Enhanced Winter Carbon Export Observed by BGC-Argo in the Northwest Pacific Ocean

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Abstract The winter- and spring-time mixed-layer pump (MLP) significantly augments the global carbon transport from the surface mixed layer to deeper waters when ephemeral surface phytoplankton blooms are repeatedly mixed to depth. Exploiting unusual 190 + daily BGC-Argo profiling measurements within a recirculation gyre, we show repetitive MLP episodes generating a January–March averaged particulate organic carbon (POC) export of ~110 mg C m−2 day−1 in the midlatitude (31°N) Northwest Pacific. Subsampling this dataset on a 5- or 10-day cycle yielded an order of magnitude less export, or even totally missed all the MLP events. The evidence here supports the need for new strategies if the BGC-Argo program is to adequately quantify ocean carbon cycling and its effects on biological systems. We propose that a handful of floats be tasked with daily profiling, and machine learning strategies be used to link these data with satellite derived measurements to estimate the synoptic-scale MLP export.

Plain Language Summary The Biogeochemical-Argo program (BGC-Argo) is an essential tool for quantifying carbon export from surface waters to the ocean interior, which is critical for understanding and forecasting changes in atmospheric CO2. Using novel, high-frequency (1-day cycle during 9-month period) BGC-Argo data, we estimated the carbon export in the midlatitude Northwest Pacific Ocean stemming from unexpectedly continuous mixed-layer pump (MLP) events. Such events occur when wintertime phytoplankton blooms developed during calm wind periods then are injected to depth by storms. This process generated remarkably high carbon export over winter, with values ranging from 18% to 30% of that from the massive North Atlantic spring bloom. These events, however, are largely (80%) or entirely missed using the longer standard float cycling intervals (5–10 days) accepted by the BGC-Argo program. The findings here suggest that some high-frequency BGC-Argo observations are necessary for more accurately estimating the global carbon export.

1. Introduction

The magnitude of carbon transport from surface waters into the deep ocean exerts a major control on global climate, a main pathway to sequester atmospheric carbon dioxide (Gruber et al., 2019; Sarmiento et al., 1998). Carbon export is largely governed through biological processes whereby particulate organic carbon (POC), in the form of living cells or detritus, gravitationally settles across the boundary separating the surface mixed layer from the underlying mesopelagic waters, known as the biological gravitational pump (BGP) (Boyd et al., 2019; Buesseler et al., 2020). Current estimates of BGP export from global biogeochemical models are in the range of 4–9 Pg C/yr (Bopp et al., 2013; DeVries & Weber, 2017; Siegel et al., 2014); however, these estimates do not take into account additional physically mediated export pathways that could significantly augment this export (Boyd et al., 2019). These particle “injection” processes occur when surface waters containing POC are subducted below the mixed layer by small-scale (i.e., 1–100 km) physical processes (Levy et al., 2001; Lacour et al., 2017; Llort et al., 2018; Omard et al., 2015) and by mixed-layer pump (MLP) processes, where surface POC is transported into deeper waters by increased wind mixing (Bishop et al., 1986; Dall’Olmo & Mork, 2014; Gardner et al., 1995).

There is evidence that carbon export via the MLP can be important at high latitudes during the late winter-spring-summer transition (Dall’Olmo et al., 2016; Lacour et al., 2019), but measuring this process is hindered by limited data availability. Quantifying the magnitude and spatial heterogeneity of the MLP globally is critical not only for understanding how climate forcing will alter atmospheric/deep ocean...
coupling but also for the fact that current estimates of BGP appear not in balance with either mesopelagic carbon budget (Emerson, 2014) or nutritional demands of subsurface biota (Dall’Olmo et al., 2016; Lacour et al., 2019).

