

Evolution of a Subducted Carbon-Rich Filament on the Edge of the North Atlantic Gyre

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Key Points:

- Biogeochemical (BGC) Argo profiling floats were used to characterize particulate organic carbon (POC) subduction in the subpolar North Atlantic
- POC subducted from the surface layers during winter or spring can remain in coherent filaments for months after formation
- The persistence of these features emphasizes the importance to understand the circulation at depth to properly quantify its sequestration fate—"Stommel's Demon" applied to POC

Supporting Information:

- Supporting Information S1

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Abstract The oceanic biological carbon pump encompasses a variety of mechanisms by which CO₂, fixed into organic form by phytoplankton, is transported from the sunlit surface layers to the interior ocean. Here, we investigate submesoscale and mixed layer subduction, estimated to represent ~20% of global particulate organic carbon (POC) export. Seven Biogeochemical (BGC) Argo profiling floats were analyzed for evidence of subduction of POC in the North Atlantic Ocean, revealing a pattern in the seasonality. Although vertical processes that give rise to subduction are enhanced during late winter and spring, the bio-optical evidence for intrusions—namely a deep local maxima in POC, co-located with a temperature and salinity anomaly—were more commonly observed in the summer. We hypothesize that these deep intrusions can be long-lived, having been subducted months earlier and persisting at depth throughout the warm season. We present a case study of a notable anomaly, observed in 10 consecutive BGC Argo profiles on the northeastern edge of the subtropical gyre. Analysis of the profiles, complemented by remote sensing and HYCOM model output, provides insight into the history and subsequent fate of the subducted water.

Plain Language Summary The physical arm of the biological pump is a process by which organic carbon formed in the surface ocean is transported vertically (exported) to depth, where it can remain isolated from the atmosphere on seasonal to decadal time scales. Evidence of physical export is identified from optical anomalies in seven profiling floats in the subpolar North Atlantic Ocean, and used to develop a statistical summary of timing and location. We expected to find the highest number of anomalies during the winter to spring transition when vertical subduction is strongest. However, the observations show that the number of positive detections instead peak during the summer. We examine this discrepancy by reconstructing the history of a single deep anomaly observed repeatedly from July to September, and show that the water was likely subducted months earlier. We conclude that in the North Atlantic, the timing of detected features does not necessarily align with timing of mixed layer subduction and that coherent pockets of exported organic carbon can persist for months after formation. These findings emphasize the importance of understanding the deep circulation pathways in determining the fate of organic carbon exported from the surface of the ocean.

1. Introduction

In the upper ocean, primary producers harvest sunlight and fix dissolved CO₂ into organic form through photosynthesis. While much of this organic carbon is retained in the upper ocean cycling through the microbial loop, a small fraction is transported to the deep ocean where it can remain sequestered from the atmosphere on seasonal to decadal time scales. This process, referred to as the biological carbon pump, plays an important role in regulating atmospheric CO₂ concentrations and our climate system. The strength of the biological carbon pump can be quantified as the rate of particulate organic carbon (POC) export from the mixed layer or euphotic zone and is typically ascribed to three main pathways (Bianchi et al., 2013; Burd et al., 2010; Ducklow et al., 2001; Emerson, 2014; Hansell et al., 2009; Steinberg et al., 2000): (I) The gravitational pump: individual cells, aggregates, and fecal particles that are denser than the surrounding seawater and sink, (II) active vertical migration by zooplankton feeding in surface waters and excreting at depth, and (III) the physical arm by which mesoscale and submesoscale processes transport POC-rich waters downward from the surface. The analysis presented here focuses on two mechanisms of physical POC export (III); the mixed layer pump and eddy-driven subduction. This work does not explicitly address subduction of dissolved organic matter since the Biogeochemical (BGC) Argo floats do not measure it, or

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large-scale subduction by Ekman pumping since its contribution to the overall biological pump is thought to be small (Boyd et al., 2019; Resplandy et al., 2019) and Ekman depths rarely exceed mixed layer depths in the North Atlantic.

On a seasonal time scale, the mixed layer pump is established during the late winter/early spring transition when organic particles are distributed throughout the deep winter mixed layers (DWML). As the upper ocean stratifies in the spring, shallow mixed layers are formed at the surface subsequently isolating organic material within the interior (Ho & Marra, 1994). Seasonal mixed layer pumping has been shown to export POC to the interior (Carlson et al., 1994; Dall'Olmo & Mork, 2014), and can occur over a range of time and spatial scales. In high-latitude regions, large seasonal variations in mixed layer depth lead to enhanced subduction, accounting for an estimated 23% of all carbon export (Dall'Olmo et al., 2016) and providing a substantial energy input to the mesopelagic thereby reducing the carbon imbalance in these regions (Lacour et al., 2019).

Eddy-driven subduction is established in frontal regions characterized by strong horizontal surface density gradients where vertical motion can be initiated by baroclinic instabilities resulting from the slumping of outcropped isopycnals (Lapeyre & Klein, 2006). Instabilities drive frontal meander, causing strain, and convergence (Fox-Kemper et al., 2008; Hoskins & Bretherton, 1972), intensifying vorticity on either side of the front and resulting in a breakdown of the geostrophic and thermal wind balances. To restore these balances, an ageostrophic secondary circulation develops in the plane normal to the front (Mahadevan, 2006; Mahadevan & Tandon, 2006) generating eddy-like filaments along sloping isopycnal surfaces delivering submesoscale O(1–10 km) intrusions of surface waters to the interior. Where POC is enhanced in the mixed layer and decreases beneath, this mechanism results in a net downward carbon flux to the interior. Parameterizations based on models and observations suggest that instability driven subduction could contribute to as much as half of the seasonal POC export to depth in some regions (Omand et al., 2015; Stukel et al., 2017).

Observing and quantifying physical export is challenging, as instrumentation can rarely accommodate the spatial and temporal resolution required for direct measurements. The depth and duration of subduction, and the fate of the subducted water all play a part in the efficiency of this mechanism, and remain poorly constrained. In part, the challenge arises from the fact that the relative contribution of physical subduction compared to the other biological pump mechanisms is sensitive to the time scale integrated over in the assessment. For example, the springtime physical export in the North Atlantic (Figure 1a1) can, instantaneously, be as large as the sinking export (Figure 1a2), but since up to 90% of the physically subducted material remains in the seasonal pycnocline above the depth of the deep winter mixed layer (Figure 1b), the annual sequestration of physical subduction is likely only about 20% of the total (Figure 1c) (Lévy et al., 2013).

How effective either the mixed layer pump or eddy-driven subduction are at sequestering POC over the longer term (>1 year) depends on the fate of the organic material once it reaches the interior. If POC is remineralized within the thermocline and re-entrained into the deep winter mixed layer the following winter, it can ventilate back to the atmosphere as CO₂ (DeVries et al., 2012; Palevsky & Nicholson, 2018). Carbon sequestration depends not only on export from the mixed layer, but also on the respiration rates, particle aggregation or disaggregation, and horizontal transport within the interior. Essentially, this is “Stommel's Demon” applied to POC export (Stommel, 1979). In this study, we will show that coherent filaments of POC can persist for months after subduction, emphasizing the importance of understanding the deep circulation in determining net sequestration.

Llort et al. (2018) was the first to use BGC Argo deployed through the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) experiment to detect features of physical export. This study analyzed over 4,000 profiles collected between 2012 and 2016, spanning all seasons and distributed throughout the Southern Ocean. Of these, they detected 40 profiles associated with subduction events, with 75% occurring in the late spring and summer. Features were unevenly distributed and seemingly located downstream from major bathymetric features and hot spots of eddy kinetic energy. To date, a comparable basin-wide, statistical summary has not yet been completed for the subpolar North Atlantic. A starting point of this analysis was to evaluate if the current number of BGC Argo platforms in the subpolar North Atlantic could provide that statistical overview of spatial and temporal patterns in this region, similar to what has been done by Llort et al. (2018).

