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Can We Constrain Geographical Variability in the Biological Carbon Pump's Transfer Efficiency From Observations?

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Key Points:

- We present a synthesis of BCP mesopelagic transfer efficiency metrics across open-ocean biomes using multiple methods
- Error analysis shows that large uncertainties prevent attributing BCP transfer efficiency variations to geographical differences
- Diversity of methods for estimating metrics adds uncertainty, stressing the need for standardised protocols to collect and process data

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The biological carbon pump (BCP) transfers large amounts of carbon from the atmosphere into the ocean's interior, contributing to carbon sequestration. Studies on latitudinal variability in organic carbon transfer to depth have yielded inconsistent results, likely due to methodological differences. To address this, we compiled particulate organic carbon (POC) flux data and BCP metrics from time-series locations across biogeographically distinct ocean regions. We integrated multiple BCP observational techniques, including diverse collection and processing protocols, capturing diverse facets of POC flux at varying spatio-temporal resolutions. To ensure comparability, we harmonized errors and used Monte Carlo error propagation to calculate uncertainties consistently. Our analysis reveals large local uncertainties that obscure expected latitudinal variations in BCP metrics. While such variations may exist, they remain difficult to identify with current observational data. Our findings underscore the need for sustained POC flux observations, standardization of protocols, and intercalibration of technologies to identify geographic BCP patterns.

Plain Language Summary The biological carbon pump (BCP) transfers carbon dioxide from the atmosphere into the deep ocean through sinking organic particles, helping sequester carbon for long periods. Temperature is thought to strongly control how efficiently this particulate organic carbon is transferred into the ocean's interior. However, this presumed temperature control, with its large-scale geographic latitudinal variability, remains contested. Studies disagree on whether temperature enhances or reduces the efficiency of the transfer of organic particles from the surface to the deep ocean. Differences in particle collection and statistical analysis methods across research projects create significant uncertainties in assessing BCP transfer efficiency across oceanic regions. To explore these uncertainties, we analyzed BCP transfer efficiency data from six data-rich locations representing different biomes, applying a consistent error analysis approach. We found that local uncertainties are so large that they obscure expected larger-scale geographic latitudinal patterns driven by temperature, raising questions about whether such patterns exist. Our findings suggest that current observational data do not support the presence of latitudinal patterns in BCP metrics. If these patterns do exist, sustained POC flux observations, standardised data collection and processing protocols, and intercalibration of observational technologies will be essential to identify them accurately.

1. Introduction

The biological carbon pump (BCP) transfers CO_2 from the atmosphere into the deep ocean primarily through the gravitational sinking of biologically produced marine particles (Boyd et al., 2019; Volk & Hoffert, 1985), a process that contributes to oceanic carbon sequestration. Much of the particulate organic carbon (POC) produced by the surface ocean food web and exported to depth is remineralized to CO_2 in the mesopelagic zone before reaching 1,000 m, a key depth for long-term oceanic carbon sequestration (Passow and Carlson (2012), but see Ricour et al. (2023)). The BCP's efficiency in transferring POC flux through the mesopelagic zone is represented by the metric transfer efficiency (T_{eff}). It has been suggested that T_{eff} varies geographically with latitude (as well as over seasons), with certain oceanic regions argued to being more efficient in transferring POC flux beyond 1,000 m depth, making them more efficient oceanic carbon sinks. These geographical patterns in T_{eff} are hypothesized to be controlled by a variety of factors, such as seawater temperature, plankton community structure and net primary production, which affect particle degradation rates, particle ballasting and particle palatability to food-web consumers. However, there is no consensus on the distribution of these patterns. Some studies indicate that T_{eff} is higher in the warm, subtropical oceans (Buesseler & Boyd, 2009; Guidi et al., 2015; Henson

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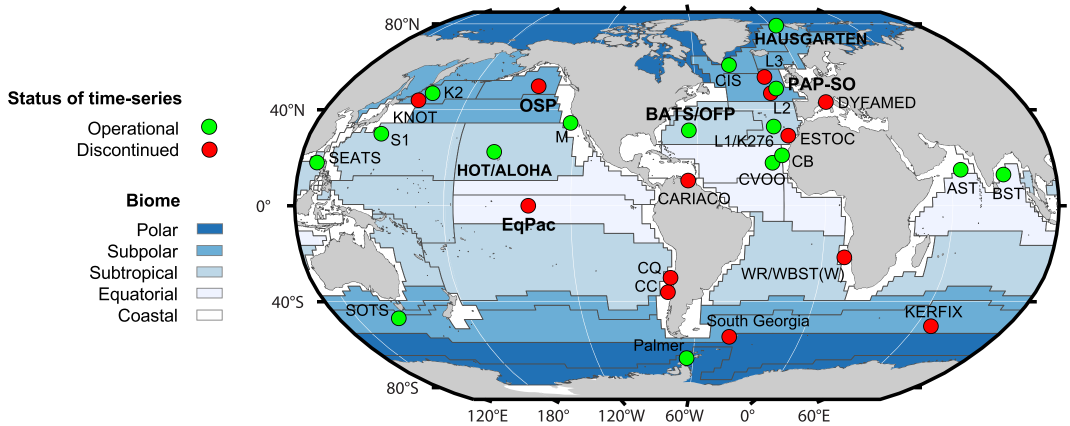

Figure 1. Geographic location of historical ship-based time-series research programs with particulate organic carbon (POC) flux data in deep-water sites (>1,000 m), with active stations (green) as of 2024. In bold are the six time-series research programs used in this study: the US Joint Global Ocean Flux Study (JGOFS) Equatorial Pacific process study experimental site (EqPac), the Hawaii Ocean Time-series (HOT) station ALOHA (HOT/ALOHA), the Bermuda Atlantic Time-Series/Oceanic Flux Program joint site (BATS/OFP), the Porcupine Abyssal Plain time-Series Observatory (PAP-SO), Ocean Station Papa (OSP), and the Long-Term Ecological Research observatory HAUSGARTEN. These sites use sediment traps on fixed-point moorings, encompassing both long-term, time-series (spanning many years) and temporary moorings (with a shorter time span but no less than 1 year). Gray contours delineate the 54 biogeochemical provinces from Longhurst (2006), color-coded by marine biome. Station details were sourced from OceanSITES (http://www.oceansites.org/), IGMETS (https://igmets.net/) and a Woods Hole Oceanographic Institution's sediment trap compilation (Benway, 2013).

et al., 2012; Lam et al., 2011), while others suggest it is higher in cold, high-latitude and equatorial upwelling regions (Cram et al., 2018; DeVries & Weber, 2017; Marsay et al., 2015; Weber et al., 2016). This existing discrepancy may be an indication that uncertainties in the observational datasets may be too large to diagnose a relation with temperature with confidence. Given that the BCP's T_{eff} has an impact on atmospheric CO_2 levels (Kwon et al., 2009; Lauderdale & Cael, 2021), this knowledge gap has significant implication for climate modeling. It affects the representation of the BCP in the Earth System Models used to predict how the ocean's capacity to sequester CO_2 via the BCP will respond to ongoing ocean warming brought about by climate change (Liu et al., 2023; Sanders et al., 2016; Siegel et al., 2016).

One reason for the diametrically opposed geographic latitudinal patterns in T_{eff}, even in data-based studies, is the reliance on one-off measurements, which risk capturing episodic events that are not representative of seasonal variation (de Melo Viríssimo et al., 2024) or the long-term average (Bisson et al., 2018). However, time-series measurements, which provide long records of data through repeated visits to ocean sites, enable the identification and exclusion of anomalous data points by comparison with the long-term average conditions, thus yielding more robust data. Although about 30 ocean time-series sites have been providing measurements of POC flux using sediment traps (Figure 1), many ocean basins, including the South Pacific, South Atlantic and Indian Ocean, lack such data due to their remote locations, rendering routine monitoring impractical. This much reduced spatial coverage is a downside of time-series measurements. A second reason for the differing patterns in T_{eff} arises from the choices related to the timing (pre-bloom, bloom, post-bloom) and depth (surface, mesopelagic, near seafloor) of data sampling, as well as the choice of technology used for data collection and methods for data processing. For instance, the dataset of Henson et al. (2012) spans all ocean basins and uses a radiometric technique ($^{234}Th/^{238}U$ radionuclide disequilibrium) to measure surface ocean POC flux, while using sediment traps for the deep ocean (1.5–3.5 km) that record a full annual cycle. In contrast, Marsay et al. (2015) compiled sediment trap data for the upper 500 m of the North Atlantic and North Pacific oceans, focusing on the summer months with a sampling period of 2–4 days.

Here, we seek to understand the consequences of the uncertainties in oceanographic POC flux measurements for robustly detecting geographic latitudinal trends by analyzing a variety of POC flux measurements and BCP metrics in a self consistent manner. Specifically, we test the null hypothesis that T_{eff} does not present coherent geographical variability and that the suggested geographical patterns could instead be methodological artifacts resulting from the choices made to collect and process POC flux measurements. We focus on six extensively sampled ocean locations spanning distinct open-ocean biomes: equatorial, subtropical, subpolar and polar oceans.

We analyze data from a variety of sources, including time-series and one-off measurements using diverse data collection methods, from traditional techniques to imaging sensors. We derive average values and uncertainties for three metrics characterizing mesopelagic POC flux transfer efficiency: Martin's *b* coefficient, the remineralization length scale coefficient and T_{eff}. Our analysis reveals large uncertainties in these metrics which obscure geographical differences. These results suggest that limitations of currently available data may pose a major challenge to ongoing efforts to understand the geographical variations of T_{eff}, which is crucial for identifying the factors that control T_{eff} and predicting how it might change in response to climate change.

