

SIMPLE ~~EULERIAN-LAGRANGIAN~~ EULERIAN-LAGRANGIAN APPROACH TO ~~SOLVE~~SOLVING EQUATIONS FOR SINKING PARTICULATE ORGANIC MATTER IN THE OCEAN

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Abstract. ~~A gravitational sinking of the~~ Gravitational sinking of particulate organic matter (POM) is a key mechanism of the vertical transport of carbon in the deep ocean and its subsequent sequestration. The size spectrum of these particles is formed in the euphotic layer by ~~the~~ primary production and various mechanisms, including food web consumption. The ~~mass of~~ masses of the particles, as they descend, ~~changed~~ change under aggregation, fragmentation, ~~baeterial-decomposition which depends and~~ bacterial decomposition. These processes depend on the water temperature and oxygen concentration, particle sinking velocity, ~~age~~ ages of the organic particles, ballasting and other factors. In this paperwork, we developed simple Eulerian-Lagrangian approach to solve a simple Eulerian-Lagrangian approach to solving equations for sinking particulate matter when the ~~influence of the size and age of~~ effects of the sizes and ages of the particles, temperature and oxygen concentration on their dynamics and degradation processes ~~were taken into account~~ are considered. The model considers feedback between the degradation rate and the particle sinking velocity. We rely on ~~the~~ known parameterizations, but our ~~Eulerian-Lagrangian approach to Eulerian-Lagrangian approach for~~ solving the problem differs, ~~allowing which enables~~ the algorithm to be incorporated into biogeochemical global ocean models with relative ease. Two novel analytical solutions of a system of ~~the~~ one-dimensional ~~Eulerian equation for~~ Euler equations for the POM concentration and ~~Lagrangian equations for~~ Lagrange equations for the particle mass and position were obtained for constant and age-dependent degradation rates. ~~At a constant rate of particle sinking , they correspond to exponential and power-law~~ The feedback between the degradation rate and sinking velocity leads to significant differences in the vertical profiles of the POM concentration ~~. It was found that feedback between degradation rate and sinking velocity results to a significant change in POM and POM flux vertical profiles . The calculations and sinking flux, in contrast to the solutions obtained at a constant sinking velocity, where the concentration and flux profiles of the POM are similar. The calculation results~~ are compared with the available measurement data for the POM and POM flux for the latitude ~~band of 20-30~~ bands of 20-30°N in the Atlantic and Pacific Oceans and ~~50-60~~ 50-60°S in the Southern Ocean. The dependence of the degradation rate on temperature significantly affected the profiles of ~~POM concentration~~ the POM concentration and sinking flux by enhancing the degradation of sinking particles in the ocean's upper layer and suppressing it in the deep layer of

the ocean. ~~The influence of oxygen concentration in all cases considered~~ In all cases considered, the influence of the oxygen concentration was insignificant compared to that of the distribution of temperature with depth.

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1 Introduction

~~A gravitational sinking of the~~ Gravitational sinking of particulate organic matter (POM) is a key mechanism of the vertical transport of carbon in the deep ocean (gravitational biological pump) and its subsequent sequestration (Siegel et al., 2023). The biological pump mechanism provides not only the transfer and burial of carbon ~~;~~ but also nutrients, trace metals, and natural and artificial radionuclides through ~~the scavenging mechanism (Roca-Martí and Puigcorb , 2024; Maderich et al., 2022)~~ a scavenging mechanism (Roca-Mart  and Puigcorb , 2024; De Soto et al., 2018; Maderich et al., 2022). In addition to the processes of sorption and desorption, the mechanism of scavenging is controlled by the sizes of the sinking particles, their densities, the sinking velocity, and the processes of organic particle degradation (Maderich et al., 2021).

The size spectrum of the sinking particles is formed in the euphotic layer by ~~the~~ primary production and various mechanisms, including aggregation and fragmentation under the influence of mechanical factors (Burd , 2024) and through food web consumption. The ~~mass of masses of the~~ particles, as they descend in deep layers of the ocean, ~~decreases decrease~~ under the influence of grazing by filter feeders and bacterial decomposition, which depends on the water temperature and oxygen concentration (Cram et al., 2018), particle falling velocity (Alcolombri et al., 2021), ~~age ages~~ of the organic ~~partiele~~ particles (Jokulsdottir and Archer, 2016; Aumont et al., 2017) and other factors, such as ballasting (~~Armstrong et al., 2002~~) (Armstrong et al., 2002; Cram et al., 2018; Maerz et al., 2020). The POM degradation rate can be proportional to the particle ~~volume (DeVries et al., 2014; Cram et al., 2018) or the mass (volume) (DeVries et al., 2014; Cram et al., 2018) or~~ surface area (Omand et al., 2020; Alcolombri et al., 2021).

Many biogeochemical models assume that the settling velocity of particles is constant with depth (e.g., Aumont et al., 2015). Then, depending on the degradation rate, the ~~POM vertical profile can be found~~ vertical profiles of the POM concentration and sinking flux can be determined. At a constant degradation rate, the corresponding vertical ~~profile of profiles of the~~ particle mass concentration and mass flux ~~will be are~~ exponential (Banse, 1990; Lutz et al., 2002). Assuming that the degradation rate is inversely proportional to the age of ~~partiele the particles~~ (Middelburg, 1989), the vertical ~~profile of profiles of the~~ particle mass concentration and mass flux can be found as described by a power law (Cael et al. , 2021). This power law corresponds to the well-known empirical "Martin curve" (Martin et al., 1987). However, as the particle mass decreases due to ~~remineralization, the rate at which the particle falls degradation, the sinking velocity~~ also decreases. This feedback, along with other factors ~~except for the age of the partiele~~, is taken into account in several mechanistic models (e.g., DeVries et al., 2014; Cram et al., 2018; Omand et al., 2020; Alcolombri et al., 2021) ~~;~~ however, these models do not consider the ages of the particles.

An analytical solution to the equation for the distribution of POM by particle size was obtained by DeVries et al. (2014) for a constant degradation rate. However, as noted by DeVries et al. (2014), the values of the vertical flux of the POM mass at great depths ~~turned out to be 1-2~~ were 1-2 orders of magnitude less than ~~observed. It~~ those observed. This discrepancy can be assumed ~~that this discrepancy is to be~~ due to the constancy of the degradation rate with depth in the model. A decrease in the rate of degradation can also be caused by a decrease in water temperature ~~(Cram et al., 2018)~~ (e.g., Cram et al., 2018) or an increase in the ~~age of ages of the~~ sinking particles with depth.

In this paperwork, we developed ~~simple Eulerian-Lagrangian approach to solve a simple~~ Eulerian-Lagrangian approach for solving equations for sinking particulate matter when the ~~influence of the size and age of~~ effects of the sizes and ages of the particles, temperature and oxygen concentration on their dynamics and degradation processes ~~were taken into account. We rely on the known parameterizations (Kriest and Oshlies, 2008; DeVries et al., 2014; Cram et al., 2018; Omand et al., 2020) are considered. We relied on known parameterizations (Kriest and Oshlies, 2008; DeVries et al., 2014; Cram et al., 2018), but our Eulerian-Lagrangian approach to~~ Eulerian-Lagrangian approach for solving the problem is different, ~~allowing the model to be incorporated.~~ Our approach involves solving the Euler equation for the concentration of particles of a given size and the Lagrange equations for a sinking organic particle under the influence of microbiological degradation. This enables the incorporation of the proposed algorithm into biogeochemical global ocean models with relative ease. The remainder of the paper is organized as follows: ~~the~~ The equations of the model for sinking particulate organic matter are ~~given in Section presented in Sect. 2.~~ The analytical Analytical solutions for constant and age-dependent degradation rates ~~were are~~ obtained and compared with available data on the vertical concentration and mass flux of the POM in ~~Section Sect. 3.~~ The numerical Eulerian-Lagrangian A numerical Eulerian-Lagrangian method for the generalized model is ~~given in Section presented in Sect. 4.~~ The results of the simulations are discussed in Section Sect. 5. Our findings are summarized in Section Sect. 6. The equivalence of the obtained solution and the solution in (DeVries et al., 2014) for a constant rate of degradation is shown in Appendix A.

2 Model equations

We consider the vertical flux of ~~the~~ organic particles caused by gravitational forces. Focusing on the development of a numerical Eulerian-Lagrangian method and finding analytical solutions, we limit ourselves to a fairly simple one-dimensional formulation of the problem away from areas of intense currents. The vertical distribution of these particles below the euphotic layer z_{eu} is governed by the flux of settling particles equilibrated by particle degradation due to bacterial decomposition. The processes of aggregation ~~and fragmentation,~~ fragmentation and ballasting are not included in the model. ~~It is assumed steady state of the particle flux.~~ The Eulerian We limit ourselves to large-scale climatological processes that cover the water column below the euphotic layer to the bottom. We assume that the effects of time variability on the POM flux are relatively small far from this layer, and we consider the steady states of these fluxes.

