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EVOLUTION OF A SUBDUCTED CARBON-RICH FILAMENT ON THE EDGE OF THE NORTH ATLANTIC GYRE

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EVOLUTION OF A SUBDUCTED CARBON-RICH FILAMENT ON THE
EDGE OF THE NORTH ATLANTIC GYRE

BY

ALEXIS R. JOHNSON

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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2020

ABSTRACT

The oceanic biological carbon pump encompasses a variety of mechanisms by which CO_2 , 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, the physical arm of the biological pump, estimated to represent approximately 20% of global organic carbon (POC) export. Seven biogeochemical Argo (BGC) profiling floats were analyzed for evidence of physical subduction of POC in the North Atlantic Ocean. While we do not yet have enough measurements to reveal basin wide spatial trends, a notable pattern is found in the seasonality, suggesting that while subduction events are more likely to occur during winter, the bio-optical indicators - namely a deep local maxima in POC and O_2 - are more common in the spring and summer. We show that these deep features are potentially long-lived, having been subducted in late winter or spring and persisting throughout the warm season. To demonstrate, we focus on a set of notably strong POC anomalies, observed in ten consecutive BGC Argo profiles on the northeastern edge of the subtropical gyre. Analysis of the physical, bio-optical and biogeochemical profiles, complemented by remote sensing and modeling, provides insight into the history and subsequent fate of that water mass. This work highlights the potential of bio-optically and biogeochemically-equipped floats for process-style assessments of the biological carbon pump and the value added by increasing the number of BGC floats throughout the oceans.

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CHAPTER 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 timescales. This process, here referred to as the oceanic biological carbon pump (OBCP), plays an important role in regulating atmospheric CO₂ concentrations and our climate system.

The strength of the OBCP is quantified as the rate of organic carbon export from the mixed layer or euphotic zone and is typically ascribed to three main pathways (Ducklow et al., 2001; Steinberg et al., 2000; Hansell et al., 2009; Emerson, 2014; Burd et al., 2010; Bianchi et al., 2013): I) The gravitational pump: individual cells, aggregates and fecal particles that are denser than the surrounding seawater and sink into the mesopelagic ocean, II) active vertical migration by zooplankton feeding in surface waters and excreting at depth, and III) the physical arm of the pump by which meso- and submesoscale processes draw down organic carbon rich waters from the surface.

The relative contribution of physical mechanisms to the OCBP are not well constrained, in part due to the complexity of the biological pump. In addition to the myriad scales of temporal and spatial variability, carbon can travel through a vast array of pathways within oceanic food webs, all with unique timescales and efficiencies. Uncertainty can also be attributed to the challenges associated with observing and quantifying physical export as most instrumentation rarely allows for both the spatial and temporal resolution required for direct measurements.

It is imperative that we continue to address these uncertainties using emerging technologies and models to constrain how the various mechanisms of the biological pump may respond to a warming climate.

Some of the significant advancements in quantifying POC export and sequestration rates in the subpolar North Atlantic are compiled in Figure 1. This schematic summarizes the evolution and distribution of POC throughout a seasonal cycle by contrasting the proportion of POC between the surface and deepest winter mixed layer (WML) depth (on the positive Y-axis) to the proportion of POC below the deepest winter mixed layer (on the negative Y-axis). POC in the mixed layer (brown region) rises during the onset of the spring bloom. Post-bloom, a portion of that POC remains in the mixed layer, while a portion is exported to the interior above the WML by mechanisms of physical subduction/mixing, estimated to contribute to as much as half of all export from the mixed layer (see A in Figure 1, blue region, Omand et al., 2015; Dall’Olmo et al., 2016; Stukel et al., 2017) . A second portion is exported from the mixed layer through particle sinking and active transport (green region).

As the seasonal cycle progresses, the overall POC content above the WML declines gradually as the bloom carbon is respired and a small fraction, estimated to be about 10% of the total POC produced (see B in Figure 1, Körtzinger et al., 2008; Quay et al., 2012; Palevsky et al., 2016), will escape to depths below the deepest winter mixed layer where it may remain sequestered for at least one seasonal cycle (Figure 1B). Most of the POC exported out of the ML in spring is re-entrained. Levy et al. (2013) estimates that 20% of total OBCP export (ie. integrated over the entire year and below the WML) can be attributed to physical mechanisms while sinking and active transport are the main contributors (see C in Figure 1).

Figure 1. Schematic of POC export, re-entrainment and sequestration with magnitude estimates compiled from the literature. Time is on the x-axis, beginning and ending in the winter with the deepest winter mixed layers. Total POC is on the y-axis. POC between the surface and the depth of the deepest winter mixed layer is above the axis and POC below the depth of the deep winter mixed layer is below. The amount of POC within the mixed layer is in maroon. A) The proportion of POC physically exported from the mixed layer (blue) vs. POC exported by sinking or active transport (green). B) The proportion of POC re-entrained into the deep winter mixed layer vs. exported below (i.e. sequestered). C) The proportion of sequestered POC physically exported vs. exported by sinking or active transport.

