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Nonlinear Processes in Geophysics
Discussions
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# *Interactive comment on* "Modeling the dynamical sinking of biogenic particles in oceanic flow" *by* Pedro Monroy et al.

**Pedro Monroy et al.**

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Response to Referee 1:

We acknowledge Referee 1 for the careful reading and constructive comments. Referee 1 qualifies the paper as '**interesting and, in general, very well written**' and the results '**are quite interesting and I think relevant both in modeling and interpretation of the data**'. However, he/she presents a list of specific comments that we have addressed through our detailed responses below, together with specific changes made in the manuscript. Page, figure and line numbers refer to the revised version of the manuscript.

**- I think the authors should specify whether eqs 9,10,11 are evolved using the same realization of noise or not. I mean when considering the effect of the dif-**

**ferent term the comparison is done using the same realization of the noise? If not what is the impact on the displacement due only to noise?**

All the simulations were performed using the same realization of noise. Although this was already stated in the previous version, we have reworded the corresponding sentence to make it clearer (page 11, paragraph after Eq. (11)): *"We use in each case identical initial conditions and the same sequence of random numbers for the noise terms. In this way we guarantee that any difference in particle trajectories arises from the inclusion or not of the inertial and Coriolis terms in Eqs. (8)-(11)."*

As additional information we show in Figures 1 and 2 in this Response letter the influence of noise on horizontal and vertical displacements versus time, respectively. We have run Eq. (9) with and without noise for a set of N=6000 particles and have computed the root mean square horizontal and vertical distances between the two cases as a function of time (and for different values of settling velocity). Noise-induced differences are larger than the ones induced by the Coriolis and inertial ones (Figs. 4 and 6 of the manuscript). Therefore the use of different realizations of noise would prevent us to observe the (weak) influence of Coriolis and inertia.

**- Maybe I'm missing something, while I understand that the mean displacement does not depend much on the various term (Coriolis and inertial term) I find a little surprising the fact that also individual displacement seems to be poorly sensitive. The reason is as follows. I do expect the particle dynamics to be chaotic (correct me if I'm wrong) consequently the presence of different term on the dynamics (assuming same noise, otherwise even the simple presence of noise would produce the same effect) should cause at least a small displacement that it is then amplified by chaos, so I cannot properly understand why this effect is not seen. Can the authors please comment on this?**

The referee is completely right: the particle dynamics is chaotic. In the ocean, exponential growth of horizontal distances is observed up to scales of about 40 km (Poje et al, 2010). Thus, it is expected to observe this exponential distance growth, assuming the same noise realization, when comparing trajectories with or without the inertial or Coriolis terms. Since this is an important issue, also requested by Referee 2, we have added a new Figure 4 to our manuscript. It shows the time evolution of the root mean square difference per particle between horizontal displacements computed from Eq. (9) and Eq. (10) in the text, that is, without and with Coriolis forces. Exponential growth with an exponent of about 0.08 days-1 is observed. Comparison between inertial and non-inertial dynamics (not shown in the paper, but shown in this Response letter as Fig. 3) gives the same exponential behavior and the same exponent, although with difference two orders of magnitude smaller. This exponent corresponds to the Lyapunov exponent, whose value is in the range of results obtained by Bettencourt et al. (2012) for the same region and model.

This is not contradictory with the statements in the paper about negligible effect of the Coriolis or inertial terms. For example, despite the exponential growth the largest horizontal differences attained (for the Coriolis case) at the largest times are still of only 1-10 km (as reported in Figs. 4 and 5), much smaller than typical horizontal displacements at these times (hundreds of km).

In addition to the new Fig. 4 in the manuscript, we have included a reference to Bettencourt et al. and some sentences that discuss about this (Sect. 4).

- Poje, A.C et al. (2010). Resolution dependent relative dispersion statistics in a hierarchy of ocean models. Ocean Modelling, 31, 36-50.

- Bettencourt; J.H. et al. (2012). Oceanic three dimensional Lagrangian Coherent Structures: A study of a mesoscale eddy in the Benguela upwelling region. Ocean Modelling 51, 73-83.