The Euler particle concentration transport equation and the Lagrangian Lagrange equations for the individual particles are solved. The ~~Eulerian Euler~~ equation for the POM concentration $C_{p,d}$ [kg m^{-3}] ~~with particle~~ for particles of equivalent spherical

diameter d [m] is written as

$$\frac{\partial W_{p,d} C_{p,d}}{\partial z'} + \gamma C_{p,d} = 0, \quad (1)$$

where $W_{p,d}$ [m d⁻¹] is the settling velocity of a particle of diameter d ; z' [m] is the vertical coordinate directed ~~downward~~ downwards from the depth of the euphotic zone ($z' = z - z_{eu}$); ~~and~~ and γ [d⁻¹] is the degradation rate. The boundary condition
90 for Eq. (1) is

$$z' = 0: \quad C_{p,d} = C_{p,d}(0), \quad (2)$$

where $C_{p,d}(0)$ is ~~a~~ the prescribed POM concentration ~~on~~ at the lower boundary of the euphotic layer z_{eu} .

We consider the particle dynamics in the Lagrangian coordinate system. The porosity of organic particle aggregates increases with increasing particle size (Mullin, 1966). The relationship between the organic matter mass m_d and diameter d of porous
95 particles can be parameterized according to the particle fractal dimension

$$m_d = c_m d^\zeta. \quad (3)$$

Here, ζ ($\zeta \leq 3$) is a dimensionless scaling argument, and c_m is a prefactor coefficient (Alldredge and Gotschalk, 1988).

The Stokes-type settling velocity $W_{p,d}$ depends on the ~~density~~ difference between the density of water and the density of ~~partieles~~ the particle, the particle shape, and the kinematic viscosity. To ~~take into account the whole~~ consider the entire
100 ensemble of aforementioned factors that impact ~~the sinking~~ we approximated sinking, we approximate the sinking law by power dependence, which is widely used in ~~the~~ particle flux models ~~(e.g. (DeVries et al., 2014))~~ (e.g., DeVries et al., 2014):

$$W_{p,d} = \frac{\partial z'}{\partial t} = c_w d^\eta, \quad (4)$$

where t is time, η ($\eta \leq 2$) is ~~the~~ a dimensionless scaling argument and c_w [m^{1- η} d⁻¹] is a prefactor coefficient. ~~Note that~~
~~Figure~~ The measurements of (McDonnell and Buesseler, 2010) show that formulations of sinking velocity as a function of
105 only equivalent particle size can be insufficient because the shapes of the particles (e.g., faecal pellets) can significantly affect
the sinking velocity. Fig. 1 from (Cael et al., 2021) also demonstrates the difficulties of describing the sinking ~~speed~~ velocities
of particles of various sizes, shapes and structures with a single universal dependence. Therefore, ~~relation~~ Eq. (4) should be
considered only ~~as~~ a first approximation ~~in~~ when describing the complex dynamics of particles.

~~Consider the particle dynamics in the Lagrangian coordinate system. The mass of the particle m_d is related to the particle~~
110 ~~diameter d as~~

$$m_d = c_m d^\zeta,$$

~~where ζ ($\zeta \leq 3$) is the dimensionless scaling argument and c_m is a prefactor coefficient (DeVries et al., 2014). Equation (3)~~
~~takes into account the fact that with an increase in particle size, the porosity of organic particles increases (Mullin, 1966).~~

~~We restrict consideration to the case when~~ We consider the case in which the mass of a particle that is descending with
115 velocity $W_{p,d}$ decreases over time t as a result of microbial degradation. This process can be described by a first-order reaction

with a reaction rate γ [d⁻¹]. The corresponding equation for m_d [kg] is written as

$$\frac{\partial m_d}{\partial t} = -\gamma(\theta)m_d^\theta. \quad (5)$$

Parameter $\theta = 1$ when the degradation rate is proportional to the particle ~~volume mass~~, and $\theta = 2/3$ when the degradation rate is proportional to the surface area of the particle (Omand et al., 2020).

120 In general~~case~~, the degradation rate depends on many factors. Here~~we take into account~~, we consider only several of them: the age of the organic particle t [d], the temperature of the sea water T [°C], and the concentration of oxygen $[O_2]$ [μ M];

$$\gamma = \gamma(t, T(z'), [O_2](z')). \quad (6)$$

~~Details of the parameterization~~The parameterization used in Eq. (6) will be given in Section is presented in detail in Sect. 4.

3 Analytical solutions

125 3.1 Age-independent degradation rate

First, we consider the case ~~when in which~~ the degradation rate of the particle is ~~age-independent (Age-Independent Degradation~~age independent (age-independent degradation rate (AID) model). Furthermore, we suppose that the mass loss is proportional to the ~~particle volume mass of the particle~~ ($\gamma = \gamma_0$, $\theta = 1$) and ~~it~~ does not depend on temperature ~~and or~~ oxygen concentration ($\gamma_0 = \text{const}$). Then, the solution of Eq. (5) is

$$130 \quad m_d = m_{0d} \exp(-\gamma_0 t), \quad (7)$$

where $m_{0d} = c_m d_0^\zeta$ is the initial value of ~~particle mass of the particle mass for~~ diameter d_0 . Initially, ~~these particles are the~~particle is placed at depth ~~$z = z'$. The diameter of the particle varies with $z' = 0$.~~Combining Eq. (7) and Eq. (3) yields the change in the particle diameter over time as

$$d = d_0 \exp\left(-\frac{\gamma_0 t}{\zeta}\right). \quad (8)$$

135 ~~Assuming the quasi-equilibrium descending~~Assuming the quasiequilibrium descent of the particle in the Stokes regime~~we~~estimated, as described by Eq. (4), and taking into account that $W_{p,d} = \partial z' / \partial t$, we estimate the dependence of ~~$W_{p,d}$ the~~particle depth z' on t using Eq. (8):

$$\underline{W_{p,d}} = \frac{\partial z'}{\partial t} = c_w d_0^\eta \exp\left(-\frac{\eta \gamma_0 t}{\zeta}\right). \quad (9)$$

~~The vertical path z' travelled by a particle is~~By integrating Eq. (9) from the initial particle depth $z' = 0$ at $t = 0$, we find the
140 vertical path travelled by the particle:

$$z' = \frac{\zeta c_w d_0^\eta}{\eta \gamma_0} \left[1 - \exp\left(-\frac{\eta \gamma_0 t}{\zeta}\right) \right]. \quad (10)$$

~~Eliminating~~ By eliminating time from Eqs. (9) and (8) by using Eq. (10) ~~we obtained~~, we obtain $W_{p,d}$ and d as the functions of z' :

$$W_{p,d} = H(z') c_w d_0^\eta (1 - \psi z'), \quad (11)$$

$$145 \quad d = H(z') d_0 (1 - \psi z')^{\frac{1}{\eta}}, \quad (12)$$

where

$$\psi = \frac{\eta \gamma_0}{\zeta c_w d_0^\eta} > 0. \quad (13)$$

These solutions describe a layer of finite thickness $h_0 = \psi^{-1}$ below which there are only trivial solutions $W_{p,d} = d = 0$. To consider this finding, the Heaviside function is used. The Heaviside function is $H(z') = 1$ if $z' \leq \psi^{-1}$ and $H(z') = 0$ if $150 \quad z' > \psi^{-1}$. Taking into account Eq. (11) ~~we solved~~, we solve Eq. (1) with the boundary condition in Eq. (2) to obtain

$$C_{p,d} = H(z') C_{p,d}(0) (1 - \psi z')^{\frac{\zeta - \eta}{\eta}}. \quad (14)$$

The solution (14) describes the vertical profile of the POM concentration ~~caused by~~ for particles of diameter d under the prescribed particle size distribution $N(d_0) [\text{m}^{-4}]$ at $z' = 0$. This distribution can be approximated by power dependence $\sim d_0^{-\epsilon}$ the power dependence (e.g., Kostadinov et al., 2009)

$$155 \quad N(d_0) = M_0 d_0^{-\epsilon},$$

where ϵ is a power-law exponent and M_0 is a constant that can be estimated from the total concentration of sinking POM at $z' = 0$. To obtain the size distribution of $C_{p,d}(0)$, we use a small increment of particle size Δd_0 assuming that under the assumption that the concentration is uniform within the interval Δd_0 . Then, the distribution $C_{p,d}(0)$ as a product of $N(d_0)$, $m_{0,d}$ and Δd_0 is given by

$$160 \quad C_{p,d}(0) = M_0 d_0^{-\epsilon} m_{0,d} \Delta d_0 = M_0 c_m d_0^{\zeta - \epsilon} \Delta d_0, \quad (15)$$

~~where M_0 is a constant which can be estimated from the total concentration of sinking POM at $z' = 0$.~~

