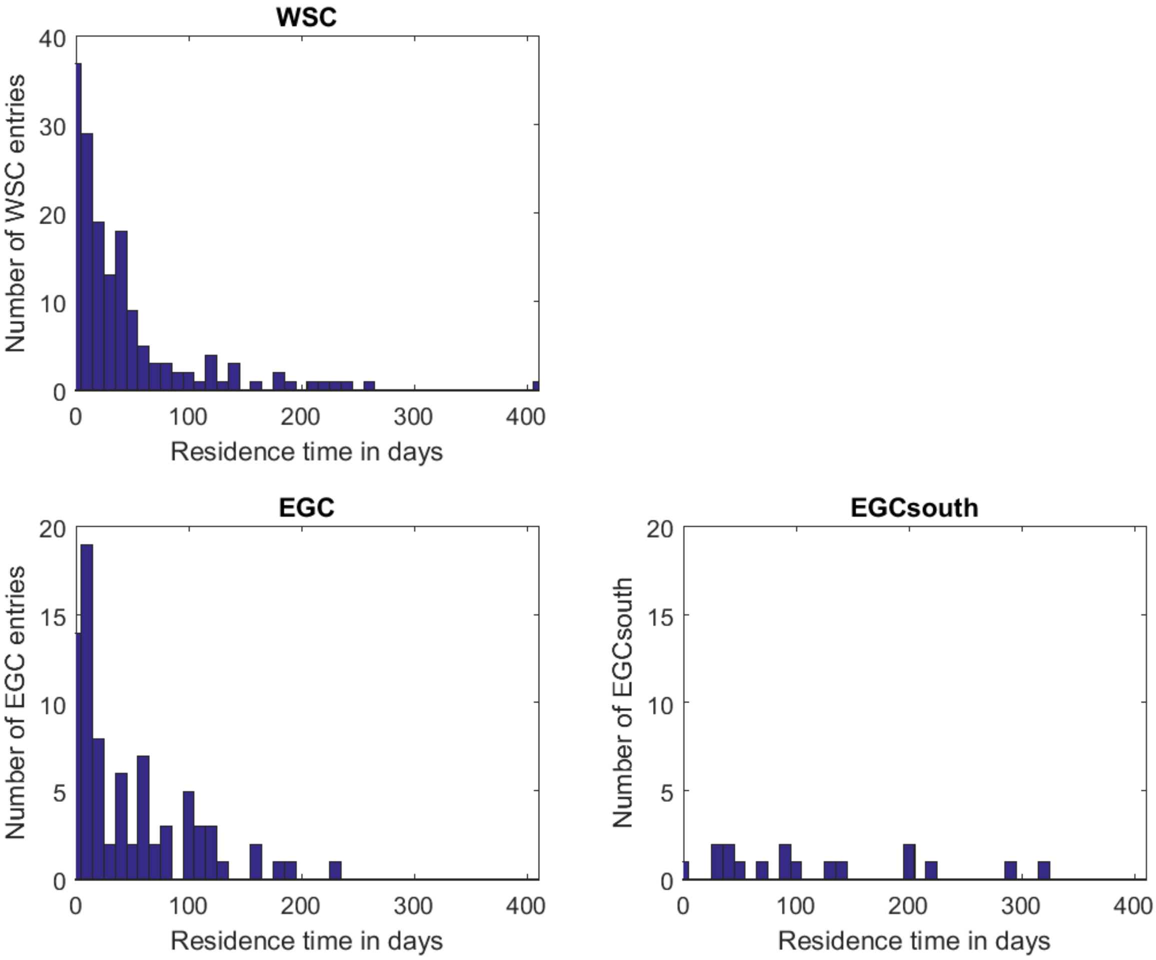


Figure 24. Residence time (in days) of a float entering the Nordic Seas boundary currents. Please note the different vertical axes for the WSC and the EGC, respectively the EGCsouth.

Mean residence time (figure 24 and figure 25) in the WSC area is ~ 42 days, with a maximum of 410 days. In the EGC the mean residence time is similar, with ~47 days, but the maximum stay was less with 226 days. Probably due to lower current speeds the mean residence time in the EGCsouth was longer at 119 days and a maximum of 317 days. But it also displays the most heterogeneous distribution.