**- Fig.5 shows that the effect of Coriolis forces becomes more important for small $v_s$, moreover the curve seems to be non-monotonic, especially for the vertical displacement it appears like if there is a sort of minimum at $v_s \approx 20$ m/s. Could**

**the authors comment on these aspects.**

We have added the following explanation in Sect. 4 while Figs. 5 and 6 have been redrawn with scales to make this point clearer. *"The behavior can be understood as resulting from two factors: on the one hand smaller $v_s$ requires larger $t_f$ to reach the final depth, and larger integration time $t_f$ allows for accumulation of larger differences between trajectories. On the other hand the Coriolis and inertial terms in Eqs. (10)-(11) are proportional to $\tau_p(1-\beta) = v_s/g$ so that their magnitude decreases for smaller $v_s$. The combination of these two competing effects shapes the curves in Figs. 5 and 6, which for the vertical-difference case turn-out to be non-monotonic in $v_s$ or $t_f$ ."*

**- The explanation proposed by the authors for understanding particle clustering is quite sounding and interesting. It would be nice if the authors could compare and comment their explanation with that provided in Bec, et al Phys. Rev. Lett., 112, 184 501 and also in K Gustavsson, et al. "Clustering of particles falling in a turbulent flow" Phys. Rev. Lett., 112, 214501 (2014). Essentially the authors argue that in the limit of large St (i.e. for large settling velocities) the particles fall rapidly with respect to the characteristic time of the flow so that effectively is like the flow becomes "delta-correlated" so that inertial dissipative dynamics becomes responsible for clustering instead of the compressibility effect typical of small St. How does clustering depends on $v_s$ here? If I understand the argument by the authors the larger $v_s$ the more appropriate becomes the approximation of vertical shift, then I think the idea of the fluid becoming "delta-correlated" should apply also here and so the dynamics become as in a compressible 2d and delta-correlated flow. Is this correct? if yes less effective clustering should be present for small $v_s$. Please comment.**

We recall that the focus of our paper is not on particle clustering but on quantifying and assessing the importance of different terms in the dynamics in the trajectories of particles whose characteristics are typical of biogenic particles observed in the ocean. We have included a last section with some comments on clustering just to answer a natural question that arose during our investigation: If inertia and Coriolis are negligible, why are there observations of clustering for this type of particles in the ocean? We show that spatial inhomogeneities can arise simply by the geometric way in which measurements are done. We do not claim this is the only explanation, but it is certainly the simplest one.

In our discussion on clustering we consider complete absence of inertia, i.e. $St = 0$. Then the mechanisms described in the two papers mentioned by the referee, both based on the effect of inertia, i.e. finite St, are necessarily not operating in our results. More specifically:

- In [Bec, et al Phys. Rev. Lett., 112, 184501 (2014)] several asymptotic regimes are considered. The one mentioned by the referee is the case of St»1. In this situation fluid velocity can be approximated by a delta-correlated noise. Within this nice approximation the authors are able to obtain analytical results on the effect of inertia on particle clustering. This regime is exactly the opposite of our St=0. In our case particle adapts to the flow faster than any change in the flow field, so that a delta-correlation approximation is not appropriate to our situation.

- In [Gustavsson, et al. Phys. Rev. Lett., 112, 214501 (2014)] also several asymptotic regimes are considered. The one mentioned by the referee is that of large “gravity parameter” F. In this case inertial particles fall very fast and strong clustering may occur by a mechanism of multiplicative amplification of the inhomogeneities already induced by a finite St. Again, this mechanism is absent in our $St = 0$ case.

Since it was not the focus of our paper we did not study systematically how our geometric clustering mechanisms depends on $v_s$ (this is left for future work). Intuitively, the larger $v_s$ the better will be the approximation from which we derive Eq. (16), i.e that a horizontal surface remains horizontal under evolution. This does not directly imply having less or more clustering.

In the revised manuscript we now refer to Bec (2014) and Gustavsson (2014) at the end





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of Sect. 3 as examples of clustering mechanisms arising from inertia. We have also added the sentence *“We expect the approximation to become better for increasing* $v_s$*, because of the shorter sinking time during which vertical deformations could develop” just before the last sentence before Eq. (16).*

**- Stratification: I think the authors should specify whether the model used consider stratification or not. In general stratification is present in the ocean and it may impact sensibly particle dynamics (especially when $\beta$ is not too far from 1) and, in particular, particle clustering, for a recent study in this direction the authors may refer to A. Sozza et al "Large scale confinement and small-scale clustering of floating particles in stratified turbulence", Phys. Rev. Fluids 1, 052401 (2016)**

Certainly, there is density stratification in the ROMS numerical simulations used in our study. But we do not think that this is a relevant mechanism of clustering for the range of densities of biogenic particles we are studying, which is approximately $1050 - 2700 kg/m^3$. The reason is that fluid density ranges between $1020 - 1030 kg/m^3$ for surface waters, with large values of the order $1045 - 1050 kg/m^3$ arising only in very deep waters (several kilometers depth). Indeed, we consider here a constant size and density for each particle along its downward course; this means that we neglect biogeochemical and (dis)aggregation processes that may occur in nature but that are currently poorly known (and overly complex to be modelled in our framework, e.g. Maggi et al. 2013).