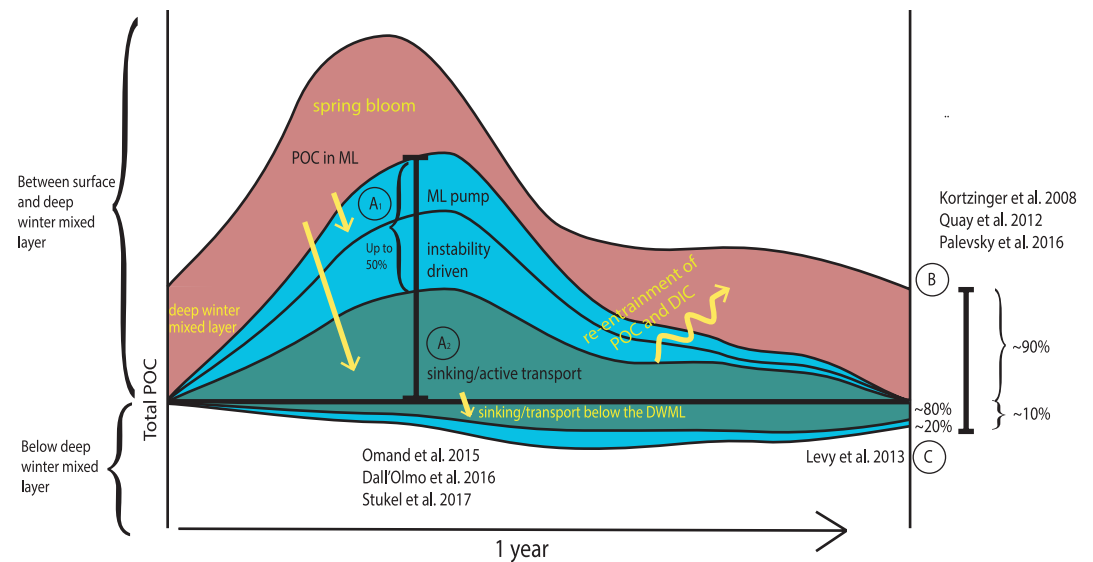


Figure 1. A conceptual rendering of an annual cycle of POC in the mixed layer (red), the seasonal pycnocline (blue and green regions above the x-axis), and sequestration below the depth of the deep winter mixed layer (blue and green regions below the x-axis). Starting at the left side, the mixed layer is at its deepest, and all POC is in the mixed layer (red). As the water column restratifies, some of the POC from the mixed layer is subducted (a_1 : blue) or exported through sinking or active transport (a_2 : green) into the seasonal pycnocline (Dall'Olmo et al., 2016; Omand et al., 2015; Stukel et al., 2017). In the fall, the mixed layer deepens and re-entrains a majority of the previously exported POC (much of which has been remineralized to dissolved inorganic carbon, DIC) (b: Kortzinger et al., 2008; Palevsky et al., 2016; Quay et al., 2012), leaving behind a small portion within the interior that has been advected out of the region of deep mixing (blue region below DWML) or has sunk past this depth (green region below DWML) (Levy et al., 2013). This deep POC (c) is sequestered from the atmosphere for at least one annual cycle. The decrease in integrated POC above and below the winter mixed layer reflects remineralization of organic material to DIC.

The subpolar North Atlantic has long been characterized by deep winter mixed layers, strong horizontal frontal regions, and a pronounced spring phytoplankton bloom. The regional patterns in export flux that result from the combination of these processes are not as well established. Theory and models suggest both eddy-driven subduction and the mixed layer pump are initiated in frontally intensified regions and enhanced by strong atmospheric forcing. Thus, the Northeastern Atlantic in particular, has been the focus of a number of subduction studies (Joyce et al., 1998; Marshall et al., 1993; Weller et al., 2004) as the region is characterized by strong horizontal buoyancy gradients where the Gulf Stream interacts with northern subpolar waters. The Labrador and Irminger Seas are also theorized to be hotspots for physical export as they experience intermittent and deep mixing which enhances both the mixed layer pump and phytoplankton production in the surface waters. Thompson et al. (2016) used a year-long record of glider observations in the North Atlantic subtropical gyre to show that the baroclinic instabilities required for submesoscale vertical motions are more prevalent during the winter months (December–April). These conditions initiate instabilities that can drive subduction from the mixed layer.

The spring phytoplankton bloom in the subpolar North Atlantic is one of the largest and most intense globally, and typically occurs in April or May. Forced by the restratification of the mixed layer, the abundance of nutrients and enhanced sunlight (Siegel et al., 2002; Sverdrup, 1953; Townsend et al., 1994), organic carbon in the surface layers peaks around this time and steadily decreases throughout the summer until it rapidly declines in the fall. The bloom intensity is not homogeneous as phytoplankton are stirred by eddies and growth is amplified by restratification, convective mixing, and strong atmospheric forcing (Dutkiewicz et al., 2001; Mahadevan et al., 2012; Williams & Follows, 2003). Lacour et al. (2019) used BGC Argo floats, spatially concentrated within and near the Labrador Sea, to explore the seasonal mixed layer pump. They found a strong correlation between POC stocks in the remnant layer (defined as the vertical region of the water column between the maximum chlorophyll gradient and the density defined mixed layer depth) and

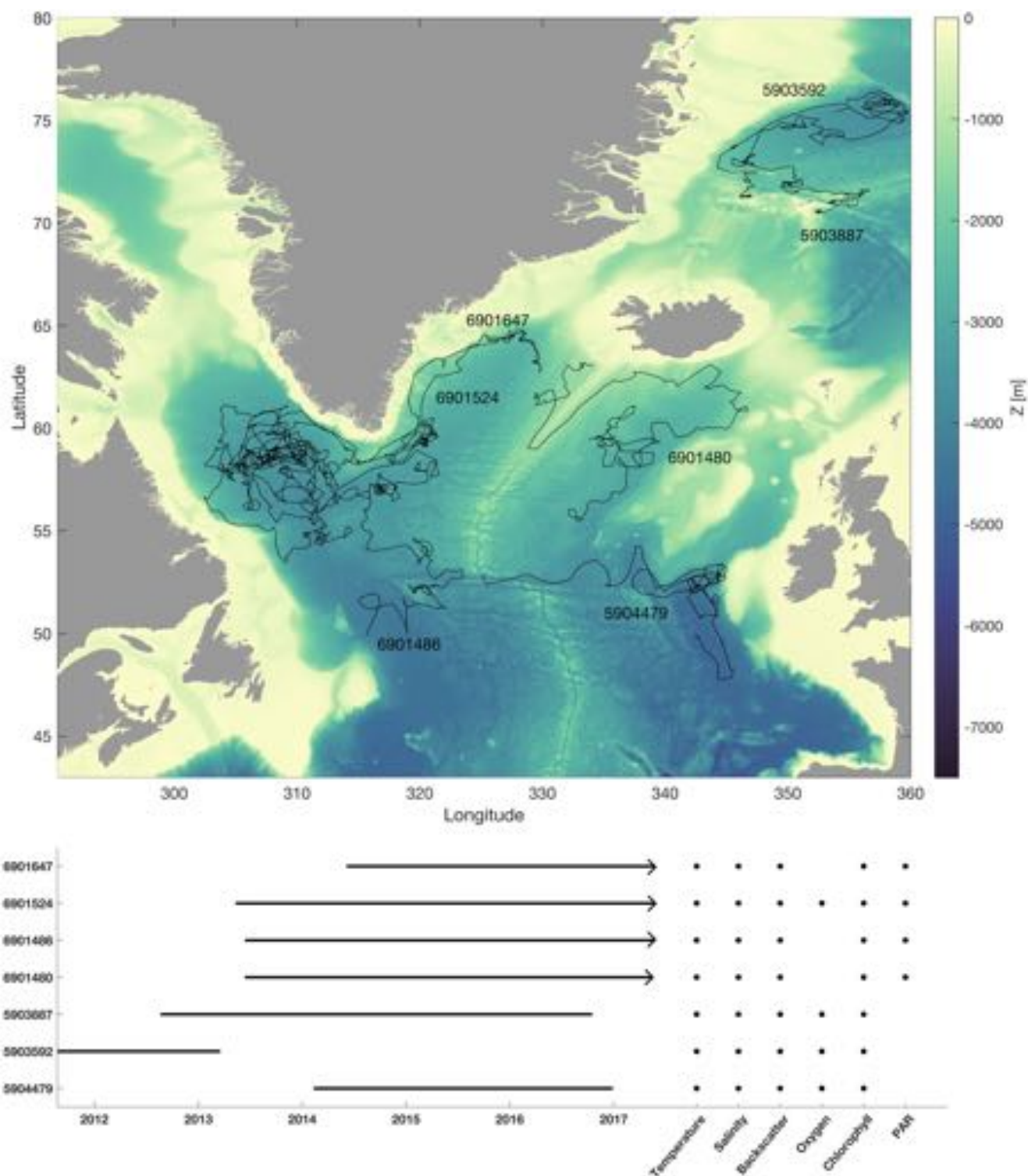


Figure 2. Labeled trajectories of the BGC Argo floats analyzed in this study (top) with corresponding lifespan and measured variables (bottom). BGC, Biogeochemical.

the variability of the mixing layer depth forced by the intermittency of the net heat flux in the spring over a time frame of about 1 month.

Part I of this study utilizes a subset of the BGC Argo floats in the subpolar North Atlantic to observe bio-optically derived features of physical subduction, and aims to expand the statistical analysis of Llort et al. (2018) to this region. In Part II, we examine a single float record and reconstruct the history of a subducted POC-rich filament on the edge of the subpolar and subtropical gyres.

2. Data and Methods

Data from seven BGC Argo floats (Figure 2) were searched to identify features of physical carbon export. Measurements were collected during ascent every 2–10 days (depending on the float mission). The floats used for this analysis were required to have sensors co-located that provide temperature, salinity, and optical backscatter with a vertical resolution of 2 m in the mesopelagic zone (100–1,000 m). Ideally, the floats also measured dissolved oxygen, chlorophyll fluorescence, and photosynthetic available radiation (PAR) but these were not a strict requirement for this analysis (see chart of the measured variables in Figure 2). The seven floats that met our criteria at the time of analysis can be obtained from the Global Data Assembly Centre (ARGO GDAC: <https://www.seanoe.org/data/00311/42182/>) together representing a total of 1,956 profiles over all seasons in the subpolar North Atlantic Ocean.