The MLP operates through cyclical variation in the mixed layer depth (MLD) on diurnal (Gardner et al., 1999; Woods & Onken, 1982) and interseasonal time scales (Bishop et al., 1986; Dall’Olmo & Mork, 2014; Gardner et al., 1995; Ho & Marra, 1994). During winter and early spring, when surface mixing on average is deeper than the critical depth, phytoplankton specific net accumulation rate becomes negative (Evans & Parslow, 1985; Sverdrup, 1953). Recently, there has been an alternative suggestion that the higher zooplankton grazing pressure also contributes to slow or no phytoplankton biomass accumulation in mid-winter (Behrenfeld, 2010; Behrenfeld & Boss, 2014). Even during winter, there exist intermittent periods of weakened wind stress that lead to shallow stratification (Birge, 1916; Bishop & Wood, 2009). The enhanced phytoplankton growth associated with this stratification (Townsend et al., 1994) becomes diluted and is transported to deeper waters when the wind strengthens and deepens the mixed layer. This injected POC, as well as dissolved organic phases, later becomes isolated, or “detrained” when the storm abates and a new shallow mixed layer re-forms (Carlson et al., 1994; Dall’Olmo et al., 2016). Although some portion of the detrained organic matter may return to surface waters in subsequent mixing events, a significant portion will gravitationally sink downward, contributing to overall carbon export from the surface layer. Indeed, sinking rates of phytoplankton and POC are likely to increase below the photic zone with the deteriorating cell physiology and particle aggregation, enhancing the downward flux of the BGP (Boyd et al., 2019; Buesseler et al., 2007).

During the late-winter to early-spring transition, this cyclical onset and disruption of stratification can lead to substantial export of plankton biomass before the spring bloom occurs in both high-latitude (Dall’Olmo et al., 2016) and midlatitude (Carlson et al., 1994) regions. Dall’Olmo et al. (2016) calculated this interseasonal global MLP export to be ~0.26 Pg C/yr (4% of the estimated global export) using satellite-derived surface POC estimates and MLD determined from Argo float profiles. This export increased to ≥23% at latitudes above 35° where the mixed layer is more dynamic. Even so, they were unable to correct for surface lateral advective processes that can generate vertical signatures similar to MLP events (Ho & Marra, 1994). Perhaps more problematic, Dall’Olmo et al. (2016) could only detect MLD changes on ~10-day time scales due to the prescribed Argo profiling intervals (Roemmich et al., 2019). However, rapid wind speed changes and surface heating can generate more rapid changes of MLD and phytoplankton biomass (Taylor & Ferrari, 2011; Townsend et al., 1992), leading to a potentially significant undersampling of MLP events. A higher temporal resolution of sampling is needed to ensure that rapid transitions between shallow and deep mixing are captured adequately.

The recently implemented BGC-Argo program of autonomous profiling floats has more flexible profiling protocols than the core-Argo program (Bittig et al., 2019; Claustre et al., 2020; Roemmich et al., 2019). The BGC-Argo initiative seeks to quantify the magnitude and variability of the biological pump (Biogeochemical-Argo Planning Group, 2016) by supplementing the core-Argo pressure, temperature, and salinity measurements with up to six additional properties—oxygen, pH, nitrate, downwelling light, chlorophyll fluorescence, and optical backscattering—in a fleet of 1,000 BGC-Argo floats distributed across the world oceans. With these additional parameters, the BGC-Argo program can provide a better platform for detecting POC export from MLP events (Chai et al., 2020). Although the BGC-Argo sampling strategy will, at a minimum, match the 10-day core-Argo profiling interval, it allows modifications to a more scientifically desirable cycle periods of 5–7 days for observing biological processes (e.g., observing spring/summer bloom transitions). However, this faster cycling would shorten the expected float lifetime significantly (Bittig et al., 2019), so the question is what sampling frequency is necessary to adequately capture the dynamics of MLP?

