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Where and When the Mesopelagic Carbon Budget Balances, if at All

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Key Points:

- Assessing the different sources and sinks of mesopelagic (100–1,000 m) carbon helps us understand the flow of carbon from the surface to depth
- Sources and sinks rarely balance over the period for which oceanic measurements are taken, due to seasonal variations in fluxes
- Assuming steady state when calculating mesopelagic carbon budgets overlooks significant seasonal factors and is ill-advised

Supporting Information:

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

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Abstract The ocean biological carbon pump (BCP) transports organic matter from the surface to the deep ocean. Accurately quantifying the efficiency of the BCP is essential for understanding potential climate feedbacks and entails measuring the flux of organic material in and out of the mesopelagic layer (approximately 100–1,000 m). Observational estimates are often restricted to measuring the BCP efficiency over short timescales. Here we use an ocean biogeochemical model to diagnose where, and on what timescales, the mesopelagic is sufficiently in steady state that balancing the carbon budget may be possible. For the majority of the ocean the sources and sinks of organic carbon in the mesopelagic do not balance on timescales shorter than 1 year. Assuming steady state risks falsely inferring the existence of missing processes or the magnitudes of known ones to close the budget and will lead to incorrect estimates of the strength of the BCP.

Plain Language Summary Up to 90% of the sinking organic carbon created in the surface ocean is broken down back into its dissolved state within the mesopelagic (approximately 100–1,000 m), therefore any changes in the governing processes have a significant impact on how much carbon is locked away in the deep ocean. Balancing mesopelagic carbon budgets, which involves assessing the relative contributions of the inputs and outputs of carbon, helps us understand the flow of organic carbon and hence the amount stored in the deep ocean. We use a simplified but perfectly understood model system to analyze the seasonal budget of the different processes acting on organic carbon in the mesopelagic. While the sources and sinks balance over 1 year, they rarely balance on shorter timescales. This is due to the complex interplay between the seasonal variability in the amount of organic carbon sinking from the surface, vertical mixing, and horizontal movement, and may be why balancing the biological carbon pump has proved difficult using observations. Understanding these interacting effects will help reduce uncertainty in the efficiency with which carbon is transported from the surface ocean and stored in the deep ocean.

1. Introduction

The ocean biological carbon pump (BCP) involves the transport of organic matter from the surface ocean to greater depths. Without this pump one model study estimated that atmospheric carbon dioxide (CO_2) levels would be approximately 200 ppm higher than they were in the pre-industrial era (e.g., Parekh et al., 2006), although this is subject to how the model handles CO_2 feedbacks (Oschlies, 2009). Understanding the efficiency of the BCP is therefore very important, particularly if it is to be correctly represented in the ocean biogeochemical component of Earth System Models used to make future climate predictions.

Sinking particulate organic carbon (POC) and dissolved organic carbon (DOC) are remineralized into dissolved inorganic constituents, and up to 90% of this remineralization may occur within the mesopelagic layer (approximately 100–1,000 m depth range) (Buesseler & Boyd, 2009). The greater the percentage of organic matter that escapes remineralization within the mesopelagic layer, the more efficient the BCP. The magnitude and efficiency of the BCP can be estimated from shipboard observations by assessing the fluxes of mesopelagic organic carbon and their attenuation with depth (Boyd et al., 2019). This requires observations of all fluxes into and out of the mesopelagic, including gravitational sinking, seasonal detrainment from the surface mixed layer (Dall'Olmo et al., 2016; Lacour et al., 2019), biological behaviors such as diurnal vertical migration and seasonally diapausing zooplankton (Boyd et al., 2019 and references therein), and lateral advection of particulate and dissolved carbon (Wang et al., 2022), as well as processes within the mesopelagic that create or remove organic matter (e.g., respiration).

When the system is in steady state (i.e., temporally invariable) for the duration of the observations, the balance of all fluxes equates to zero and the amount of organic carbon within the mesopelagic does not change with time.

Non-steady state conditions occur when a temporally varying source of organic carbon is not immediately balanced by a temporally varying sink, for example, a seasonal pulse of detritus exported from the surface will temporarily increase the mesopelagic organic carbon inventory until it has time to sink to depths beyond the mesopelagic or be remineralized (Giering et al., 2017).

In reality, only a subset of observations can be acquired, instead of observations of all fluxes over long time periods. Assuming the system is in steady state requires the magnitude of missing fluxes to be inferred in order to close the mesopelagic organic carbon budget (e.g., Santana-Falcon et al., 2017). However, steady state conditions cannot be guaranteed, particularly when observing over a short period of time and/or in a region which exhibits strong seasonality.