While physical subduction of POC may not be the primary driver of deep sequestration, the mechanisms, spatial and temporal distribution and variability remains under observed, with uncertainties in how these processes may alter the OBCP under global change. In an attempt to further this understanding, we focus here on this physical arm, and two known mechanisms; the mixed layer pump and eddy-driven subduction.

On a seasonal timescale, the mixed layer pump is established during the late winter/early spring transition when organic particles are distributed throughout the deep winter mixed layers. As the upper ocean stratifies in the spring, shallow mixed layers are formed at the surface subsequently isolating organic material within the interior (Ho and Marra, 1994; Gardner et al., 1995) where carbon can no longer be exchanged with the atmosphere. Seasonal mixed layer pumping has been shown to export a significant amount of POC to the interior (Carlson et al., 1994; Dall’Olmo and Mork, 2014), and can occur over a large 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 is often initiated by baroclinic instabilities resulting from the slumping of outcropped isopycnals (Lapeyre and Klein, 2006). Instabilities force the front to meander causing strain and convergence (Hoskins and Bretherton, 1972; Fox-Kemper et al., 2008), 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 and Tandon, 2006; Mahadevan, 2006) generating eddy-like filaments along sloping isopycnal surfaces delivering submesoscale $O(1-10\text{km})$ intrusions of surface waters to the interior. Where POC is enhanced in the mixed layer and decreases below, 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 (Figure 1A) (Omand et al., 2015; Stukel et al., 2017).

How effective either of these mechanisms are at sequestering POC over the longer term (> 1 year) will depend on the fate of carbon 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 CO_2 (DeVries et al., 2012; Palevsky and 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.

Originally theorized by Stommel (1979), a complete understanding of the physical mechanisms of subduction and the contribution to the biological pump has been hindered by a lack of observations, owing to the fact that subduction events can be episodic and occur on a wide range of spatial and temporal scales. The Subduction Experiment was the first field campaign designed to fully observe the mechanisms leading to Ekman layer convergence and subduction in the North Atlantic. Beginning in 1991, the two year deployment was aimed at addressing the formation and evolution of water parcels subducted into the interior using a combination of temperature tracking bobber floats, SeaSoar surveys and a surface mooring array outfitted with a suite of oceanographic and meteorological instru-

mentation (Joyce et al., 1998; Weller et al., 2004). Technological limitations hindered the direct measurement of physical subduction as a means of carbon sequestration until isopycnal RAFOS floats provided Lagrangian time history evolutions of oxygen utilization along density surfaces during the transition from mixed layer to interior (Lazarevich et al., 2004). This early work highlighted the localized and episodic nature of physical subduction, introducing the need for autonomous large scale, multiyear observations (Riser and Johnson, 2008; Martz et al., 2008; Nicholson et al., 2008). In 2008, the North Atlantic Bloom Experiment sampled the onset of the spring bloom with four Seagliders following a Lagrangian float. Results from this experiment showed that process-style observations, complimented by a high resolution physical-biological model, can help quantify eddy-driven subduction of carbon in coherent filaments (Omand et al. 2015) .

Biogeochemical (BGC) Argo profiling floats have provided an opportunity to extend this type of detailed analysis to larger spatial and temporal scales with distributed observations. Llort et al. (2018) was the first to observe episodic subduction events basin wide using BGC Argo to provide a synoptic view of timing and location in the Southern Ocean. Lacour et al. (2019) used a similar approach with Argo to evaluate the intraseasonal dynamics of the mixed layer pump in the North Atlantic and estimated a basin scale average of daily carbon export. Due to the fairly sparse (10 day cycles) nature of Argo profiles, both studies are limited to a statistical analysis of carbon sequestration and lack inference of subduction location or fate once in the interior.

Part I of this study capitalizes on the fairly high density of BGC Argo floats in the subpolar North Atlantic to observe features of physical subduction and aims to expand the statistical analysis typified in Llort et al. (2018) to a basin with exceptionally high primary productivity. In Part II, we focus on a single float

record and reconstruct the history of a subducted POC rich filament on the edge of the subpolar and subtropical gyres. We argue that an increasing number of BGC Argo floats deployed will likely facilitate this type of process style assessment of physical carbon export and sequestration, on a much larger scale than previously possible.

