Resolution-dependent variations of sinking Lagrangian particles in general circulation models
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Abstract

Any type of non-buoyant material in the ocean is transported horizontally by currents during its sinking journey. This lateral transport can be far from negligible for small sinking velocities. To estimate its magnitude and direction, the material is often modelled as a set of Lagrangian particles advected by current velocities that are obtained from Ocean General Circulation Models (OGCMs). State-of-the-art OGCMs are strongly eddying, providing results with a spatial resolution in the order of 10 km on a daily frequency. Many long term climate modelling simulations (e.g. in paleoclimate) rely on lower spatial resolution models that do not capture mesoscale features. It remains unclear how much the absence of mesoscale features in low-resolution models influences the Lagrangian particle transport. In this study, we simulate the transport of sinking Lagrangian particles using low- and high-resolution OGCMs, and assess the lateral transport differences resulting from the difference in spatial and temporal model resolution. We find major differences between the transport in the non-eddying OGCM and in the eddying OGCM. Addition of stochastic noise to the particle trajectories in the non-eddying OGCM parameterises the effect of eddies well in some cases (e.g. in the North Pacific gyre). The effect of a coarser temporal resolution (5-daily versus monthly) is smaller compared to a coarser spatial resolution (0.1° versus 1° horizontally). We recommend to apply sinking Lagrangian particles only with velocity fields from eddying OGCMs, requiring high-resolution models in e.g. paleoceanographic studies. To increase the accessibility of our particle trace simulations, we launch planktondrift.science.uu.nl, an online tool to reconstruct the surface origin of sedimentary particles in a specific location.

Introduction

Sinking particles are involved in fundamental processes in the ocean. They serve as a primary mode of carbon export out of the exogenic carbon pool and deliver sediment to the world ocean floor: An important archive for understanding the climate system. The lateral advection of the sinking particles by ocean currents complicates the estimation of downward particle fluxes captured by sediment traps [1], the paleoceanographic reconstructions based on sedimentary microplankton distributions [2-5], and the
estimation of micro-plastic distributions in the ocean [6]. Initially buoyant micro-plastic in the ocean sinks when it gets biofouled and its density increases [7], meaning that a large fraction of the plastic in the ocean has already sunk to the ocean floor [8]. The lateral transport of sinking particles can be estimated using Ocean General Circulation Models (OGCMs) and Lagrangian tracking techniques [9]. The Lagrangian techniques are used to model the sinking particle trajectories in the modern ocean [10–14], specifically for sinking microplankton [15,16] and microplastic [17].

Where possible, these Lagrangian techniques make use of an eddying flow field. However, eddying simulations are not available for all applications to provide such a flow field. For example, model simulations of the geological past use OGCMs with at most 1° horizontal (non-eddying) resolution [18–22]. The latter is due to the fact that palaeoclimate model simulations require coupled climate model simulations (because the atmospheric forcing is not known from observations) and long spin-up times (typically a few 1000 model years) in order to reach a reasonable climate equilibrium.

The spatial and temporal resolution of the underlying flow field generated by OGCMs will affect the spreading of particles in the Lagrangian tracking. It has already been shown that Lagrangian trajectories of neutrally buoyant particles are sensitive to the temporal resolution in an OGCM with ∼ 2° horizontal resolution [23], and the temporal resolution influences the divergence timescale of trajectories in an OGCM of 0.1° horizontal resolution [24].

The spatial resolution of the OGCM determines if the flow is eddying, which played an important role in the simulations of sinking particles near the northern Gulf of Mexico [25] and in the Benguela region [13]. Eddying OGCMs generate a different time-mean flow compared to non-eddying OGCMs which parameterise the eddy effects [26,27]. The interplay between eddies and the mean flow is found to be important for the representation of internal variability of the flow (i.e. the variability of the system under constant atmospheric forcing) [28]. This results in a better representation of interannual or multidecadal variability [29] and the separation location of western boundary currents such as the Gulf Stream [30]. Additionally, eddies cause mixing of tracers (e.g. heat and salinity). The non-eddying OGCMs rely on parameterisations of this tracer mixing such as the Gent-McWilliams (GM) parameterisation [31,32], which shows difficulties to represent this effect locally [33,34].