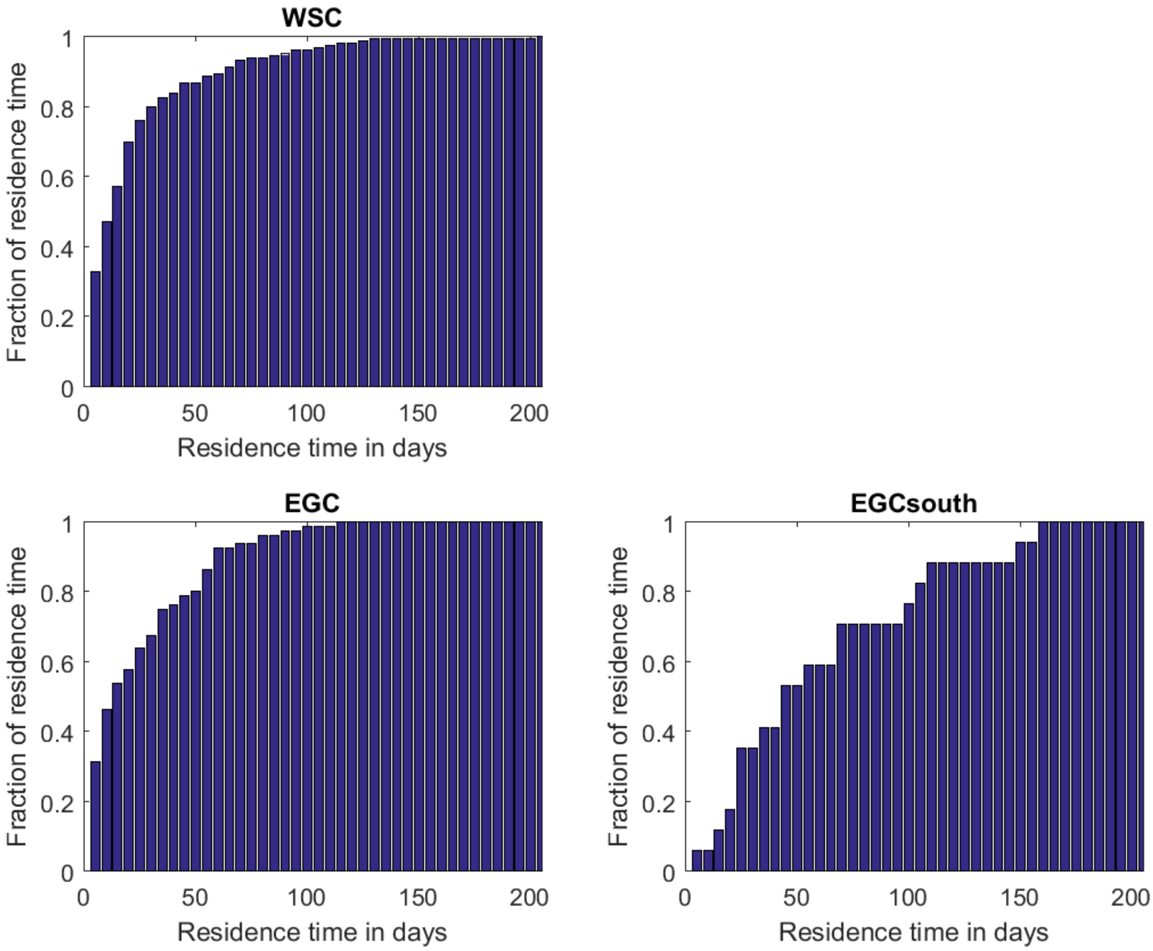


Figure 25. Cumulative pdf of the residence time for the boundary currents.

4. Gulf of Cadiz

Spatial sampling characteristics

In this analysis it was decided to extend the region of interest to the west and north because one of the main regions of the formation of meddies is the southwestern coast of Iberian Peninsula. Thus, the final region for the historical analysis of the GoC was defined by the following coordinates: latitude 35-40° N and longitude 5-10° W (Figure 26). The time period analysed was from 2008 to 2020.