The total concentration C_p is calculated as ~~sum of $C_{p,d}$ over~~ the sum of concentrations $C_{p,k}$ in the k -th interval of size d over the total number of n_d intervals:

$$C_p(z') = \sum_{i=0}^{n_d} C_{p,d,i} = M_0 c_m \sum_{i=0}^{n_d} d_{0,i}^{\zeta - \epsilon} H(z') (1 - \psi z')^{\frac{\zeta - \eta}{\eta}} \Delta d_{0,i}, \quad (16)$$

165 ~~where $d_{0,k} = k \Delta d_0 + d_0^{\min}$, $\Delta d_0 = (d_0^{\max} - d_0^{\min}) / n_d$, and $d_0^{\min}$ and $d_0^{\max}$ are the minimal and maximal values, respectively, of d_0 .~~ At $\Delta d_0 \rightarrow 0$, the total concentration of sinking POM C_p [kg m^{-3}] in the range from $d_0^{\min}$ to $d_0^{\max}$ can be calculated as

$$C_p(z') = M_0 c_m \int_{d_0^{\min}}^{d_0^{\max}} d_0^{\zeta - \epsilon} H(z') (1 - \psi z')^{\frac{\zeta - \eta}{\eta}} d\tilde{d}_0. \quad (17)$$

~~Total~~The total mass flux F_p [kg m⁻²d⁻¹] can be calculated in a similar way:

$$F_p(z) = \sum_{i=0}^{n_d} C_{p,d,i} W_{p,d,i} = M_0 c_m c_w \sum_{i=0}^n \binom{n_d}{k=0} d_{0,i}^{\eta+\zeta-\epsilon} H(z') (1 - \psi z')^{\frac{\zeta}{\eta}} \Delta d_0. \quad (18)$$

170 Here, $W_{p,k}$ is the sinking velocity in the k -th interval of size d over a total of n_d intervals.

At $\Delta d_0 \rightarrow 0$:

$$F_p(z) = M_0 c_m c_w \int_{d_0^{min}}^{d_0^{max}} \tilde{d}_0^{\eta+\zeta-\epsilon} H(z') (1 - \psi z')^{\frac{\zeta}{\eta}} d\tilde{d}_0. \quad (19)$$

The problem for which we obtained the solution (14) for the POM concentration $C_{p,d}$ is similar to that solved by DeVries et al. (2014) for the particle size spectrum equation. In Appendix A, we show the equivalence of these solutions.

175 3.2 Age-dependent degradation rate

The degradation rate as a function of POM age t [d] can be described by following Middelburg (1989) as

$$\gamma(t) = \frac{\beta}{\alpha + t}, \quad (20)$$

where α [d] and β are empirical constants. We define such a model as an age-dependent degradation rate (ADD) model.

The time dependencies for d and $W_{p,d} = \partial z' / \partial t$ with parameterization of the degradation rate Eq. (20) are obtained

180 similarly to those in Section 3.1. They are written as expressed as

$$d = d_0 \left(\frac{\alpha}{\alpha + t} \right)^{\beta/\zeta}, \quad (21)$$

$$W_{p,d} \frac{\partial z'}{\partial t} = c_w d^\eta \left(\frac{\alpha}{\alpha + t} \right)^{\eta\beta/\zeta}. \quad (22)$$

~~The~~ Integrating Eq. (22) from the initial particle depth $z' = 0$ at $t = 0$, we find the path travelled by a sinking particle is as

$$z' = c_w d_0^\eta \frac{\alpha\zeta}{\zeta - \eta\beta} \left[\left(1 + \frac{t}{\alpha} \right)^{(\zeta - \eta\beta)/\zeta} - 1 \right]. \quad (23)$$

185 ~~Eliminating time from Eqs~~By eliminating time from Eqs. (20), (21) and (22)we obtained depth-dependent solutions, we obtain depth-dependent solutions in the same way as in Eqs. (11)-(12):

$$W_{p,d}(z') = c_w d_0^\eta (1 + \phi z')^{-\frac{\eta\beta}{\zeta - \eta\beta}}, \quad (24)$$

$$\gamma(z') = \frac{\beta}{\alpha} (1 + \phi z')^{-\frac{\zeta}{\zeta - \eta\beta}}, \quad (25)$$

$$d(z') = d_0 (1 + \phi z')^{-\frac{\beta}{\zeta - \eta\beta}}, \quad (26)$$

190 where

$$\phi = \frac{\zeta - \eta\beta}{\alpha\zeta c_w d_0^\eta}. \quad (27)$$

Integrating Eq. (1) with a boundary condition the boundary condition in Eq. (2) and taking into account considering Eqs. (24) and (25) we found a, we obtain the following solution for $C_{p,d}$ as:

$$C_{p,d}(z') = C_{p,d_0} (1 + \phi z')^{\frac{(\eta-\zeta)\beta}{\zeta-\eta\beta}}. \quad (28)$$

195 Assuming that the density of distribution of The density of the distribution of the particle mass concentration at $z=0$ is approximated by $z'=0$ is assumed to be approximated by a power law (15) we. We can obtain the total concentration of sinking POM C_p in the range of d_0 from d_0^{min} to d_0^{max} as

$$C_p(z') = M_0 c_m \int_{d_0^{min}}^{d_0^{max}} \tilde{d}_0^{\zeta-\epsilon} (1 + \phi z')^{\frac{(\eta-\zeta)\beta}{\zeta-\eta\beta}} d\tilde{d}_0. \quad (29)$$

The corresponding total mass flux $F_p(z)$ is written as

$$200 \quad F_p(z') = \int_{d_0^{min}}^{d_0^{max}} W_{p,d} C_{p,d} d\tilde{d}_0 = M_0 c_m c_w \int_{d_0^{min}}^{d_0^{max}} \tilde{d}_0^{\eta+\zeta-\epsilon} (1 + \phi z')^{\frac{\zeta\beta}{\zeta-\eta\beta} - \frac{\zeta\beta}{\zeta-\eta\beta}} d\tilde{d}_0. \quad (30)$$

3.3 Comparison of analytical solutions

The obtained analytical solutions have several important properties. At First, we compare these solutions with the solutions obtained under the assumption of a constant sinking velocity $W_{p,d} = W_p(d_0)$, the solution of when

$$W_{p,d} = c_w d_0^\eta.$$

205 The solution of Eq. (1) for a constant degradation rate γ corresponds to the exponential profile of the particle concentration

$$C_p(z', d_0) = C_p(0, d_0) \exp\left(-\frac{\gamma_0 z'}{c_w d_0^\eta}\right), \quad (31)$$

while for whereas the time-dependent degradation rate (20) it corresponds to the power-law distribution of the POM concentration

$$C_p(z', d_0) = C_p(0, d_0) \left(\frac{\alpha c_w d_0^\eta}{\alpha c_w d_0^\eta + z'}\right)^\beta. \quad (32)$$

210 Both of these solutions are frequently used to approximate observed particle flux profiles, e.g. (Martin et al., 1987) and (Lutz et al., 2002). The corresponding profiles normalized to values at the base of the euphotic layer $C_p(z_{eu})$ and $F(z_{eu})$ are shown in Fig. 1 where, (Martin et al., 1987; Lutz et al., 2002). Notably, a solution of the form (32) can alternatively be obtained under the assumption of a constant degradation rate and a linear increase in the sinking velocity (Kriest and Oshlies, 2008; Cael and Bisson

215 The corresponding profiles of C_p and F_p profiles were obtained by summation of n profiles in (16) summing the n_d profiles in Eqs. (31) and (32). The values of $C_p(z_{eu})$ and $F(z_{eu})$ were calculated using Eq. (15). The model parameters (η , ζ , γ_0 ,

Table 1. ~~The baseline~~ Baseline model parameters.

Parameters	Value/range	Unit	Reference
η	1.17	-	Smayda (1970)
ζ	2.28	-	Mullin (1966)
γ_0	0.03	d^{-1}	Kriest and Oshlies (2008)
c_w	$2.2 \cdot 10^5$	$\text{m}^{1-\eta} \text{d}^{-1}$	Kriest and Oshlies (2008)
ϵ	4.2	-	Kostadinov et al. (2009)
Q_{10}	2 – 3	-	Cram et al. (2018)
T_{ref}	4	$^{\circ}\text{C}$	Cram et al. (2018)
K_O	8	μM	Cram et al. (2018)
α	30	d	Aumont et al. (2017)
β	1	-	Aumont et al. (2017)
d_0^{max}	2000	μm	DeVries et al. (2014)
d_0^{min}	20	μm	DeVries et al. (2014)
n_d	990	—	DeVries et al. (2014)

$c_w, \epsilon, \alpha, \beta, d_0^{max}, d_0^{min}, n$ and n_d) in Table 1 were ~~as chosen by DeVries et al. (2014) and Aumont et al. (2017).~~ As seen the same as in (DeVries et al., 2014) and (Aumont et al., 2017). As shown in Fig. 1, with ~~such parameters~~ these parameters, C_p and F_p decay much faster for ~~AID than for the AID model than for the ADD model.~~ Note that Notably, C_p and F_p tend to exhibit exponential or power-law profiles only at great depths. At the same time Moreover, at a constant particle velocity, the ~~weighted vertical mass-weighted sinking~~ velocity of particles (Fig. 1e) for both AID and ADD models the speed

$$\overline{W}_p(z') = \frac{F_p(z')}{C_p(z')}$$

increases with depth.