In this paper, we will assess how the sinking Lagrangian particle trajectories vary for different temporal or spatial resolutions of an OGCM. We investigate the effect of eddies on the particle trajectories. Moreover, we study whether a stochastic lateral diffusion of Smagorinsky type could parameterise the effects of the eddies in the non-eddying OGCM. We apply this analysis to an example of sinking microplankton used in [16] (specifically focusing on dinoflagellate cysts).

We disseminate our results further with an interactive website: https://www.planktondrift.science.uu.nl. This online tool simulates the surface origin of particles that sink to the bottom of the present-day ocean. The tool can also be used to determine how the microplankton in the bottom sediments at any location of choice relates to the environment at these origin locations (e.g. temperature, salinity, primary productivity) in the present-day ocean (see also [16]).

**Method**

We make use of present-day global ocean model simulations of the Parallel Ocean Program (POP) with 0.1° ($R_{0.1}$; eddying) and 1° ($R_{1°}$; non-eddying) horizontal resolution to advect virtual particles (also used in [34,36,37]). Both versions of POP are configured to be as consistent as possible with each other, but there are some differences (see the supplementary material of [36]).
We apply the same particle tracking approach as in [16]. This means that we release particles at the bottom of the ocean every three days, and compute their trajectories in the changing flow field back in time. We stop a particle if it reaches 10m depth. The particles are released at a 1° x 1° global grid. While the particles are advected back in time, a constant sinking velocity \( w_f \) is added to the particle trajectories. The addition of a constant sinking velocity to an advected particle is shown to be a proper way to incorporate the effect of gravity on a sinking particle [38]. We used Parcels version 2.0.0 [39] to calculate the particle trajectories, which is compatible with the Arakawa B-grid that POP uses.

The sinking velocity of particles in the ocean varies substantially. The sinking speed \( w_f \) of microplastics is in the order of 3.4-50 m day\(^{-1} \) [8], for single dinoflagellate cysts \( w_f \) ranges from 6 – 11 m day\(^{-1} \) [40], and the sinking speed can become several hundreds of meters per day for marine snow aggregates (e.g. 10-287 m day\(^{-1} \) [41]). The larger \( w_f \), the shorter the travel time of the particles will be and the less the particle distributions at the surface will spread. Here, we focus on two sinking speeds: \( w_f = 6 \) and 25 m day\(^{-1} \), to study the dependence of the results on the sinking speed, i.e. we represent the sinking of individual dinoflagellate cysts and small aggregates, respectively. More scenarios of sinking speed \( w_f \) were investigated in [16].

The particle trajectory is integrated using the velocity field of POP and a stochastic term parameterising the effect of unresolved processes on the velocity. This last term is equivalent to diffusion in Eulerian models [9] and is a function of the diffusivity \( \nu \). Here we define \( \nu \) as a function of the mesh size and the flow shear, following the Smagorinsky [35] parameterisation, which is commonly used in OGCMs and Large Eddy Simulations (LES). This implies that the particle trajectories are computed by:

\[
\vec{x}(t - \Delta t) = \vec{x}(t) + \int_t^{t-\Delta t} \vec{v}(\vec{x},\tau) d\tau + \vec{c}\Delta t + \vec{q}\sqrt{2\nu(\vec{x})}\Delta t, 
\]

with \( \vec{x}(t) \) the three-dimensional position of the particle at time \( t \), \( \vec{v}(\vec{x},t) \) the flow velocity at location \( \vec{x} \) and time \( t \) (linearly interpolated in space and time from the flow field), and \( \vec{c} = (0 \quad 0 \quad -w_f)^T \) the sinking velocity. The flow consists of two components in the non-eddying POP model: \( \vec{v} = \vec{v}_a + \vec{v}_b \), where \( \vec{v}_a \) is the Eulerian flow field that is solved by POP, \( \vec{v}_b \) is the bolus velocity from the GM parameterisation, which represents the flow that is responsible for the mixing of tracers along isopycnals [31,32], \( \vec{v}_b = \vec{0} \) in the eddying POP model.