2.1. Biogeochemical Sensors and Derived Properties

Floats used for this study were equipped with WET Labs ECO sensors. The backscatter channel (b_{bp}) sensor, central to this analysis, emits pulses of light at a known wavelength (here 700 nm) which is scattered by seawater and suspended particulates and detected at an obtuse angle. The backscatter signal strength depends on the size, shape, and composition of the particles and, when subtracted from the coefficient for pure seawater, is a proxy for suspended particle concentration.

Quality-controlled backscatter data were smoothed using a five point median filter to remove high frequency fluctuations from the background signal. These fluctuations, commonly referred to as “spikes,” are associated with large sinking particles or aggregates (Briggs et al., 2011). The background b_{bp} signals, associated with small particles in the water column, are then converted into POC_{bbp} using an empirical formula which varies based on particulate composition and location. Here, we applied a formula defined for the North Atlantic during the spring bloom by Cetinić et al. (2012): $POC_{bbp} [mgC\ m^{-3}] = 3.5 \times 10^4 \times b_{bp} [m^{-1}] - 14.4$.

Chlorophyll-a fluorescence (ChlF) is a widely used proxy for phytoplankton biomass and is measured by WET Labs ECO pucks on BGC Argo floats. Fluorometers emit pulses of light absorbed by chlorophyll molecules in the blue part of the visible spectrum that are fluoresced or re-emitted in the red spectrum. The ChlF profiles were spike filtered in the same fashion as b_{bp} . ChlF data were not used quantitatively in this analysis but rather to confirm that the backscatter anomalies were often also associated with elevated ChlF, verifying that these optical features were biologically derived. ChlF was additionally used to approximate the depth of the euphotic zone as described in the Supplementary Information (S1).

Oxygen was measured by either Sea-Bird or Aanderaa oxygen optode sensors on the floats. These optode sensors measure the emitted luminescence phase shift relative to the excitation which is reduced in the presence of oxygen. On BGC Argo floats, oxygen optode sensors are typically calibrated and drift corrected by measurements of atmospheric O_2 each time the float surfaces (Bittig & Körtzinger, 2015). To identify features of physical subduction, dissolved oxygen concentration was used with temperature, salinity, and pressure to calculate apparent oxygen utilization (AOU), a measure of biological activity a water parcel has experienced since it was last in equilibrium with the atmosphere. AOU was calculated as the oxygen saturation level based on the physical properties minus the measured oxygen ($AOU = DO_{sat} - DO_{measured}$).

Photosynthetic available radiation (PAR) was measured by Sea-Bird Scientific OCR series radiometers on some of the floats. These radiometers have three channels for wavelength-specific irradiance and a sensor for photosynthetically available radiation. The sensors integrate the downwelling cosine irradiance in the

visible spectrum and provide an estimate of the light available for primary productivity in the water column. Euphotic depth, the regions of the upper ocean with enough light to support photosynthesis, is defined as the depth where PAR is 1% of the surface value. The PAR sensors were used to validate our method for deriving euphotic depth as described in the Supplementary Material.

2.2. Supporting Data

This analysis includes three additional sources of supporting data, HYCOM, MODIS ocean color, and MIMOC. The HYbrid Coordinate Ocean Model (HYCOM) is an ocean general circulation model publicly available at <https://www.hycom.org>. The hybrid coordinate system is isopycnal in the open ocean, bathymetric following in coastal regions and z-level in the mixed layer or unstratified ocean. In the North Atlantic, HYCOM output has a $1/12^\circ\text{lon} \times 1/24^\circ\text{lat}$ horizontal resolution, 41 vertical layers, and temporal frequency of 3 h. The model uses the Navy Coupled Ocean Data Assimilation (NCODA) system which uses the 24-h model forecast as a first guess and assimilates available satellite and in-situ observations of ocean temperature, salinity, wind, and currents. HYCOM temperature and salinity were found to be in excellent agreement with the float data used here. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the NASA Aqua satellite, measures sea surface temperature and POC binned into monthly and 8-days averages at 9 km spatial resolution. NASA MODIS-Aqua data were obtained from <https://oceandata.sci.gsfc.nasa.gov>. The Monthly Isopycnal and Mixed Layer Ocean Climatology (MIMOC) (Schmidt et al., 2013) is a collection of monthly ocean property maps assimilated with 50 years of Argo and shipboard CTD measurements and obtained from <https://www.pmel.noaa.gov/mimoc/>.

2.3. Identifying Subducted Anomalies

Evidence of physical subduction of organic carbon was manually identified in the seven BGC Argo float records using the following criteria (first defined in Omand et al. (2015)): (I) A subsurface local maximum of median filtered POC_{bbp} below the mixed layer and euphotic zone (II) associated with elevated values in ChlF and/or a decrease in AOU with (III) corresponding anomalies in the temperature and salinity profiles (Figure 3). The sign (positive vs. negative) of the temperature and salinity anomalies varied, depending on the characteristics of the originating water. After directing effort toward an automated identification algorithm, we decided to search through the profiles manually. We found that older features were not always colocated with a minimum in AOU, and the size and strength of features varied widely. However, since each biogeochemical property used in this analysis was measured from independent sensors, by confirming that multiple biogeochemical and physical parameters were correlated over the scale of the feature, we were able to minimize any false identifications based on spurious data. All 1,956 float profiles were vetted in this fashion.

2.4. Basin Scale Parameterization of Physical Subduction

In an effort to examine the physical context for the spatial and temporal patterns of the detected features, we utilized a basin scale parameterization of mixed layer instabilities derived by Fox-Kemper et al. (2008). This approach parameterizes the overturning stream function ψ_e ($\text{m}^2 \text{s}^{-1}$) which can result in the exchange of water between the mixed layer and pycnocline and resembles a type of vertical diffusivity resulting from ageostrophic dynamics: $\psi_e \sim C_e M^2 H^2 f^{-1}$ where $C_e = 0.08$ is a scaling constant, M^2 (s^{-2}) is the horizontal buoyancy gradient derived from the daily HYCOM $1/12^\circ$ grid central-differenced surface density for the calendar year 2015, H (m) is the mixed layer depth obtained from MIMOC interpolated to a corresponding horizontal grid resolution and f (s^{-1}) is the Coriolis parameter. The lateral density gradients (M^2) derived from this method were comparable in magnitude to that found from the OSMOSIS experiment (Thompson et al., 2016) lending some confidence that we are able to approximate the relevant frontal properties using the model output.

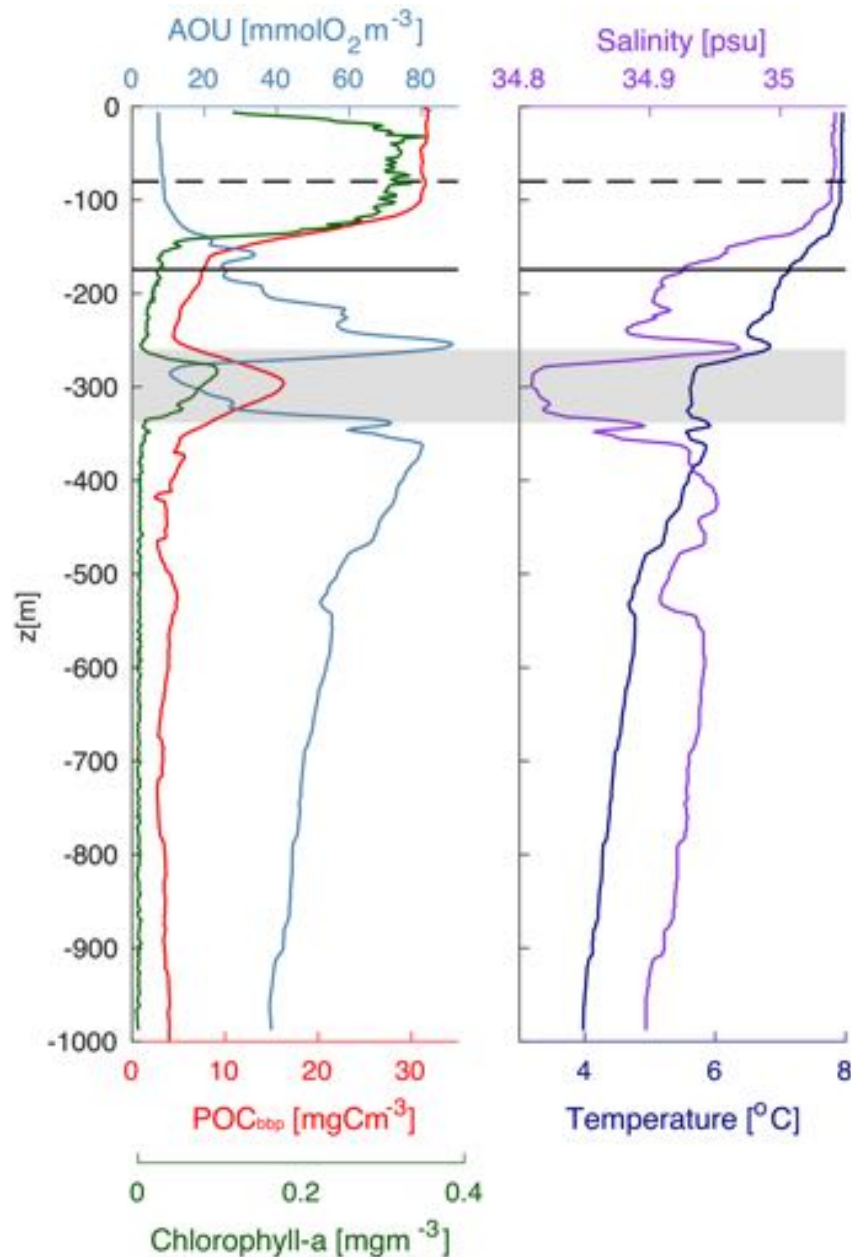


Figure 3. An example of a detected subduction feature (gray shaded region) below the mixed layer and euphotic depth (dashed and solid horizontal lines, respectively) from float 5904479. Feature was observed on April 7, 2014 at 52.648°N, 332.312°E. Biogeochemical properties are shown on the left and physical properties on the right.