If fluxes were observed over a long enough period, episodic and seasonal variations in sources and sinks could be accounted for. Unfortunately, observational timescales are often too short to achieve this. Timescales also vary greatly across mesopelagic budget studies. Taking just the gravitational sinking of organic material as an example, timescales can range from instantaneous snapshots (e.g., Marine Snow Catchers as by Riley et al. (2012)), to several days (e.g., short term drifting sediment traps as by Lalande et al. (2008)), to a month (e.g., using the thorium method (Haskell et al., 2013)) and longer (e.g., long term moored sediment traps as by Zúñiga et al. (2007)). Therefore, both global-scale and localized studies attempting to balance the mesopelagic carbon budget are often unsuccessful (Burd et al., 2010; Giering et al., 2023; Steinberg et al., 2008) and successful closures (e.g., Giering et al., 2014) are the exception rather than the norm.

To explore the extent and consequences of non-steady state assumptions, we use a global ocean biogeochemical model which simulates the seasonal cycle of particulate and dissolved organic carbon, coupled to a representation of the ocean's circulation. This model set-up provides an idealized, perfectly observed environment to investigate where, and on what timescales, the mesopelagic is likely to be sufficiently in steady state that closing the carbon budget may be possible. This work thus also highlights the timescales and locations where attempts to close the mesopelagic carbon budget are likely to be most severely affected by non-steady state conditions.

2. Methodology

The methodology outlined below is designed to explore the balance between material entering and leaving the mesopelagic in a model-based situation where everything is known. From a global ocean biogeochemical model, we extract fluxes of gravitationally sinking POC, organic carbon creation and respiration within the mesopelagic, and both vertical and horizontal physical transport of organic carbon (POC and DOC). We then calculate the mesopelagic organic carbon budget for each month of one modeled year, as 1 month is equivalent to the typical duration of a process cruise. Most important to our budget analysis is that we know there are no missing modeled carbon inputs or outputs. The model will, of course, be omitting specific processes that occur in the real ocean, but our concern here is to assess how spatial and temporal variability can affect mesopelagic carbon budgets by using this simplified but perfectly understood system.

2.1. Ocean Biogeochemical Model

The global ocean biogeochemical model is the Model of Oceanic Pelagic Stoichiometry (MOPS: Kriest et al., 2020). The model currency is phosphorous with carbon fluxes calculated by applying the Redfield C:P ratio of 106 (Redfield, 1934). MOPS has nine state variables and represents oxygen-dependent remineralization as well as tracking the cycling of nutrients between plankton and the seawater (see Kriest and Oschlies (2015) for a diagram of the model structure). All parameter values given below are the same as in the model configuration named ECCO* in Kriest et al. (2020).

2.1.1. Model Choice

The model selected is relatively simple with only first-order ecological actors and processes included, with the BCP represented by only two forms of nonliving organic material, and without processes such as diel/seasonal zooplankton migration (Bandara et al., 2021), dark carbon fixation (Pachiadaki, 2017), whale falls (Smith et al., 2015), etc. This choice is deliberate as the model provides the minimum structure needed to assess the impact of temporal and spatial variability on budgeting. MOPS was chosen for this study because it has successfully previously been applied to ocean biogeochemistry questions (e.g., Kriest et al., 2020) and has already been adapted to run within a computationally efficient "offline" general circulation (see Section 2.2).

2.1.2. Euphotic Zone Creation of POC and DOC

In the model's euphotic zone (0–102.5 m) phytoplankton growth is limited by light and nutrient availability, and phytoplankton are grazed by zooplankton. Phytoplankton and zooplankton have a linear specific mortality rate (conversion to DOC) of 0.01 d^{-1}. 15% of other plankton loss terms (i.e., zooplankton quadratic mortality, photosynthate exudation, and messy feeding by zooplankton) immediately disintegrate to DOC, while the remaining 85% becomes POC. This only occurs in the euphotic zone.