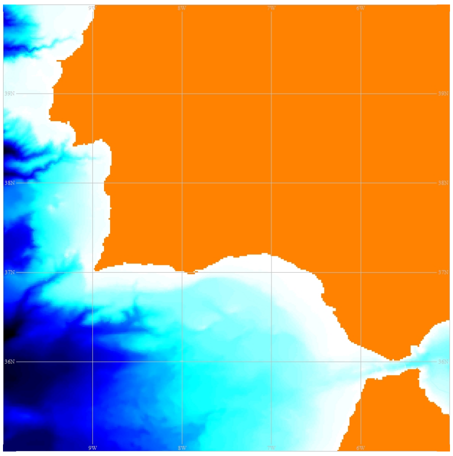


Figure 26. Gulf of Cadiz study case area.

A total of 13 floats were found to be deployed or that entered into the GoC in this period of time. This small number of floats makes the analysis not conclusive, and results and conclusions should be looked at with caution.

Deployments of floats and profiles over time

The number of Argo floats per year located in the GoC are presented in Figure 27. The number of floats per year varied between 1 and 4 but in half of the years this number was 1.

58% (7) are deployed in the GoC and 42% (5) enter the GoC from other areas where they were deployed.

The resident time within the GoC is on average 184 days per float (about 5 months), ranging from 8 days to 624 days, and an average of 169 days per year.

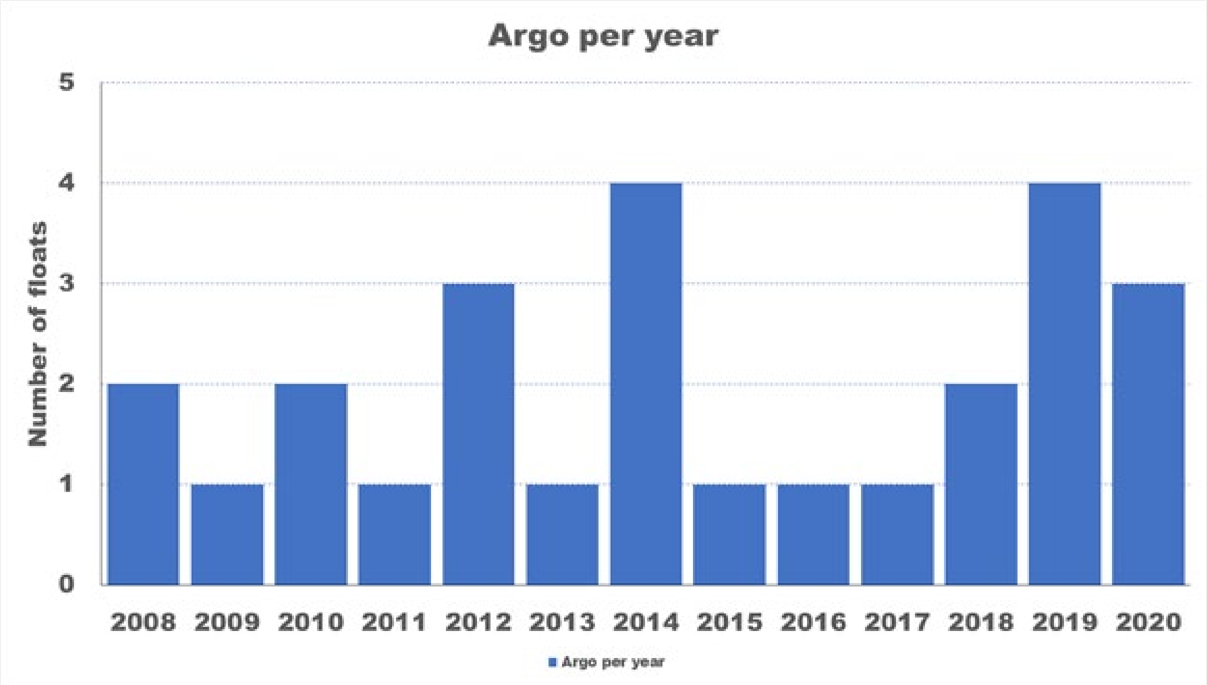


Figure 27. Number of Argo floats per year located in the Gulf of Cadiz from 2008 to 2020 (which includes the 2 Euro-Argo RISE floats).