3. PART I: Timing and Location of POC-Rich Intrusions in the North Atlantic

3.1. Physical Context

Hotspots of mixed layer instabilities were examined using the parameterization described in Section 2.4 and derived by Fox-Kemper et al. (2008). The 2015 annual average is shown in the Supplementary Material (S2). Large ψ_e is a potential predictor of a large subduction rate, as shown at the frontal boundary of the East Greenland Current and the region of high submesoscale activity in the Iceland Basin. To obtain a view of the temporal variations, ψ_e was calculated along each float trajectory for the corresponding time step of model output (Figure 4b). Results from the parameterization are generally in agreement with Thompson

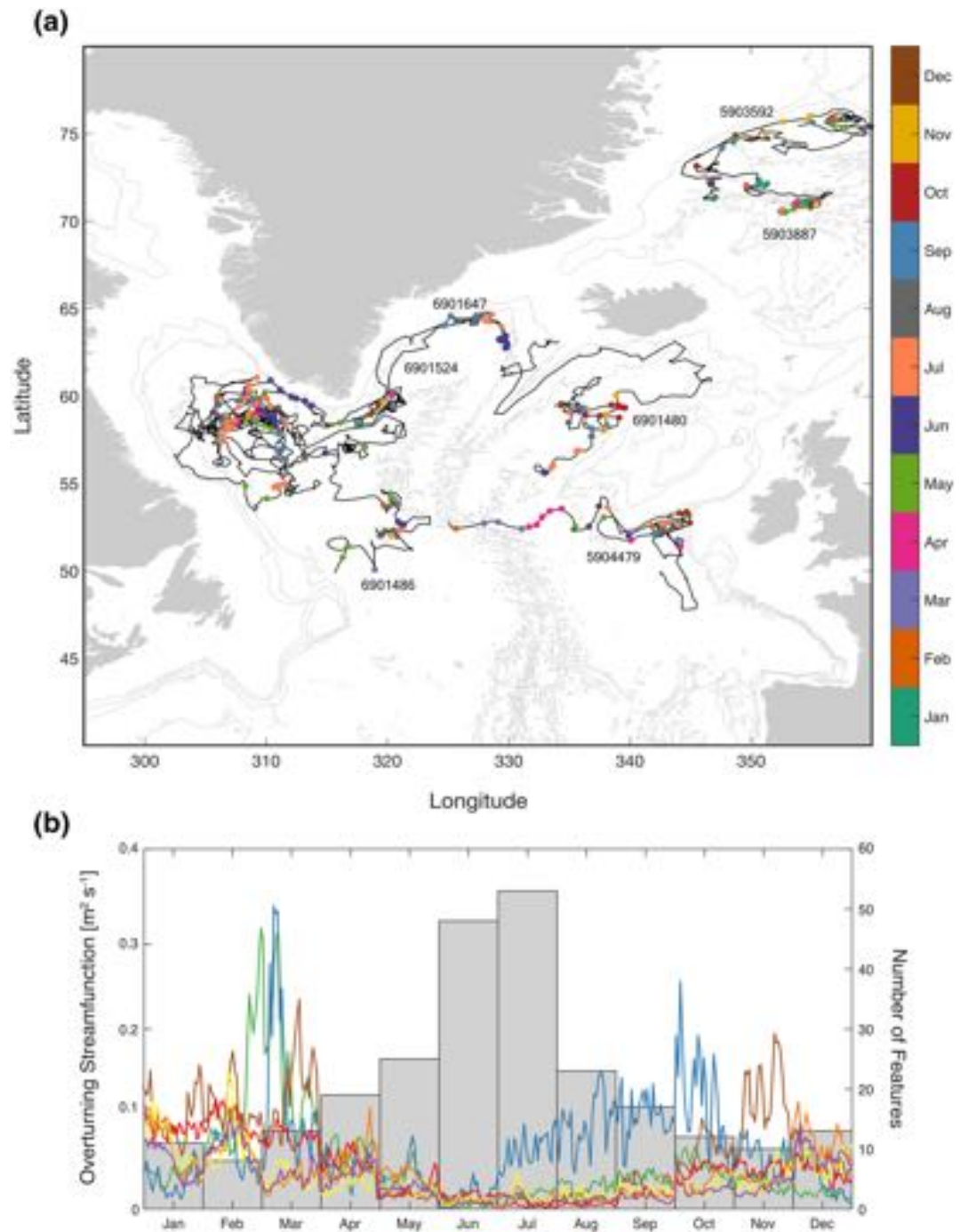


Figure 4. (a) Identified feature locations overlaid on contours of bathymetry in the North Atlantic and colored by the month of the year in which they were observed. (b) A histogram of the number of features detected each month (gray bars) overlaid with the ψ_e extracted from the corresponding model grid cell along the trajectory of each float. This panel demonstrates that although subduction processes are often largest in winter, the POC_{bbp} features are detected most frequently in the summer. Floats correspond to the following colors: float 5904479 (red), float 6901480 (brown), float 5903887 (green), float 5903592 (blue), float 6901486 (yellow), float 6901647 (purple), and float 6901524 (orange).

et al. (2016), showing the highest rates of physical subduction in winter. In summer, the rates drop very low for all but float 5903592 (blue) which hugs the Greenland Current and remains high throughout the year.

3.2. BGC Argo Float Analysis

The seven BGC Argo floats used in this study were broadly distributed throughout the North Atlantic, with three in the Labrador Sea region, two in the Greenland Sea, one in the Iceland Basin, and one in the North Atlantic Current on the eastern side of the basin. Evidence of subduction was detected in every float record. In total, about 13% of all profiles contained features characterized by the criteria described in Section 2.2. The spatial patterns in these features (Figure 4a) were not obviously related to the spatial distribution of ψ_e (S2).

Temporal trends, on the other hand, were evident. Anomalies were least often observed during the early winter months, increasing in occurrence during the spring and early summer and peaking in June and July (Figure 4b, histogram). This pattern persists after the data is normalized for profile effort, suggesting that the pattern is indeed representative of basin-wide seasonality and not a sampling bias. The summertime peak in occurrence is in apparent disagreement with Lacour et al. (2019) who finds conditions in the North Atlantic that favor mixed layer pump subduction of POC in the spring months. Additionally, as physical subduction heightens in the late winter months, as shown by Thompson et al. (2016) and our parameterization (Figure 4b, colored lines), we theorized that maximum physical subduction of organic carbon would occur when physical export mechanisms coincide with the onset of the spring bloom.

We believe that this apparent discrepancy can be explained by a few factors. One, the method of feature detection described in Section 2.4 requires that the anomalies be below the mixed layer, meaning that either the anomaly was advected laterally under more stratified water, or that seasonal stratification has become established above it. Additionally, we require a detectable anomaly in POC_{bbp} —something that is less likely to occur in the winter when primary production is very low. This method favors detection of events that occurred during the spring bloom and persisted for long enough to laterally intrude beneath other water masses or until the water column stratifies above them.

Second, we suspect that these features can be long-lived, making the histogram of their occurrences more like an integrated probability (a cumulative distribution function) instead of a probability distribution such as that reflected by the parameterized overturning stream function in Figure 4b. However, because these features do not last forever—as they are remineralized and mixed away over time—their temporal distribution is really more likely a hybrid between a PDF and a CDF. This additionally means that we cannot assume the time and location of observation always corresponds to the time and location of subduction since long-lived anomalies could be subjected to significant advection once within the interior.

4. PART II: Case Study of a Single Deep Anomaly

Results from Part I imply that the anomalies detected during summer are long-lived, and were more likely formed in late winter or spring. We explore this idea in more detail by focusing on a single float, Apex float 5904479 in the southeastern region of the North Atlantic, located on the boundary between subpolar and subtropical gyres (see Figure 2). This float record contained a number of strong and well-defined anomalies in backscatter-derived POC_{bbp} . These anomalies appeared when the float was located on the edge of the North Atlantic Current close to the site of previous subduction experiments (Joyce et al., 1998; Marshall et al., 1993; Weller et al., 2004). This location is also of interest because it is in proximity to the North Atlantic EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) field site.