The presence of feedback between γ and $W_{p,d}$ leads to ~~a significant change in these~~ significant changes in the C_p and F_p profiles. In the case of a constant γ_0 , the vertical distribution of the concentration $C_{p,d}$ for one surface fraction of POM size d_0 is limited by a finite layer of thickness $h_0 = (\zeta c_w d_0^\eta)(\eta \gamma_0)^{-1}$. ~~Partieles~~ The particles in this layer sink at a linearly decreasing velocity. The ~~mass of particles also decreases with depth to a depth where masses of the particles also decrease with depth until a depth at which~~ they are completely remineralized is reached. The size distribution for a single particle at depth z' is ~~$N(d, z') = C_{p,d} m_d \sim (1 - \psi z')^{-1}$~~ $N(d, z') = C_{p,d} m_d^{-1} \sim (1 - \psi z')^{-1}$. At $z' \rightarrow h_0$, $N(d, z') \rightarrow \infty$ ~~while as~~ while as $m_d \rightarrow 0$. The finite thickness of the layer of sinking particles with the parameters given in Table 1 varies ~~in the range from 41.3 from 45.4 m~~ at $d_0 = 20 \mu\text{m}$ to 9937 m at $d_0 = 2000 \mu\text{m}$. ~~Note that Notably,~~ Note that Notably, the solution to the problem in a different formulation (Omand et al., 2020) has ~~qualitatively the same~~ the same qualitative character. However, the ~~profiles of~~ total POM concentration and total POM flux decay asymptotically approaching to the exponential exponential profiles, in contrast to the profiles (1714)

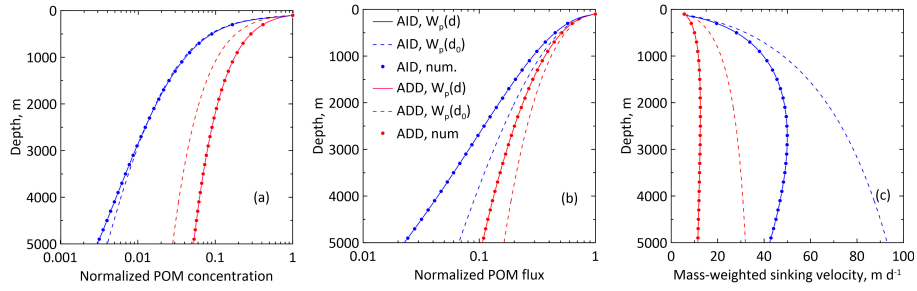


Figure 1. The normalized total POM concentration C_p (a), total POM flux F_p (b), and weighted vertical velocity of the particles (c) for the AID (blue lines) and ADD (red lines) models calculated from the analytical and numerical solutions. The dashed line corresponds to the solution of (1) at constant $W_p(d_0)$, while the solid line corresponds to the solution of the problem at variable $W_p(d)$. The small circles correspond to the numerical solutions obtained via the AID and ADD models.

and (11) for one class of particle sizes d_0 on $z' = 0$. These profiles, normalized to values at the base of the euphotic layer, are shown in Fig. 1 where the C_p and F_p profiles were obtained by summation of via the summation of the n_d profiles in Eqs. (16) and (18). The baseline parameters for calculation are given in Table 1. These parameter values match those used by DeVries et al. (2014). Therefore, the curves in Fig. 1 also coincide with the corresponding curves in Fig. 1c from (DeVries et al., 2014) calculated using another but, which were calculated using an equivalent formulation of the same problem, as shown in the Appendix.

In contrast to the AID model solution (16), the POM concentration profile (28) decays asymptotically with depth at $\zeta > \eta$ and $\zeta > \eta\beta$ for the ADD model (20). These conditions are met for the parameters listed in Table 1. The rate of degradation γ also decays with depth; the corresponding exponent in (25) differs from the parameter. Unlike the models (Kriest and Oshlies, 2008; Cael and Bisson, 2018) that use the same "Martin curve" power-law dependence (32) for the concentration and mass flux of POM with the exponent β in, the exponent in the obtained solution (28) depends not only on β but also on the parameters that characterize the sinking velocity (η) and the particle mass fractal dimension (ζ).

The sensitivity of the models with a constant sinking rate (32). A sensitivity to the AID model parameters was considered by DeVries et al. (2014). They found that of the four parameters controlling the flux profile reported that four parameters (η , ζ , γ_0 , and ϵ) the most significant control the flux profile and that the most significant factor is the slope of the particle distribution ϵ on $z' = 0$, which has the greatest influence on the depth distribution of particles. As follows from the particles. In Fig. 2 in which the variables are presented in logarithmic coordinates, only the vertical distribution of C_p is close to the power distribution with an exponent of about approximately 1, while whereas the distribution with the depth of the total particle flow depth of F_p significantly deviates from the power-law dependence power law (Martin's law). The sensitivity of the concentration and flux profiles to the values of parameters α and β parameters is examined in Figure 2. An increase in the parameter α leads to a deepening of the concentration and particle flux profiles, while whereas an increase in the β leads to a shallowing of these profiles.

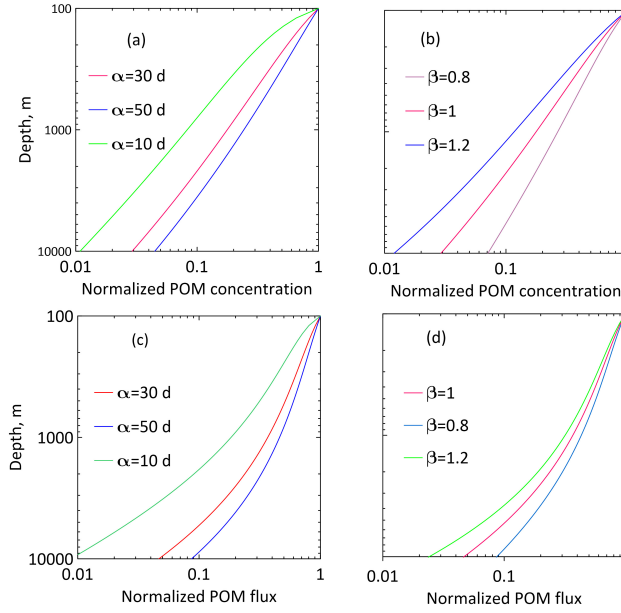


Figure 2. ~~The normalized~~ Sensitivity of the normalised total particle concentration C_p (a) and total particle flux F_p (b) ~~sensitivity~~ to parameters α and β .

The relative maximal absolute errors [%] of the calculated AIDR and ADDR solutions for C_p and F_p are presented in Table S1. We compare the solutions at spectral resolutions $n_d = 100$ and $n_d = 10$ with the baseline calculation at $n_d = 990$. These estimates demonstrate the necessity of fine resolution of the spectre of particles at the lower boundary of the euphotic zone for obtaining accurate profiles of the POM concentration and sinking flux. In this case, the particle concentration profile is more sensitive to the spectral resolution than the sinking flux profile is.

4 Numerical model

4.1 Numerical algorithm

The model discussed in the previous section is based on several simplifying assumptions that ~~made it possible to obtain~~ make obtaining analytical solutions to the system of equations possible. However, when we expand the model to include new important factors in the processes of sinking and remineralization of POM, analytical solutions to the problem can no longer be obtained. Therefore, a ~~numerical Eulerian-Lagrangian approach to solving the new~~ numerical Eulerian-Lagrangian approach for solving this problem was developed.

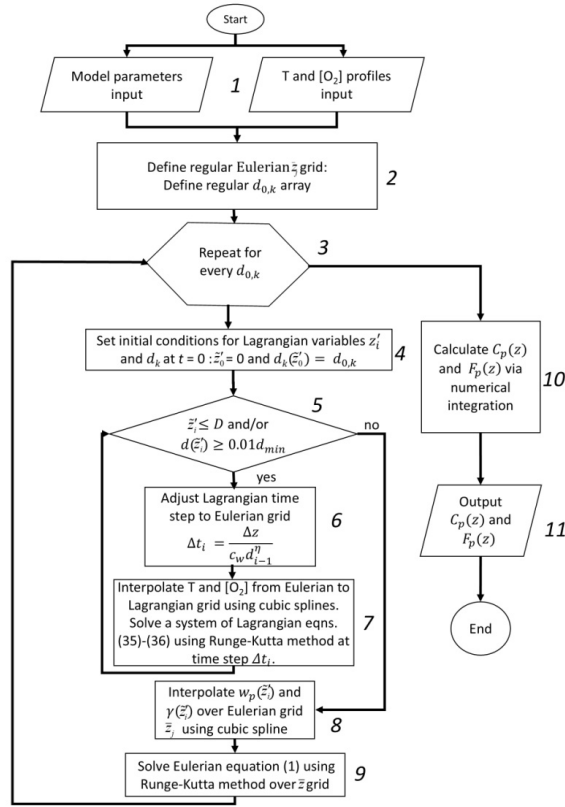


Figure 3. The Eulerian-Lagrangian-Eulerian-Lagrangian method flow chart for equations of sinking particulate organic matter.