CHAPTER 2

Methods

2.1 Biogeochemical Argo Profiling Floats

Profiles from a fleet of seven biogeochemical (BGC) Argo floats deployed in the North Atlantic (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. 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 meters in the mesopelagic zone (100-1000m). Ideally, the floats also measured oxygen, chlorophyll fluorescence and photosynthetic active radiation (PAR) but these were not a strict requirement for this analysis. Floats meeting these criteria were obtained from two sources: VilleFrance Oceanographic Autonomous Observations PROVIO profiling floats (<http://www.oao.obs-vlfr.fr>) and University of Washington's Teledyne Apex BGC floats with data hosted by the Monterey Bay Aquarium Research Institute (<http://biogeochemical-argo.org>). The four VilleFrance floats operating in the Labrador Sea collected a total of 1,396 profiles since the first float was deployed in 2013. Three Apex Bio Argo floats collected a total of 560 profiles since the first float was deployed in 2011. Together, the seven BGC Argo floats collected 1,956 profiles over all seasons in the subpolar North Atlantic ocean.

Figure 2. Labeled trajectories of BGC Argo floats in the North Atlantic (top) with corresponding lifespan and measured variables (bottom).

2.2 Biogeochemical Sensors and Derived Properties

All floats used for this study were equipped with WET Labs ECO puck meter three channel sensor designed to measure optical backscatter (b_{bp}). This sensor emits pulses of light at a known wavelength (here 700 nm) which is scattered by seawater and particulates and detected at an obtuse angle. The backscatter

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 supplied through the VilleFrance and MBARI sites was smoothed using a five point running mean filter to remove and separate high frequency fluctuations in depth from the background concentrations. 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 using an empirical formula which varies based on particulate composition and location. Here we choose to apply the formula defined for the North Atlantic during the spring bloom by Cetinić et al. (2012): $POC [mgC m^{-3}] = 3.5 \times 10^4 \times b_{bp} [m^{-1}] - 14.4 \pm 5.8$.

Chlorophyll-a concentration (chlF) is a common proxy for phytoplankton biomass and is approximated by WET Labs ECO puck series Chl-a fluorometers on BGC Argo floats. Fluorometers emit pulses of light absorbed by chlorophyll molecules in the blue part of the visible spectrum (420-440nm) and fluoresced or re-emitted in the red spectrum (565 - 580nm). To analyze data for evidence of physical subduction, the supplied chlF profiles were five point median filtered. This data was not used quantitatively in this analysis but rather to confirm that 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 section 2.3.

Oxygen was approximated by either Seabird or Aanderaa oxygen optode sensors on BGC Argo 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 calibrated and drift corrected by measurements of atmospheric O_2 each time the float surfaces (Bitting and Körtzinger, 2015). To identify features of physical subduction, oxygen was used 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 active 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. PAR sensors integrate the downwelling cosine irradiance in the visible spectrum and provide an estimate of the light available or primary productivity in the water column. Euphotic depth, the regions of the upper ocean with enough light to support photosynthesis, is typically 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 section 2.3.

2.3 Estimation of Mixed Layer and Euphotic Depths

The criteria used in this study to identify features of physical export require POC below the depth of the mixed layer and the euphotic zone. As such, this analysis requires parameterization of each. The mixed layer is the depth of the homogeneous surface layer where POC produced at the surface can be physically mixed within and is often defined as a relative change in density from some near surface ($\sim 5m$) value ($\Delta\rho$). A suitable value for $\Delta\rho$ can depend on a variety of factors, including location and season, and can thus be highly variable in time and space. In some cases, $\Delta\rho$ can be most accurately represented as the change in density from the near surface to the depth just above the maximum vertical density

gradient or buoyancy frequency (N^2). Over an entire float history, we compared a number of values for $\Delta\rho$ to N^2 and found a value of $\Delta\rho = 0.05$ best represented the maximum vertical density gradient and therefore the mixed layer depth in the North Atlantic (Figure 3).

Figure 3. Float 6901647 comparison of mixed layer depth (black) and euphotic zone (gray) calculations overlaid on buoyancy frequency over the full water column (top) and zoomed into the top 200 meters (bottom). MLD calculated with $\Delta\rho = 0.05$ and $\Delta\rho = 0.01$ are represented by the solid and dashed black lines respectively. Z_{eu1} , Z_{eu2} , Z_{eu3} and Z_{eu4} are represented by the dashed, dot/dashed, dotted and solid gray lines respectively.