Ten consecutive profiles collected between July and September 2015 showed a strong subsurface POC_{bbp} peak occurring between 150 and 450-m depth (Figure 5). This POC_{bbp} record also shows additional weaker anomalies occurred during the spring and summer in 2014 over a similar depth range. These features were accounted for in our statistical assessment from Part I. We also make note of a broad, deep backscatter spike appearing in July 2015. Due to the depth, vertical extent, and a lack of AOU/Chl a /T/S anomaly, we think this may be evidence of a deep sedimentary plume rather than POC.

During this 2-month period, the float completed a clockwise loop seemingly associated with an anticyclonic eddy on the order O(10–100 km) (see white line in Figure 7). The peak POC_{bbp} was patchy, ranging from

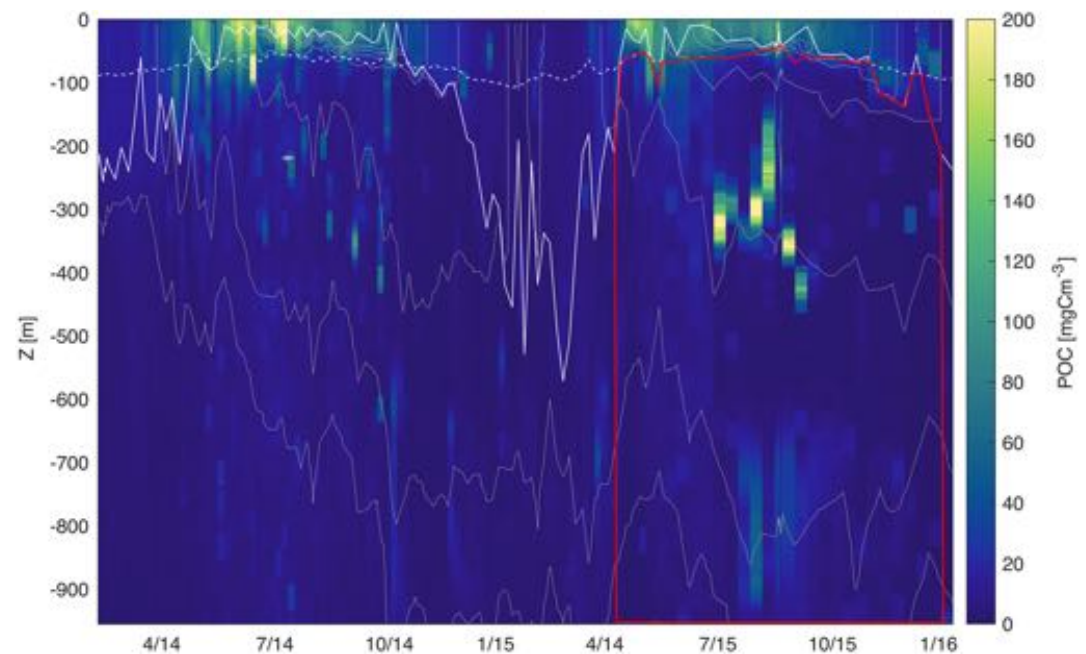


Figure 5. Backscatter-derived POC record from float 5904479. The features of interest are found between 150 and 450-m depth in July through September 2015. The mixed layer depth is shown as the thick white line, isopycnals in gray, and euphotic depth as the dashed line. The red box defines the region of data used in the T-S diagram of Figure 6. POC, particulate organic carbon.

roughly 100 to 200 mgC m^{-3} , and approximately followed the $27.15 \pm 0.05 \text{ kg m}^{-3}$ isopycnal (Figure 5). Tracing this isopycnal back in time to the surface suggests outcropping during the previous spring. However, because BGC Argo floats are Lagrangian only at 1,000 m parking depth, we do not assume that the carbon-rich feature originated when and where the float observed the outcropping. It is clear in fact that the float did not observe the POC_{bbp} during subduction, because the concentration is not high along the path of the density contour. Instead, we used the corresponding temperature and salinity anomalies on the feature and assume that in the absence of major diffusion, water mass properties are conserved once they are exported from the mixed layer. The POC_{bbp} anomalies occurred at an inflection point in T-S space (Figure 6) indicating that the anomalous water is “spicier” (warmer and saltier) than surrounding waters and further reinforcing the likelihood that these features occurred along isopycnal intrusions originating elsewhere. Temperature and salinity ranged between 10.6 and 11.2°C and 35.41 – 35.51 psu. To predict the timing and location of subduction, we traced this combination of temperature and salinity to the mixed layer in the HYCOM ocean model.

4.1. Reconstructing the Origin of the Anomaly

HYCOM model output analyzed from the year previous to these observations (July 2014 to July 2015) shows 6 months (December 2014 to May 2015) where the physical properties of the mixed layer matched those detected on the feature (Figure 7). The regions that possess this T-S combination (colored regions) are notably localized, and generally occur south of where the features were observed. We note that an identical analysis was completed with MIMOC climatology and provided very similar results to the HYCOM analysis, with the same temporal and spatial offset.

We next used Aqua MODIS SST and POC averaged over these regions to evaluate how physical and biological properties covaried throughout the year (Figure 8) and specifically during the months identified where mixed layer properties aligned with the feature (gray shaded region). Overall, we find spatially and temporally averaged sea surface temperature and POC declined through December and into January. Both were at a minimum in March, just before a spring bloom caused POC to spike to a maximum in April. At this time, temperature increased, presumably as the surface layers stratified and the mixed layer shoaled. In May, surface POC dropped from its peak but remained fairly high, gradually decreasing over the summer

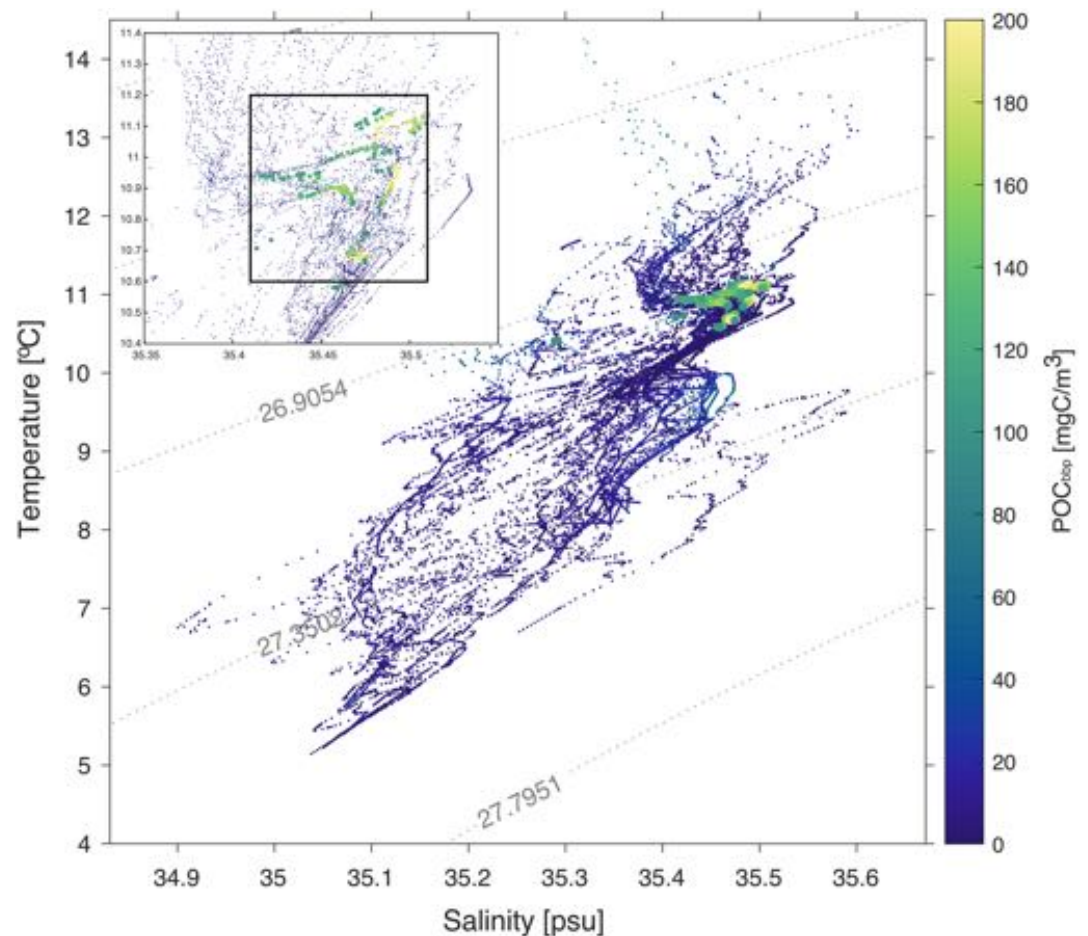


Figure 6. Temperature and salinity diagram of float 5904479 below the euphotic and mixed layer depths (region defined in red in Figure 5) with colors representing POC concentration. The inset (top left) focuses into the feature, found between 35.4 and 35.5 psu and 10.6°C–11.2°C (black box). POC, particulate organic carbon.

months. This suggests that April 2015 was the only month where POC was high enough in the source region to explain the observed concentrations on the features.