The effect of stratification discussed in Sozza et al. appears when particle density equals water density, so that particles get confined vertically in the isopycnal surface given by the condition "density of particle = density of fluid", which cannot be fulfilled in the ranges we consider here.

In this revised version of the manuscript we briefly mention at the end of Sect. 2.2 the work of Sozza et al., and we mention the weak impact of stratification on the value of





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$v_s$ in the paragraph following Eq. (11).

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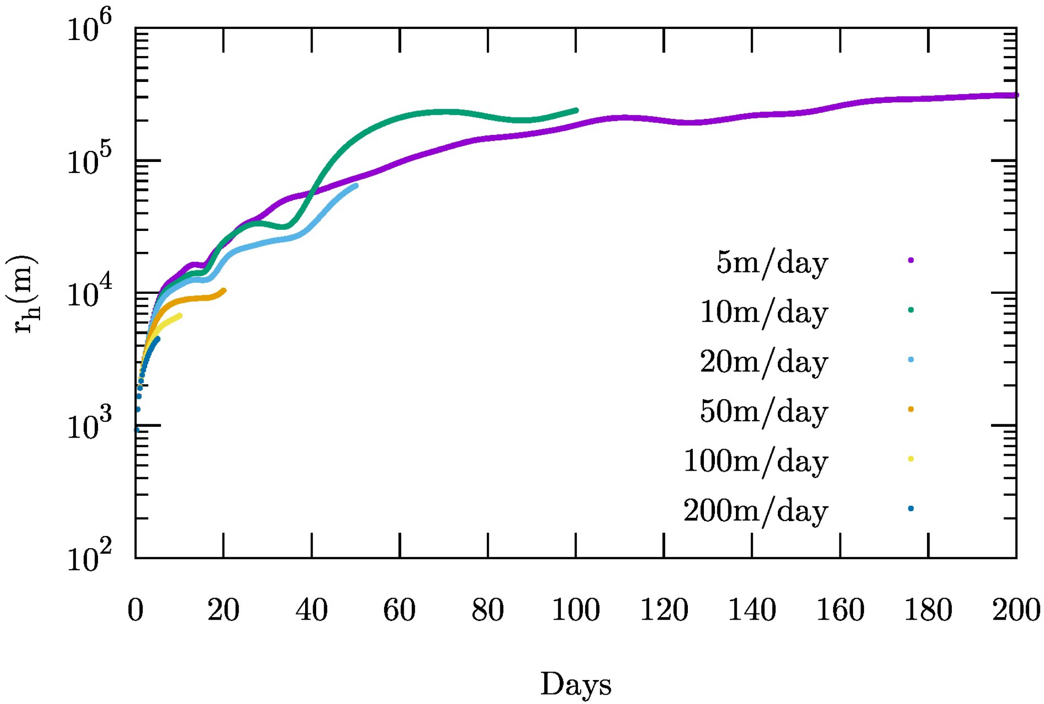


**Fig. 1.** Root mean square difference per particle, as a function of time, between horizontal particle positions computed with Eq. (9) with and without noise.