The last term of Eq. [1] is the horizontal diffusivity term (only used in the non-eddying model), where \( \vec{q} = (R_1 \quad R_2 \quad 0)^T \) represents (independent) white noise in the zonal and meridional direction, with mean \( \mu_R_1 = \mu_R_2 = 0 \) and variance \( \sigma^2_{R_1} = \sigma^2_{R_2} = 1 \), and

\[
\nu(\vec{x}) = c_\nu A \left( \frac{\partial u}{\partial x} \right)^2 + \frac{1}{2} \left( \frac{\partial v}{\partial y} + \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2, \]

where \( A \) is the horizontal surface area of the grid cell where the particle is located, \( u = u(\vec{x}) \) and \( v = v(\vec{x}) \) are respectively the (depth dependent) zonal and meridional velocity components. As such, the magnitude of the stochastic noise depends on the local velocity field, and its variance increases linearly over the time that a particle is advected. The Smagorinsky viscosity depends strongly on the flow shear compared to other parameterisations [42].

The strength of the noise can be determined with the parameter \( c_\nu \geq 0 \). Multiple methods exist in LES to determine the value of \( c_\nu \) in each application [43]. The velocity gradients \( \left( \frac{\nu}{\sigma^2 A} \right) \) in the non-eddying version of POP typically range from \( 10^{-9} \text{s}^{-1} \) to
10^{-7}s^{-1} and \( A \approx 10^4 \) km\(^2\), so the estimated standard deviation of the zonal and meridional stochastic noise (\( \tilde{\sigma}_x(t), \tilde{\sigma}_y(t) \)) after 20 days (\( \Delta t \approx 1.6 \cdot 10^5s \)) range from 6\( \sqrt{\tilde{\sigma}_x} \) km to 60\( \sqrt{\tilde{\sigma}_x} \) km. These scales are similar to the mesoscale: 10-30 days and 10-100 km for meoscale eddies [4].

Altogether, we apply the particle tracking analysis in four different model configurations (see Table 1), and compare the distributions of particles at the ocean surface after the backtracking from a single release location; 130 particles are used at every release location to determine the particle distributions.

Table 1. The configurations with simulations in varying OGCM resolutions

| Configuration | horizontal resolution | output | diffusion | remark |
|---------------|-----------------------|--------|-----------|--------|
| \( R_{0.1} \)  | 0.1\(^\circ\)         | 5-daily| \( c_x = 0 \) | Reference case, \( \tilde{v}_b = 0 \), eddying |
| \( R_{0.1m} \) | 0.1\(^\circ\)         | monthly| \( c_x = 0 \) | \( \tilde{v}_b = 0 \), eddying |
| \( R_{1m} \)    | 1\(^\circ\)           | monthly| \( c_x = 0 \) | non-eddying |
| \( R_{1md} \)  | 1\(^\circ\)           | monthly| \( c_x \in [0.25, 0.5, 1.0, 1.5, 2.0, 5.0] \) | non-eddying |

We use three measures to compare the particle distributions between the configurations (see Fig 1b-d): (i) the average lateral distance (km) travelled from the release location (along the red lines in Fig 1), (ii) the surface area spanned by the particles approximated by the summed surface area of the \( 1^\circ \times 1^\circ \) grid boxes (blue boxes in Fig 1), and (iii) the Wasserstein distance \( W_d \) as a measure of difference between two distributions resulting from two simulations. The Wasserstein distance is the minimum distance that one has to displace the particles resulting from one simulation (along the dashed lines in Fig 1d) to transform it into another particle distribution (and is calculated with [45]).

Results

We first analyse the overall differences between the configurations \( R_{0.1m}, R_{1m}, R_{1md} \) and the reference configuration \( R_{0.1} \) in terms of the three measures described above (see Fig 1). Thereafter, we show specific release locations to explain why the configurations with lower spatial resolution do or do not provide similar solutions to the reference configuration \( R_{0.1} \).