2. Materials and Methods

2.1. Float Data

In this study, we investigated the MLP events based on daily profiling from a BGC-Argo float over an 8-month period, which was at a location south of Japan in the Northwest Pacific Ocean (NWP) (Figure 1a). The float, deployed in September 2018, was quickly entrained into a 300–400 km anti-cyclonic recirculation gyre,
called “Shikoku Recirculation Gyre (SRG)” (Sugimoto et al., 1986). It stayed in the gyre until the end of April 2019, and was successfully recovered in early June. This serendipitous trajectory meant that the float sampled a quasi-homogenous water mass in the SRG, without significant potential interactions of horizontal advective intrusion and other processes (Ho & Marra, 1994; Mitsudera et al., 2001). To minimize the boundary frontal effects, we only considered the profiles within the SRG core, which was defined as less than a normalized distance of 0.6 from the SRG center (see Text S1 and Figure S1, analysis to confirm that there were insignificant submesoscale processes in the SRG core).
The float was equipped with a CTD ("SBE41CP" manufactured by Seabird) measuring temperature, salinity, and pressure, and an optical sensor package ("ECO Triplet" manufactured by WET Labs) measuring chlorophyll-a concentration (Chla; units: mg m⁻³), fluorescent dissolved organic matter (FDOM; units: ppb), and particulate backscattering coefficient at 700 nm (bbp(700); units: m⁻¹). It profiled at night (around 22:00 local time) to avoid phytoplankton fluorescence non-photochemical quenching, with ~1 m vertical resolution in the upper 1,000 m. Chla and bbp(700) profiles were dark-corrected based on the on-float measurement before deployment and then smoothed with a 5-point moving median filter to remove noises. Chla was further corrected based on match-up satellite Chla data using an exponential function (see Text S2 and Figure S2). bbp(700) was converted to POC concentration, based on the empirical relationship (Equation 1) established in the subtropical waters (Stramski et al., 2008) and the assumption that the spectral slope of particulate backscattering coefficients is −1 (Maritorena et al., 2002). The mixed layer depth (MLD) is defined as the depth where the seawater density increase relative to the surface reaches 0.005 kg m⁻³ (Brainerd & Gregg, 1995), and this MLD corresponds to the actively mixing surface layer.

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POC = 53.607 \times bbp(700) \times (555/700)^{-1} + 2.5\]  

(1)

2.2. Ancillary Data

Ancillary data used in this study include the following: daily 9-km sea-surface Chla and POC from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua satellite provided by National Aeronautics and Space Administration (NASA); daily 25-km Absolute Dynamic Topography (ADT) and 6-hourly 25-km multisatellite blended sea-surface wind (SSW) provided by the Copernicus Marine Environment Monitoring Service (CMEMS); daily 4-km finite-size Lyapunov exponent (FSLE) provided by the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO); daily 12.5-km air-sea net heat flux (Qnet) from the ERA-Interim (a reanalysis dataset) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF); and daily 0.08° HYbrid Coordinate Ocean Model (HYCOM) data provided by Florida State University.

2.3. Identification of MLP Events

The identification method of MLP was modified from Lacour et al. (2019), including three criteria: (1) the first day \(t_0\) of an MLP event is identified if a fast deepening of MLD happens on the following day: \((\text{MLD}_{t+1} - \text{MLD}_t) > 30 \text{ m}\); (2) the deepest MLD must be deeper than 90 m; and (3) the last day \(t_2\) is identified when MLD did not shoal further on the next day. The duration of an MLP event is \(t_2 - t_0\), and its exported carbon is calculated as the difference between the integrated POC from MLD₂ to 200 m at \(t_2\) and that from MLD₀ to 200 m at \(t_0\).

3. Results

3.1. Continuous Surface Winter Blooms and Mixed-Layer Pump Events in Winter

The daily vertical profiles observed in the SRG revealed the seasonal transition from warm stratified waters in fall to cooler wintertime conditions in December and to springtime warming in April (Figure 1b). Salinity variation over this period was nominal (Figure S3), consistent with a quasi-Lagrangian behavior of the float in near-surface waters (i.e., following the same water mass over time). MLD was shallow (~30 m) and stable in late fall (November), became highly variable over winter, and transitioned back to shallow, stratified conditions in spring (December-April) (Figure 1b). The minimum MLD during the winter phase was ephemerally similar to that in spring and fall but repeatedly dipped well below 100 m before shoaling again. The shallow stratification during winter was well correlated with satellite-derived low surface wind condition (Figure S4). To demonstrate the spatial representativeness of float sampling, we analyzed the regional averages of MLD, sea-surface temperature (SST), and salinity (SSS) from HYCOM data within the SRG core and found good consistency between the float observations and HYCOM regional averages (see Text S3 and Figure S5).