2. Data and Methods

2.1. Data Sources

We compiled a dataset of oceanic POC flux measurements from two traditional collection methods—sediment traps and radionuclides—at six extensively sampled open-ocean time-series study sites (Figure 1, sites in bold). Spanning 1978–2022, the dataset includes time-series, one-off measurements and cross-project data from international programs such as JGOFS (Joint Global Ocean Flux Study), GEOTRACES and EXPORTS (EXport Processes in the Ocean from RemoTe Sensing), along with pivotal local programs like HOT and BATS. The selected six sites—EqPac (central equatorial Pacific upwelling system), HOT/ALOHA (subtropical NE Pacific), BATS/OFP (subtropical NW Atlantic), PAP-SO (subpolar NE Atlantic), OSP (subpolar NE Pacific) and HAUSGARTEN (polar Atlantic-Arctic boundary)—cover a range of biomes, from cold equatorial and high-latitude regions to the warmer subtropical areas, a geographical gradient where other studies have shown variations (e.g., Marsay et al. (2015) and Henson et al. (2012)). Our site selection criteria, which excluded some locations shown in Figure 1, were as follows: (a) open-ocean biomes to ensure that particle fluxes primarily reflect local ocean biogeochemical factors rather than terrestrial inputs from continents; (b) visits by multiple research teams, providing data using diverse collection methods; and (c) extensive coverage across multiple depths to capture mesopelagic attenuation processes. Tables S1–S6 in Supporting Information S1 summarize the references used, including data acquisition and quality control details, and Text S2 in Supporting Information S1 outlines the data processing methods.

The primary data collection method featured in our compilation is long-term time-series sediment traps on bottom-tethered moorings (i.e., near-seafloor measurements). To enhance data representation in the upper water column, we supplemented time-series measurements with data from shorter-term studies conducted in these locations using surface-tethered sediment traps, neutrally buoyant sediment traps and radionucldies. Despite the different integration times of sediment traps and radionucldies (Th-based estimates typically integrate over 3 weeks whereas trap measurements can span from days to months, Buesseler et al. (2007)), individual data points show good overlap (Figure 2).

In addition to POC flux measurements from sediment traps and radionuclides, we explored an alternate collection method: marine particle imaging using the Underwater Vision Profiler 5 (UVP5). Particle data from the UVP5, sourced from the compilation by Kiko et al. (2022), was converted into POC flux using the approach outlined by Bisson et al. (2022) (Text S3 in Supporting Information S1). The use of an underwater camera like the UVP5 offers significantly higher depth and temporal resolution than traditional POC flux sampling methods and has gained popularity over the past decade as a valuable proxy for POC flux (Chai et al., 2020; Claustre et al., 2021; Giering et al., 2020; Siegel et al., 2023).

2.2. Calculation of Metrics

Our study evaluates three BCP mesopelagic transfer efficiency metrics: Martin's *b* coefficient, which assumes a power-law decay of POC flux with depth (Martin et al., 1987); the remineralization length scale coefficient (z^*), which assumes an exponential decay (Armstrong et al., 2002); and the fraction of POC flux exported from the euphotic zone (~50–200 m) that reaches the base of the mesopelagic ocean (~1,000 m) (T_{eff} between z_{eu}–z_{meso}), which makes no assumption on manner of decay (Buesseler & Boyd, 2009). These three metrics are interrelated (can be derived from one another) and the equations for each are provided in Text S1 in Supporting Information S1.

Metrics were derived from five distinct data groups: (a) POC flux measurements from sediment traps and radionuclides (compiled specifically for this study), (b) POC flux estimates from the UVP5 (sourced from Kiko

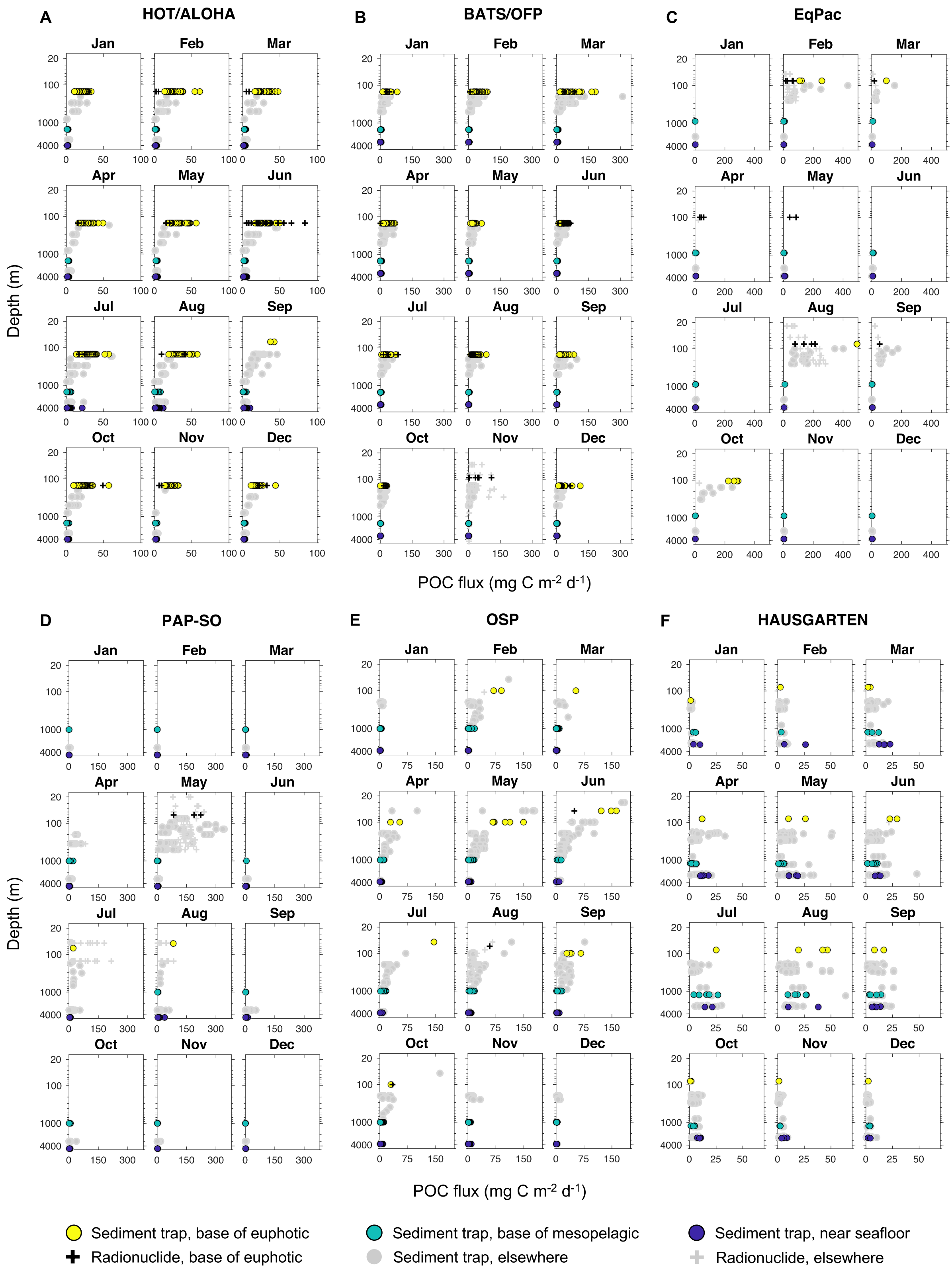

Figure 2. Compilation of particulate organic carbon (POC) flux measurements from sediment traps and radionuclides at the six ocean time-series sites used in this study, showcasing data distribution by month and depth ($N = 7162$). Colored data points represent different collection methods and depth zones (see Table S7 in Supporting Information S1) and are used for data summaries in Figures S1–S2 in Supporting Information S1. Note the y-axis in $\log_{10}$ scale, and the x-axis typically limited to the maximum POC flux value at each site.

et al. (2022)), (c) published BCP metrics calculated from canonical fits to POC flux data from sediment traps, radionuclides, UVP5 and in situ filtration systems (Buesseler & Boyd, 2009; Francois et al., 2002; Guidi et al., 2015; Lam et al., 2011; Mouw, Ciochetto, et al., 2016), (d) published BCP metrics calculated from statistical fits to physical and biogeochemical data (Henson et al., 2012; Marsay et al., 2015), and (e) published BCP metrics estimated using a diagnostic model constrained by biogeochemical data (Weber et al., 2016). This approach allowed us to incorporate metrics from a range of collection methods (e.g., collection technology, timing of the sampling, depth resolution) and processing methods (e.g., data aggregation, error propagation and metric calculation) across local and international programs. Table S8 in Supporting Information S1 lists the contributing studies with local scope, while details of data processing for each data group are documented in Texts S2–S6 in Supporting Information S1.

Error quantification for POC flux data from sediment traps and radionuclides (group i) distinguishes between random and systematic errors (Text S2 in Supporting Information S1), following the ISO Guide to the Expression of Uncertainty in Measurement (GUM, 2020). For UVP5 data (group ii), uncertainties were derived from particle sampling volumes, as described by Bisson et al. (2022) (Text S3 in Supporting Information S1). Error propagation to monthly POC flux averages in both groups was performed using MATLAB's Worst-Case Propagation of Uncertainty algorithm (Ridder, 2023). For all data groups (i to v), error propagation from monthly POC flux estimates to BCP metrics, or between metrics, was performed using a Monte Carlo-based approach implemented in MATLAB by Robens (2023) (described in Text S7 in Supporting Information S1). This approach simulates the probability distribution of the metrics, from which we can directly derive their confidence intervals, offering a simpler alternative to more complex calculations typically required for error propagation when multiple sources of uncertainty are involved.

3. Results

POC flux measurements from sediment traps and radionuclides (Figure 2) show good agreement in their ranges, supporting their combined use for calculating monthly averaged POC fluxes (Figure S2 in Supporting Information S1). While overlap is not always expected (e.g., Buesseler et al., 2006), here the two methods align well. Both reveal substantial depth heterogeneity, with better coverage of the mesopelagic and bathypelagic zones compared to the surface, and enhanced sampling of the surface ocean during warmer months (e.g., OSP and PAP-SO). Most monthly POC flux profiles show a typical depth decay (except HAUSGARTEN), indicative of subsurface attenuation processes. Notably, surface ocean POC fluxes vary up to 10-fold (e.g., HOT/ALOHA in June; BATS/OFP in March; EqPac in August; PAP-SO in July; OSP in May).

Compared to UVP5-derived POC flux (Figure S5 in Supporting Information S1), sediment trap and radionuclide measurements show less overlap, with UVP5 estimates generally being higher, a trend confirmed by the BCP metrics derived from POC fluxes (Figure S6 in Supporting Information S1 and Tukey-Kramer post-hoc test, $p \leq 0.05$). A matchup analysis of UVP5 and combined sediment trap and radionuclide POC flux data (Figure 3) reveals a low (HOT/ALOHA and BATS/OFP) to moderate (OSP and PAP-SO) correlation between these collection methods (Spearman's rank, all statistically significant with $p \leq 0.05$, except HOT/ALOHA). This substantial mismatch was also noted by Fender et al. (2019, see their Figure 3).