2.1.3. Mesopelagic POC

Particulate organic carbon enters the mesopelagic either by physical mixing or by gravitational sinking, and is removed either by remineralization, sinking or mixing out of the mesopelagic, or by burial into the sediment in regions where the seafloor intersects the mesopelagic. Particulate organic carbon is converted to dissolved inorganic carbon (DIC) by remineralization, at a rate of 0.05 d^{-1}. The model assumes a linear increase in sinking speed with depth to give a flux attenuation profile similar to a Martin curve (Martin et al., 1987) whereby particle flux $F(z) \propto z^{-b}$ where the exponent b, after parameter tuning by Kriest et al. (2020), is 1.46. This leads to an approximate particle sinking speed of 5 m d^{-1} at 160 m and 40 m d^{-1} at 1,160 m. Upon reaching the sea floor, a fraction of the detritus is buried and instantaneously removed from the water column, while the remainder is resuspended to be treated as sinking detritus again.

2.1.4. Mesopelagic DOC

Dissolved organic carbon in the model is assumed to be representative of recalcitrant DOC (Hansell, 2013) and remineralizes at a rate of 0.000472 d^{-1}. This rate is two orders of magnitude slower than for POC, therefore DOC has a longer residence time. Dissolved organic carbon enters the mesopelagic either by physical mixing of DOC directly, or by death of plankton which have been mixed into the mesopelagic. Plankton mixed below the euphotic zone are initially assumed to be alive but not growing or feeding. Instead, they die at an imposed rate of 0.01 d^{-1}, instantly becoming DOC. Although they do not sink, they will be gradually mixed downwards. Mesopelagic DOC is removed either by remineralization or physical transport out of the mesopelagic. As the model is spun-up for 3,000 years (see Section 2.2), it achieves a repeating seasonal cycle in which this mixing and death of plankton balance. As such, there is no year-on-year accumulation of them within the mesopelagic. The global distribution of mesopelagic DOC in MOPS (Figure S1 in Supporting Information S1) is similar to estimates (Roshan & DeVries, 2017) near 300 m, although slightly high in concentration in the Southern Ocean. Modeled DOC is globally lower than estimates near 600 m approximately by a factor of 2, and of similar global magnitude but opposing local distribution near the surface.

2.2. Ocean Circulation

As well as biogeochemical sources and sinks of mesopelagic organic carbon, physical processes also influence the carbon budget at a location. Therefore, it is important to include ocean circulation and mixing in this assessment. MOPS is coupled here to an ocean circulation derived from the ECCO (Estimating the Circulation and Climate of the Ocean) project (Stammer, 2004). ECCO's domain extends from 80°S to 80°N at a horizontal resolution of 1 × 1 degree, with 23 vertical levels (six within the euphotic zone) from 5 m at the surface to 5,450 m at abyssal depths. ECCO's physical dynamics are implemented here via the Transport Matrix Method (TMM: S. Khatiwala, Visbeck, and Cane, 2005; S. Khatiwala, 2007; S. Khatiwala, 2018). This method efficiently simulates the transport of biological and chemical tracers in the ocean and was used here to facilitate the spin-up of MOPS to equilibrium under ECCO's circulation, making use of monthly average matrices of explicit (predominantly horizontal) and implicit (predominantly vertical) transport information. The spin-up process typically takes multiple millennia (Primeau & Deleersnijder, 2009; Wunsch & Heimbach, 2008), and the TMM was used here for a 3,000-year spin-up period, after which there is minimal model drift. Note that each year of the spin-up had the same seasonal variation in physical circulation and mixing (Kriest & Oschlies, 2015). Once equilibrated, the monthly averaged biogeochemical tracer distributions of one full year were used for our mesopelagic carbon budget analysis.