Global analysis

In general, we find that a reduction of the temporal resolution (\( R_{0.1m} \) vs. the reference case \( R_{0.1} \)) does not have a major effect on the \( W_d \) (Fig 2). The travel time of the particles is perhaps too short for the errors in \( R_{0.1m} \) to grow substantially, and remains lower compared to \( R_{1m} \). The global average \( W_d \) between \( R_{0.1m} \) and the reference case (\( W_d(R_{0.1}, R_{0.1m}) \)) is the same as the check of \( R_{0.1} \) with itself (the global average \( W_d(R_{0.1}, R_{0.1}) \); dashed versus dotted in Fig 2). In this ‘check’, we did the same analysis as in \( R_{0.1} \), but with a 1.5 day shift of the particle release times. As a result, the particle distributions will be different in the check, but as similar as one could get to the particle distributions of \( R_{0.1} \) in the other configurations.

On the other hand, altering the spatial resolution in \( R_{1m} \) and \( R_{1md} \) does lead to different values of the \( W_d \). We find that a value of \( c_x \) minimizes the \( W_d \) (\( c_x = 2 \) for both sinking speeds \( w_f = 6, 25 \) m day\(^{-1} \); Fig 2). For \( c_x = 2 \), the approximated zonal and meridional standard deviation of the diffusion (\( \tilde{\sigma}_x(t), \tilde{\sigma}_y(t) \)) ranges between 8 km and 80 km in 20 days (depending on the strength of the local velocity gradients in the model). At this value of \( c_x \), the magnitude of the fluctuations from the eddies lead to
Fig 1. Schematic illustration of (a) the backtracking analysis and (b)-(d) the three measures which are used to compare the particle distributions at the ocean surface. (a) Three-dimensional illustration: The particles are released at the bottom every three days for a period of six years, backtracked until they get close to the surface (10m depth), which results in a particle distribution at the surface. A map of (b) the average lateral distance (km) traveled from the release location (along the red lines), (c) the surface area (blue; km\(^2\)) spanned by the particle distribution (approximated by the summed surface area of the 1° × 1° blue boxes), (d) the Wasserstein distance (\(W_d; \text{km}\)), which is the minimum distance that one has to displace the particles (along the dashed lines) of to transform one distribution into another distribution.

the optimal parameterisation, such that the particle distributions spread enough to better match with the particle distributions in the reference case. However, we find that the global averaged \(W_d\) for \(c_s = 2\) is approximately eight times larger compared to the check \((W_d(R_{0.1}, R_{0.1}))\) for \(w_f = 6 \text{ m day}^{-1}\), which implies that the particle distributions differ substantially from the reference case. In all configurations \(R\), \(W_d(R_{0.1}, R)\) is lower in areas where the divergence of particle trajectories is relatively small, such as areas of relatively low eddy kinetic energy (e.g. in the gyres), and in areas where the travel time of the particles is relatively short because of the shallow bathymetry (or the particles sink faster).

In terms of the surface area spanned by the particle distributions (Fig 1b), \(R_{0.1m}\) does show a difference with \(R_{0.1}\) as can be seen from the global averages of this measure (Fig 3). Particles are more likely to follow similar pathways in \(R_{0.1m}\) if they are located close to each other (see animation S2 in the supporting material). As a result, the particles will end up in clusters closer to each other at the surface. Hence, the surface area of the particle distributions is on average smaller in \(R_{0.1m}\) compared to \(R_{0.1}\).