Figure 4 compares three metrics of BCP mesopelagic transfer efficiency (Martin's b, z^*, T_{eff}) across various studies at our six study locations. Visibly, there is considerable variability within each location, making it difficult to identify differences between biomes. In fact, statistical analysis reveals no significant differences between locations for any of the metrics (Kruskal–Wallis ANOVA, $p > 0.05$), implying that distinct ocean biomes, as represented by our locations, do not display significantly different BCP mesopelagic transfer efficiencies, thus accepting the null hypothesis of this study. Our results contrast with previous studies suggesting geographic latitudinal differences in these metrics and, in an effort to explain them, arguing that temperature may control their large-scale geographical variability. In Figure 4, such a temperature-based control of T_{eff} would imply a left-to-right transition from warm (subtropical) to cold (upwelling equatorial, polar and subpolar) biomes. While this pattern is evident in individual studies (e.g., Marsay et al. (2015), Weber et al. (2016), and Mouw, Ciochetto, et al. (2016) show an increase of T_{eff} left-to-right, while Henson et al. (2012) and Guidi et al. (2015) show a decrease), such patterns do not hold when considering all studies collectively. Moreover, the sediment trap/radionuclide and UVP5 datasets processed in this study—for which we did not have prior expectations of a specific pattern—do not appear to follow a consistent trend.

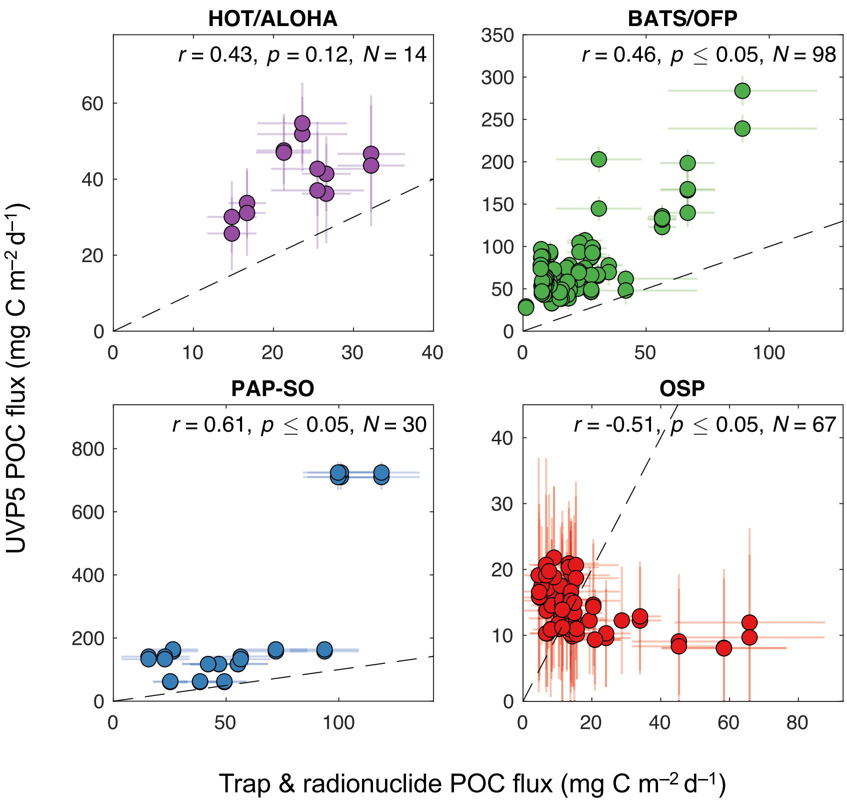

Figure 3. Comparison of particulate organic carbon (POC) flux matchups between Underwater Vision Profiler 5 (UVP5) estimates and sediment trap/radionuclide combined measurements at the four ocean study sites used in this study with spatio-temporal matchups. Matchups were identified using a depth tolerance of 5 m, time tolerance of 2 days and a latitude/longitude tolerance based on geographic search coordinates (see Tables S1–S6 in Supporting Information S1 for sediment trap/radionuclide data and Figure S4 in Supporting Information S1 for UVP5 data). UVP5 error bars reflect uncertainty propagated from water sampling volumes imaged during casts conducted on the same day, while sediment trap/radionuclide error bars reflect the combined random and systematic measurement uncertainties in the collection of POC flux. Spearman's rank correlation coefficient (r), p-value and number of local matchups (N) are provided. A total of $N = 209$ matchups were identified from 7,162 sediment trap/radionuclide measurements of POC flux and 43,703 UVP5-derived estimates.

4. Discussion and Conclusions

In this study, we tested the null hypothesis that the BCP's mesopelagic transfer efficiency does not present coherent geographic latitudinal variability by analyzing, in a self consistent manner, an extensive compilation of open-ocean data covering distinct ocean biomes. Previous studies have suggested that T_{eff} is strongly controlled by temperature (although the sign of the relationship is disputed), which should be reflected in geographic latitudinal variations (Buesseler & Boyd, 2009; Cram et al., 2018; DeVries & Weber, 2017; Guidi et al., 2015; Henson et al., 2012; Lam et al., 2011; Marsay et al., 2015; Weber et al., 2016). However, our analysis reveals no such statistically significant geographical variations in T_{eff}, accepting the null hypothesis. If such geographical trends do exist, they are obscured by natural variability (associated with location, depth and season; Figure 2) as well as differences in working protocols (associated with data collection and processing methods; Text S2–S6 in Supporting Information S1).

Latitudinal gradients reflect the uneven distribution of sunlight and heat across the Earth's surface, closely linking them to temperature. Many marine ecosystem variables, such as phytoplankton growth, heterotrophic respiration and phytoplankton cell size, are temperature-dependent. However, the invoked mechanisms through which temperature affects T_{eff} differ among authors. For instance, Henson et al. (2012) suggested that in warm, low-latitude systems, the tighter coupling between phytoplankton growth and zooplankton grazing—resulting in the increased production of fecal pellets, which are fast-sinking particles that are transferred more efficiently—along with the smaller size of phytoplankton cells—producing particles that are less palatable and harder to digest, resulting in slower decomposition of POC—leads to higher T_{eff}. In cold, upwelling systems, the reverse

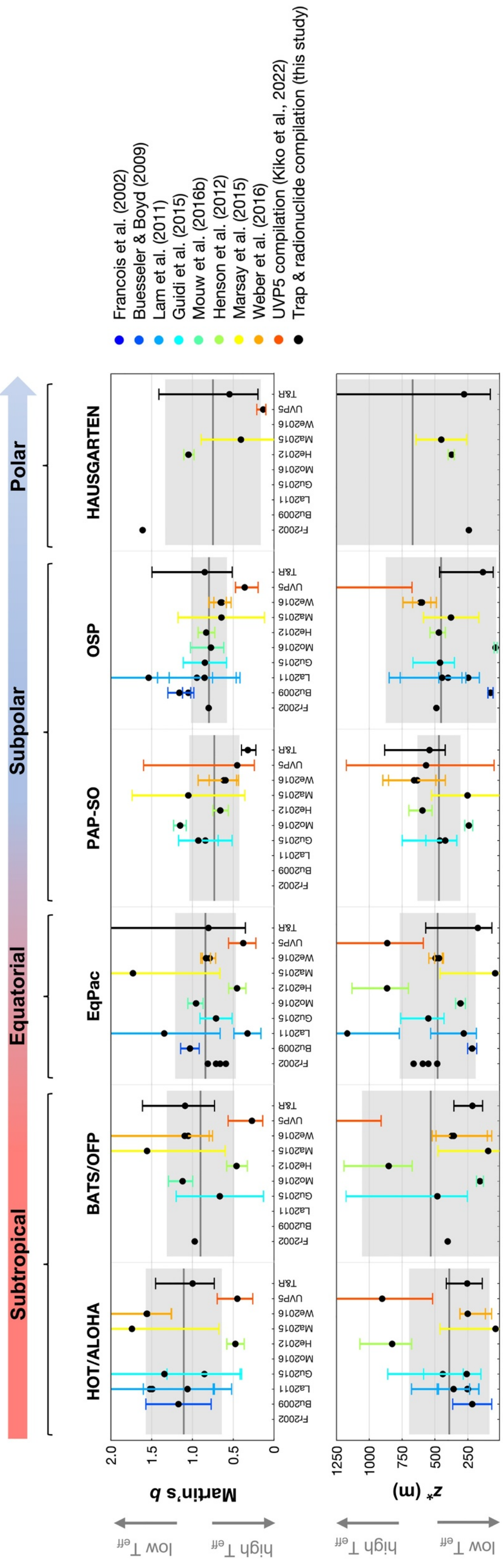
Subtropical
Equatorial
Subpolar
Polar
HOT/ALOHA
BATS/OFP
EqPac
PAP-SO
OSP
HAUSGARTEN
Francois et al. (2002)
Buesseler & Boyd (2009)
Lam et al. (2011)
Guidi et al. (2015)
Mouw et al. (2016b)
Henson et al. (2012)
Marsay et al. (2015)
Weber et al. (2016)
UVP5 compilation (Kiko et al., 2022)
Trap & radionuclide compilation (this study)
Martin's b
z* (m)
Teff
low Teff
high Teff

Figure 4.

pattern is observed. In contrast, Marsay et al. (2015) attributed lower T_{eff} in warmer systems to slower heterotrophic metabolism, leading to slower degradation of POC, with the smaller size of phytoplankton cells contributing to slow-sinking particles.