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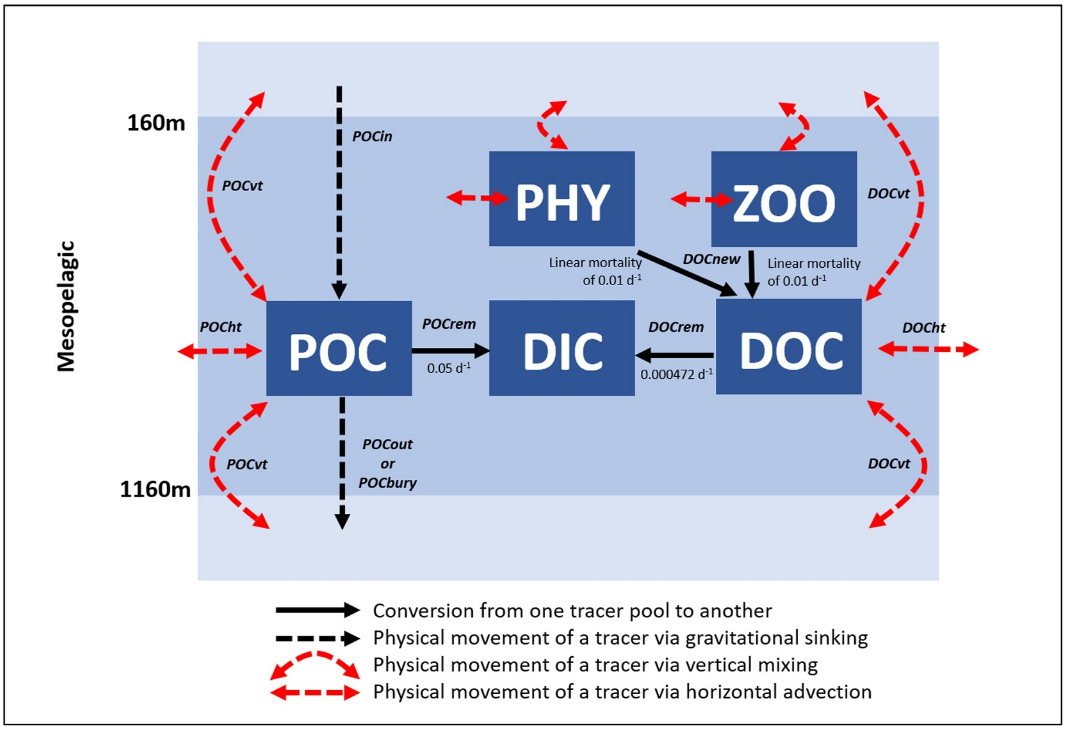

Figure 1. Flow of modeled organic carbon in and out of the mesopelagic. Abbreviations "vt" and "ht" indicate vertical and horizontal transport respectively, and "rem" denotes remineralization.

2.3. Budget Calculation

Here we define the mesopelagic organic carbon budget as the sum of its inputs, outputs, and interior consumption, including all physical and biogeochemical processes associated with particulate and dissolved organic carbon (see Figure 1). In a steady state, all inputs, outputs and consumption should balance.

Of ECCO's 23 depth levels, 160 and 1,160 m were deemed most suitable as the bounds of the mesopelagic layer, as they are similar to the commonly accepted mesopelagic boundaries 100–200 and 1,000 m (Buesseler & Boyd, 2009; Sutton et al., 2017). The budget (B_i, in units of mmol C m^{-2} d^{-1}), calculated at each location i, averaged over 1 month, is defined as below.

$$B_i = POCbudget_i + DOCbudget_i \tag{1}$$

$$POCbudget_i = POCin_i - POCout_i - \left(\sum_{k=8}^{14} POCrem_{i,k} \times \Delta z_k\right) - POCbury_i + POCht_i + POCvt_i \tag{2}$$

$$DOCbudget_i = \left(\sum_{k=8}^{14} DOCnew_{i,k} \times \Delta z_k\right) - \left(\sum_{k=8}^{14} DOCrem_{i,k} \times \Delta z_k\right) + DOCht_i + DOCvt_i \tag{3}$$

The budget (B_i) is the sum of both the POC and DOC budgets ($POCbudget_i$ and $DOCbudget_i$), which in turn are the net sum of the individual sources and sinks of mesopelagic POC and DOC, respectively. The POC budget (Equation 2) includes the gravitational POC flux sinking in ($POCin_i$) and out ($POCout_i$) of the mesopelagic [mmol C m^{-2} d^{-1}], the sum of POC removal ($POCrem_{i,k}$) via remineralization [mmol C m^{-3} d^{-1}] for each depth layer within the mesopelagic (k) weighted by each depth layers' thickness (Δz_k), buried POC ($POCbury_i$) if the seabed lies within the mesopelagic [mmol C m^{-2} d^{-1}], and the net change in mesopelagic POC due to vertical ($POCvt_i$) and horizontal ($POCht_i$) transport [mmol C m^{-2} d^{-1}]. The DOC budget (Equation 3) includes the sum of the new DOC ($DOCnew_{i,k}$) created by plankton losses and DOC removal ($DOCrem_{i,k}$) via remineralization [mmol C m^{-3} d^{-1}] for each depth layer within the mesopelagic (k) weighted by each depth layers' thickness (Δz_k), and the change in mesopelagic DOC due to vertical ($DOCvt_i$) and horizontal ($DOCht_i$) transport [mmol C m^{-2} d^{-1}]. Note that k, the index of the ECCO model depth level, ranges from the depth index corresponding to the top (16m; $k = 8$) to the base (1,160 m; $k = 14$) of the mesopelagic. When Equation 1 is balanced ($B_i = 0$), the biological and physical processes balance. A non-zero result indicates the system is not in steady state. A positive B indicates inputs of organic carbon into the mesopelagic exceed outputs and consumption, and therefore carbon is accumulating within the mesopelagic, and vice versa for a negative B.