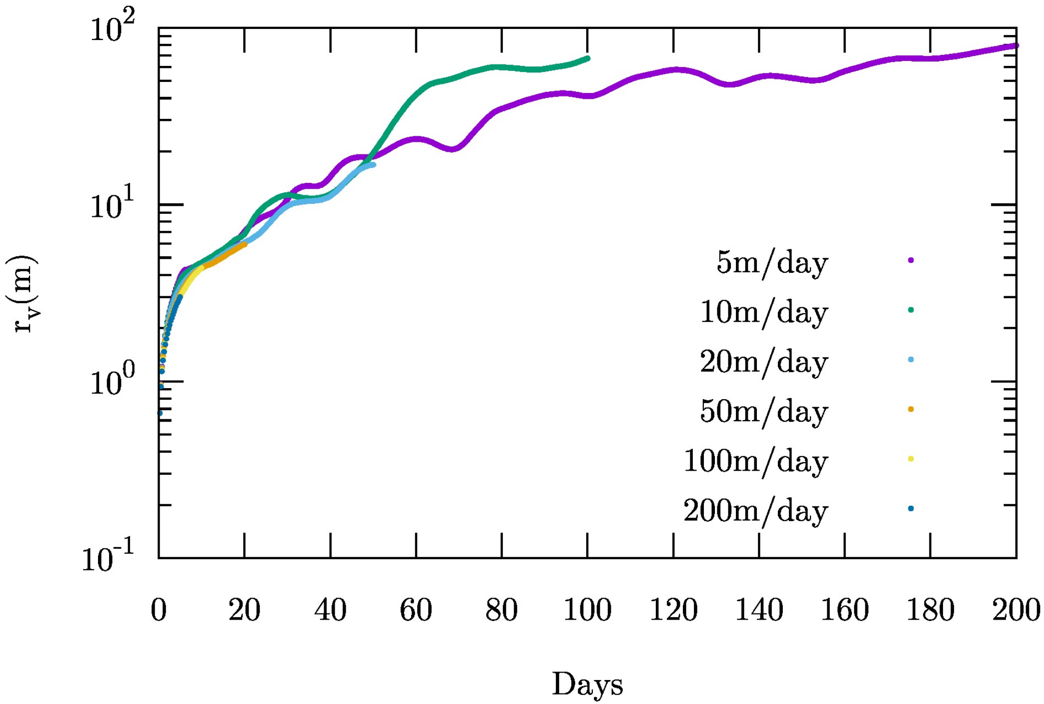


**Fig. 2.** Root mean square difference per particle, as a function of time, between vertical particle positions computed with Eq. (9) with and without noise.



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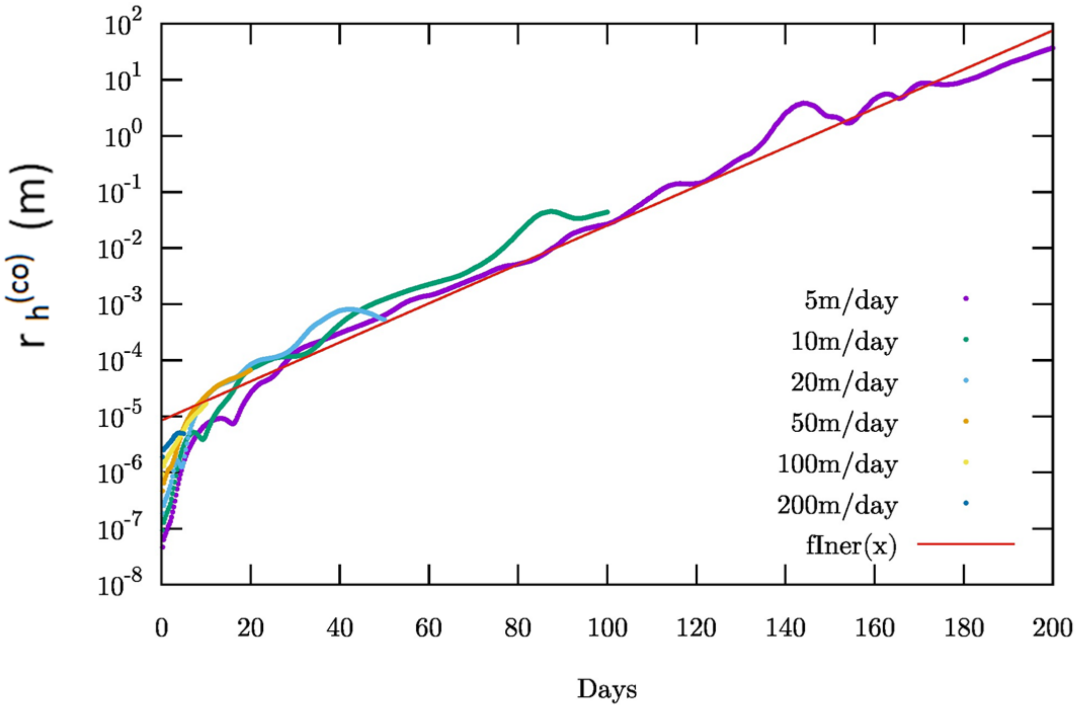


**Fig. 3.** Root mean square difference per particle, as a function of time, between horizontal particle positions computed with Eq. (9) and with Eq. (11), i.e. with and without inertia.



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