The absence of a clear latitudinal gradient in BCP transfer efficiency metrics across studies (Figure 4)—despite distinct latitudinal patterns observed in individual studies—can be attributed to six factors we identified. First, differences in protocols for error quantification and error propagation may limit comparability between studies (Text S2 in Supporting Information S1). Second, mathematical artifacts can affect metric calculation; for instance, the coefficients *b* and z^* are sensitive to the curve fitting method applied and reference depths (Text S2 in Supporting Information S1; Figure S3 in Supporting Information S1; Olli (2015)), while UVP5-based BCP metrics are sensitive to range of particle size classes and assumptions made in the calibration of the power-law coefficients linking particle size to POC flux (Bisson et al., 2022; Iversen et al., 2010; McDonnell & Buesseler, 2012). Third, the collection method to acquire POC flux data introduces variability (Figure 3; Cael et al. (2018); Fender et al. (2019); Bisson et al. (2022)), as methods differ in integration times (e.g., up to a year for a sediment trap and instantaneous for UVP5), POC flux facets detected (e.g., UVP5 detect passively sinking particles, like marine snow, and actively sinking particles, like zooplankton, whereas radionuclides measure only passively sinking), or detection sensitivities (e.g., UVP5 is insensitive to very small and very large particles while radionuclides are highly sensitive to physical processes in the water column). Fourth, the temporal sampling window varies, with studies often focusing on different seasonal periods (pre-bloom, bloom or post-bloom period), which may be more or less representative of the annual average (Bisson et al., 2018), and data gaps exist, particularly during winter months at higher latitudes (e.g., OSP and PAP-SO, Figure 2). Fifth, the depth resolution of sampling varies across projects, affecting the choice of reference depths to obtain POC flux profiles (Figure S3 in Supporting Information S1 and Buesseler, Boyd, et al. (2020)). Lastly, the dynamic nature of POC flux requires large sample sizes for accurate long-term estimates, rendering one-off (episodic) measurements potentially biasing and undersampling at different depths and times a concern (Cael et al., 2018, 2021). Indeed, the diametrically opposed temperature-driven geographical patterns in Henson et al. (2012) and Marsay et al. (2015) likely stems from differences in the POC flux datasets they used, which amalgamate various collection technologies, depth ranges covered, timings and sample sizes. Thus, researchers must carefully consider these factors before attributing spatial or long-term representativeness to their estimated metrics, as dataset limitations can significantly impact results.

One implication of a lack of identifiable geographic latitudinal variability in T_{eff} is that temperature may not be its dominant control. Indeed, other factors controlling T_{eff} have been proposed, such as net primary production and phytoplankton community composition (Cram et al., 2018; Francois et al., 2002; Guidi et al., 2009; Lam et al., 2011). Furthermore, a recent study by de Melo Viríssimo et al. (2024) examined the seasonal variability in T_{eff} and concluded that the high seasonality in POC flux attenuation patterns could preclude attributing a single annual average mode of geographical behavior to T_{eff}. Accounting for these additional factors could reveal geographical patterns that temperature alone has not identified in our study.

Determining the fractional contribution of the six factors outlined above to measurement uncertainty would be a valuable exercise but was beyond the scope of our null hypothesis testing exercise. While sustained observations from time-series sites could help sectioning uncertainty into its various contributors, future efforts should also focus on reconciling methods and uncertainty quantification in raw POC flux data, alongside collecting equivalent data from a broader range of contrasting sites. Our approach provides a first-hand exploration of uncertainty in POC flux measurements across a diverse array of methods, reflecting the real-world, multiple-choice challenges researchers face when selecting data to validate their studies. Given the variety of data collection and processing methods, we opted to incorporate data from all available methods, addressing the researcher's practical dilemma of dataset selection while recognizing the limits of detailed uncertainty quantification.

Figure 4. Comparison of published BCP mesopelagic transfer efficiency metrics (Martin's *b* coefficient, z^* coefficient and T_{eff} between z_{eu}–z_{meso}) across six sites associated with time-series programs (HOT/ALOHA, BATS/OFP, EqPac, PAP-SO, OSP and HAUSGARTEN) arranged by ocean biome (from warm subtropical, to cold equatorial, subpolar and polar). The individual values shown are the median and 68% confidence intervals (equivalent to one standard deviation). The dark gray horizontal line represents the group simple mean of study references, with overlaid gray bounds indicating standard deviation. For publications that employed different methods to collect/process raw POC flux data, or sampled at different seasons of the year, their average values are reported separately and represented as distinct scatter points (see Text S8 in Supporting Information S1 for further explanation). The *y*-axis of *b* and z^* is limited to a range of reasonable values (assessed after Henson et al. (2012) and Marsay et al. (2015)); note that some values confidence intervals extend beyond this range and are truncated. All plotted values are provided in Dataset S2.

Traditionally, assessing the BCP's mesopelagic transfer efficiency relied on sediment traps and ^{234}Th measurements. The advent of new technologies, like low-powered optical scattering and chlorophyll fluorescence sensors mounted on autonomous platforms such as gliders and floats (Briggs et al., 2011, 2020), and the UVP6 (Picheral et al., 2022), brings a transformative change in the way oceanographers observe POC fluxes. These technologies offer unprecedented spatio-temporal resolutions, especially crucial in the undersampled mesopelagic zone (100–1,000 m). However, as new technologies proliferate, there is a parallel need to work toward studies that intercompare them. Our analysis in Figure 3 highlights the importance of exercising caution when inferring large-scale patterns in POC fluxes from a single collection method or when combining datasets from different technologies, as each captures different facets of POC flux at varying spatio-temporal resolutions. Such comparative studies are crucial for end-users of the data, enabling them to make informed decisions about the most suitable data to use for their specific research purposes. Importantly, uncertainties in oceanographic observations propagate into climate models which, depending on their parametrization, variably project either enhanced or decreased mesopelagic transfer efficiency under future climate change scenarios. This discrepancy in even the directionality—the enhancement or reduction of POC flux processes—has obvious ramifications for our ability to predict the long-run effects of global warming in the ocean.

Data Availability Statement

The raw POC flux data compiled for this study and plotted in Figure 2 are available from the references cited in Tables S1–S6 in Supporting Information S1. The data plotted in Figure 4 are available in Dataset S2. All analyses were done using MATLAB (R2021a, MathWorks Inc) and the code and processed data are available in the GitHub repository https://github.com/annarufas/Rufas_etal_2024_GRL and is archived at Rufas (2024). MATLAB's Worst-Case Propagation of Uncertainty algorithm (Ridder, 2023) and MATLAB's Monte Carlo Error Propagation algorithm (Robens, 2023) were used to perform error propagation, and MATLAB's Shapiro-Wilk and Shapiro-Francia normality tests (BenSaïda, 2024) were used for our ANOVA analysis. Required MATLAB's toolboxes include "Curve Fitting", "Optimization", and "Statistics and Machine Learning."

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References

Armstrong, R. A., Lee, C., Hedges, J. I., Honjo, S., & Wakeham, S. G. (2002). A new, mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of POC with ballast minerals. *Deep-Sea Research II*, *49*(1–3), 219–236. https://doi.org/10.1016/S0967-0645(01)00101-1

BenSaïda, A. (2024). Shapiro-Wilk and Shapiro-Francia normality tests [software]. *MATLAB Central File Exchange*. Retrieved from https://uk.mathworks.com/matlabcentral/fileexchange/13964-shapiro-wilk-and-shapiro-francia-normality-tests

Benway, H. M. (2013). Woods Hole oceanographic institution POC flux. [dataset]. Retrieved from https://www2.whoi.edu/site/changingocean/wp-content/uploads/sites/84/2019/07/TS_at_a_glance_MASTER_FULL_153188.xls

Bisson, K. M., Kiko, R., Siegel, D., Guidi, L., Picheral, M., Boss, E., & Cael, B. B. (2022). Sampling uncertainties of particle size distributions and derived fluxes. *Limnology and Oceanography: Methods*, *20*(12), 754–767. https://doi.org/10.1002/lom3.10524

Bisson, K. M., Siegel, D. A., DeVries, T., Cael, B. B., & Buesseler, K. O. (2018). How data set characteristics influence ocean carbon export models. *Global Biogeochemical Cycles*, *32*(9), 1312–1328. https://doi.org/10.1029/2018GB005934

Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., & Weber, T. (2019). Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature*, *568*(7752), 327–335. https://doi.org/10.1038/s41586-019-1098-2

Briggs, N., Dall'Olmo, G., & Claustre, H. (2020). Major role of particle fragmentation in regulating biological sequestration of CO_2 by the oceans. *Science*, *367*(6479), 791–793. https://doi.org/10.1126/science.aay1790

Briggs, N., Perry, M. J., Cetinić, I., Lee, C. M., D'Asaro, E. A., Gray, A. M., & Rehm, E. (2011). High-resolution observations of aggregate flux during a sub-polar North Atlantic spring bloom. *Deep-Sea Research I*, *58*(10), 1031–1039. https://doi.org/10.1016/j.dsr.2011.07.007

Buesseler, K. O., Benitez-Nelson, C. R., Moran, S. B., Burd, A., Charette, M., Cochran, J. K., et al. (2006). An assessment of particulate organic carbon to thorium-234 ratios in the ocean and their impact on the application of 234Th as a POC flux proxy. *Marine Chemistry*, *100*(3–4), 213–233. https://doi.org/10.1016/j.marchem.2005.10.013

Buesseler, K. O., & Boyd, P. W. (2009). Shedding light on processes that control particle export and flux attenuation in the twilight zone of the open ocean. *Limnology & Oceanography*, *54*(4), 1210–1232. https://doi.org/10.4319/lo.2009.54.4.1210

Buesseler, K. O., Lamborg, C. H., Boyd, P. W., Lam, P. J., Trull, T. W., Bidigare, R. R., et al. (2007). Revisiting carbon flux through the ocean's twilight zone. *Science*, *316*(5824), 567–570. https://doi.org/10.1126/science.113795

Buesseler, K. O., Boyd, P. W., Black, E. E., & Siegel, D. A. (2020). Metrics that matter for assessing the ocean biological carbon pump. *Proceedings of the National Academy of Sciences*, *117*(18), 9679–9687. https://doi.org/10.1073/pnas.1918114117

Cael, B. B., Bisson, K., Conte, M., Duret, M. T., Follett, C. L., Henson, S. A., et al. (2021). Open ocean particle flux variability from surface to seafloor. *Geophysical Research Letters*, *48*(9). https://doi.org/10.1029/2021GL092895

Cael, B. B., Bisson, K. M., & Follett, C. L. (2018). Can rates of ocean primary production and biological carbon export be related through their probability distributions? *Global Biogeochemical Cycles*, *32*(6), 954–970. https://doi.org/10.1029/2017GB005797