The euphotic zone (Z_{eu}) is the uppermost layer of the ocean with enough light to support photosynthesis and is typically calculated as the depth at which PAR (I) is 1% of its surface value (Z_{eu1}). Z_{eu} can also be parameterized by fitting a

linear slope to $I(z)$ as $\log(I(z)) = -kz + \log(I_{\text{surf}})$ and calculating $Z_{\text{eu}} = \frac{4.6}{k} (Z_{\text{eu2}})$. Similarly, Z_{eu} can also be parameterized by fitting an exponential function as $I_{\text{model}} = I_{\text{surf}}e^{-kz}$ and finding the optimal slope that minimizes the error between I_{model} and $I(z)$ to calculate $Z_{\text{eu}} = \frac{4.6}{k} (Z_{\text{eu3}})$. For the floats equipped with radiometers (Figure 2B), Z_{eu} was calculated using each of these methods and compared against a method established by Morel and Berthon (1989) which uses an empirical relationship between surface PAR and depth integrated chlF to recursively calculate Z_{eu} as follows (Z_{eu4}):

$$Z_{\text{eu}} = \begin{cases} 568.2 \langle C_{\text{tot}} \rangle^{-0.746}, & \text{if } Z_{\text{eu}} < 102m \\ 200.0 \langle C_{\text{tot}} \rangle^{-0.293}, & \text{if } Z_{\text{eu}} > 102m \end{cases} \quad (1)$$

Where C_{tot} is the depth integral of chlF from the Z_{eu} depth to the surface. We find that the Morel and Berthon (1989) method (Figure 3, solid gray line) is a smoother representation of the euphotic zone depth because it is estimated from chlorophyll, a property with less profile-to-profile variability than irradiance. Nonetheless, this method adequately captures the variability in seasonality observed in the additional calculations of euphotic depth and can therefore be applied to the floats without radiometers (Figure 3, dashed, dotted lines).

2.4 Identifying Subducted Anomalies

Evidence of physical subduction was visually identified in the seven biogeochemical float records using the following criteria (defined by Omand et al. 2015): I) A subsurface local maximum of baseline POC (filtered to remove spikes) 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 4). As features were identified visually and qualitatively, there is no threshold for how large anomalies must be to qualify as a feature.

Additionally, the only property required to have an anomalous feature is POC. It is fairly common to find features without a chlorophyll anomaly and possible, although less common, to find features without an AOU anomaly. Temperature and salinity may also lack a distinctive anomaly and the sign (positive vs. negative) of the anomaly will depend on where the feature originated from and the physical characteristics of the subducted water. Each biogeochemical property used in this analysis is measured from independent sensors, and so by confirming that multiple biogeochemical and physical parameters are correlated over the scale of the feature we minimize the possibility of a false identification based on spurious data. All 1,956 float profiles were vetted in this fashion.

A similar methodology has been developed by Lloret et al. (2016) who identifies subduction events in the Southern Ocean based on AOU and spice anomalies from the running mean profile. Here, an AOU and spice threshold are used to identify only strong features to eliminate false detection and eliminate other mechanisms that may cause a spice anomaly in the mesopelagic. Features are not identified by POC anomaly, instead POC is integrated over the feature and used to estimate the amount of organic matter subducted.

Figure 4. Example feature of physical subduction from float 5904479. Biogeochemical properties are on the left and physical properties on the right. Feature is found in the shaded region centered near 300m depth where a peak in POC (red) is associated with a peak in chlF (green) and a decrease in AOU (blue). Feature is also associated with an anomaly in both temperature (navy) and salinity (purple).

2.5 Supporting Datasets

This analysis includes three additional types of supporting data, 1) HYCOM 2) MODIS and 3) 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 has a $1/12^\circ$ lon x $1/24^\circ$ lat horizontal resolution, 41 vertical layers and temporal frequency of 3 hours. The model uses the Navy Coupled Ocean Data Assimilation (NCODA) system which uses the 24-hour model forecast as a first guess and assimilates available satellite and in-situ observations.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument aboard the Aqua satellite, passing over the equator from south to north, acquiring data in 26 spectral bands to view the entire Earth's surface every 2 days. MODIS measures a variety of physical and biogeochemical sea surface properties. Here, MODIS sea surface temperature and particulate organic carbon binned into monthly and 8-day averages at a 9 km spatial resolution were obtained from <https://oceandata.sci.gsfc.nasa.gov>.

The Monthly Isopycnal and Mixed Layer Ocean Climatology (MIMOC) is a monthly temperature and salinity and mixed layer depth climatology developed by NOAA and freely available at www.pmel.noaa.gov/mimoc. MIMOC has 0.5° spatial resolution and 81 standard pressure levels from the surface to 1950 dbar. The climatology is built from Argo profiling floats CTD data and supplemented by shipboard measurements.

CHAPTER 3

Results

3.1 The Big Picture: Timing and Location

Physical POC export and subduction is episodic, evolves quickly and occurs on a variety of temporal and spatial scales. A comprehensive statistical region-wide summary has historically been difficult to obtain as many observational studies are limited by time or spatial constraints. Llort et al. 2018 was the first to observe features of physical POC export using a fleet of biogeochemical Argo profiling floats to summarize spatial, vertical and temporal distribution of subduction in the Southern Ocean. This study analyzed over 4,000 profiles collected between 2012 and 2016, spanning all seasons and distributed throughout the basin. Similar feature detection methods as described here revealed 40 profiles associated with subduction events with 75% occurring in the late spring and summer. Features were unevenly distributed across the Southern Ocean and seemingly located downstream from major bathymetric features and subsequent hot spots of eddy kinetic energy. To date, a comparable basin-wide, statistical summary has not yet been completed in the North Atlantic. Therefore, this analysis was originally intended to evaluate if the current number of BGC Argo platforms could provide that statistical overview of spatial and temporal patterns in this region, similar to what has been done in the Southern Ocean by Llort et al. (2018).