3. Results

3.1. The Annual Mesopelagic Organic Carbon Budget

The sum of the annually averaged components of the budget (not shown) yields an annual budget of zero (within ±0.004 mmol C m^{-2} d^{-1}, which is equal to the model drift still occurring after a 3,000-year spin-up). Therefore, all components have been accounted for and at every location the mesopelagic is in steady state over one full year.

Over 1 year there is a net input of 2.38 PgC yr^{-1} of POC into the global mesopelagic due to gravitational sinking (2.65 PgC yr^{-1} sinking in and 0.27 PgC yr^{-1} sinking out) and a net input of 0.73 PgC yr^{-1} due to vertical mixing. Additionally, 0.94 PgC yr^{-1} of DOC is created within the mesopelagic due to the mortality of phytoplankton and zooplankton which have been mixed out of the euphotic zone, as well as an additional net input of 1.7 PgC yr^{-1} of DOC due to vertical mixing. These inputs are balanced by remineralization.

3.2. The Seasonal Mesopelagic Organic Carbon Budget

The seasonal budget is shown in Figures 2a–2d, allowing us to explore the extent to which biological and physical processes balance on the shorter timescales over which shipboard measurements are commonly made. Annual primary production and mixed layer depth are shown in Figure S2 in Supporting Information S1 and the seasonal individual budget components in Figures S3–S10 in Supporting Information S1.

We simultaneously sample at two depth horizons for the sinking POC flux. Any change in the POC inputs from above the mesopelagic layer requires sufficient time to sink through the mesopelagic layer to then be seen in the transport out of the base of the mesopelagic. Increasing POC flux into the top of the mesopelagic associated with seasonal phytoplankton blooms or vertical mixing causes a positive imbalance in Equation 1, as the non-remineralized portion of this additional POC takes time to sink out of the bottom of the mesopelagic. Therefore, there is a period of time when organic carbon is accumulating within the mesopelagic. This positive imbalance in the mesopelagic organic carbon budget is seen to occur in the Northern Hemisphere during the boreal winter (driven by winter mixing) and spring months and in the Southern Hemisphere during the austral equivalents. The opposing negative imbalance is then seen during the months of decreasing detrital flux into the top of the mesopelagic, during each hemisphere's respective summer and autumn months.

Figure 2e shows the number of months the mesopelagic budget is near steady state, which is defined as an imbalance of less than 0.35 mmol C m^{-2} d^{-1} for each location. This threshold is 25% of the global (volume-weighted) and annual mean $|B_i|$, that is, the spatial and temporal mean of the magnitude of the budget imbalance B_i defined in Equation 1. Applying a fixed threshold globally provides a first-order perspective of how often the mesopelagic can be considered to not be in steady state. However, it does mean that regions of low productivity with a budget fluctuating within the bounds of this threshold will still be considered in steady state. We find that less than 25% of the global mesopelagic area is in steady state for 3 or more months of the year. Regions which are rarely in steady state include western boundaries and areas of deep mixing, while localized areas within the east Pacific are near steady state for up to 6 months of the year.

Figure 2f shows the dominant component of the mesopelagic organic carbon budget over all months when the budget is not in steady state. This is not meant to imply that it is the component causing the mesopelagic to not be in steady state, but just that it is most influential to the overall budget. In areas of high export production POC flux and POC remineralization dominate the budget in non-steady state months. For the remaining global ocean DOC sources and sinks dominate the budget, specifically horizontal transport of DOC in the tropical regions and DOC remineralization in the subtropics.