Chai, F., Johnson, K. S., Claustre, H., Xing, X., Wang, Y., Boss, E., et al. (2020). Monitoring ocean biogeochemistry with autonomous platforms. *Nature Reviews Earth & Environment*, *1*(6), 315–326. https://doi.org/10.1038/s43017-020-0053-y

Claustre, H., Legendre, L., Boyd, P. W., & Levy, M. (2021). The oceans' biological carbon pumps: Framework for a research observational community approach. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.780052

Cram, J. A., Weber, T., Leung, S. W., McDonnell, A. M. P., Liang, J. H., & Deutsch, C. (2018). The role of particle size, ballast, temperature, and oxygen in the sinking flux to the deep sea. *Global Biogeochemical Cycles*, *32*(5), 858–876. https://doi.org/10.1029/2017GB005710

de Melo Viríssimo, F., Martin, A. P., Henson, S. A., & Wilson, J. D. (2024). Seasonality in carbon flux attenuation explains spatial variability in transfer eficiency. *Geophysical Research Letters*, *51*(4). https://doi.org/10.1029/2023GL107050

DeVries, T., & Weber, T. (2017). The export and fate of organic matter in the ocean: New constraints from combining satellite and oceanographic tracer observations. *Global Biogeochemical Cycles*, *31*(3), 535–555. https://doi.org/10.1002/2016GB005551

Fender, C. K., Kelly, T. B., Guidi, L., Ohman, M. D., Smith, M. C., & Stukel, M. R. (2019). Investigating particle size-flux relationships and the biological pump across a range of plankton ecosystem states from coastal to oligotrophic. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00603

Francois, R., Honjo, S., Krishfield, R. A., & Manganini, S. J. (2002). Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. *Global Biogeochemical Cycles*, *16*(4), 1087. https://doi.org/10.1029/2001gb001722

Giering, S. L. C., Cavan, E. L., Basedow, S. L., Briggs, N., Burd, A. B., Darroch, L. J., et al. (2020). Sinking organic particles in the Ocean—Flux estimates from in situ optical devices. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00834

Guidi, L., Legendre, L., Reygondeau, G., Uitz, J., Stemmann, L., & Henson, S. A. (2015). A new look at ocean carbon remineralization for estimating deepwater sequestration. *Global Biogeochemical Cycles*, *29*(7), 1044–1059. https://doi.org/10.1002/2014GB005063

Guidi, L., Stemmann, L., Jackson, G. A., Ibañez, F., Claustre, H., Legendre, L., et al. (2009). Effects of phytoplankton community on production, size and export of large aggregates: A world-ocean analysis. *Limnology & Oceanography*, *54*(6), 1951–1963. https://doi.org/10.4319/lo.2009.54.6.1951

GUM. (2020). Guide to the expression of uncertainty in measurement. Part 6: Developing and using measurement models. *Joint Committee for Guides in Metrology, JCGM GUM-6:2020*. Retrieved from https://www.bipm.org/documents/20126/2071204/JCGM_GUM_6_2020.pdf

Henson, S. A., Sanders, R. J., & Madsen, E. (2012). Global patterns in efficiency of particulate organic carbon export and transfer to the deep ocean. *Global Biogeochemical Cycles*, *26*(1), GB1028. https://doi.org/10.1029/2011GB004099

Iversen, M. H., Nowald, N., Ploug, H., Jackson, G. A., & Fischer, G. (2010). High resolution profiles of vertical particulate organic matter export off Cape Blanc, Mauritania: Degradation processes and ballasting effects. *Deep-Sea Research I*, *57*(6), 771–784. https://doi.org/10.1016/j.dsr.2010.03.007

Kiko, R., Picheral, M., Antoine, D., Babin, M., Berline, L., Biard, T., et al. (2022). A global marine particle size distribution dataset obtained with the Underwater Vision Profiler 5. *Earth System Science Data*, *14*(9), 4315–4337. https://doi.org/10.5194/essd-14-4315-2022

Kwon, E. Y., Primeau, F. W., & Sarmiento, J. L. (2009). The impact of remineralization depth on the air-sea carbon balance. *Nature Geoscience*, *2*(9), 630–635. https://doi.org/10.1038/ngeo612

Lam, P. J., Doney, S. C., & Bishop, J. K. (2011). The dynamic ocean biological pump: Insights from a global compilation of particulate organic carbon, CaCO3, and opal concentration profiles from the mesopelagic. *Global Biogeochemical Cycles*, *25*(3), GB3009. https://doi.org/10.1029/2010GB003868

Lauderdale, J. M., & Cael, B. B. (2021). Impact of remineralization profile shape on the air-sea carbon balance. *Geophysical Research Letters*, *48*(7). https://doi.org/10.1029/2020GL091746

Liu, Y., Moore, J. K., Primeau, F., & Wang, W. L. (2023). Reduced CO_2 uptake and growing nutrient sequestration from slowing overturning circulation. *Nature Climate Change*, *13*(1), 83–90. https://doi.org/10.1038/s41558-022-01555-7

Longhurst, A. R. (2006). *Ecological geography of the sea* (2nd ed.). Academic Press. https://doi.org/10.1016/B978-0-12-455521-1.X5000-1

Marsay, C. M., Sanders, R. J., Henson, S. A., Pabortsava, K., Achterberg, E. P., & Lampitt, R. S. (2015). Attenuation of sinking particulate organic carbon flux through the mesopelagic ocean. *Proceedings of the National Academy of Sciences*, *112*(4), 1089–1094. https://doi.org/10.1073/pnas.1415311112

Martin, J. H., Knauer, G. A., Karl, D. M., & Broenkow, W. W. (1987). Vertex: Carbon cycling in the northeast Pacific. *Deep-Sea Research*, *34*(2), 267–285. https://doi.org/10.1016/0198-0149(87)90086-0

McDonnell, A. M. P., & Buesseler, K. O. (2012). A new method for the estimation of sinking particle fluxes from measurements of the particle size distribution, average sinking velocity, and carbon content. *Limnology and Oceanography: Methods*, *10*(5), 329–346. https://doi.org/10.4319/lom.2012.10.329

Mouw, C. B., Ciochetto, A., Mckinley, G. A., Gloege, L., & Pilcher, D. J. (2016). Phytoplankton size impact on export flux in the global ocean. *Global Biogeochemical Cycles*, *30*(10), 1542–1562. https://doi.org/10.1002/2015GB005355

Olli, K. (2015). Unraveling the uncertainty and error propagation in the vertical flux Martin curve. *Progress in Oceanography*, *135*, 146–155. https://doi.org/10.1016/j.pocean.2015.05.016

Passow, U., & Carlson, C. A. (2012). The biological pump in a high CO_2 world. *Marine Ecology Progress Series*, *470*, 249–271. https://doi.org/10.3354/meps09985

Picheral, M., Catalano, C., Brousseau, D., Claustre, H., Coppola, L., Leymarie, E., et al. (2022). The Underwater Vision Profiler 6: An imaging sensor of particle size spectra and plankton, for autonomous and cabled platforms. *Limnology and Oceanography: Methods*, *20*(2), 115–129. https://doi.org/10.1002/lom3.10475

Ricour, F., Guidi, L., Gehlen, M., DeVries, T., & Legendre, L. (2023). Century-scale carbon sequestration flux throughout the ocean by the biological pump. *Nature Geoscience*, *16*(12), 1105–1113. https://doi.org/10.1038/s41561-023-01318-9

Ridder, B. (2023). Worst-case propagation of uncertainty [software]. *MATLAB Central File Exchange*. Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/48139-worst-case-propagation-of-uncertainty

Robens, C. (2023). Monte Carlo error propagation [software]. *MATLAB Central File Exchange*. Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/57672-monte-carlo-error-propagation

Rufas, A. (2024). annarufas/Rufas_etal_2024_GRL: Repository for submitted paper to GRL (Nov 2024) (v1.1.1) [collection]. https://doi.org/10.5281/zenodo.14225221

Sanders, R. J., Henson, S. A., Martin, A. P., Anderson, T. R., Bernardello, R., Enderlein, P., et al. (2016). Controls over ocean mesopelagic interior carbon storage (COMICS): Fieldwork, synthesis, and modeling efforts. *Frontiers in Marine Science*, *3*, 136. https://doi.org/10.3389/fmars.2016.00136

Siegel, D. A., Buesseler, K. O., Behrenfeld, M., Benitez-Nelson, C. R., Boss, E. S., Brzezinski, M. A., et al. (2016). Prediction of the export and fate of global ocean net primary production: The EXPORTS science plan. *Frontiers in Marine Science*, *3*, 22. https://doi.org/10.3389/fmars.2016.00022

Siegel, D. A., Devries, T., Cetinić, I., & Bisson, K. M. (2023). Quantifying the ocean's biological pump and its carbon cycle impacts on global scales. *Annual Review of Marine Science*, *15*(1), 329–356. https://doi.org/10.1146/annurev-marine-040722-115226

Volk, T., & Hoffert, M. I. (1985). Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes. In W. S. Broecker & E. T. Sundquist (Eds.), *The carbon cycle and atmospheric CO_2: Natural variations archean to present* (pp. 99–110). American Geophysical Union (AGU). https://doi.org/10.1029/GM032p0099

Weber, T., Cram, J. A., Leung, S. W., DeVries, T., & Deutsch, C. (2016). Deep ocean nutrients imply large latitudinal variation in particle transfer efficiency. *Proceedings of the National Academy of Sciences*, *113*(31), 8606–8611. https://doi.org/10.1073/pnas.1604414113

References From the Supporting Information

Antia, A. N., Koeve, W., Fischer, G., Blanz, T., Schulz-Bull, D., Scholten, J., et al. (2001). Basin-wide particulate carbon flux in the Atlantic Ocean: Regional export patterns and potential for atmospheric CO_2 sequestration. *Global Biogeochemical Cycles*, *15*(4), 845–862. https://doi.org/10.1029/2000GB001376

Bacon, M. P., Cochran, J. K., Hirschberg, D., Hammar, T. R., & Fleer, A. P. (1996). Export flux of carbon at the equator during the EqPac time-series cruises estimated from 234Th measurements. *Deep-Sea Research II*, *43*(4–6), 1133–1153. https://doi.org/10.1016/0967-0645(96)00016-1

Baker, C. A., Estapa, M. L., Iversen, M. H., Lampitt, R. S., & Buesseler, K. O. (2020). Are all sediment traps created equal? An intercomparison study of carbon export methodologies at the PAP-SO site. *Progress in Oceanography*, *184*, 102317. https://doi.org/10.1016/j.pocean.2020.102317