We can further corroborate our hypothesis that the anomaly was subducted months earlier than detection, with an analysis of the apparent oxygen utilization (AOU). Once subducted, the bloom material likely underwent bacterial remineralization, depleting POC on the feature and increasing the AOU—a reflection of the biologically mediated oxygen change since the water was last in contact with the atmosphere. The AOU associated with these anomalies ranged between 20 and 30 mmol O₂ (not shown), values that are low for this depth, but also positive—indicating that bacterial respiration has offset any (super)saturation contributed by bloom photosynthesis. By assuming an AOU_{surf} value of roughly 0 mmol O₂ m⁻³ (reflective of the spring bloom which can typically range between -10 and 5 mmol O₂ m⁻³), we can estimate a remineralization rate and make a back-of-the-envelope calculation of what the POC concentration might have been when the feature was at the surface.

Since subduction, we assume an elapsed time (Δt) of 90 days and a change in AOU (ΔAOU) of 25 mmol O₂ m⁻³. Thus, we estimate a remineralization rate (r) according to (1)

$$\Delta \text{AOU} = r \times \Delta t \quad (1)$$

of 0.27 mmol O₂ m⁻³ d⁻¹. Remineralization rates can vary locally and depend on a number of factors, including species composition, nutrient, and oxygen availability as well as temperature and other physical

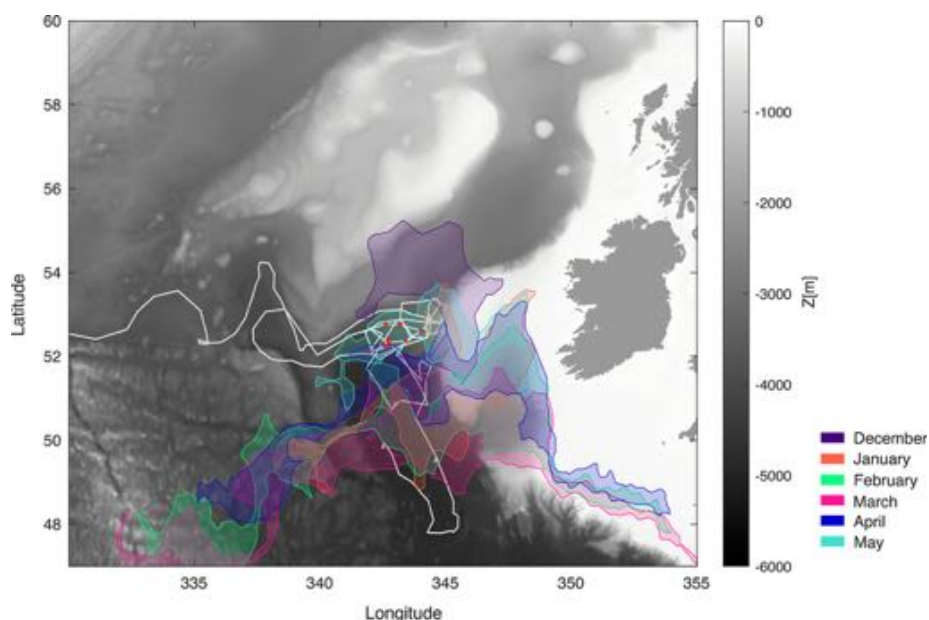


Figure 7. Regions where mixed layer temperature ranges between 10.6°C and 11.2°C and salinity between 35.41 and 35.51 psu by month from HYCOM model output. Regions are overlaid on bathymetry and float trajectory where red dots indicate the feature location. HYCOM, HYbrid Coordinate Ocean Model.

parameters. As such, there exists a very large range and uncertainty in remineralization rates of any particular water parcel. In the North Atlantic, rates have been reported between 0.02 and 0.4 mmol O₂ m⁻³ d⁻¹ (Jenkins, 1982; Omand et al., 2015; Palter et al., 2005). Our rate is consistent with the higher end of this range, unsurprising given the high concentration of available organic substrate, and consistent with rates for similar features detected during the North Atlantic Bloom Experiment of 2008 (NAB08). These higher remineralization rates are likely reflective of elevated bacterial activity as fresh, labile, bloom material is consumed, whereas the lower number reported in Jenkins (1982) and Palter et al. (2005) represent more of a basin average.

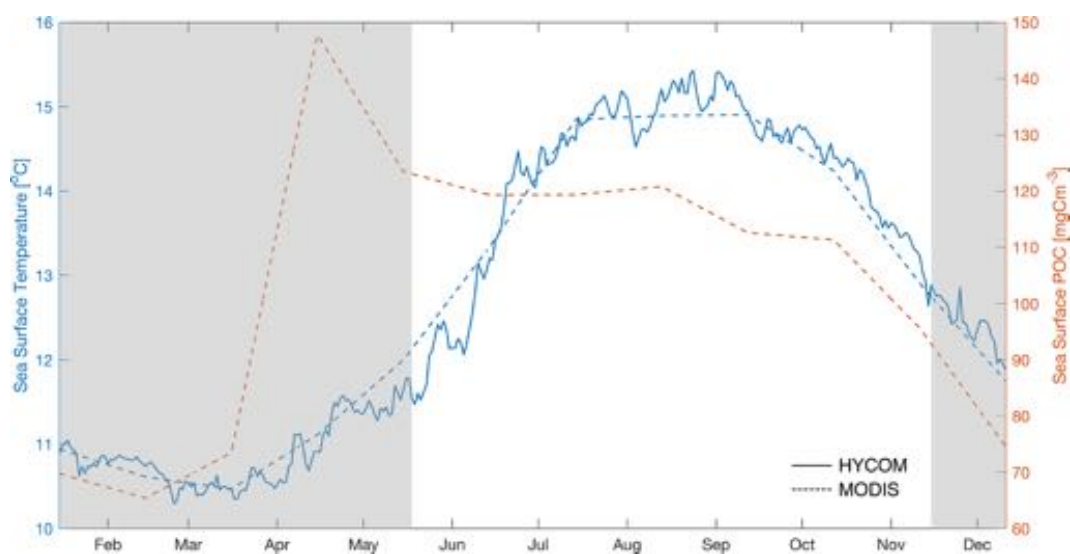


Figure 8. Sea surface temperature (blue) and sea surface POC (red) throughout 2015 averaged over regions found in Figure 7. HYCOM data are plotted in solid and MODIS-Aqua in dashed lines. Months where physical properties of the mixed layer align with those on the feature are shaded in gray. POC, particulate organic carbon; HYCOM, HYbrid Coordinate Ocean Model; MODIS, Moderate Resolution Imaging Spectroradiometer.

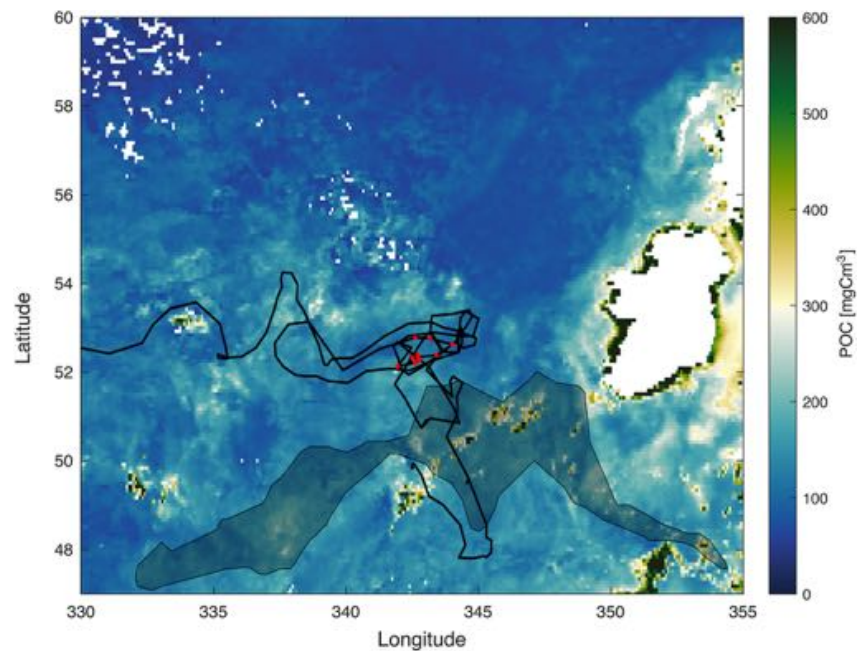


Figure 9. Sea surface POC measured by satellite MODIS during the first week of April 2015. Green patches indicate locations where POC at the surface is high enough to be the originating bloom of our feature. Shaded region indicates where HYCOM mixed layer temperature and salinity matches that on the feature. Trajectory of float 5904479 is shown in black and feature location in red. POC, particulate organic carbon; MODIS, Moderate Resolution Imaging Spectroradiometer; HYCOM, HYbrid Coordinate Ocean Model.