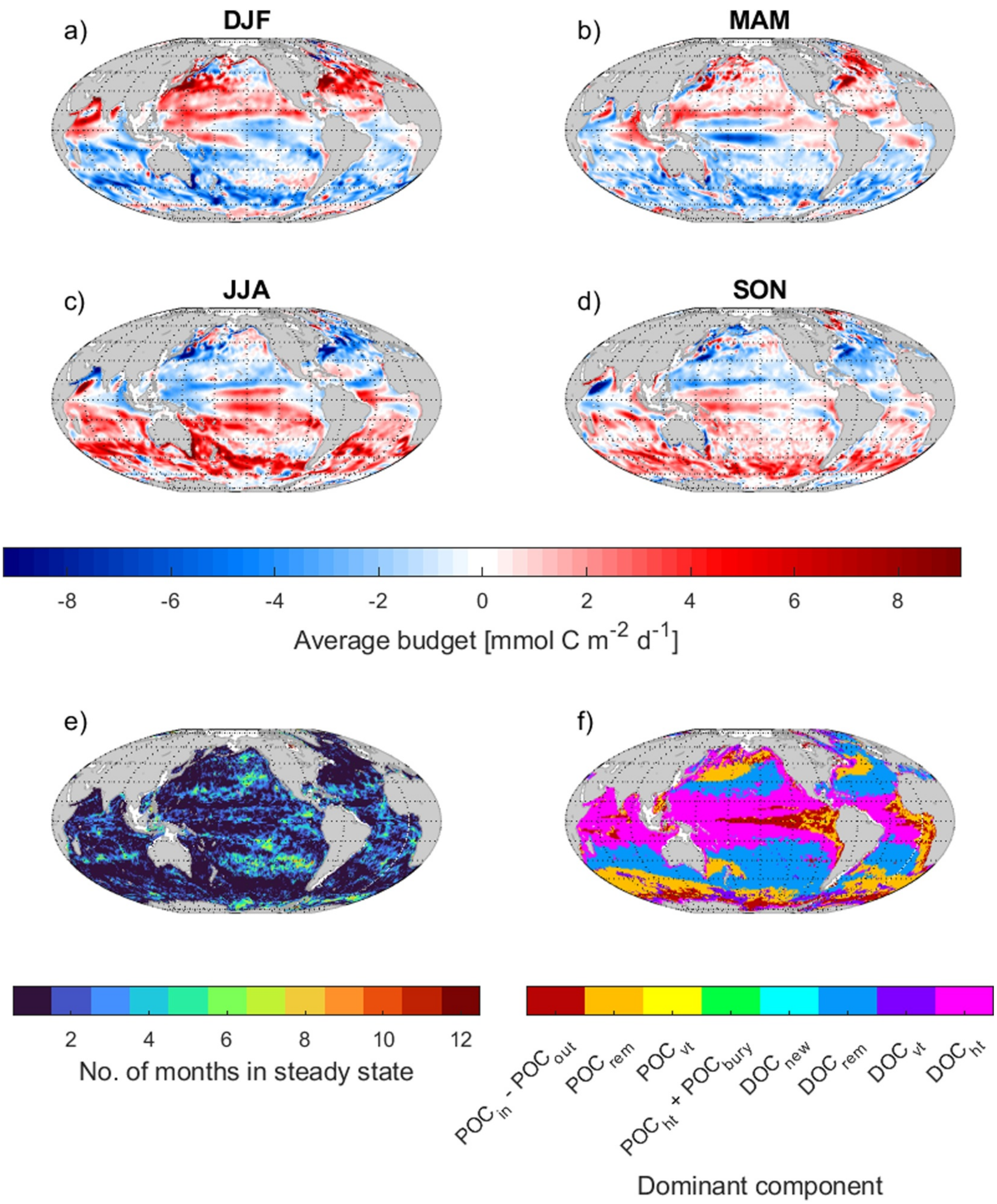

Figure 2. Seasonally averaged mesopelagic organic carbon budget [mmol C m^{-2} d^{-1}], averaged over (a) December, January and February, (b) March, April and May, (c) June, July and August, and (d) September, October and November. Positive values show a net input of organic carbon into the mesopelagic, and negative values a net removal. (e) The total number of all months when the mesopelagic organic carbon budget is in steady state, that is, less than ±0.35 mmol C m^{-2} d^{-1}. (f) The dominant component of the budget over all the months when the mesopelagic is not in steady state, either POCin - POCout, POCrem, POCvt, POCht + POCbury, DOCnew, DOCrem, DOCvt, or DOCht.

3.3. Sensitivity to Biogeochemical Parameters

Observed respiration rates vary geographically (Sulpis et al., 2023) and parameterizations of remineralization vary across models (Cael & Bisson, 2018). Therefore, to explore the sensitivity to different rates of remineralization while retaining the simplicity of our approach, the mesopelagic budget analysis was repeated 4 more times using different parameter values: two with a b value lower (FastPOC) and higher (SlowPOC) than the default configuration to explore sensitivity in POC remineralization, and two with a faster (Fast DOC) and slower DOC

(SlowDOC) remineralization rate than the default. FastPOC has a b of 0.858 (Martin et al., 1987) commonly used in biogeochemical models, and the b in SlowPOC is equidistant above the default as FastPOC is below. SlowDOC has a DOC remineralization rate half that of the default, and in FastDOC it is equidistant above the default as SlowDOC is below. Table S1 in Supporting Information S1 shows how these parameters influence the percentage of global mesopelagic in steady state, averaged over 12 months.