Bates, N., Johnson, R. J., Lopez, P. Z., Hayden, M., May, R., Derbyshire, L., et al. (2023). Determination of carbon, nitrogen, and phosphorous content in sinking particles at the Bermuda Atlantic Time-series Study (BATS) site from 1988-2022 using a Particle Version 1. *Interceptor Trap System (PITS)*. [dataset]. https://doi.org/10.26008/1912/bco-dmo.894099.1

Bauerfeind, E., & Nöthig, E.-M. (2011). Biogenic particle flux at AWI HAUSGARTEN from mooring FEVI3 at 2400 m [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.757777

Bauerfeind, E., Nöthig, E.-M., Beszczynska, A., Fahl, K., Kaleschke, L., Kreker, K., et al. (2009). Particle sedimentation patterns in the eastern Fram Strait during 2000–2005: Results from the Arctic long-term observatory HAUSGARTEN. *Deep-Sea Research I*, *56*(9), 1471–1487. https://doi.org/10.1016/j.dsr.2009.04.011

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015a). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI10 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855467

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015b). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI13 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855468

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015c). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI18 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855470

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015d). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI1 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855463

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015e). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI20 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855471

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015f). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI22 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855472

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015g). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI24 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855473

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015h). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI2. [dataset]. https://doi.org/10.1594/PANGAEA.855464

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015i). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI3 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855465

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015j). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI7 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855466

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015k). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI11 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855561

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015l). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI14 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855562

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015m). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI17 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855563

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015n). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI19 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855564

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015o). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI21 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855565

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2015p). Biogenic particle flux at AWI HAUSGARTEN northern station HGN from mooring FEVI8 [dataset]. *Technical Reports Series*. Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven. https://doi.org/10.1594/PANGAEA.855566

Bauerfeind, E., Nöthig, E.-M., Lorenzen, C., Knüppel, N., & Soltwedel, T. (2017). Biogenic particle flux at AWI HAUSGARTEN central station HGIV from mooring FEVI16. [dataset]. https://doi.org/10.1594/PANGAEA.879532

Behrenfeld, M., & Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology & Oceanography*, *42*(1), 1–20. https://doi.org/10.4319/lo.1997.42.1.0001

Benitez-Nelson, C., Buesseler, K. O., Karl, D. M., & Andrews, J. (2001). A time-series study of particulate matter export in the North Pacific Subtropical Gyre based on 234Th:238U disequilibrium. *Deep-Sea Research I*, *48*(12), 2595–2611. https://doi.org/10.1016/S0967-0637(01)00032-2

Bishop, J. K. (1998). JGOFS EqPac TT007 POC flux from MULVFS casts. [dataset]. Retrieved from http://usjgofs.whoi.edu/jg/serv/jgofs/eqpac/tt007/mulvfs_POC.html

Bishop, J. K. (1999). Transmissometer measurement of POC. *Deep-Sea Research I*, *46*(2), 353–369. https://doi.org/10.1016/S0967-0637(98)00069-7

Bishop, J. K., Calvert, S. E., & Soon, M. Y. (1999). Spatial and temporal variability of POC in the northeast subarctic Pacific. *Deep-Sea Research II*, *46*(11–12), 2699–2733. https://doi.org/10.1016/S0967-0645(99)00081-8

Bishop, J. K. B., & Wood, T. J. (2008). Particulate matter chemistry and dynamics in the twilight zone at VERTIGO ALOHA and K2 sites. *Deep-Sea Research I*, *55*(12), 1684–1706. https://doi.org/10.1016/j.dsr.2008.07.012

Buesseler, K. O. (1998). The decoupling of production and particulate export in the surface ocean. *Global Biogeochemical Cycles*, *12*(2), 297–310. https://doi.org/10.1029/97GB03366

Buesseler, K. O., Andrews, J. A., Hartman, M. C., Belastock, R., & Chai, F. (1995). Regional estimates of the export flux of particulate organic carbon derived from thorium-234 during the JGOFS EqPac program. *Deep-Sea Research II*, *42*(2–3), 777–804. https://doi.org/10.1016/0967-0645(95)00043-P

Buesseler, K. O., Lamborg, C. H., Cai, P., Escoube, R., Johnson, R., Pike, S., et al. (2008a). Particle fluxes associated with mesoscale eddies in the Sargasso Sea. *Deep-Sea Research II*, *55*(10–13), 1426–1444. https://doi.org/10.1016/j.dsr2.2008.02.007

Buesseler, K. O., Pike, S., Maiti, K., Lamborg, C. H., Siegel, D. A., & Trull, T. W. (2009). Thorium-234 as a tracer of spatial, temporal and vertical variability in particle flux in the North Pacific. *Deep-Sea Research I*, *56*(7), 1143–1167. https://doi.org/10.1016/j.dsr.2009.04.001

Buesseler, K. O., Steinberg, D. K., Michaels, A. F., Johnson, R. J., Andrews, J. E., Valdes, J. R., & Price, J. F. (2000). A comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap. *Deep-Sea Research I*, *47*(2), 277–294. https://doi.org/10.1016/S0967-0637(99)00056-4

Buesseler, K. O., Trull, T. W., Steinberg, D. K., Silver, M. W., Siegel, D. A., Saitoh, S. I., et al. (2008b). VERTIGO (VERtical transport in the Global Ocean): A study of particle sources and flux attenuation in the North Pacific. *Deep-Sea Research I*, *55*(14–15), 1522–1539. https://doi.org/10.1016/j.dsr2.2008.04.024

Buesseler, K. O., Benitez-Nelson, C. R., Roca-Martí, M., Wyatt, A. M., Resplandy, L., Clevenger, S. J., et al. (2020b). High-resolution spatial and temporal measurements of particulate organic carbon flux using thorium-234 in the northeast Pacific Ocean during the EXport Processes in the Ocean from RemoTe Sensing field campaign. *Elementa: Science of the Anthropocene*, *8*(1), 030. https://doi.org/10.1525/elementa.030

Carr, M.-E. (2002). Estimation of potential productivity in Eastern Boundary Currents using remote sensing. *Deep-Sea Research II*, *49*(1–3), 59–80. https://doi.org/10.1016/S0967-0645(01)00094-7

Casey, K. S., Kearns, E. J., Halliwell, V., & Evans, R. (2004). AVHRR Pathfinder version 5.0 global 4km sea surface temperature (SST) climatologies for 1985-2001 [dataset]. Retrieved from https://www.ncei.noaa.gov/archive/accession/AVHRR_Pathfinder-NODC-v5.0-climatologies

Ceballos-Romero, E., Le Moigne, F. A. C., Henson, S. A., Marsay, C. M., Sanders, R. J., García-Tenorio, R., & Villa-Alfageme, M. (2016). Influence of bloom dynamics on particle export efficiency in the North Atlantic: A comparative study of radioanalytical techniques and sediment traps. *Marine Chemistry*, *186*, 198–210. https://doi.org/10.1016/j.marchem.2016.10.001

Charette, M. A., Bradley Moran, S., & Bishop, J. K. (1999). 234Th as a tracer of particulate organic carbon export in the subarctic northeast Pacific Ocean. *Deep-Sea Research II*, *46*(11–12), 2833–2861. https://doi.org/10.1016/S0967-0645(99)00085-5

Clevenger, S. J., Benitez-Nelson, C. R., Roca-Martí, M., Bam, W., Estapa, M. L., Kenyon, J. A., et al. (2024). Carbon and silica fluxes during a declining North Atlantic spring bloom as part of the EXPORTS program. *Marine Chemistry*, *258*, 104346. https://doi.org/10.1016/j.marchem.2023.104346

CMEMS. (2024a). Global Ocean colour (Copernicus-GlobColour), bio-geo-chemical, L4 (monthly and interpolated) from satellite observations (1997-ongoing). [dataset]. https://doi.org/10.48670/moi-00281

CMEMS. (2024b). Global Ocean physics reanalysis. [dataset]. https://doi.org/10.48670/moi-00021

Collier, R., & Dymond, J. (1994). EqPac sediment trap particulates collected from the U.S. JGOFS eqpac moored sediment trap array in the equatorial pacific in 1992 during the U.S. JGOFS equatorial pacific (EqPac) project. [dataset]. Retrieved from http://www.bco-dmo.org/dataset/2609

Conte, M. H. (2022). Primary particle flux data (500, 1500, and 3200m depths) of the OFP sediment trap time-series in the northern Sargasso Sea from 1978-2020 Version 3. [dataset]. https://doi.org/10.26008/1912/bco-dmo.704722.3

Conte, M. H., Ralph, N., & Ross, E. H. (2001). Seasonal and interannual variability in deep ocean particle fluxes at the Oceanic Flux Program (OFP)/Bermuda Atlantic Time Series (BATS) site in the western Sargasso Sea near Bermuda. *Deep-Sea Research II*, *48*(8–9), 1471–1505. https://doi.org/10.1016/S0967-0645(00)00150-8

Deuser, W. G., Ross, E. H., & Anderson, R. F. (1981). Seasonality in the supply of sediment to the deep Sargasso Sea and implications for the rapid transfer of matter to the deep ocean. *Deep-Sea Research Part A*, *28*(5), 495–505. https://doi.org/10.1016/0198-0149(81)90140-0

Dunne, J. P., Armstrong, R. A., Gnanadesikan, A., & Sarmiento, J. L. (2005). Empirical and mechanistic models for the particle export ratio. *Global Biogeochemical Cycles*, *19*(4), GB4026. https://doi.org/10.1029/2004GB002390

Dunne, J. P., Murray, J. W., Rodier, M., & Hansell, D. A. (2000). Export flux in the western and central equatorial Pacific: Zonal and temporal variability. *Deep-Sea Research I*, *47*(5), 901–936. https://doi.org/10.1016/S0967-0637(99)00089-8

Dymond, J., & Collier, R. (1988). Biogenic particle fluxes in the equatorial Pacific: Evidence for both high and low productivity during the 1982-1983 El Niño. *Global Biogeochemical Cycles*, *2*(2), 129–137. https://doi.org/10.1029/GB002i002p00129

Dymond, J., & Lyle, M. (1994). Particle fluxes in the ocean and implications for sources and preservation of ocean sediments. In NRC (Ed.), *Studies in geophysics: Material fluxes on the surface of the Earth* (pp. 125–142). National Academy Press.