Here we will limit ourselves to the case where, we consider the case in which the degradation rate depends on the age of the organic particle (ADD model), the temperature of the sea water T and the concentration of oxygen $[O_2]$:

$$\gamma = \gamma(t, T(z'), [O_2](z')) = \left(\frac{\beta}{\alpha + t} \right) \left(Q_{10}^{\frac{T - T_{ref}}{10}} \right) \left(\frac{[O_2]}{K_O + [O_2]} \right), \quad (33)$$

where Q_{10} is the temperature coefficient, T_{ref} is a reference temperature, K_{O_2} (kg m^{-3}) and K_O (μM) is an oxygen dependence parameter (Cram et al., 2018). When γ does not depend on age (AID model) then, then

$$\gamma = \gamma_0 \left(Q_{10}^{\frac{T - T_{ref}}{10}} \right) \left(\frac{[O_2]}{K_O + [O_2]} \right) : \quad (34)$$

The system of Lagrangian-Lagrange equations for particle depth and size derived from Eqs. (4)-(5) is as follows:

$$\frac{\partial d}{\partial t} = - \frac{\gamma(t, T(z'), [O_2](z'))}{\zeta} \frac{\gamma(t, T(z'), [O_2](z'))}{\zeta} d, \quad (35)$$

$$\frac{\partial z'}{\partial t} = c_w d^n. \quad (36)$$

The initial conditions are that at $t=0: z'=0$ and $d=d_{0,i}$; $z'=0$ and $d=d_{0,i}$.

The procedure of finding for determining the profiles of $C_p(z')$ and $F_p(z')$ is as-presented in Fig. 3. It includes 11 steps.

Step 1 The model parameters and temperature and oxygen concentration profiles are read from the input files.

280 Step 2 The-A regular Eulerian grid $\bar{z}'$ is set-up-established from 0 to the ocean depth D on-with n_z equal intervals Δz with levels $\bar{z}' = j \cdot \Delta z$, where $j = (0, n_z)$. The particle size spectrum at the lower boundary of the euphotic layer is divided on-into n_d equal intervals of size Δd in the range from d_{min} to d_{max} . For every particles-particle size $d_{0,k}$, $k = (0, n_d)$.

Step 3 Sequential-steps 4-9 Steps 4-9 are performed for every $d_{0,k}$, where $k = (0, n_d)$. Thenmove-to-the-Step 10-, Step 10 is performed.

285 Step 4 Set-the-initial-conditions-for-The initial conditions are set for the Lagrangian particle depth $\tilde{z}'_k(t_i)$ and size $d = d_{0,k}$ equations at $t_i = 0$.

Step 5 If the Lagrangian particle depth $\tilde{z}'_k(t_i)$ is equal to or greater than the ocean depth D and/or-particle-diameter-on-or the particle diameter at this depth level $d = d_{0,k}$ is equal to or less than 1% of minimum-diameter-size the minimum diameter d_{min} then-perform- Step 8 else-perform-Step 6- is performed; otherwise, Step 6 is performed.

290 Step 6 The timescale is divided on-the-into intervals Δt_i , $i = (0, n_t)$ over which equations-Eqs. (35)-(36) are integrated. To align the resulting $\tilde{z}'_k(t_i)$ and regular depth grid $\bar{z}'$, the i -th timestep duration is calculated as $\Delta t_{i,k} = \Delta z / (c_w d_{i,k}^\eta)$.

Step 7 Using-the-The Lagrangian formulation with respect to time t solve-a-is used to solve the system of equations (35)-(36) using-Runge-Kutta's-via the Runge-Kutta method of the 4th order. The-eubic-Cubic spline interpolation is used to calculate the temperature and oxygen concentration at $\tilde{z}'_k(t_i)$.

295 Step 8 The $w_p(\tilde{z}'_k(t_{i+1}))$ and $\gamma(\tilde{z}'_k(t_{i+1}))$ profiles at-on the Lagrangian grid of-are-interpolated-using-are interpolated via a cubic spline over the Eulerian grid $\bar{z}'$.

Step 9 The- $C_p(d)(\bar{z}')$ - $C_{p,d}(\bar{z}')$ is calculated by solving Eulerian-the Euler equation (1) with-Runge-Kutta-via the Runge-Kutta method over the regular grid $\bar{z}'$. Thenmove-to-Step 3-, Step 3 is performed.

Step 10 The total POM concentration $C_p(\bar{z}')$ and POM flux $F_p(\bar{z}')$ are obtained via numerical integration of $S(p, d)(\bar{z}')$ and $w_p(\bar{z}')$ by using the composite Simpson's 1/3 rule.

300 Step 11 Model-output-The model outputs the total POM concentration $C_p(\bar{z}')$ and POM flux $F_p(\bar{z}')$.

The code for the proposed algorithm, along with the data used in this study, is archived on Zenodo (Kovalets et al., 2025a, b).

4.2 Numerical model setup

The-simulations-Simulations were carried out for the-water-column-of-depth-a water column with a depth of $D = 5000$ m ; $n_z = 1000$, and $\Delta z = 1$ m. We calculate-calculated the vertical profiles of the POM concentration C_p and flux F_p using AID and ADD models for the degradation rate. The rest-of-the-remaining model parameters, except-with-the-exception of η , were adopted from Table 1. In-Fig-1-the-The profiles of C_p and F_p were calculated using-an-above-algorithm-and-via the above algorithm with $\eta = 1.17$ to-be-compared-with-analytical-solutions-for-for comparison with the analytical solutions with the AID and ADD parameters from Table 1. As seen-in-the-figure-shown in Fig. 1, the numerical and analytical profiles coincide.

310 The ~~calculations~~ calculation results were compared with the available measurement data for C_p and F_p for the latitude ~~band of 20–30~~ bands of 20–30°N in the Atlantic and Pacific Oceans and ~~50–60~~ 50–60°S ~~of in~~ in the Southern Ocean. These calculations aimed to assess the relative ~~influence effects~~ of the vertical distribution distributions of temperature and oxygen in the Atlantic, Pacific and Southern ~~oceans on profiles~~ Oceans on the profiles of C_p and F_p . For the Atlantic Ocean, the C_p and F_p data are compiled in (Aumont et al., 2017) and (Lutz et al., 2002) ~~while for~~ For the Pacific Ocean, ~~they are given~~ these values are presented in (Martin et al., 1987) and (Druffel et al., 1992). The Southern Ocean data for the Pacific and Atlantic sectors are ~~given presented~~ presented in (Aumont et al., 2017) and (Lutz et al., 2002). The ~~required for calculations averaged~~ calculations required for averaging over the region and time profiles of T and $[O_2]$ were ~~constructed using performed with~~ the measurement data from (Boyer et al., 2018). These averaged profiles are shown in Fig. S1 in the Supplement. ~~It is necessary to emphasize the~~ Notably, there is great uncertainty not only in the choice of model parameter values but also in the ~~processes’~~ parameterization ~~parameterization of the processes~~. This is explained by both an insufficient understanding of the physical and biogeochemical processes ~~and~~ the lack of a sufficient number of measurements in the deep layers of the ocean. In particular, the observation results (Cael et al., 2021) show large deviations in the parameters of the sinking ~~velocity-particle~~ velocity-particle size relationship (4). In ~~the recent models~~ recent models, the parameter η ~~varies in range~~ has varied from 0.26 (Alcolombri et al., 2021) to 2 (Omand et al., 2020). Therefore ~~in simulations we compare effect~~ in the simulations, we compared the effects of η on the C_p and F_p profiles for two values: $\eta = 1.17$ (Smayda, 1970) and $\eta = 0.63$ (Cael et al., 2021).

5 Modelling results

5.1 Comparison of simulations with measurements

Figures ~~4–6~~ 4–6 show the profiles of C_p and F_p ~~normalised~~ normalized to $C_p(z_{eu})$ and $F_p(z_{eu})$. They were calculated using the numerical algorithm described in Section Sect. 4.1. These profiles are compared with ~~normalised~~ normalized measurements in 330 the subtropical zones of the Atlantic ~~and Pacific oceans, and also~~ (Fig. 4) and Pacific (Fig. 5) Oceans and in the Atlantic and Pacific sectors of ~~Southern Ocean to consider~~ the Southern Ocean (Fig. 6) to consider the effects of temperature and oxygen concentration ~~effects on~~ POM. When the modelling results are compared with the measurement data, the significant scatter of the measurement data presented in Figs. 4–6 must be noted. This scatter is due both to the difficulties of measuring the concentration and flux of particles and to regional differences in the influx of particles and in the surrounding ocean.