Mesoscale eddies are abundant in the reference configuration \(R_{0.1}\), while they are absent in the low spatial resolution configuration \(R_{1m}\). Therefore, tracked particles tend to end up in a much more confined area at the surface in the lower resolution configuration \(R_{1m}\) than in the reference configuration (Fig 3). The stochastic noise in \(R_{1md}\) induces fluctuations in the particle trajectories, leading to a larger surface area of the particle distributions. In \(R_{1md}\), the global average surface area of the particle
distributions increases monotonously with increasing magnitude of the noise ($c_s$). Locally, the surface area of the particle distributions shows a different pattern in $R_{1md}$ compared to the reference $R_{0.1}$ (Fig 3 vs c). In contrast to the magnitude of the noise, the direction of the noise vector does not depend on the flow field (it is horizontally isotropic). Therefore, the surface area of the particle distributions in configuration $R_{1md}$ is overestimated in the tropics compared to the reference configuration $R_{0.1}$, where the flow is mostly zonal.

The average lateral travel distances of the particles are globally also different between the four configurations (Fig 4). In the configuration with lower spatial resolution $R_{1m}$, the average lateral displacement is more extreme compared to the reference configuration (i.e. it is larger in regions with relatively large displacement and lower in regions with low displacement; Fig 4a). The average travel distance in $R_{0.1m}$ (not shown) is similar to the reference case $R_{0.1}$ (see Fig 3 for the global averages).

The average lateral displacement becomes globally more smoothed and less ‘extreme’ if the Smagorinsky diffusion is added to the flow dynamics in $R_{1md}$ compared to $R_{1m}$ (Fig 4c). The more smoothed pattern of the travel distances explains why the globally averaged lateral travel distance is minimal at $c_s = 0.25$ (for $w_f = 6$ m day$^{-1}$ in Fig 4a), and not at $c_s = 0$. The coefficient $c_s$ influences the lateral displacement in two ways. First, more displacement is added per time step if the noise is stronger (for larger $c_s$), and the lateral displacement will on average be larger for larger $c_s$. Second, the noise will be larger in areas with strong flow ($u$ and $v$ in Eq. 1 and 2). Hence, for small $c_s$ the noise is large enough for the particles to travel outside of the areas with a relatively
**Fig 3.** (a), (b), (c) The surface area of the backtracked particle distributions with $w_f = 6 \text{ m day}^{-1}$ respectively in configuration $R_{0.1}$, $R_1$, $R_{1md}$ with diffusion strength $cs = 5.0$. (d) Globally averaged surface area of the particle distributions in all configurations (for several values of $c_s$ in $R_{1md}$). $w_f = 6 \text{ m day}^{-1}$ in black and $w_f = 25 \text{ m day}^{-1}$ in red.

**Fig 4.** (a), (b), (c) The average horizontal distance between the release location and the final backtracked location at the ocean surface with $w_f = 6 \text{ m day}^{-1}$ respectively in configuration $R_{0.1}$, $R_1$, $R_{1md}$ with diffusion strength $cs = 5.0$. (d) Global averaged lateral travel distance in all configurations (for several values of $c_s$ in $R_{1md}$). $w_f = 6 \text{ m day}^{-1}$ in black and $w_f = 25 \text{ m day}^{-1}$ in red.

strong flow and large displacement (such as in the Southern Ocean), such that the globally averaged lateral displacement is lower than for $c_s = 0$.

The loss of information in $R_{0.1m}$ due to the monthly averaging of the flow fields in $R_{0.1}$ is more clear in the difference plots of the surface area and travel distance of the particle distributions (Fig 5). The surface area of the particle distributions is mostly
lower in $R_{0.1m}$ compared to $R_{0.1}$ (Fig 5a). The particles tend to be advected by a similar flow field in $R_{0.1m}$ if they are located close to each other. Hence, groups of particles are trapped in the same eddies, and travel from origin locations at the ocean surface which are closer to each other. This could result in notably different backtracked particle distributions, especially if the shear of the flow field is high (see for instance the location 45.5°S, 39.5°E of Fig 5a). Comparison between the reference configuration $R_{0.1}$ (red) and the temporally averaged configuration $R_{0.1m}$ (blue) at two release locations ($w_f = 6 \text{ m day}^{-1}$). (a) 45.5°S, 39.5°E at 2068m depth (red on top of blue) (b) 46.5°S, 42.5°E at 2238m depth (blue on top of red). the supporting information or on planktondrift.science.uu.nl).