Surface Chla followed an inverse pattern, being very low in the well-stratified condition of late fall, increasing by 100% in December (from 0.1 to 0.2 mg m⁻³) likely in conjunction with nutrient infusion from the deepening of mixed layer. The winter phase was characterized by blooms that were associated with the periodic
cycling between shallow and deep mixed layers, illustrating in detail the MLP process (Figure 1c). Satellite-derived Chla generally was consistent with this temporal pattern of float-determined Chla (Figure S6). The observed POC concentration closely followed surface Chla but also depicted the vertical export of carbon into the mesopelagic zone (Figure 1d). The levels of fluorescent dissolved organic matter (FDOM), a proxy for dissolved organic carbon released through degradation of POC, generally increased at or immediately below MLD (~50–150 m) and accumulated above 200 m during the winter period. More substantial increases in FDOM were observed between 200 and 350 m in March coinciding with repeated episodes of POC export via the MLP (Figures 1d and 1e), although shoaling of deep, lower temperature water in late March may have contributed to this temporal pattern.

3.2. Quantification of MLP Efficiency

Quantifying the MLP requires sufficiently high temporal resolution data that capture both rapid transitions in MLD along with the redistribution of slowly sinking organic matter (Dall'Olmo et al., 2016; Denman & Gargett, 1983). Lacour et al. (2019) estimated MLP carbon export by considering three successive steps: (1) the presence of an established shallow mixed layer (MLD₀) with elevated phytoplankton biomass at t₀; (2) a deep mixing event at t₁ that dilutes the surface bloom, mixing it to MLD₁ while entraining nutrients to the surface; and (3) the subsequent establishment of a new shallow pycnocline (MLD₂) that caps the subsurface carbon-enriched remnant layer (Figure 2). They calculated POC flux as the difference in depth-integrated POC entrained (MLD₁ to MLD₂) versus the depth-integrated POC existing before the mixing event (MLD₀ to MLD₁) (Figure 3). This approach is well suited when assuming steady state conditions, which was necessary in their case because of their coarser sampling intervals (2–10 days). However, mechanistically, the MLP is not a steady-state process, with MLP events in some cases occurring over a single day (black line in Figure 1b). Moreover, some portion of those particles mixed downward can be expected to sink below the new, deeper pycnocline (MLD₁) before the next event and thus would not be quantified as exported. We modified the method of Lacour et al. (2019) to consider all particles from MLD₀ and MLD₂.
to 200 m (as the reference depth) to calculate the time-integrated deep entrainment of POC over successive MLP episodes (Figure 2).

Seven distinct MLP episodes were identified between January and early March (Figure 3a), and our modified calculation method yielded a combined POC export of 8.927 g C m\(^{-2}\), or 30% greater than that calculated using the maximum MLD method of Lacour et al. (2019) (Table 1 & Table S1). Averaging this export over the winter season (January-March) gives an export rate of ~110 mg C m\(^{-2}\) d\(^{-1}\), about 18–30% of the surface carbon export estimated for the North Atlantic spring bloom (Martin et al., 2011), or about twice the annually averaged POC flux at 100 m at both stations S1 (subtropical NWP) and K2 (subpolar NWP) (Honda et al., 2015). We also analyzed the sensitivity of these results to different reference depths (i.e., 180, 220, and 250 m) and MLD definitions (i.e., density threshold of 0.01 and 0.015 kg m\(^{-3}\)) and found insignificant variation in the total POC export, varying between 8.044 and 9.731 g C m\(^{-2}\) with an average of 9.007 g C m\(^{-2}\) (see Figure S7).