A lower b value (a proxy for a faster sinking of POC; see supplementary material Section B in Supporting Information S1) reduces the time lag between POC sinking in and out of the mesopelagic, thereby budget disequilibria occur less often. A faster DOC remineralization rate also reduces how often budget disequilibria occur, as faster remineralization more rapidly compensates DOC mixed into the mesopelagic.

4. Discussion

The modeled mesopelagic organic carbon budget is in steady state over a 1-year period, having been spun-up to a repeating seasonal cycle using climatological forcing. However, on shorter timescales it is rarely in steady state due to the seasonality of processes such as vertical mixing and primary productivity. This finding has important implications for robustly quantifying the efficiency of the biological carbon pump on the basis of field observations.

4.1. The Seasonal Mesopelagic Budget

The main drivers of the disequilibria are seasonality in creation of organic material in the surface ocean and subsequent input to the mesopelagic, the transit time through the mesopelagic, and remineralization within. The cause of the disequilibria is that seasonal change in export to the mesopelagic can occur faster than organic material is either consumed within or leaves the mesopelagic. For the majority of the ocean we find there is a time lag of 25–58 days between the peak in POC flux into and out of the mesopelagic (see Section B of the supplementary material in Supporting Information S1). Additionally, the model grid cell size ranges from 111 km by 20 km at the poles to 111 km by 111 km at the equator, therefore for DOC to travel through one grid cell at the equator within 1 month it must travel faster than 6 cm s^{-1}. Away from energetic boundary currents, fronts and eddies, currents are often slower than this, leading to a time lag greater than 1 month. When this time lag is longer than the duration of observations, which in this study is 1 month, the mesopelagic is not in steady state.

The spatial variation in the disequilibria arise due to the seasonality in export and physical transport varying with location. The seasonal cycle will influence where organic carbon is laterally transported because horizontal gradients in organic carbon will vary throughout the year, for example, when the North Atlantic spring bloom progresses northwards from March to June. This leads to further spatial variations in the seasonal imbalances in the mesopelagic budget which are often overlooked by field estimates where horizontal variability is not (or cannot be) measured.

4.2. The Consequences of Model Assumptions

The resulting number of months in steady state (shown in Figure 2e) is sensitive to the choice of threshold defining steady state. This was chosen to be 25% of the global mean absolute budget (0.35 mmol C m^{-2} d^{-1}) which resulted in 3% of the ocean in steady state for 6 or more months of the year, while a doubling of this threshold increased this to 16% (see Figure S11 in Supporting Information S1). The threshold of 25% is similar to the uncertainties associated with in situ observations (Giering et al., 2014; Steinberg et al., 2008).

Due to the spatial resolution of the model (1° × 1°), numerical diffusion may mute the effect transport has on budget disequilibria, potentially leading to an overestimation of how often the mesopelagic is in steady state. In addition to this, the disequilibria caused by the lateral movement of POC and DOC may have a larger influence on observational measurements taken at a point location than estimated here because they are not representing a large area. It should be noted that some field studies deliberately site their observations inside eddies to minimize lateral advection (e.g., Estapa et al., 2019). A side effect is that it is not clear how findings then translate to the larger ocean. Also due to the resolution of the general circulation model used here, the transport of carbon by mesoscale eddies (and other sub grid-scale processes) was omitted, which may lead us to incorrectly estimate the influence of physical transport of carbon on the mesopelagic budget (Zhang et al., 2014). Particularly as related spatial variability in POC and DOC might amplify this effect, mesoscale processes are likely to lead to additional short term imbalances at a location. Other processes not included in the model are biological behaviors such as diurnal vertical migration and seasonally diapausing zooplankton (Boyd et al., 2019 and references therein). However, adding more processes that have a seasonal signal will be unlikely to make steady state conditions more common.