Fig 5. The differences between $R_{0.1m}$ and $R_{0.1}$ ($R_{0.1m}$ subtracted from $R_{0.1}$) in terms of (a) the surface area of the particle distributions (Fig 1c) and (b) the average travel distances of the particle distributions (Fig 1b).

Regional analysis

In general, the particle trajectories in the lower spatial resolution configuration $R_{1m}$ without diffusion are different compared to the trajectories in the reference configuration $R_{0.1}$, because these trajectories lack the fluctuations provided by eddies and hence they disperse less. The only trajectory spread in $R_{1m}$ is caused by flow variability on a larger timescale, such as seasonality. We focus here on some specific locations to see how this can lead to different particle distributions.

If Smagorinsky diffusion is added to the dynamics of the flow ($R_{1md}$), the fluctuations from the eddies are parameterised and the trajectories spread more. The North Pacific gyre is a location where this parameterisation works well (Fig 6a). Within the gyre, the diffusion is relatively low in the reference configuration and the eddies spread the particle trajectories uniformly in all directions. Adding fluctuations to the flow field in $R_{1md}$ using stochastic noise captures the spread of these eddies in $R_{0.1}$ well. Occasionally the parameterisation also works well in locations with larger shear and eddy activity compared to the North Pacific gyre. For example, for a location in the Antarctic Circumpolar Current (ACC, Fig 6b), the mean flow field in $R_{1m}$ is similar to the mean flow field in $R_{0.1}$. The stochastic noise can again adequately capture the effect of fluctuations provided by the eddies on the particle distributions.

However, it is well known that non-eddying OGCMs do not get the mean flow field right in all of the locations, because the eddies influence the mean flow field through rectification. The Agulhas region is such an example where the mean flow field is different in $R_{1m}$ compared to the reference case $R_{0.1}$ (Fig 6c). The analysis in $R_{1md}$ provides a particle distribution which only comprises a subset of the particle distribution from the analysis in $R_{0.1}$. If the strength of the noise ($c_s$) is increased here, at most the spread of the particle distribution increases, but one will not find that any
Fig 6. Comparison between reference configuration \( R_{0.1} \) (red), configurations \( R_1 \) (yellow) and \( R_{1md} \) with \( c_s = 2 \) (blue) at four different locations (yellow on top of blue, blue on top of red; \( w_f = 6 \text{ m day}^{-1} \)). Each distribution consists of \( \sim 160 \) particles. The release locations at (a) 40.5°N, 140.5°W and respectively 4601 and 4542 m depth in \( R_{0.1} \) and \( R_{1m} \), (b) 49.5°S, 119.5°W and respectively 3122 and 3249 m depth in \( R_{0.1} \) and \( R_{1m} \), (c) 44.5°S, 20.5°E and respectively 4249 and 4249 m depth in \( R_{0.1} \) and \( R_{1m} \), (d) 52.5°S, 142.5°E and respectively 3070 and 2916 m depth in \( R_{0.1} \) and \( R_{1m} \).

Discussion

We assessed the variations of Lagrangian trajectories of sinking particles in flow fields which were generated by OGCMs of different resolutions. We released sinking particles at the bottom of the ocean, tracked them backwards in time until they reached the surface, and investigated how the particle distributions at the ocean surface depend on the OGCM resolution.

If the model output of the high-resolution OGCM is averaged from 5-daily to monthly data, the particle tracking analysis provides similar results in most cases. However, in some specific regions with large shear, we find notable differences of the backtracked particle distributions at the ocean surface.

Overall, the sinking Lagrangian particles give unrealistic results in the non-eddying models, because (1) the backtracked distributions show too little spread due to the absence of ocean eddies and (2) these models do not capture the mean flow fields correctly at most locations. Lateral stochastic diffusion in the low-resolution configuration (re-)introduced part of the eddy fluctuations and hence increased the
dispersion of particle trajectories and the spread of the backtracked particle distributions. Hence this method is promising for locations where the OGCMs are able to capture the mean flow field. The Smagorinsky diffusion was insufficient to parameterise the eddies in most areas.