Float characteristics and frequent configuration

The main characteristics of these floats are:

- The average cycling frequency is in 46% (6) of the cases 10 days but there are 23% (3) of them within 4 days, 15% (2) within 5 days, and 8% (1) within 8 and 1 day.
- 92% (12) have a parking depth of 1000 m and 8% (1) of 350 m
- 92% (12) have ARGOS transmission and only 8% (1) Iridium one.

4 Strategy

Introduction

The current EA strategy (10.13155/48526) has no component for BC regions except for a paragraph in section 2 about the Gulf Stream Extension. Here, we would like to propose a new chapter fully dedicated to “Monitoring BC regions” and based on the current structure used in other chapters. Obviously, this BC chapter will be a continuously evolving text, that will take into account feedback from the implementation of our recommendations. In this first version, as part of D2.3, we will focus on lessons learned from the historical sampling of such regions and explaining what we think to be the European needs and system requirements to reach specific monitoring goals. We will also explain what are the technical advances needed.

1. Gulf Stream Extension

European needs

Weather in Europe is influenced by the atmospheric dynamic over the North Atlantic Ocean. More precisely, the Gulf Stream Extension is one region where air-sea interactions are the most intense and where cyclogenesis (the process of atmospheric storms creation) takes place, which ultimately leads this oceanic region to influence the climate of Europe on seasonal to decadal time scales (Palter, 2015). It is also known that the frontal Gulf Stream system has a deep (i.e. high in altitude) impact on the atmospheric dynamic (e.g. Minobe et al, 2008). Beyond the historical, but wrong, belief that ocean heat transport by the Gulf Stream is the origin of the wild climate of Western Europe (Seager et al, 2002), we want to stretch here the European needs for a better resolved Gulf Stream frontal structure in order to improve the representation of small scale air-sea interactions linked to cyclogenesis and ultimately of weather and climate predictions (e.g. Haarsma et al, 2019; Hirata et al, 2019; Kjellsson et al, 2020). Improving ocean state estimates accuracy and effective resolution in the Gulf stream Extension can be achieved, although not entirely, with an improved ocean sampling with Argo floats, the only ocean interior autonomous and real time monitoring system.

What exists

From 2002 to 2019, a total of 23.531 profiles have been sampled in the GSE area. This sampling can be considered as homogeneous over the seasonal cycle, with about 330 profiles per season (3 months length) each year. Although this represents 3 to 4 times the open ocean Argo sampling target, this is not sufficient to properly resolve the intense meso-scale activity of the GSE.

These 23.531 profiles were sampled from 368 floats, among which only 102 (28%) were deployed in the area. Since 2011, between 5 and 15 floats have been deployed in the GSE. So, more than ⅔ of the floats entering the area were deployed outside of it, mostly to the South of the region. We note a short residence time of floats in the GSE: 27% of the floats stay less than 10 days; 50% of the floats stay less than 30 days, 80% of the floats stay less than 6 months in the area, nearly none of the floats take the shortest path to cross the area from West to East. This highlights the intense eddy activity in the area and its impact on the trajectories of the floats.

The vast majority of floats have the following mission configuration parameters:

- 50% of the floats cycle at 5 days (10% at 1 day and 40% at 10 days)
- 95% of the floats drift at 1000db

We also noted that 60% of the profils have less than 150 points, 20% between 400 and 600 and 20% between 800 and 1000 points.

Lastly, we found that the most frequent float model sampling the Gulf Stream area is the APEX from Webb Research, and then the Solo2; and that if we count the number of profiles managed by each DAC, we have 13 741 profiles managed by AOML (USA), 6 514 by MEDS (Canada) and 3 276 by (Ifremer, France).

Requirements and Technical advances needed

In order to fulfill the European needs with regard to the Gulf Stream Extension region observation with Argo floats, it is required that:

- we increase the residence time of argo floats into the GSE, or that the distance between profiles be reduced to better resolve the sub to meso scale,
- the vertical sampling scheme be increased in order to better resolve the near surface and interior gradient regions (mixed layer and pycnocline transition layer).