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 Northeast Atlantic in particular, has been the focus of a number of subduction studies (Marshall et al., 1993; Joyce et al., 1998; 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 hot-spots for physical export as these regions experience intermittent and deep mixing which enhances both the mixed layer pump and phytoplankton production in the surface waters.

In comparison to spatial patterns in the North Atlantic, both biological and physical temporal patterns are better understood. Lacour et al. (2019) uses BGC Argo floats, spatially concentrated within and near the Labrador Sea, to explore the seasonal mixed layer pump and export of organic carbon out of the mixed layer. Here, export is defined as the transfer of organic carbon from the turbulent, highly variable mixing layer depth characterized by the maximum chlorophyll gradient, to the density defined, more stable remnant layer (layer between mixing and mixed layer depth). They find a strong correlation between POC stocks in the remnant layer and 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 one month. Additionally, Thompson et al. (2016) uses a full year long record of glider observations in the North Atlantic subtropical gyre to show that the baroclinic instabilities required for submesoscale vertical motions and high frequency variations in mixed layer depth are more prevalent during the winter months (December - April). These conditions initiate instabilities that drive subduction from the mixed layer. The onset of the spring phytoplankton blooms in the North Atlantic is one of largest and most intense globally, and typically occurs in April or May. Forced by the re-stratification of the mixed layer, the abundance of nutrients and enhanced sunlight

(Sverdrup, 1953; Townsend et al., 1994; Siegel et al., 2002), organic carbon in the surface layers peaks around this time and steadily decreases throughout the summer until it rapidly declines in the fall. Spring blooms are not homogeneous across the region as phytoplankton growth is amplified by convective mixing and strong atmospheric forcing resulting in patches of blooms (Dutkiewicz et al., 2001; Williams and Follows, 2003).

Spatial and temporal patterns of physical submesoscale subduction are explored in the North Atlantic Basin using a parameterization derived by Fox-Kemper et al. (2008). This approach parameterizes the overturning streamfunction ψ_e [$\text{m}^2 \text{s}^{-1}$] which can be thought of as analogous to the 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 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 year-long average is shown in Figure 5A. Large ψ_e is a predictor of a large subduction rate, as shown at the frontal boundary of the East Greenland Current and the branching region of the North Atlantic Current. To obtain a sense of temporal variation, the parameterized ψ_e is calculated along each float trajectory for the corresponding time step of model output (Figure 5B). Results from the parameterization are generally in agreement with Thompson et al. (2016), showing highest subduction rates in winter. In summer, the rates drop very low for all but float 5903592 (pink) which hugs the Greenland Current and therefore remains highest throughout the year. Note that this parameterization reflects the ageostrophic vertical overturning that tends to occur on submesoscales. It does not include mixed layer or other mechanisms of subduction.

Figure 5. Float trajectories overlaid on parameterization of instability driven subduction in the North Atlantic following Fox-Kemper et al. (2008) (top). The physical parameterization is integrated along the trajectory of each float for each time-step and plotted over the course of the year (bottom).

The seven biogeochemical Argo floats used in this study are spatially diverse, located 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. Together, the floats collected almost

2,000 profiles throughout the North Atlantic and evidence of physical subduction was detected in every float record. In total, about 13% of all profiles contained features characterized by the criteria described in section 2.4. Certainly there were anomalies found near regions of large ψ_e (compare Figure 5A and 6A), but with relatively few floats, it is difficult to deconvolve the spatial from temporal drivers. It is likely that the statistical confidence gained with more floats equipped with bio-optical sensors will be required before spatial trends can be robustly identified in these anomalies.

Temporal trends on the other hand, were evident. Anomalies were least frequently observed during the late fall and early winter months, increasing during the spring and early summer until peaking in June and July (Figure 6B). This pattern persists after the data is normalized for profile frequency (Figure 6C), suggesting that the pattern is indeed representative of basin wide seasonality and not just sample effort. This summer maximum in feature occurrence is in apparent disagreement with Thompson et al. (2016) and Lacour et al. (2019) which find conditions in the North Atlantic that favor submesoscale and mixed layer pump subduction in the winter and spring months respectively. It is also in apparent disagreement with our parameterization which finds that ψ_e goes to almost zero in the summer months along most of the float trajectories (Figure 5B).