However, subsampling our daily profile data to simulate the prescribed BGC-Argo protocols (5–10 day profile intervals) failed to capture the majority of the MLP events. For example, subsampling our data on a rolling 5-day basis (i.e., beginning the interval on day 1, day 2, day 3, etc.) in each case identified only a single MLP episode (Figure 3b), with an estimated POC export that was 79% lower (1.91 ± 1.03 g C m\(^{-2}\)). More notably, MLP events were only detected in about half of the rolling 10-day (i.e., core-Argo) profiling interval (e.g., Figure 3c), and the total estimated POC export (when detected) was again 78% lower (1.92 ± 1.25 g C m\(^{-2}\)) than estimated from the daily profile data. These findings show that the planned protocols for the BGC-Argo program (Biogeochemical-Argo Planning Group, 2016) will substantially underestimate global carbon export flux from MLP processes.

Chla covaried closely with changes in POC between the MLD and 200 m (Figure S8a), indicating a tight coupling between recent phytoplankton production and particle abundance, as expected for recently exported material (i.e., little overall degradation). Chla was low between 200 and 400 m, and decoupled from the POC, which increased from January through March (Figure S8b). Very little POC accumulated below 400 m (Figure S8c). Based on estimated global mean sequestration time scales, the remineralized carbon from this injected POC would be retained for 100–200 years before re-entering the surface mixed layer (Boyd et al., 2019), which is substantial for adding energy and food supply to the mesopelagic organisms in this region (Dall’Olmo et al., 2016).

Table 1

| No. | Dates         | Duration | MLD change                  | Carbon export from our method | Carbon export from Lacour’s method |
|-----|---------------|----------|-----------------------------|------------------------------|-----------------------------------|
| 1   | 25 Jan to 30 Jan | 5 days   | 35 m to 174 m to 23 m       | +1.662 g C m\(^{-2}\)       | +1.332 g C m\(^{-2}\)             |
| 2   | 30 Jan to 5 Feb | 6 days   | 23 m to 154 m to 35 m       | −1.301 g C m\(^{-2}\)       | −0.792 g C m\(^{-2}\)             |
| 3   | 12 Feb to 14 Feb | 2 days   | 29 m to 164 m to 43 m       | −1.732 g C m\(^{-2}\)       | −2.235 g C m\(^{-2}\)             |
| 4   | 15 Feb to 18 Feb | 3 days   | 66 m to 104 m to 10 m       | +2.830 g C m\(^{-2}\)       | +4.140 g C m\(^{-2}\)             |
| 5   | 21 Feb to 26 Feb | 5 days   | 30 m to 112 m to 39 m       | +0.943 g C m\(^{-2}\)       | +0.732 g C m\(^{-2}\)             |
| 6   | 27 Feb to 2 Mar | 3 days   | 60 m to 146 m to 13 m       | +3.522 g C m\(^{-2}\)       | +3.358 g C m\(^{-2}\)             |
| 7   | 3 Mar to 6 Mar  | 3 days   | 15 m to 90 m to 23 m        | +3.003 g C m\(^{-2}\)       | +0.297 g C m\(^{-2}\)             |
| Total|               |          |                             | +8.927 g C m\(^{-2}\)      | +6.832 g C m\(^{-2}\)             |

Note. Lacour’s method refers to the maximum MLD method in Lacour et al. (2019), and our method is described in Figure 2. MLD Change represents the MLD on the first day (t\(_0\)), the maximal MLD (t\(_1\)), and the MLD on the last day (t\(_2\)) of each MLP event.
4. Discussion and Conclusions