Using an estimated value of $\Delta\text{AOU} = 25 \text{ mmol O}_2 \text{ m}^{-3}$ and the feature-averaged POC_{feat} of 150 mgC m^{-3} , molecular weight (12 g mol^{-1}), together with the photosynthetic quotient ($\text{PQ} = 1.5$, the ratio of oxygen released to carbon dioxide acquired during bacterial respiration), we were able to predict a value of POC_{surf} :

$$\text{POC}_{\text{surf}} = \text{POC}_{\text{feat}} + 12 \frac{\Delta\text{AOU}}{\text{PQ}} \quad (2)$$

This similarly back-of-the-envelope calculation suggests a surface POC of around 350 mgC m^{-3} . This concentration is within the range of patchy spring blooms in the North Atlantic, which can reach POC concentrations of up to 600 mgC m^{-3} or higher (Ducklow et al., 1993).

Remotely sensed sea surface POC during April confirms the existence of a patchy spring bloom (Figure 9). During the first week of April, elevated patches of high POC occurred mainly to the south of the float observation—overlapping with our predicted subduction region (gray shaded region, Figure 9). Together, these observations provide further evidence that this POC_{bbp} rich feature observed by float 5904479 was subducted in April 2015 on nominally the 27.15 kg m^{-3} isopycnal. Once exported from the mixed layer, it was laterally advected about 300 km to the north, where it was observed by float 5904479 in July through early September.

4.2. Fate of the Subducted Water

The overall efficacy of the biological pump depends, not only on the amount of carbon exported from the mixed layer, but also the portion of that carbon which remains below the mixed layer. While physical subduction can seasonally account for a large percentage of the export out of the mixed layer (Figure 1a1), much of this carbon is re-entrained the following winter (Figure 1b), ultimately rereleasing any organic carbon back to the atmosphere over a seasonal cycle as depicted in Figure 10a. If that carbon is exported below the depth of the deep winter mixed layer (Figure 1c), for example, by moving laterally to a region where winter mixing is weaker (Figure 10b), it can remain sequestered from the atmosphere on multiyear time scales. This is, in effect, the ventilation of the thermocline or “Stommel’s Demon” applied to POC

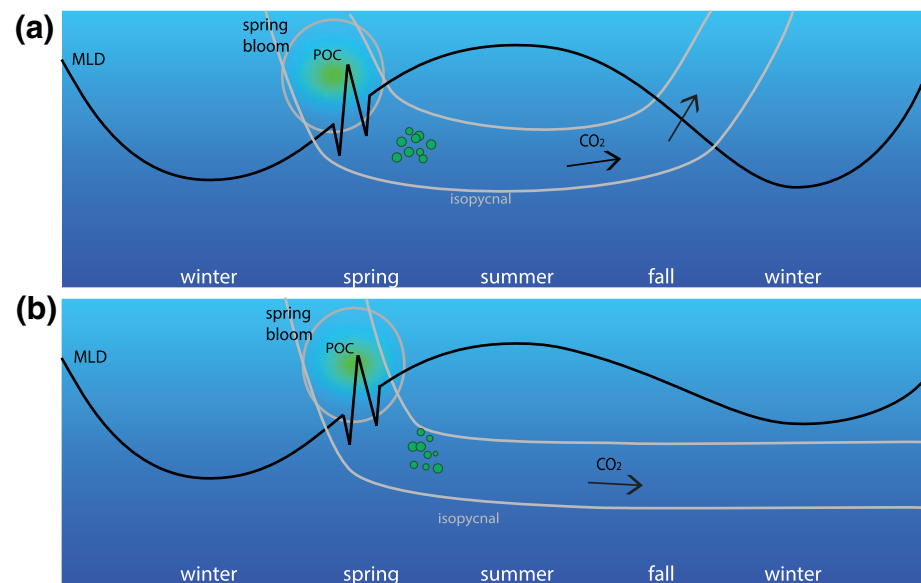


Figure 10. Lagrangian cartoon of POC export from the surface mixed layer during the spring bloom and subsequent fate the following winter. (a) A scenario in which POC is transported north or retained in the subpolar gyre. (b) A scenario in which POC is transported into the subtropical gyre where winter mixed layers are shallow. Black line represents mixed layer depth and gray lines represent isopycnals. POC, particulate organic carbon.

(Stommel, 1979). During summer 2015, float 5904479 was located between the subpolar and subtropical gyres. This is a unique location in context of large-scale subsurface circulation as the fate of the organic carbon ultimately depends on which gyre these anomalies enter—potentially resulting in either of the scenarios depicted in Figure 10.

To further assess where the features in our case study may have originated, and where they may end up when mixed layers deepen during the following winter, 10,000 particles were seeded within HYCOM north/southward velocity fields at the estimated time, depth, and location of subduction (April 1, 2015, 300-m depth, red box Figures 11 and 12, respectively). Simulated particle trajectories were constructed by calculating the magnitude and direction of the current velocity at the location of the particle and advancing it forward in time and space, where velocities were recalculated at the updated position and time step. This process was repeated for one full year to account for the deepest winter mixed layers in the region. A small number of particles were grounded on the slope of the Porcupine Bank and Rockall Plateau and were subsequently removed from the analysis. The resulting particle distribution was evaluated at the date of the last time the anomaly was observed by the float (early September 2015) and at the final time step on April 1, 2016.

Between April and September 2015, of the 10,000 particles released from the subduction region ~47% remained within a 300-km radius (Figure 11). This result substantiates our suspicion that due to fairly weak mean flows at depth, a subducted parcel of water could persist without being laterally transported a significant distance away from the generation site.

After 1 year (April 2015–2016), the final distribution of particles is further diffused (Figure 12). Of the 10,000 particles released, only 8% now remain within the 300-km radius. Of the particles found to travel further than the local radius, 58% traveled to the north, and appear to branch off into two directions, most to the northeast and into the Faroe Shetland Channel while the remainder are diverted to the northwest toward the Reykjanes Ridge. The remaining 42% of the particles traveled to the south where they were entrained by the eastern component of the subtropical gyre.

The final particle distributions were compared to the deepest winter mixed layers, calculated from HYCOM over this time range (contours, Figure 12), to examine whether they traveled to regions that could result in long-term (>1 year) sequestration. HYCOM allows us to only account for horizontal velocity fields to

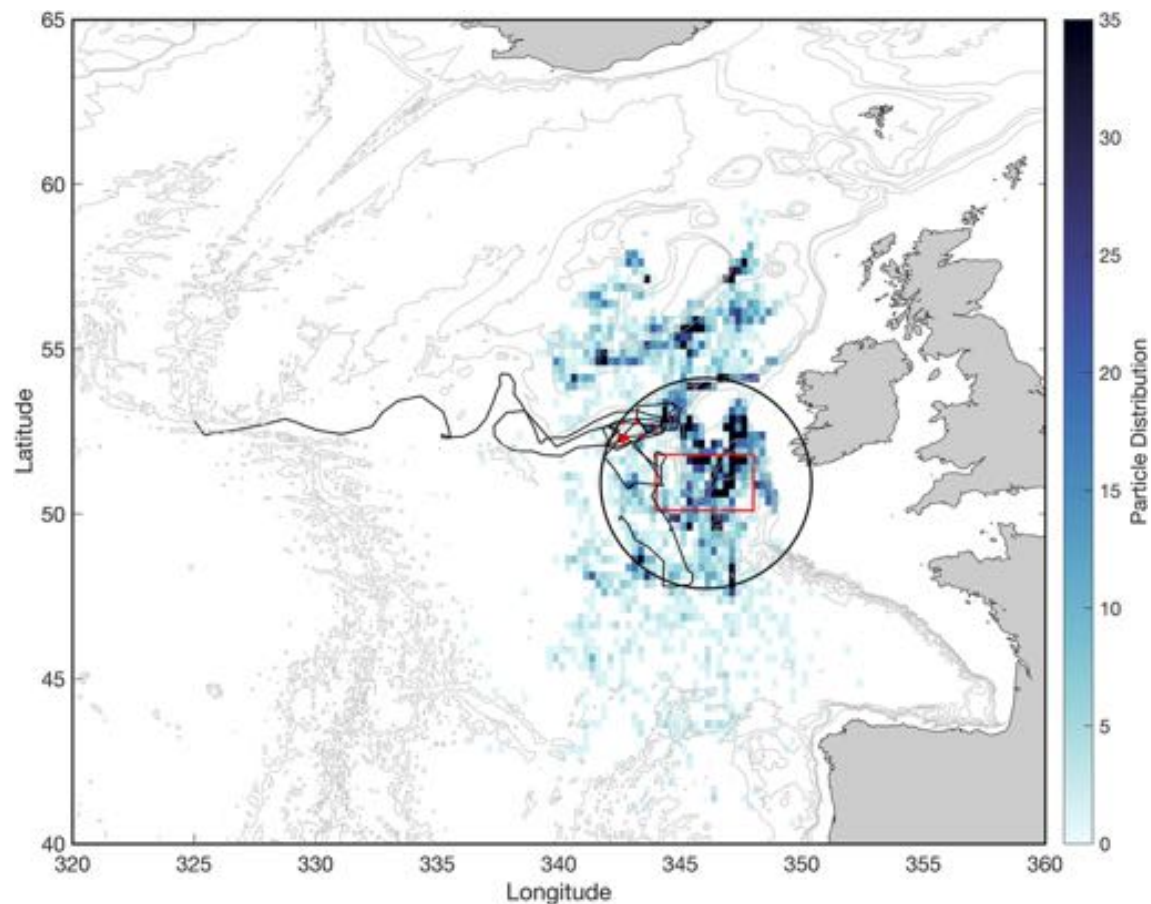


Figure 11. Distribution (number per grid cell) of 10,000 particles released within the subduction region (red box) centered near 51°N, 346°W and allowed to run until September 2015. The black circle indicates the 300-km radius around this region, encompassing the observed features (red dots). The particle distribution is overlaid on contours of bathymetry (light gray).

calculate particle trajectories, neglecting any additional along isopycnal vertical subduction, diffusivity, or sinking transport that may act on the POC-rich feature once within the interior. However, we expect that this cursory estimate can at least provide an approximation of how likely the fate of this anomaly is to follow either of our two sequestration scenarios (Figure 10).