We believe that this discrepancy can be explained by recognizing that 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 - something that is less likely to occur in the winter when primary production is very low. Thus, we think this method favors detection of events that occurred during the spring bloom

Figure 6. (A) Observed feature locations overlaid on contours of bathymetry in the North Atlantic. Features are colored by the month of the year in which they were observed. (B) Raw temporal patterns of observations by month and (C) normalized by the total number of profiles each month.

and persisted for long enough to laterally intrude beneath other water masses or until the water column stratifies above them. We thus cannot assume the time and location of observation always corresponds to the time and location of subduction since long-lived anomalies could be subject to significant advection once within the interior.

3.2 Reconstruct History of Notably Carbon Rich Feature

Observations from BGC Argo floats show the highest occurrence of features during the summer months, an apparent disagreement with previous literature and the physical parameterization. We hypothesize that features can be long-lived, persisting within the interior for months after subduction which potentially explains the temporal discrepancy. This hypothesis was explored in more detail by focusing on a single float, Apex float 5904479 in the southeastern region of the North Atlantic, uniquely located on the boundary between subpolar and subtropical gyres (labeled in Figure 2). This float record contained the most notably strong and well defined anomalies in backscatter-derived POC of all the floats we examined. At that time, the float was located on the edge of the North Atlantic Current (the region selected for a number of past subduction studies), where horizontal buoyancy gradients are strong and mixed layers depths are variable. This location was also of interest because it is in close proximity to the North Atlantic EXPORTS region, the NASA-led field campaign focused on quantifying the pathways of the biological carbon pump.

Ten consecutive profiles collected between July and September 2015 showed a strong subsurface POC peak occurring between 200 and 400 meters depth (Figure 7). We observe additional less distinct features of POC export during the spring and summer the year previous between 200 and 500 meters depth. We also find a large deep feature in July and October of 2015 around 800m. Due to the depth and vertical extent, this is more likely evidence of a deep sedimentary plume rather than POC.

Figure 7. Backscatter-derived POC record from float 5904479. The feature of interest is found in July and August between 300 and 400 meters depth. Mixed layer depth is shown in thick white, isopycnals in gray and euphotic depth as the dashed line. The red box defines the region shown in figure 8 which includes the entire water column below the euphotic and mixed layer depths.

This work focuses on the POC rich feature observed between July and September, 2015. During this time, the float completed a clockwise loop seemingly associated with an anticyclonic eddy on the order $O(10-100 \text{ km})$. The peak POC was patchy, ranging from roughly $100-200 \text{ mgC m}^{-3}$. The depth varies, but appears to be approximately following the $27.15 \pm .05 \text{ kg m}^{-3}$ isopycnal (white contour, Figure 7). Anecdotally, this isopycnal outcropped to the surface during the previous spring, around the same time the mixed layer is highly variable and shoaling. However, because BGC Argo floats are Lagrangian only at 1000m parking depth, we do not assume the carbon rich feature originated when and where the float observed this isopycnal outcrop. Instead, we used the corresponding temperature and salinity anomalies on the feature and assume that in the absence of major dif-

fusion, water mass properties are conserved once they are exported from the mixed layer. The POC anomalies occurred at an inflection point in T-S space (Figure 8) indicating that the water is ‘spicier’ (warmer and saltier) than surrounding waters and further reinforcing the likelihood that these anomalies occurred through an along isopycnal intrusion originating elsewhere. Temperature and salinity ranged between 10.6-11.2°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.

Figure 8. Temperature and salinity diagram of float 5904479 below the euphotic and mixed layer depths (region defined in red in figure 7) with colors representing POC concentration. Feature is found between 35.4-35.5psu and 11°F. The inset (top left) focuses into the feature.

HYCOM model output analyzed over from the year previous to these observation (7/2014-7/2015) shows six months where the physical properties of the mixed layer matched those on the feature: between December 2014 and May 2015 (Figure 9). The regions that possess this T-S combination (colored regions) are notably local, and generally south of where the features were observed. An identical analysis was completed with MIMOC climatology and provided vary similar results to the 2015 HYCOM data, with the same temporal and spatial offset.

Figure 9. Regions where mixed layer temperature ranges between 10.6-11.2 and salinity between 35.41-35.51 by month from HYCOM model output. Regions are overlaid on bathymetry and float trajectory where red dots indicate the feature location.

We next used Aqua MODIS (SST and POC products) averaged over these regions to evaluate how physical and biological properties co-vary throughout the year (Figure 10) and specifically during the months identified where mixed layer properties aligned with the feature (gray shaded region, Figure 10). We compared

the seasonal variation in SST to the same region HYCOM provides a sea surface temperature finding a good agreement (blue solid and dashed lines). Overall, we find sea surface temperature and POC declined through December and into January. Both were at a minimum in March, just before the spring bloom caused POC to spike to a maximum in April. At this time, temperature starts to increase as the surface layers stratify and the mixed layer shoals. In May, POC drops from it's peak but remains fairly high, gradually decreasing over the summer months. As the float anomalies show an exceptionally high POC concentration of about 150 mgC m^{-3} compared to typical summer values, we hypothesize that they were derived from the surface during the April bloom, and persisted within the interior for approximately three months prior to observation.