In terms of technical advances, the major needs are:

- An effective and automatic 2-way communication system between DAC and floats, in order to seemingly change float configuration parameters (e.g. cycling frequency), this is more than Iridium enabled floats,
- A virtual fleet set of experiments to determine the impact of foreseen float configuration changes onto the North Atlantic Argo sampling.

2. Western Mediterranean BC

European needs

The relative small size of the Mediterranean Sea could accentuate the impact of global warming. So, an increase of physical data could help to identify such changes.

Currently, the typical modified standard parameters for the floats are; cycles of 5 days and parking depth between 350 to 1200.

To improve the knowledge about Boundary currents' physical characteristic status, there is a need to have more data available. It is necessary to deploy more floats in the areas (no registered deployment in the Algerian current). This fact could lead to a better understanding of the boundary currents and thus, the Western Mediterranean circulation. The implementation of biogeochemical floats could be used to understand the whole associated ecosystem.

What exists

Since 2003, only some floats have been deployed inside the boundary currents defined (NC: 8; BC: 1; AC: 0). The total number of profiles registered in the BC are 1805 (NC: 1258; BC: 414; AC: 133) and 2961 in the associated Rossby areas (NR: 1360; SR: 547;AR: 1054) mainly due to the drift of the floats.

Mostly due to the Northern Current, Autumn is the season with more profiles registered and October is the month with a higher value of profiles.

In these areas, the main models of profilers have been Arvor, Apex and Provor.

The residence time ranges vary from 3 to 7 cycles per area. The most registered cycling frequency is 5 days for all boundary currents and the associated Rossby areas. The parking depths (dbar), in the historical data, are set to 350, 700, 1000 and 1200 depending on the area. The most representative vertical sampling scheme is the same for all areas defined (surface: 1 dbar; intermediate: 10 dbar; bottom: 25 dbar) except in the Northern Current (surface: 2 dbar).

Requirements

Recommendations for the Boundary Currents in the Western Mediterranean Sea:

1. The Endurance Line Canales is a ship opportunity (RV SOCIB) to launch the floats. A similar opportunity in the south basin (Algerian current) could help to better study the area.

2. Increase Argo floats deployment in some areas (e.g. Algerian Current Boundary Box).
3. Increase the parking depth of the floats until values deeper than the expected bathymetry, trying to limit the drift at the sea bottom level.
4. Increase the number of floats equipped with biogeochemical sensors.

Technical advances needed

It is necessary to increase the sampling in the south basin (Algerian area).

International collaboration with all the Mediterranean countries (especially in the southern area) it will be necessary to recover and redeploy the floats if they are stranding.

A more efficient use of Ship-of-Opportunity (SOOP) is needed to guarantee frequent deployments.

To improve the validation of the floats parameters, CTD data from ships should be included in the reference Database for the DMQC.

3. Nordic Seas BC

European needs

The plans and European needs for the Nordic Seas Argo deployment strategy were analysed over the SIDERI (Strengthening International Dimension of Euro-Argo Research Infrastructure) and particularly E-AIMS (Euro-Argo Improvements for the GMES marine service) – Deliverable 2.5.1 and 2.5.2. The experiences gained after this period allow the completion of those conclusions or the formulation of new ones. Additionally fast melting of the Arctic Ocean sea ice cover causes opening of the North-East Passage. This forces the need for a thorough monitoring of the northern region, especially WSC, and immediate access to data. At present only Argo floats can provide this.

The European needs are:

1. Intensification of floats deployment
2. Changes deployment strategy (lower parking depth (500 m ?), higher frequency of profiling;
3. Smaller, cheaper floats (shorter lifetime in the Arctic)
4. Under ice navigation systems (RAFOS, Inertial Navigation);
5. Complementary BGC floats
6. Floats recovering ?
7. Better European coordination and collaboration with Russia

What exists

In the West Spitsbergen Current region measurements conducted from research vessels are performed mostly during the summer, other seasons, particularly winter are undersampled. The Institute of Oceanology Polish Academy of Sciences (IOPAN) long – term research project AREX continues measurements in this region every summer, performing about 200 CTD/O2/LADCP profiles (Walczowski at al., 2017). Other institutions, mostly Norwegians (IMR) also perform monitoring cruises to these regions. Round year data are provided mostly by moorings and are not available on short time scales. Therefore the Argo floats are the only source of winter real time data and progress has been made in recent years to sample in the WSC by float deployments through IOPAN. The few floats deployed in the WSC made a significant contribution to the study of these regions. The choice of our launching area and mission parameters has also evolved with time but needs to be optimized with the virtual fleet experiments.