Altogether, we recommend to compute the sinking Lagrangian particle trajectories only in eddying OGCMs. We used the Smagorinsky parameterisation in this paper as a first attempt to represent the subgrid-scale processes if the eddies are absent in the flow. Other types of parameterisations could be applied. Several other parameterisations for eddy-induced mixing of tracers are available in POP [49]. However, the improvement of either the Eulerian or Lagrangian parameterisation of the subgrid scale variability in the flow remains a challenge in ocean modelling [50].

These conclusions have implications for Lagrangian particles in paleoceanographic models. OGCMs used in most paleo studies will not generate a flow field which is locally representative for the time period of interest. Since Lagrangian particles use the local flow field, the Lagrangian technique requires eddying paleoceanographic models that are representative for the considered time period. For the application of Lagrangian particle tracking techniques in paleoceanographic models, which are usually not eddying, we recommend to test model results first against independent information of ocean flow, such as biogeographic patterns of microplankton [51,52].

This study reveals the importance of eddying model simulations for sinking Lagrangian particles. The simulations of sinking particles in eddying OGCMs allow for the assessment of the surface origin location of sedimentary particles before they sink to the bottom. Hereby we launch planktondrift.science.uu.nl to disseminate these results, and allow users to verify the surface-ocean location of origin for sedimentary particles.

We also tested an additional configuration without the bolus velocity in the non-eddying POP model (i.e. the same as $R_{1md}$ and $R_{1m}$, but where $v_b = 0$). The results for this configuration are very similar to the results that are obtained in configuration $R_{1md}$ and $R_{1m}$ in this paper. The bolus velocity is weaker compared to the Eulerian flow velocity (typically $v_b$ is approximately 5% of $v_a$ at the surface layer), and it does not make a relevant difference at the time scales on which we apply the Lagrangian particles here. The results for this additional configuration can be found and downloaded from the planktondrift.science.uu.nl website.

The website planktondrift.science.uu.nl contains the results which are presented in this paper, for every release location in every configuration. Users of the tool can choose a location at the bottom of the ocean, see where the sinking particles originated from for different parameters (e.g. the sinking speed $w_f$, or the magnitude of the noise $c_s$), and download these origin locations. The website allows anyone who works with e.g. sedimentary microplankton assemblages or plastic to see how the sinking particles could be displaced laterally, and what the environment (e.g. sea surface temperature and salinity) is at the displaced location using POP or other OGCMs. Hence, the advection bias [16] of the sedimentary assemblages can be determined in the present-day ocean.

**Supporting information**

**S2** Animation (back in time) of particle backtracking analysis ($w_f = 6 \text{ m day}^{-1}$) with particle release at the Uruguayan margin (47.9°E and 37.15°S, $\sim 4800\text{m depth}$). (a) the configuration $R_{0.1}$ with 5-daily model output and (b) the configuration $R_{0.1m}$ with monthly model output.
Fig S1. Comparison between the reference configuration $R_{0.1}$ (red) and the temporally averaged configuration $R_{0.1\text{m}}$ (blue) at two release locations ($w_f = 6 \text{ m day}^{-1}$). (a) 45.5°S, 39.5°E at 2068m depth (red on top of blue) (b) 46.5°S, 42.5°E at 2238m depth (blue on top of red).

Acknowledgments

The code used for this work and the results are distributed under the MIT license and can be found at the website https://github.com/pdnooteboom/PO_res_error. This work was funded by the Netherlands Organization for Scientific Research (NWO), Earth and Life Sciences, through project ALWOP.207. The use of the SURFsara computing facilities was sponsored by NWO-EW (Netherlands Organisation for Scientific Research, Exact Sciences) under the project 17189. The European Research Council under the European Community’s Seventh Framework Program provided funding for this work by ERC Starting Grant #802835 (OceaNice) to PKB. PD and EvS are supported through funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement no. 715386, TOPIOS). PN thanks Jasper de Jong and Daan Reijnders for their help with the implementation of the Smagorinsky parameterisation in Parcels.

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