Previous studies of the MLP have focused on winter-to-summer transition period (Dall'Olmo et al., 2016; Dall'Olmo & Mork, 2014; Lacour et al., 2019) when there were large oscillations in surface water temperatures (e.g., April; Figure 1b). These longer durations of more substantial transition not only can magnify single POC export events but also are more readily captured when surface waters are sampled on only 5–10 day intervals. They are recognized as a meaningful contribution to particle injection into the ocean interior (Boyd et al., 2019). The work here shows an unexpectedly strong winter-time export in this midlatitude region, substantially extending the window of time where MLP processes can be important. It is notable that this export flux approaches a third of that estimated for the North Atlantic spring bloom (perhaps greater given differences in maximum annual mixed layer depth; Palevsky & Doney, 2018), but it is spread sufficiently over time that it has escaped recognition until now. The findings are reinforced by two considerations: the daily profiling frequency enables more precise assessment of the mixing and transport dynamics, and the serendipitous entrainment of the profiling float within an anti-cyclonic recirculation gyre, which minimized the potential complications introduced by lateral advective processes (Omand et al., 2015).

Even so, the winter-time MLP is expected to become less frequent at higher latitudes where reduced insolation limits the formation of ephemeral, shallow (i.e., sunlit) stratification necessary to initiate the bloom phase. Indeed, a BGC-Argo float positioned roughly due north at 41°N (Float 2902755) showed no evidence for MLP activity, yet it was profiling on a 5-day cycle so it is possible that events that did occur were not captured in the dataset (e.g., Figure 3). It is reasonable to expect that climate-driven shifts in temperature and wind conditions might expand the latitudinal zones where winter-time MLP processes are significant. These changes, combined with the anticipated general shallowing of the maximum annual MLD (Palevsky & Doney, 2018), might partially offset the projected decreases in export flux over the next century (Bopp et al., 2013; Laufkötter et al., 2016).

Our findings highlight the need to quantify winter MLP activity in midlatitude regions. Assigning all BGC-Argo floats in midlatitude regions to daily profiling intervals, however, is programmatically impractical, as the associated cost due to shorter float lifetimes would threaten the sustainability of the global BGC-Argo program. One solution would be to detail a small subset of (sacrificial) daily-profiling floats during different periods in targeted regions to quantify more broadly the degree of this undersampled carbon export. Machine learning algorithms can then link related parameters from satellites and the MLD (from core-Argo and BGC-Argo) to POC export estimates (from the sacrificial BGC-Argo floats) to integrate the wintertime carbon export from MLP processes. A preliminary test of this approach (neural network based, see Text S4) using the comparatively limited data set here showed a high potential correlation between neural network-based estimate of integrated POC flux and that from the in-situ data presented here (Figure S9). Although encouraging, the reliability of such machine learning techniques will depend on having sufficient daily profile data on the broader temporal and spatial scales than a few BGC-Argo floats could provide.

The BGC-Argo program is an essential asset for understanding global ocean biogeochemistry, and it is well structured to study major aspects of the BGP (Boyd et al., 2019; Biogeochemical-Argo Planning Group, 2016; Chai et al., 2020; Claustre et al., 2020). However, our findings show that carbon export via MLP processes during winter occurs on time scales too short to be adequately sampled with the ~5–10 day profiling intervals planned in the current BGC-Argo program. Although the data here are from only a single float deployment, the degree of under-estimated carbon export is striking, shrinking values by order of magnitude (5-day interval) or frequently missing MLP episodes entirely (10-day interval). These outcomes necessitate rethinking the balance between float operational lifetimes and the primary goals of the global BGC-Argo program—to increase our knowledge on the temporal variability of biogeochemical processes, including carbon sequestration, ocean acidification, oxygen minimum zones, and the transformations of biological systems (Biogeochemical-Argo Planning Group, 2016). New strategies are needed to properly account for MLP activity, which shapes these processes in mid-latitude regions.

Data Availability Statement

BGC-Argo: ftp://ftp.ifremer.fr/ifremer/argo/dac/csi/o/2902750/; satellite Chla and POC: https://oceancolor.gsfc.nasa.gov/l3/; ADT and SSW: ftp://my.cmems-du.eu/Core/; FSLE: https://www.aviso.altimetry.fr/; air-

XING ET AL. 7 of 9
sea heat flux: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim HYCOM: https://www.hycom.org/.

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XING ET AL.