We find that ~90% of particles released from the subduction site travel to regions where the maximum mixed layer depth exceeded 500 m. This suggests that nearly all of the particles would be re-entrained within the deep winter mixed layer and subsequently mixed back up to the surface, where any organic carbon would be released back into the atmosphere within one seasonal cycle. Only about 2% of particles end up in regions where the maximum mixed layer depth did not exceed 300 m where it is possible for these particles to remain sequestered at depth for more than one seasonal cycle. Again neglecting any vertical transport, it appears highly unlikely that any of the POC observed on the sampled feature could have remained sequestered by April 2016. As the number of BGC Argo floats increases throughout the oceans, analysis of the ratios of bio-optical proxies (i.e., b_{bp} :Chl in Lacour et al. (2019)) that enable estimation of the “age” of subducted features can be complimented by Lagrangian studies such as the analysis presented here.

5. Summary

All of the BGC Argo float data available at the completion of this analysis (mid-2019) in the subpolar North Atlantic were analyzed for evidence of physical POC subduction on a basin-wide, multiyear scale. Visually identifying features based on optical backscatter reveals potential features of subduction in about 13% of all profiles, not all of which are necessarily definitive of subduction but fit the criteria defined here. The

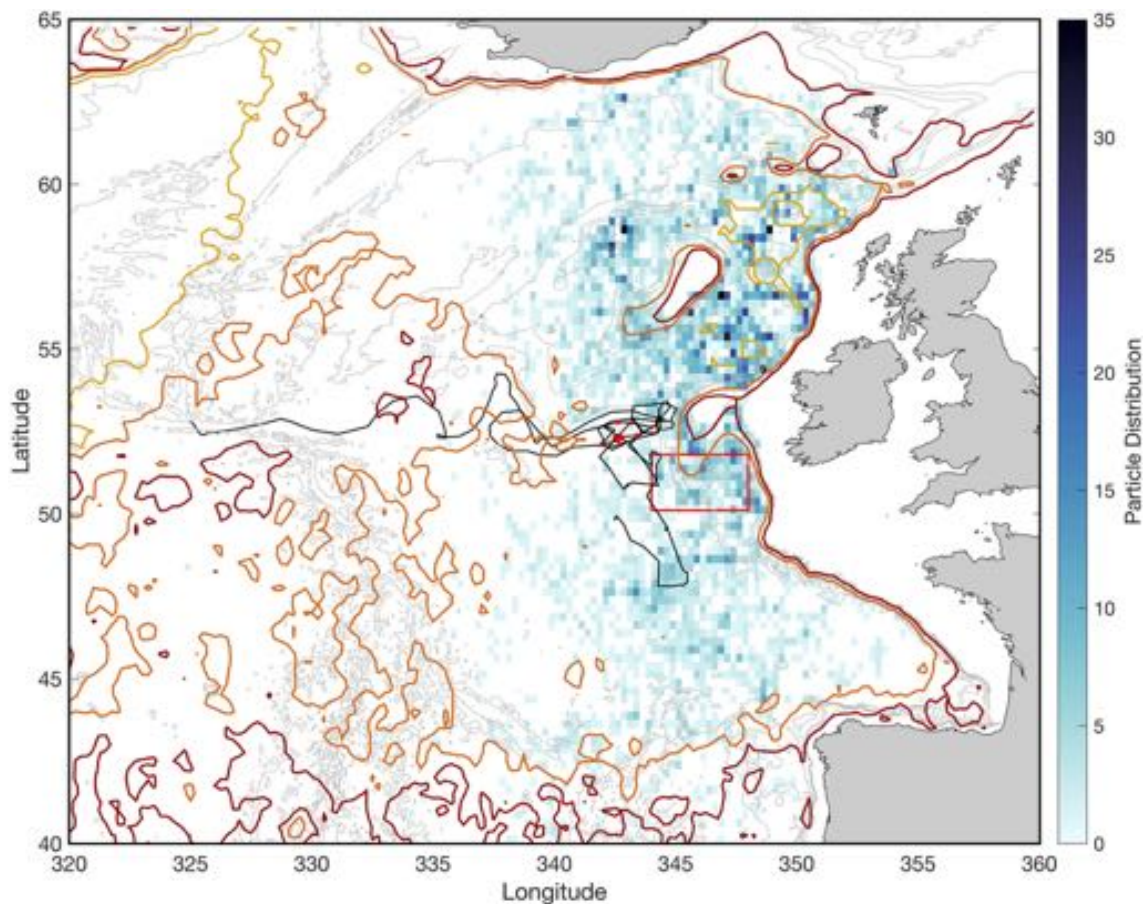


Figure 12. Distribution of 10,000 particles released within the subduction region (red box) centered near 51°N, 346°W and allowed to run until for 1 full year (April 2015–2016). Colored contours represent where the climatological seasonal maximum mixed layer depth is 300 m (dark red), 500 m (dark orange), and 1,000 m (dark yellow). Particle distribution is overlaid on contours of bathymetry (light gray).

complex circulation and bathymetry of this region precluded capture of any clear spatial patterns; however, temporal trends show a distinct peak in occurrences during the summer months, an apparent disagreement with previous literature, which suggests subduction is strongly intensified during late winter to spring. We hypothesize that this can, at least partially, be explained by our identification technique (we are more likely to detect the features once the onset of stratification has made them distinct from the water above them), and the result suggests that features can persist at depth for months after subduction. To explore this hypothesis in more depth, we focused on a single, POC-rich, feature in the North Atlantic and combined remote sensing, modeling, and in-situ observations in an attempt to reconstruct its history from time of subduction.

In July and August of 2015, a fully equipped BGC Argo profiling float (5904479) observed a distinctive POC-rich feature in 10 consecutive profiles located between the Southern Rockall Trough and the Northern Porcupine Abyssal Plain regions, where the North Atlantic Current branches into the subpolar and subtropical gyres. Assuming that the physical properties (temperature and salinity) remained unchanged since subduction from the mixed layer, the source region for this water occurred between December and May earlier that year. We further postulate that the source water must have had POC concentrations of at least equal to or higher than the observed features. The surface POC from satellite remote sensing was high enough to account for the feature only during the month of April, during the local spring bloom. Thus, we conclude that this feature likely persisted locally within the interior for more than 3 months.

An interesting result that emerged from this analysis is that despite the fairly long time since subduction, the feature appeared subject to limited lateral advection, and was observed within a 300-km radius of its

likely origination site. A possible explanation for this is its location; The Southern Rockall Trough, west of Porcupine Bank, is a relatively quiet region, characterized by low mean flow and eddy kinetic energy (Bower et al., 2002). Modeled particle trajectories in this region substantiate this claim, finding that after 5 months about half of the particles released traveled less than 300 km away from the subduction region. The weak advection at depth likely assisted in maintaining the striking coherence and longevity of this feature within the interior. This stands in contrast to recent results from the Circumpolar Current of the Southern Ocean (Llort et al., 2018). Here, we suspect that the lower rate of feature detections (1%) is due to rapid transport of subducted features away from generation sites and strong eddy activity which would dissipate anomalies.

In conclusion, this work represents a first effort to use profile anomalies in BGC Argo floats to broadly characterize POC subduction in the subpolar North Atlantic Ocean. We found evidence of strong POC anomalies that persisted throughout the summer, suggesting that phytoplankton carbon, brought downward by physical processes during the winter or spring, can remain in organic form for many months. The transport or fate of these persistent anomalies will affect the degree to which they affect net carbon sequestration. This study highlights to us that BGC Argo can be used for both process-style and statistical assessments of the biological carbon pump and that the robustness of these approaches would be significantly improved by increasing the number of BGC floats, in particular those measuring backscatter, throughout the oceans.

Data Availability Statement

Biogeochemical Argo data used in this study are available for download from Argo float data and meta-data from Global Data Assembly (Argo GDAC: <https://www.seanoe.org/data/00311/42182/>). Supporting data are available for download from HYCOM GOFS 3.1 (<https://www.hycom.org>), NASA Ocean Color MODIS-Aqua, Binned Monthly (<https://oceandata.sci.gsfc.nasa.gov>), and the National Oceanic and Atmospheric Administration Monthly Isopycnal and Mixed Layer Ocean Climatology (<https://www.pmel.noaa.gov/mimoc/>).

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