335 The C_p and F_p profiles in Figures ~~4–6~~ 4–6 were obtained for three variants of the degradation model. In the first variant (plots a and d), C_p and F_p do not depend on ~~temperature and the temperature or~~ oxygen concentration. ~~in In~~ the second variant (plots b ~~and e~~ and e), they do not depend on the oxygen concentration, and in the third variant (c ~~and f~~ and f), they depend on ~~temperature,~~ the temperature and oxygen concentration. The first variant is described by analytical solutions for the AID and ADD models. The features of these solutions are discussed in Section 3.3. The profiles of C_p and F_p are sensitive to the value of η . The 340 solutions with $\eta = 0.63$ decay ~~slower than obtained for more slowly than those with~~ $\eta = 1.17$ as follows also from analytic solutions do, as shown by the analytic solutions in Figs. 4a, 4d, 5a, 5d, 6a, and 6d.

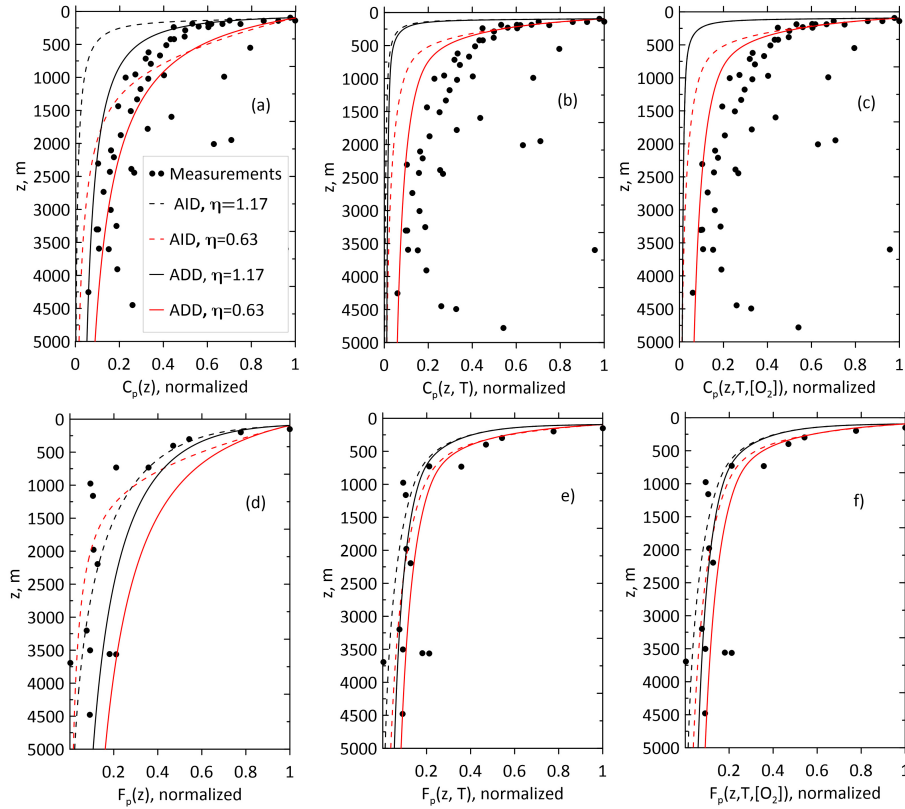


Figure 4. The normalized total POM concentration C_p (a-ea-c) and total POM flux F_p (d-fd-f) versus measurement data in the Atlantic Ocean at 20-30°N (Aumont et al., 2017; Lutz et al., 2002). Three columns of panels correspond to the model without dependency of temperature and oxygen (panels a and d), additional temperature dependence (panels b and e), and both additional dependencies (panels c and f).

Using the use of the AID model leads led to a more rapid decay of C_p with depth than was observed in all the ocean profiles. At the same time, the decay of F_p with depth occurs more slowly in most of the measured profiles. The using of ADD model (Figs. 4-6) results in more smooth profiles, however qualitatively. Moreover, the application of the ADD model resulted in smoother profiles in all oceans; however, the AID and ADD profiles are close.

As can be seen from Fig. 4-6, qualitatively close. As shown in Figs. 4b, 4e, 5b, 5e, 6b, and 6e, the dependence of the degradation rate on temperature significantly affected the profiles of C_p and F_p enhancing profiles; namely, it enhanced the degradation of sinking particles in the upper layers of the ocean and suppressing-suppressed it in the deep layers of the ocean. The influence of the oxygen concentration in all cases considered-the cases considered (Figs. 4c, 4f, 5c, 5f, 6c, and 6f) was less significant compared-to-than that of the distribution of temperature with depth. Overall, including temperature and concentration dependence in the degradation rate relationship improves-improved the agreement with ocean measurements. The normalized Mean-Bias-Errors (MBE)-when-taking-into-account-mean bias errors (MBEs) when considering the dependence of

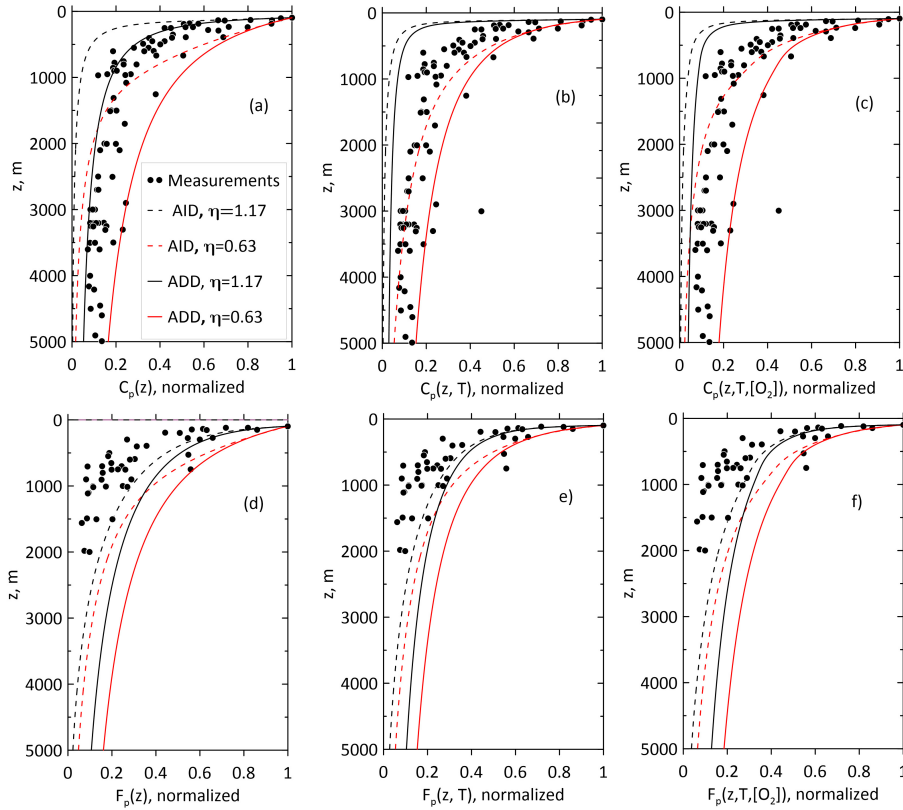


Figure 5. ~~The normalized~~ Normalized total POM concentration C_p (a-ea-c) and total POM flux F_p (d-fd-f) versus measurement data in the Pacific Ocean at 20-30°N (Martin et al., 1987; Druffel et al., 1992). Three columns of panels correspond to the model without dependency of temperature and oxygen (panels a and d), additional temperature dependence (panels b and e), and both additional dependencies (panels c and f).

the degradation rate on temperature and oxygen concentration (third variant) ~~are reduced~~ decreased from 9% to -3% compared to ~~first variant~~ those of the first variant, when this dependence was not ~~taken into account~~. ~~For third variant the Root Mean Square Deviation considered.~~ For the third variant, the root mean square deviation (RMSD) decreased by half ~~comparatively with compared with that of the first variant.~~ ~~Notice that both~~

Notably, both the AID and ADD models somewhat ~~underestimates~~ underestimated F_p when the dependence on temperature ~~is taken into account~~. ~~As follows from Figs. 4-6 was considered.~~ As shown in Figs. 4-6, the use of a ~~AID model leads the AID model led~~ to a more rapid decay of S_p and C_p with depth than was observed in all ocean profiles. ~~At the same time~~ Moreover, ~~the decay of F_p with depth occurs~~ occurred more slowly in most of the measured profiles. The ~~using of use of the~~ ADD model (Figs. 4-6) ~~results in more smooth profiles, however~~ qualitatively ~~4-6) resulted in smoother profiles; however, qualitatively,~~ the AID and ADD profiles are ~~close~~ similar. Notably, profiles C_p and F_p in Fig. 3c, 3f and 4c, 4f are quite close despite the differences between the temperature and oxygen concentration profiles in the 20-30°N band of the Atlantic and Pacific Oceans