Due to the vertical resolution of the general circulation model, the top of the mesopelagic layer was fixed to 160m depth, while in reality the upper bound of the mesopelagic can be defined as the mixed layer depth or euphotic depth, which varies both spatially and throughout the year. With a fixed mesopelagic, during deep mixing months carbon is brought into the mesopelagic via vertical mixing. Contrastingly, with a depth-varying mesopelagic, deep mixing never extends into the mesopelagic and therefore carbon is not brought down into the mesopelagic during deep mixing months but instead when the mixed layer depth (and hence the mesopelagic) shoals during spring. Either approach results in a seasonal pulse of organic material to the mesopelagic which is not immediately balanced by an outward flux.

Finally, the results shown here are specific to the MOPS model. If this study were repeated using other existing ocean biogeochemical models of various complexities (Kwiatkowski et al., 2014), they would likely produce a range of estimates for where and when the mesopelagic carbon budget balances. This is because different models handle biogeochemical processes differently, and therefore the sources and sinks of mesopelagic organic carbon will vary in both time and space between models. However, we have shown that despite varying POC sinking speed and DOC remineralization rate, only roughly one fifth of the global mesopelagic is in steady state on average over the year. Additionally, all models will contain seasonally varying processes of similar magnitudes and timing. Therefore it is unlikely that a different conclusion would be drawn using a different model.

4.3. The Consequences for Observations

As shown here, the ocean is often not in steady state on the short timescales typically associated with shipboard observations. Therefore, there are times and places where the assumption of steady state is particularly ill-advised. Either observations should be taken over longer timescales of at least 1 year, or budget imbalances due to non-steady state conditions over shorter timescales need to be accounted for. The former is rarely feasible with ships (although may be possible using autonomous vehicles), and therefore the latter will often be necessary.

Disequilibria caused by the time lag effect need to be accounted for, particularly when using observations that only provide a ‘snapshot’ of the system. The vertical time-lag effect of POC flux has previously been accounted for by removing the estimated excess of carbon due to the time lag, which is the sum of the difference between the actual loss of POC and the apparent loss of POC between two depth levels (Giering et al., 2017). This method requires assumptions to be made, such as remineralization rate and particle sinking speed not changing over time. This is true in MOPS but may not be true in the real ocean. Both the vertical and horizontal time lag effect of POC flux can be removed by using a plume-tracking approach, whereby the vertical flux attenuation is calculated in the direction the water is moving, rather than as a simple function of depth (Briggs et al., 2020). It is similarly difficult to account for the time lag associated with all components of the budget, such as horizontal transport of DOC, as it requires estimating velocities and having observations of DOC “upstream”.

Even if all the sources and sinks of organic carbon are accounted for, there are large uncertainties associated with measuring each component of the mesopelagic carbon budget (e.g., Giering et al., 2014) and therefore it is possible to erroneously conclude closure of the budget has been achieved. For example, the amount of DOC vertically mixed into the mesopelagic is difficult to estimate from observations because the three-dimensional flux along density surfaces may be considerably larger than the vertical mixing flux (e.g., Lovecchio et al., 2023). The large uncertainties associated with measuring the carbon budget, and processes omitted often due to necessity, call into doubt the value of balancing carbon budgets for the mesopelagic, at least until observational uncertainties become sufficiently small to robustly assess whether a particular system is in steady state.

5. Conclusions

In this study we examine the hypothesis that the mesopelagic organic carbon budget is at steady state on timescales less than a year. Using a global ocean biogeochemical model we find that, for the majority of the world ocean, the budget is not in steady state on a seasonal timescale due to the seasonality of processes such as vertical mixing and primary productivity and subsequent export to the mesopelagic. Less than 25% of the global mesopelagic area is in steady state for 3 or more months of the year. While localized areas within subtropical gyres can be in steady state for up to 6 months of the year, regions with western boundary currents and areas of deep mixing are in steady state for less than 2 months of the year. The dominant component of the budget during non-steady state months are POC flux and POC remineralization in areas of high export production, horizontal transport of DOC in the tropical regions, and DOC remineralization in subtropical regions, which highlights the differing regional importance of measuring these processes when calculating carbon budgets. These findings have important implications for robustly quantifying the efficiency of the BCP on the basis of field observations. The seasonal and spatial patterns of the model's divergence from the steady state assumption should inform attempts to balance the mesopelagic budget at observational monitoring sites. Incorrectly assuming steady state and overlooking observational uncertainty is likely to lead to erroneous estimates of the strength of the BCP and hamper wider marine carbon cycle budgeting.

Data Availability Statement

The base TMM and MOPS code used here can be downloaded from S. Khatiwala (2018), which includes instructions on how to download the relevant transport matrices and forcing fields. All data and code required to recreate the figures shown in this study can be downloaded from Oliver (2024).

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