Figure 10. Sea surface temperature (blue) and sea surface POC (red) throughout 2015 averaged over regions found in figure 6. HYCOM data is 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.

Over those months, the bloom material has likely undergone substantial bacterial remineralization, depleting POC on the feature and increasing the apparent oxygen utilization (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 - 30 mmol O₂, values that are fairly 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 mmolO₂ m⁻³ (reflective of the spring bloom which can typically range between -10 - 5 mmolO₂ m⁻³), we can estimate a remineralization rate and make a back-of-the-envelope calculation to estimate what POC might have been when the feature was at the surface.

If we take the time and AOU change since subduction as $\Delta t = 90$ days and $\Delta \text{AOU} = 25 \text{ mmolO}_2 \text{ m}^{-3}$, we arrive at an estimate for the remineralization rate (r)

$$\Delta \text{AOU} = r \times \Delta t \quad (2)$$

of $0.27 \text{ mmolO}_2 \text{ m}^{-3} \text{ d}^{-1}$. Remineralization is highly localized and depends on a number of factors, including species composition, nutrient and oxygen availability as well as temperature and other physical parameters. As such, there exists 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 $0.4 \text{ mmolO}_2 \text{ m}^{-3} \text{ d}^{-1}$ (Jenkins, 1982; Palter et al., 2005; Omand et al., 2015). Our rate is consistent with the higher end of this range, and with rates for similar subducted features 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.

Using an estimated value of $\Delta \text{AOU} = 25 \text{ mmolO}_2 \text{ m}^{-3}$ and the feature-averaged POC_{feat} of 150 mgC m^{-3} , molecular weight (12 g mol^{-1}), together with the pho-

tosynthetic quotient ($PQ = 1.5$, the ratio of oxygen released to carbon dioxide acquired during bacterial respiration), we are able to predict a value of POC_{surf} :

$$POC_{surf} = POC_{feat} + 12 \frac{\Delta AOU}{PQ} \quad (3)$$

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 mgCm^{-3} or higher (Ducklow et al., 1993).

Remotely sensed sea surface POC during April confirms the existence of a patchy spring bloom (Figure 11). 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 11). Together, these observations provide further evidence that this POC 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.

Figure 11. 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.

CHAPTER 4

Discussion and Conclusions

All of the Biogeochemical (BGC) Argo float data available to date (till 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 complex circulation and bathymetry of this region precluded capture of any clear spatial patterns, however temporal trends show a distinct peak in observations 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 be at least partially 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 suggest features can persist at depth for months after subduction. To explore this theory 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 it's history from time of subduction.

In July and August of 2015, a fully-equipped Biogeochemical 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 was likely fairly local, within ~ 1000 km, occurring between De-

cember and May earlier that year. Because the POC on these features remained very high, we postulate that the source water must have concentrations of at least equal or higher. 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 postulate that this feature likely persisted locally within the interior for more than three months.

An interesting result that emerged from this analysis is that despite the fairly long time since subduction, the feature was subject to limited lateral advection, observed within a 300 km radius of it's 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). The weak advection may have assisted in maintaining the striking coherence of this feature within the interior, and it is likely that similar methods applied elsewhere may not be as revealing. The Circumpolar Current of the Southern Ocean, for example, would rapidly transport subducted features away from generation sites and strong eddy activity could dissipate physical and biogeochemical anomalies in the water column. Despite the relatively weak subsurface currents, this region is considered a hot-spot for enhanced subduction due to strong horizontal buoyancy gradients between the northern and southern edges of the subtropical and subpolar gyres (Marshall et al., 1993; Thompson et al., 2016).

4.1 What was the subduction mechanism?

The criteria used here to classify features of physical subduction cannot conclusively indicate which physical mechanism, instability driven submesoscale vertical velocities or mixed layer subduction, is responsible for exporting surface waters to the interior. Both can give rise to patchy biogeochemical and physical anomalies

below the mixed layer and euphotic zone, and in many cases it is likely that both act in concert with each other. Submesoscale subduction driven by mixed layer instabilities can occur anytime that sufficient upper ocean conditions are met - namely strong horizontal buoyancy gradients combined with weak stratification, particularly at the base of the mixed layer. Often, strong vertical velocities arise along a frontally intensified region, and because of the highly localized nature of this mechanism, it is perhaps more likely to produce adherence to a common isopycnal, such as what was observed here. Mixed layer subduction on the other hand, would likely have a less characteristic surface expression as it depends on the depth and temporal variability of the mixing layer depth. Variability in mixing depth can arise from processes that enhance convection, storms, Ekman dynamics and/or the frontal instabilities described above. The onset of stratification in spring and summer isolate these deeply mixed surface waters at depth.