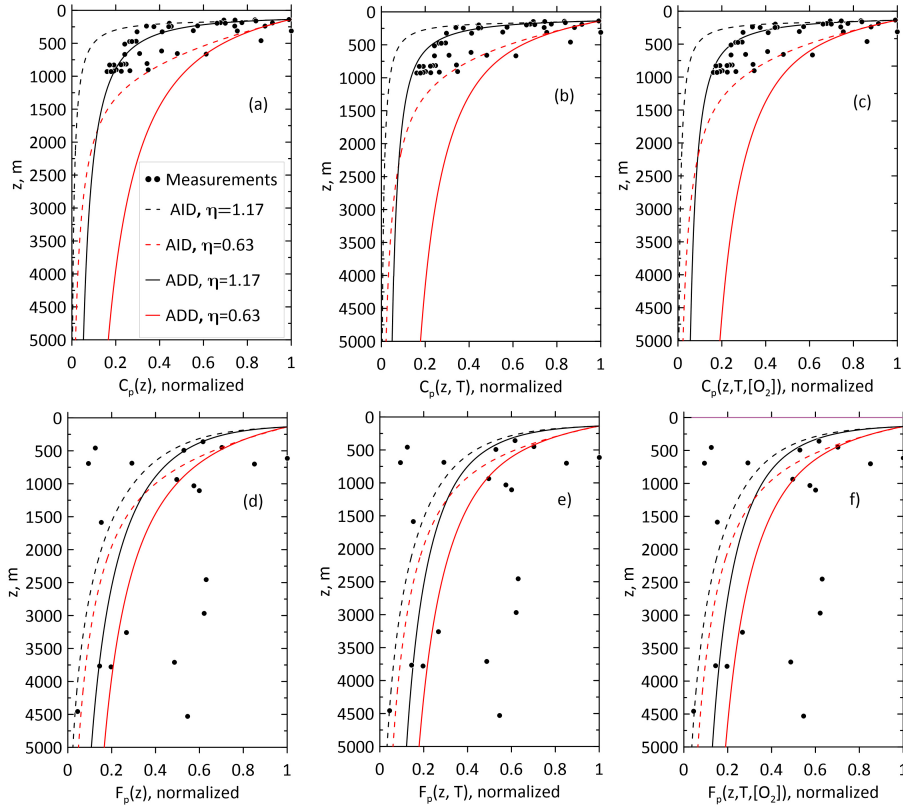


Figure 6. The normalized Normalized total POM concentration C_p (a-ea-c) and total POM flux F_p (d-fd-f) versus measurement data in the Southern Ocean at 50-60°N (Aumont et al., 2017; Lutz et al., 2002). Three columns of panels correspond to the model without dependency of temperature and oxygen (panels a and d), additional temperature dependence (panels b and e), and both additional dependencies (panels c and f).

(Fig. S1a-S1b). These profiles in the colder, oxygen-saturated waters of the Southern Ocean (Fig. S1c) attenuate more slowly with depth.

As follow from Fig. 4-6

5.2 Sensitivity study

As shown in Figs. 4-6, the model output was sensitive to the parameters with high uncertainty, such as η . Therefore, a sensitivity study was carried out for the model parameters in Table S1. We used the one-at-a-time method to quantify the effect of the variation of variation in a given parameter on the model output while all other parameters were kept at their initial values (Hamby, 1994; Lenhart et al., 2002; Soares and Calijuri, 2021). The effects of variations in these parameters were estimated for the particle transfer efficiency (TE). Define TE_{1000} is defined as the ratio of the concentration of POM-POM flux at the lower level of the euphotic layer z_{eu} to the concentration-flux at the lower boundary of the mesopelagic layer $z = 1000$.

and TE_{5000} is defined as the ratio of the concentration of POM-POM flux at the lower level of the euphotic layer to the concentration flux in the bottom layer at $z = 5000\text{m}$.

The range for parameters is defined as follows: The ranges for the parameters were defined for a constant ratio $r > 1$. The minimum parameter value p_{min} was set to be proportional to the reference value p_{ref} with a ratio value $1/r < 1$ and of $1/r$, whereas the maximum value p_{max} was set to be proportional to the reference value p_{ref} with a ratio value $r > 1$ to the reference value. For all of r . For the parameters in Table S1, the value of r was chosen to be the same ($r = 1.25$). This value satisfies to, which satisfies the ranges of all parameters. the parameters.

The model output sensitivity was estimated using a sensitivity index (SI) defined as

$$SI = \frac{TE(p_{max}) - TE(p_{min})}{TE(p_{ref})}, \quad (37)$$

where $TE(p_{max})$, $TE(p_{min})$ and $TE(p_{ref})$ are the simulation results for the maximal p_{max} , minimal p_{min} , and reference p_{ref} parameter values, respectively. Calculations of SI were carried out for the Pacific Ocean for the AID and DDR models using with the reference, maximal and minimal values of the parameters from Table S1 S2.

The sensitivity index TE_{1000} $SI(TE_{1000})$ is shown in Fig. S2 in the Supplement for the parameters of the AID model. As seen shown in the figure, TE_{1000} $SI(TE_{1000})$ was most sensitive to the exponent ζ in the power law dependence of the particle mass on the particle size (43) and to the exponent ϵ in the power law dependence of the particle size distribution at the lower boundary of the euphotic layer (4315). The sign of the index shows if the model reacts indicates whether the model reacted codirectionally to the input parameter change, i.e., if whether the parameter increase/decrease corresponds to the corresponded to an increase/decrease of in the model output parameter. The nature of the dependence of TE_{1000} on ζ and ϵ is different. The increase was different. An increase in ζ results resulted in an increase in TE_{1000} , i.e., an increase in the mass of a particle increases increased the transfer efficiency. At the same time, the increase Moreover, an increase in ϵ results resulted in a decrease in TE_{1000} , i.e., an increase in the slope of the spectral particle size distribution leads led to a decrease of in the transfer efficiency. The dependence of TE_{1000} on T_{ref} and K_O was weak ($SI \ll 1$), whereas the dependence on γ_0 , η and Q_{10} was moderate. The sensitivity index $SI(TE_{5000})$ for the parameters of the AID model is shown in Fig. S3. As seen shown in the figure, it is qualitatively similar to that in Fig. S2. Four parameters ($\gamma_0, \zeta, \eta, \epsilon$) show γ_0, ζ, η , and ϵ showed strong sensitivity.

The sensitivity index TE_{1000} for $SI(TE_{1000})$ values for the parameters of the ADD model is are shown in Fig. S4. Similarly, Similar to the results in Fig. S2, TE_{1000} is was most sensitive to ζ and ϵ , however, amplitudes of TE_{1000} are less than; however, the amplitudes of $SI(TE_{1000})$ were less than those for AID model. The dependence on sensitivity of the ADD model parameters (α and β) are was moderate. The sensitivity index TE_{5000} for $SI(TE_{5000})$ values for the parameters of the ADD model is are shown in Fig. S5. It similar to the TE_{1000} Similar to $SI(TE_{1000})$ for this model, but the amplitudes of TE_{5000} are greater than TE_{1000} amplitudes. More details of the magnitudes of the $SI(TE_{5000})$ values were greater than the magnitudes of the $Si(TE_{5000})$ values. Additional details on the sensitivity study are given presented in the Supplement.

In this paper

6 Discussion and conclusions

In this work, we considered ~~simple Eulerian-Lagrangian approach to solve equations describing a simple Eulerian-Lagrangian approach for solving equations that describe the~~ gravitational sinking of organic ~~particle under influence of the size and age~~ of particles under the effects of the sizes and ages of the particles, temperature and oxygen concentration on their dynamics and degradation processes. ~~The novel~~ In contrast to other approaches, our approach does not use particle spectrum equations (e.g., DeVries et al., 2014) explicitly or power-law particle size distribution assumptions (e.g., Kriest and Evans, 1999; Maerz et al., 2020). Unlike (Omand et al., 2020), we do not assume *a priori* the constancy of the particle flux in depth in steady state. Instead, solutions are found for the Euler equation for the concentration of particles of a given size and the Lagrange equations for a sinking organic particle under the influence of microbiological degradation. In the stationary case, the problem is reduced to solving a system of ordinary differential equations of the first order, in contrast to (DeVries et al., 2014), where the solution of the hyperbolic equation of the first order for the particle distribution is found. In addition, the total concentration and flux of the POM are found by summation over the particle distribution at $z' = 0$, whereas in (DeVries et al., 2014) the summation is carried out over all depths. Our approach makes the particle transport model compatible with large-scale biogeochemical models and provides an opportunity to solve the non-stationary problem in the future using Eq. (1) complemented by the time derivative of $C_{p,d}$ and necessary parameterizations of the POM sinking processes.