Estapa, M. L. (2023). EXPORTS SeaBASS North Atlantic sediment traps. [dataset]. Retrieved 2024-03-04, from https://seabass.gsfc.nasa.gov/archive/Maine/Estapa/EXPORTS/exportsna

Estapa, M. L., Buesseler, K. O., Durkin, C. A., Omand, M. M., Breves, E., Kelly, R. P., et al. (2021). Biogenic sinking particle fluxes and sediment trap collection efficiency at Ocean Station Papa. *Elementa: Science of the Anthropocene*, *9*(1), 00122. https://doi.org/10.1525/elementa.2020.00122

Estapa, M. L., Feen, M. L., & Breves, E. (2019). Direct observations of biological carbon export from profiling floats in the subtropical North Atlantic. *Global Biogeochemical Cycles*, *33*(3), 282–300. https://doi.org/10.1029/2018GB006098

Guidi, L., Stemmann, L., Legendre, L., Picheral, M., Prieur, L., & Gorsky, G. (2007). Vertical distribution of aggregates (>110 μm) and mesoscale activity in the northeastern Atlantic: Effects on the deep vertical export of surface carbon. *Limnology & Oceanography*, *52*(1), 7–18. https://doi.org/10.4319/lo.2007.52.1.0007

Guidi, L., Jackson, G. A., Stemmann, L., Miquel, J. C., Picheral, M., & Gorsky, G. (2008). Relationship between particle size distribution and flux in the mesopelagic zone. *Deep-Sea Research I*, *55*(10), 1364–1374. https://doi.org/10.1016/j.dsr.2008.05.014

Guidi, L., Calil, P. H., Duhamel, S., Björkman, K. M., Doney, S. C., Jackson, G. A., et al. (2012). Does eddy-eddy interaction control surface phytoplankton distribution and carbon export in the North Pacific Subtropical Gyre? *Journal of Geophysical Research*, *117*(G2). https://doi.org/10.1029/2012JG001984

Hayes, C. T., Black, E. E., Anderson, R. F., Baskaran, M., Buesseler, K. O., Charette, M. A., et al. (2018). Flux of particulate elements in the North Atlantic ocean constrained by multiple radionuclides. *Global Biogeochemical Cycles*, *32*(12), 1738–1758. https://doi.org/10.1029/2018GB005994

Henson, S. A., Sanders, R. J., Madsen, E., Morris, P. J., Le Moigne, F. A. C., & Quartly, G. D. (2011). A reduced estimate of the strength of the ocean's biological carbon pump. *Geophysical Research Letters*, *38*(4), L04606. https://doi.org/10.1029/2011GL046735

Higgins, J., Li, T., & Deeks, J. (2023). Chapter 6: Choosing effect measures and computing estimates of effect. Part 6.5.2: Data extraction for continuous outcomes. In *Cochrane handbook for systematic reviews of interventions*. Retrieved from https://training.cochrane.org/handbook/current/chapter-06

Honjo, S. (1990). Particle fluxes and modern sedimentation in the polar oceans. In W. Smith Jr. (Ed.), *Polar oceanography, vol 2* (pp. 322–353). Academic.

Honjo, S., & Manganini, S. J. (1993). Annual biogenic particle fluxes to the interior of the North Atlantic Ocean; studied at 34°N 21°W and 48°N 21°W. *Deep-Sea Research II*, *40*(1–2), 587–607. https://doi.org/10.1016/0967-0645(93)90034-K

Honjo, S., Manganini, S. J., & Cole, J. J. (1982). Sedimentation of biogenic matter in the deep ocean. *Deep-Sea Research*, *29*(5A), 609–625. https://doi.org/10.1016/0198-0254(82)90153-4

Honjo, S., Dymond, J., Collier, R., & Manganini, S. J. (1995). Export production of particles to the interior of the equatorial Pacific Ocean during the 1992 EqPac experiment. *Deep-Sea Research II*, *42*(2–3), 831–870. https://doi.org/10.1016/0967-0645(95)00034-N

Honjo, S., Manganini, S. J., Krishfield, R. A., & Francois, R. (2008). Particulate organic carbon fluxes to the ocean interior and factors controlling the biological pump: A synthesis of global sediment trap programs since 1983. *Progress in Oceanography*, *76*(3), 217–285. https://doi.org/10.1016/j.pocean.2007.11.003

JGOFS Office. (2006). US JGOFS program website. Retrieved 2024-03-24, from http://usjgofs.whoi.edu

Jickells, T. D., Newton, P., King, P., Lampitt, R., & Boutle, C. (1996). Comparison of sediment trap records of particle fluxes from 19° to 48°N in the northeast Atlantic and their relation to surface water productivity. *Deep-Sea Research I*, *43*(7), 971–986. https://doi.org/10.1016/0967-0637(96)00063-5

Kawakami, H., Honda, M. C., Matsumoto, K., Fujiki, T., & Watanabe, S. (2010). East-West distribution of POC fluxes estimated from 234Th in the northern North Pacific in autumn. *Journal of Oceanography*, *66*(1), 71–83. https://doi.org/10.1007/s10872-010-0006-z

Kim, G., & Church, T. M. (2001). Seasonal biogeochemical fluxes of 234Th and 210Po in the upper Sargasso Sea: Influence from atmosphere iron deposition. *Global Biogeochemical Cycles*, *15*(3), 651–661. https://doi.org/10.1029/2000GB001313

Kriest, I. (2002). Different parameterizations of marine snow in a 1D-model and their influence on representation of marine snow, nitrogen budget and sedimentation. *Deep-Sea Research I*, *49*(12), 2133–2162. https://doi.org/10.1016/S0967-0637(02)00127-9

Kuss, J., & Kremling, K. (1999). Particulate trace element fluxes in the deep northeast Atlantic Ocean. *Deep-Sea Research I*, *46*(1), 149–169. https://doi.org/10.1016/S0967-0637(98)00059-4

Lamborg, C., & Buesseler, K. (2010). VERTIGO project Sediment Trap Fluxes of mass, elements and phytoplankton pigments data from KM0414 and RR_K2 cruises Version 6. *Biological and Chemical Oceanography Data Management Office (BCO-DMO)* [dataset]. https://doi.org/10.1575/1912/4137

Lampitt, R. S., & Antia, A. N. (1997). Particle flux in deep seas: Regional characteristics and temporal variability. *Deep-Sea Research I*, *44*(8), 1377–1403. https://doi.org/10.1016/S0967-0637(97)00020-4

Lampitt, R. S., Bett, B. J., Kiriakoulakis, K., Popova, E. E., Ragueneau, O., Vangriesheim, A., & Wolff, G. A. (2001). Material supply to the abyssal seafloor in the northeast Atlantic. *Progress in Oceanography*, *50*(1–4), 27–63. https://doi.org/10.1016/S0079-6611(01)00047-7

Lampitt, R. S., Briggs, N., Cael, B. B., Espinola, B., Hélaouët, P., Henson, S. A., et al. (2023). Deep ocean particle flux in the Northeast Atlantic over the past 30 years: Carbon sequestration is controlled by ecosystem structure in the upper ocean. *Frontiers in Earth Science*, *11*. https://doi.org/10.3389/feart.2023.1176196

Lampitt, R. S., Salter, I., De Cuevas, B. A., Hartman, S. E., Larkin, K. E., & Pebody, C. A. (2010). Long-term variability of downward particle flux in the deep northeast Atlantic: Causes and trends. *Deep-Sea Research II*, *57*(15), 1346–1361. https://doi.org/10.1016/j.dsr2.2010.01.011

Laws, E. A., D'Sa, E., & Naik, P. (2011). Simple equations to estimate ratios of new or export production to total production from satellite-derived estimates of sea surface temperature and primary production. *Limnology and Oceanography: Methods*, *9*(12), 593–601. https://doi.org/10.4319/lom.2011.9.593

Laws, E. A., Falkowski, P. G., Smith, W. O., Ducklow, H. W., & McCarthy, J. J. (2000). Temperature effects on export production in the open ocean. *Global Biogeochemical Cycles*, *14*(4), 1231–1246. https://doi.org/10.1029/1999GB001229

Le Borgne, R., & Gesbert, H. (1995). Campagne océanographique FLUPAC à bord du N. O. l'ATALANTE (23 septembre au 29 octobre 1994). Recueil des données. Tome 2: Optique marine, matière organique dissoute, pigments photosynthétiques, observations microscopiques, production primaire, broutage. *Archives Science Mer Océanography*. (Tech. Rep.).

Le Moigne, F. A. C., Henson, S. A., Sanders, R. J., & Madsen, E. (2013). Global database of surface ocean particulate organic carbon export fluxes diagnosed from the 234Th technique. *Earth System Science Data*, *5*(2), 295–304. https://doi.org/10.5194/essd-5-295-2013

Le Moigne, F. A. C., Poulton, A. J., Henson, S. A., Daniels, C. J., Fragoso, G. M., Mitchell, E., et al. (2015). Carbon export efficiency and phytoplankton community composition in the Atlantic sector of the Arctic Ocean. *Journal of Geophysical Research: Oceans*, *120*(6), 3896–3912. https://doi.org/10.1002/2015JC010700

Le Moigne, F. A. C., Villa-Alfageme, M., Sanders, R. J., Marsay, C. M., Henson, S. A., & García-Tenorio, R. (2013). Export of organic carbon and biominerals derived from 234Th and 210Po at the Porcupine Abyssal Plain. *Deep-Sea Research I*, *72*, 88–101. https://doi.org/10.1016/j.dsr.2012.10.010

Lemaitre, N., Planchon, F., Planquette, H., Dehairs, F., Fonseca-Batista, D., Roukaerts, A., et al. (2018). High variability of particulate organic carbon export along the North Atlantic GEOTRACES section GA01 as deduced from 234Th fluxes. *Biogeosciences*, *15*(21), 6417–6437. https://doi.org/10.5194/bg-15-6417-2018

Locarnini, R., Mishonov, A., Baranova, O., Reagan, J., Boyer, T., Seidov, D., et al. (2023). World Ocean Atlas 2023, Volume 1: Temperature [dataset]. https://doi.org/10.25923/54bh-1613

Lomas, M. W., Bates, N., Nelson, D. M., Lipschultz, F., & Knap, A. (2009). Trap Flux from R/V Oceanus cruises OC399-03, OC408-01, OC408-02 from the Northwestern Sargasso Sea roughly 35-28N and 58-68W, water depths always exceeded 4200m; 2004-2005 (NP project). [dataset]. Retrieved 2024-03-04, from http://lod.bco-dmo.org/id/dataset/3215

Lutz, M. J., Caldeira, K., Dunbar, R. B., & Behrenfeld, M. J. (2007). Seasonal rhythms of net primary production and particulate organic carbon flux to depth describe the efficiency of biological pump in the global ocean. *Journal of Geophysical Research*, *112*(C10). https://doi.org/10.1029/2006JC003706

Mackinson, B. L., Moran, S. B., Lomas, M. W., Stewart, G. M., & Kelly, R. P. (2015). Estimates of micro-nano-and picoplankton contributions to particle export in the northeast Pacific. *Biogeosciences*, *12*(11), 3429–3446. https://doi.org/10.5194/bg-12-3429-2015

Maiti, K., Benitez-Nelson, C. R., Lomas, M. W., & Krause, J. W. (2009). Biogeochemical responses to late-winter storms in the Sargasso Sea, III: Estimates of export production using 234Th:238U disequilibria and sediment traps. *Deep-Sea Research I*, *56*(6), 875–891. https://doi.org/10.1016/j.dsr.2009.01.008

Marsay, C. M. (2012). *Particulate trace metals, carbon and nitrogen in the mesopelagic (Doctor of Philosophy)*. University of Southampton.