By our best estimation, the anomalies explored here were subducted from the mixed layer around April, which does not preclude either process. While they occur over a fairly narrow range in isopycnals, there is significant patchiness, with peak POC varying in concentration from 50 to 200 mg m^{-3} , and in depth by up to 100 m. This variability could be a consequence of episodic vertical velocities, a complex straining field that deforms and mixes the subducted field, and a patchy biological field. The O(10-100 km) looping trajectory of the float while sampling the feature is suggestive that the float was orbiting a deep eddy, yet neither satellite altimetry nor HYCOM reanalysis reveals any significant sea surface height anomalies in region during spring or summer 2015.

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 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 1A), much of this carbon is re-entrained the following winter (Figure 1B), ultimately re-releasing any organic carbon back to the atmosphere over a seasonal cycle (Figure 12a). 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 12b), it can remain sequestered from the atmosphere on multi-year timescales. 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 12.

Figure 12. Schematic of POC export from the surface mixed layer during the spring bloom and subsequent fate the following winter. A) Scenario in which POC is transported north into subpolar gyre. B) Scenario in which POC is transported south into the subtropical gyre. Black line represents mixed layer depth and gray lines represent isopycnals.

To assess where this particular POC-rich feature may end up when mixed layers deepen during the following winter, 1,000 particles were seeded within HYCOM north/southward velocity fields at the estimated time, depth and location of subduction (April 1st 2015, 300 m, red box Fig 13, 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 until the end of December, a date reflecting the onset of deep winter mixed layers in the region. 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 in December, 2015. This allows us to evaluate our hypothesis that the anomalies remained local, and additionally examine the percent of particles from this region that they may escape re-entrainment into the following deep winter mixed layer.

After about five months (date of subduction to date of final float observation), of the 1000 particles released from the subduction region approximately 48% remained within an 300 km radius (Figure 13). This result substantiates our claim that due to low mean flow, a parcel of water subducted in this region could persist at depth for a relatively long period of time without being laterally transported a significant distance away from the generation site.

Figure 13. Distribution of 1,000 particles released within the black box centered near 51°N, 346°W and allowed to run until September, 2015. The black circle represents the local radius, the distance from the center of the subduction region to the furthest observation (red dots). Particle distribution is overlaid on contours of bathymetry (light gray).

After about nine months (April to December), the final distribution of particles released from the subduction region is further diffused (Figure 14). Of the 1000 particles released, 30% have remained within the 300 km radius. 44% 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 towards the Reykjanes Ridge. The remaining particles, about 25%, travel to the south where they were entrained by the eastern component of the subtropical gyre.

The final particle distributions are compared with deep winter mixed layers, calculated from December averaged HYCOM (contours, Figure 14), to examine whether the distances traveled could be sufficient to result in longer-term sequestration. HYCOM allows us to only account for horizontal velocity fields to 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 12).

We find that throughout the range of simulated particle locations, averaged December deep winter mixed layers are not deep enough to re-entrain a feature at 300 m depth. The majority of particles, approximately 70%, remain in regions where average maximum mixed layer depths do not exceed the observation depth. Only the remaining 30% of particles, most of which are found in the Faroe Shetland Channel where mixed layers can exceed 500 m depth, experience mixed layer depths deep enough to re-capture our subducted water parcel. However, the average does not include deep winter mixing events, particularly those to occur later in the winter season, which would severely increase the chances of re-entrainment, especially in this Iceland Basin region where mixing events are common and mixed

layers are already deep. We estimate that a majority of particles that were transported to the north would end up mixing back to the surface. However the 25% of particles which appear to travel to the south have a much higher chance of sequestration. Here, maximum mixed layer depths range between 100-200m and will continue to shallow as particles advance to the south.

Figure 14. Distribution of 1,000 particles released within the black box centered near 51°N, 346°W and allowed to run until the end of December, 2015. Colored contours represent where the climatological seasonal maximum mixed layer depth is 100m (light pink), 200m (dark pink), 300m (light red), 400m (red) and deeper (maroon). Particle distribution is overlaid on contours of bathymetry (light gray).

In conclusion, this work represents a first effort to characterize POC subduction in the subpolar North Atlantic Ocean using BGC Argo floats. We found features that evidence subduction 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. We next examined a single set of deep, notably high POC anomalies observed in the southern Rockall Trough, and by combining physical, bio-optical and biogeochemical profiles, remote sensing and HYCOM model output, we attempted to reconstruct the history of that anomaly. We found that it likely originated locally, and could have subsequently travelled into either the subtropical or subpolar gyre, impacting the likelihood that the carbon associated with that features remains sequestered over timescales longer than one season. The study highlights to us that biogeochemical 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.

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