Novel analytical solutions of the system of the one-dimensional Eulerian equation for the POM concentration and Lagrangian equations for the particle mass and depth were obtained for constant and age-dependent degradation rates. ~~It was found that feedback between~~ The feedback between the degradation rate and sinking velocity results ~~to a significant change in POM and~~ POM in significant changes in the POM concentration and flux profiles. In the case of a constant γ_0 (AID model), the vertical distribution of the concentration $C_{p,d}$ for a single fraction of the POM size d_0 at z_{eu} is limited by a finite layer, unlike the exponential profile of the particle concentration that corresponds to a constant sinking velocity. Particles in this such a finite layer sink at a linearly decreasing velocity. ~~At the same time, the distribution of~~ Moreover, the distributions of the total particle concentration C_p and flux F_p ~~approaches exponential approach exponential trends~~ with depth for ~~increase of increasing~~ d_0 fractions.

In contrast to those for the AID model, the vertical ~~distribution of distributions of the~~ concentration and vertical velocity decay asymptotically with depth for the ADD model. The ~~rate of degradation in Eulerian variables decays with depth; however~~ rates of degradation of the Eulerian variables decay with depth; however, the corresponding exponent depends not only on the parameter β ~~as, as in~~ the models with a constant sinking velocity (Cael et al., 2021), but also on the parameters ~~characterizing that characterize~~ the vertical velocity of particles η and their porosity ζ . ~~With baseline parameters of the particles. With the baseline parameters,~~ the vertical distribution of C_p is close to the power distribution with an exponent of ~~about approximately~~ 1, ~~while whereas~~ the distribution with the depth of the total particle flow F_p ~~significantly deviates deviates significantly~~ from the power law dependence (“Martin’s law”). ~~Direct comparison with other models is difficult owing to differences in the parameterizations of processes, with the exception of the model (DeVries et al., 2014) for which~~ the solutions of the equations for the particle spectrum and concentration are established (Appendix A).

A new ~~Eulerian-Lagrangian numerical approach to~~ Eulerian-Lagrangian numerical approach for solving the problem in general cases was presented. ~~It allows to include in consideration of~~ The algorithm includes time steps for Lagrangian variables (sinking velocity and particle mass) and Eulerian depth steps for the concentration of particles of size d . This enables the inclusion of different parameterizations of ~~interacted~~ interacting degradation and sinking processes (e.g., DeVries et al., 2014; Cram et al., 2015). However, ~~here in this study~~, we limited ourselves to the case where the degradation rate depends on the age of the organic particle, the temperature of the sea water and the concentration of oxygen. ~~The~~ Notably, the developed numerical algorithm is suitable for arbitrary dependencies of mass and sinking velocity on the particle diameter. The proposed numerical method was tested on the obtained analytical solutions.

The ~~calculations are~~ calculation results were compared with the available measurement data for the POM and POM fluxes for the latitude ~~band of 20-30~~ bands of 20–30°N in the Atlantic and Pacific Oceans and ~~50-60~~ 50–60°S in the Southern Ocean. The dependence of the degradation rate on temperature ~~significantly affected~~ affects the profiles of the total particle concentration and flux ~~enhancing significantly; it enhances~~ the degradation of sinking particles in the upper layers of the ocean and ~~suppressing~~ suppresses it in the deep layers of the ocean. Overall, including temperature and concentration dependence in the degradation rate relationship improves the agreement with ocean measurements. In particular, the normalized MBEs when ~~taking into account~~ considering the dependence of the degradation rate on temperature and oxygen concentration ~~are were~~ reduced from 9% to -3% compared ~~to cases when~~ with cases in which this dependence was not taken into account. Similarly, on the average, average, the RMSD decreased by half when ~~taking into account temperature stratification~~ temperature stratification was considered.

~~Discrepancies between~~ The discrepancies between the model predictions and observations ~~are were~~ caused by incomplete ~~description~~ descriptions of processes and ~~uncertainty of~~ uncertainties in model parameters, as well as variability ~~of in the~~ measured POM concentration ~~profiles due and flux profiles owing~~ to vertical and horizontal variability ~~of in the~~ ocean fields. We used the one-at-a-time method to quantify the effect of the variation of one ~~the parameter from~~ parameter from the set $(\gamma_0, \eta, \zeta, \epsilon, T_{ref}, Q_{10}, K_0, \alpha, \beta)$ on the model output ~~while~~, with all other parameters ~~were~~ kept at their initial values. The effects of variations in these parameters ~~were estimated for on~~ the particle transfer efficiency TE ~~as ratio of POM flux on~~ were estimated as the ratio of the POM flux at z_{eu} to ~~value on the~~ the value at a depth of 1000 m or 5000 m. The model output sensitivity was estimated ~~using a via the~~ sensitivity index SI (37). Calculations for the Pacific Ocean ~~showed~~ revealed that TE_{1000} and TE_{5000} are most sensitive to the parameters ζ and ϵ , ~~respectively~~, for both models. Therefore, ~~calibration and optimization of~~ these parameters should be primarily ~~carried out~~ calibrated and optimized. Therefore, it was important to assess the sensitivity of the calculations to the values of the model parameters.

~~It should be noted that~~ Notably, to obtain analytical solutions and demonstrate the numerical ~~Euler-Lagrangian~~ Eulerian-Lagrangian approach, significant simplifications were made in the description of the particle dynamics. In particular, the particle sinking velocity was described in the Stokes approximation, ~~The~~ aggregation and fragmentation of particles, mineral ballasting, ocean density stratification, and temporal changes in particle flows were not ~~taken into account~~ considered. While some simplifications can be eliminated by using a numerical approach, others require significant generalization. This ~~particularly~~ applies ~~applies particularly~~ to the description of particle ballasting mechanisms. On the one hand, ballast affects the sinking

of particles, but on the other hand, ballast minerals can protect organic matter from ~~reminer~~alization (Cram et al., 2018). In addition, the mechanisms regulating the distribution of particles of different nature between aggregates and free particles are also unclear. These circumstances did not allow the inclusion of ballasting parameterizations in the present model. degradation ((Cram et al., 2018)). The processes of fragmentation and consumption of sinking particles, which are important in the upper mesopelagic layer, are poorly understood (Burd, 2024). Comparison of calculation results for different parameter values (e.g. η) did not reveal the advantage of one parameter value for both C_p and F_p , which may be due to the incompleteness of the description of the processes of the simplified model used. Therefore, for the effective application of the proposed approach in biogeochemical models, a parameterization of the main process controls of the biological carbon pump mechanism based on data from natural and laboratory measurements is necessary.

Code and data availability. The exact version of the model that was used to produce the results presented in this paper is archived on Zenodo (Kovalets et al., 2025a),

and the input data that were used to run the model and generate the plots for all the simulations presented in this paper were obtained from (Kovalets et al., 2025b).

Appendix A: Derivation of the spectral solution for the size distribution (DeVries et al., 2014)

Here we will show that, we show that the analytical solution (14) for $C_{p,d}$ is equivalent to the solution (8) from (DeVries et al., 2014) of the spectral equation for the particle size distribution. To find the particle size distribution at z' we first re-arrange equation, we first rearrange Eq. (12) obtaining the relation to obtain the relationship between d_0 and d at depth z' :

$$d_0 = d(1 + \psi z')^{1/\eta}. \quad (\text{A1})$$

The size distribution $N(d, z)$ [m^{-4}] is related with to $C_{p,d}$ and m_d as

$$C_{p,d} = N m_d \Delta d, \quad (\text{A2})$$

where Δd is a small size-increment. Combining Eqs. (14), (4), (12), and (A2) gives yields

$$N(d, z') = \frac{C_{p,d}}{m_d \Delta d} = \frac{\Delta d_0}{\Delta d} M_0 d_0^{-\epsilon} \left(1 + \frac{\eta \gamma_0}{\zeta c_w d^\eta} z' \right)^{\frac{\eta - \epsilon}{\eta}}. \quad (\text{A3})$$

In At the limit of $\Delta d \rightarrow 0$ we obtained, we obtain

$$\lim_{\Delta d \rightarrow 0} \frac{\Delta d_0}{\Delta d} = \frac{d}{dd} d_0 = \left(1 + \frac{\eta \gamma_0}{\zeta c_w d^\eta} z' \right)^{\frac{1 - \eta}{\eta}}. \quad (\text{A4})$$

Then Eq. (A3) can be written as

$$N(d, z') = M_0 d^{-\epsilon} \left(1 + \frac{\eta \gamma_0}{\zeta c_w d^\eta} z' \right)^{\frac{1 - \epsilon}{\eta}}. \quad (\text{A5})$$

This solution for N coincides with that found obtained by DeVries et al. (2014).

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