McKinna, L., Cetinić, I., Chase, A., & Werdell, P. (2019). Approach for propagating radiometric data uncertainties through NASA ocean color algorithms. *Frontiers in Earth Science*, *7*. https://doi.org/10.3389/feart.2019.00176

Morel, A., Huot, Y., Gentili, B., Werdell, P. J., Hooker, S. B., & Franz, B. A. (2007). Examining the consistency of products derived from various ocean color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach. *Remote Sensing of Environment*, *111*(1), 69–88. https://doi.org/10.1016/j.rse.2007.03.012

Mouw, C. B., Barnett, A., McKinley, G. A., Gloege, L., & Pilcher, D. J. (2016). Global ocean particulate organic carbon flux merged with satellite parameters. *Earth System Science Data*, *8*(2), 531–541. https://doi.org/10.5194/essd-8-531-2016

Murray, J. W., Downs, J. N., Jan, N., Strom, S., Wei, C.-L., & Jannasch, H. W. (1989). Nutrient assimilation, export production and 234Th scavenging in the eastern equatorial Pacific. *Deep-Sea Research*, *36*(10), 1471–1489. https://doi.org/10.1016/0198-0149(89)90052-6

Murray, J. W., Young, J., Newton, J. A. N., Dunne, J. P., Chapin, T., Paul, B., & Mccarthys, J. J. (1996). Export flux of particulate organic carbon from the central equatorial Pacific determined using a combined drifting trap-234Th approach. *Deep-Sea Research II*, *43*(4–6), 1095–1132. https://doi.org/10.1016/0967-0645(96)00036-7

Newton, J., & Murray, J. W. (1995a). JGOFS EqPac TT007 POC flux from traps. [dataset]. Retrieved from http://www.bco-dmo.org/dataset-deployment/450839

Newton, J., & Murray, J. W. (1995b). JGOFS EqPac TT011 POC flux from traps. [dataset]. https://www.bco-dmo.org/dataset-deployment/450925

NASA Goddard Space Flight CenterOcean Ecology Laboratory, O. B. P. G. (2022a). Sea-Viewing wide field-of-view sensor (SeaWiFS) level-3 mapped chlorophyll, version 2022 [dataset]. https://doi.org/10.5067/ORBVIEW-2/SEAWIFS/L3M/CHL/2022

NASA Goddard Space Flight CenterOcean Ecology Laboratory, O. B. P. G. (2022b). Sea-Viewing wide field-of-view sensor (SeaWiFS) level-3 mapped photosynthetically available radiation, version 2022. [dataset]. https://doi.org/10.5067/ORBVIEW-2/SEAWIFS/L3M/PAR/2022

Owens, S. A., Buesseler, K. O., Lamborg, C. H., Valdes, J., Lomas, M. W., Johnson, R. J., et al. (2013). A new time series of particle export from neutrally buoyant sediments traps at the Bermuda Atlantic Time-series Study site. *Deep-Sea Research I*, *72*, 34–47. https://doi.org/10.1016/j.dsr.2012.10.011

Pelland, N. A., Eriksen, C. C., Emerson, S. R., & Cronin, M. F. (2018). Seaglider surveys at Ocean Station Papa: Oxygen kinematics and upper-ocean metabolism. *Journal of Geophysical Research: Oceans*, *123*(9), 6408–6427. https://doi.org/10.1029/2018JC014091

Picheral, M., Colin, S., & Irisson, J. O. (2024). EcoTaxa, a tool for the taxonomic classification of images. Retrieved from https://ecopart.obs-vlfr.fr

Puigcorbé, V., Masqué, P., & Le Moigne, F. A. C. (2020). Global database of ratios of particulate organic carbon to thorium-234 in the ocean: Improving estimates of the biological carbon pump. *Earth System Science Data*, *12*(2), 1267–1285. https://doi.org/10.5194/essd-12-1267-2020

Puigcorbé, V., Roca-Martí, M., Masqué, P., Benitez-Nelson, C. R., van der Loeff, M. R., Bracher, A., & Moreau, S. (2017). Latitudinal distributions of particulate carbon export across the North western atlantic ocean. *Deep-Sea Research I*, *129*, 116–130. https://doi.org/10.1016/j.dsr.2017.08.016

Roca-Martí, M., Benitez-Nelson, C. R., Umhau, B. P., Wyatt, A. M., Clevenger, S. J., Pike, S., et al. (2021). Concentrations, ratios, and sinking fluxes of major bioelements at Ocean Station Papa. *Elementa: Science of the Anthropocene*, *9*(1), 00166. https://doi.org/10.1525/elementa.2020.00166

Scholten, J. C., Fietzke, J., Vogler, S., Rutgers van der Loeff, M. M., Mangini, A., Koeve, W., et al. (2001). Trapping efficiencies of sediment traps from the deep Eastern North Atlantic: The 230Th calibration. *Deep-Sea Research II*, *48*(10), 2383–2408. https://doi.org/10.1016/S0967-0645(00)00176-4

Stanley, R. H., Buesseler, K. O., Manganini, S. J., Steinberg, D. K., & Valdes, J. R. (2004). A comparison of major and minor elemental fluxes collected in neutrally buoyant and surface-tethered sediment traps. *Deep-Sea Research I*, *51*(10), 1387–1395. https://doi.org/10.1016/j.dsr.2004.05.010

Steinberg, D. K., Carlson, C. A., Bates, N. R., Johnson, R. J., Michaels, A. F., & Knap, A. H. (2001). Overview of the us JGOFS Bermuda atlantic time-series study (BATS): A decade-scale look at ocean biology and biogeochemistry. *Deep-Sea Research II*, *48*(8–9), 1405–1447. https://doi.org/10.1016/S0967-0645(00)00148-X

Stewart, G., Moran, S. B., Lomas, M. W., & Kelly, R. P. (2011). Direct comparison of 210Po, 234Th and POC particle-size distributions and export fluxes at the Bermuda Atlantic Time-series Study (BATS) site. *Journal of Environmental Radioactivity*, *102*(5), 479–489. https://doi.org/10.1016/j.jenvrad.2010.09.011

Takahashi, K., Fujitani, N., Yanada, M., & Maita, Y. (2000). Long-term biogenic particle fluxes in the Bering Sea and the central subarctic Pacific Ocean, 1990-1995. *Deep-Sea Research I*, *47*(9), 1723–1759. https://doi.org/10.1016/S0967-0637(00)00002-9

Tara Océan Foundation. (2024). Tara Oceans expedition 2009–2012. Retrieved 2024-03-24, from https://fondationtaraocean.org/en/home/

Thomalla, S., Turnewitsch, R., Lucas, M., & Poulton, A. (2006). Particulate organic carbon export from the North and South Atlantic gyres: The 234Th/238U disequilibrium approach. *Deep-Sea Research II*, *53*(14–16), 1629–1648. https://doi.org/10.1016/j.dsr2.2006.05.018

Timothy, D. A., Wong, C. S., Page, J., White, L. A., & Macdonald, R. W. (2013). Climatology of sediment flux and composition in the subarctic Northeast Pacific Ocean with biogeochemical implications. *Progress in Oceanography*, *116*, 95–129. https://doi.org/10.1016/j.pocean.2013.06.017

Torres Valdés, S., Painter, S. C., Martin, A. P., & Sanders, R. J. (2013). Compilation of downward flux observations from sediment trap deployments in the Atlantic Ocean - contribution to EURO-BASIN's Data integration. [dataset]. https://doi.org/10.1594/PANGAEA.807946

Wan, X., Wang, W., Liu, J., & Tong, T. (2014). Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. *BMC Medical Research Methodology*, *14*(135), 135. https://doi.org/10.1186/1471-2288-14-135

White, A. E., & Karl, D. M. (2023). Sediment trap flux measurements for the Hawaii Ocean Time-Series (HOT) project from december 1988 to november 2021 at station ALOHA Version 2. [dataset]. https://doi.org/10.26008/1912/BCO-DMO.737393.2

Wong, C. S., Waser, N. A. D., Whitney, F. A., Johnson, W. K., & Page, J. (2002). Time-series study of the biogeochemistry of the North East subarctic Pacific: Reconciliation of the Corg/N remineralization and uptake ratios with the Redfield ratios. *Deep-Sea Research II*, *49*(24–25), 5717–5738. https://doi.org/10.1016/S0967-0645(02)00211-4

Wong, C. S., Whitney, F. A., Crawford, D. W., Iseki, K., Matear, R. J., Johnson, W. K., et al. (1999). Seasonal and interannual variability in particle fluxes of carbon, nitrogen and silicon from time series of sediment traps at Ocean Station P, 1982-1993: Relationship to changes in subarctic primary productivity. *Deep-Sea Research II*, *46*(11–12), 2735–2760. https://doi.org/10.1016/S0967-0645(99)00082-X