IOPANs experience from the deployed floats has shown that floats' trajectories are very poorly predictable, but some general rules can be derived from the 2019 deployments at 75° N latitude (IOPAN section ‘K’). One float was deployed in the core of the WSC and followed the boundary current continuing over the shelf break to the Fram Strait. The second float was deployed in the ‘Western Branch’ of the West Spitsbergen Current branch and is expected to reach the East Greenland Current together with the recirculation.

Requirements

Oceanographic investigations in the Arctic are expensive. Also deployment of the Argo floats is more expensive than in other regions since floats deployed in the boundary currents rarely live longer than two years. That is why the deployments should be guided by the virtual fleet simulations to optimize pathways and survival rates. On the other hand data for the Arctic from WSC and its continuation the Svalbard Branch are important and with time, as the North-East Passage becomes ice-free and opens for shipping, they will become more and more valuable. For the above reasons, more partners should be encouraged and involved in Argo floats deployment. Russia's involvement is very important. In order to encourage institutions to launch the Argo in this area, it is necessary to produce smaller, cheaper floats with cheap sensors and batteries sufficient to work for two years.

Technical advances needed

In recent years, there has been great progress in the reliability of float operation. Used by IOPAN ARVOR floats work well in the Arctic and in the Baltic Sea. In the Arctic the main problem is sea ice cover. Experience shows that floats may survive under the ice, ice avoiding systems seem to work well. The problem is with the float positioning. Simple data interpolation not always fulfils its role, sometimes positions are determined even on land. Of course, we can write better algorithms (e.g. using the bottom depth to determine the position), but they never match the accuracy of GPS data. The RAFOS system is very expensive. There are currently no RAFOS transmitters in the Arctic. Another option is inertial navigation. Development of cheap and small Inertial Navigation Units (IMU) is fast. The IOPAN experiments with inertial navigation of Argo floats gave promising results. This may be one way of developing under-ice navigation. The problems are still to low precision and high energy consumption.

4. Gulf of Cadiz

At this moment with the few data available for this region it is too soon to propose a strategy for the monitoring of the region with Argo floats. We will continue the analysis of the region based on numerical simulations of Argo floats to overcome float data scarcity (see below), as well as information derived from the two Argo floats deployed under the Euro-Argo RISE project.

5. The way forward

Each of the Boundary Current systems have been synthetically addressed above. This is a first step toward a more precise Euro-Argo strategy with regard to BCs. Over the next 2 years, EA partners will implement four methods to move forward and provide observations recommendations, in link with the work carried out in WP8 (and especially D8.5 for the new strategic plan):

- Develop partnerships and collaborations to ease the realisation of deployments strategies,
- Identify possible synergies of technologies developed to implement plans dedicated to each BS systems,
- Use national resources and if possible EA ERIC capabilities to test existing floats configuration parameters changes and assess the corresponding impact on BC sampling,
- Develop and perform realistic numerical simulations of Argo virtual floats to determine the most appropriate sampling strategies (deployment plans and configuration parameters) in BC.

This last method will be implemented with the numerical Argo fleet simulator “Virtual Fleet” developed as part of Euro-Argo RISE for Task 2.3. Initially planned as an adaptation of an existing software developed by SU, the “Virtual Fleet” software was developed and released by IFREMER in June 2020. After a thorough evaluation in 2019, the SU software was abandoned because it would have been too complex to modify in order to accommodate for the Euro-Argo RISE (i) experiments (virtual Argo floats mission parameters changes, such as parking depth, drifting time) and (ii) partners usage (ease of use and testing). Since its development, the software has been shared on the EA collaborative framework and will be used by the partners for each BC system.

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