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Particles in motion: How turbulence affects plankton sedimentation from an oceanic mixed layer

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[1] A long-standing question in the dynamics of oceanic surface mixed layers (SML) is whether or not turbulence inhibits the rate of sedimentation through the layer. Results from previous studies have shown that turbulence can both retard and accelerate particle settling. Here we attempt to resolve this issue by demonstrating how both results can in fact be obtained from the same turbulence model for only slightly different implementations of the experimental set-up. Increasing turbulence will produce an increase in particle sedimentation if the SML is modelled as a homogeneous layer with a constant turbulent intensity throughout. However, if a more realistic representation of the SML is used, in which the turbulent intensity is allowed to decrease toward the base of the SML, then an increase in turbulence will lead to an increase in the residence time of particles in the SML. **Citation:** Ross, O. N. (2006), Particles in motion: How turbulence affects plankton sedimentation from an oceanic mixed layer, *Geophys. Res. Lett.*, *33*, L10609, doi:10.1029/2006GL026352.

1. Introduction

[2] The knowledge of the residence time of planktonic particles in the oceanic surface mixed layer (SML) is of interest to several areas of research including climate prediction modelling (to estimate the carbon export from the SML) [e.g., *Schlitzer*, 2002; *Berelson*, 2002] as well as primary production studies [e.g., *Huisman and Sommeijer*, 2002]. From our everyday experience we feel it intuitively apparent that stirring keeps particles suspended in a fluid for longer than if the fluid was at rest (e.g., dust particles being suspended by strong winds, small tea leaves ‘stirred-up’ in a cup). The commonplace nature of this observation has caused it to become an established paradigm in marine ecology: turbulence is necessary to keep phytoplankton suspended in the SML and the phytoplankton rely on this in order to photosynthesise [e.g., *Tooby et al.*, 1977; *Bleiker and Schanz*, 1997; *Arin et al.*, 2002; *Huisman and Sommeijer*, 2002]. While this paradigm has long been used without any direct empirical or theoretical support, more recent studies seem to suggest the opposite, viz. that turbulence in fact accelerates plankton sedimentation by increasing their effective sinking velocity [*Ruiz et al.*, 2004]. Which one is now correct? A search through the more theoretical literature yields support for both camps, the decrease [*Fung*, 1993; *Ruiz*, 1996; *Deleersnijder et al.*, 2006] and the increase [*Maxey*, 1987; *Lande and Wood*, 1987; *Wang and Maxey*, 1993; *Franks*, 2001] in sedimentation rate with turbulence. It appears that the difficulty is partly related to the different particle species under consideration (i.e., particles with and without inertia which show very different settling behaviour) and further complicated by the inherent difficulties associated with turbulence modelling and measurements.

[3] The present study attempts to elucidate this apparent contradiction by demonstrating how both solutions can be obtained from the same turbulence model by choosing only slightly different implementations of the mixed layer. The results are assessed in the context of which representation of the SML is likely to give the best approximation to a real turbulent environment.

2. Method

[4] These issues are addressed through a 1D Lagrangian random walk technique to describes the vertical displacement of individual particles in response to turbulence (represented by the eddy diffusivity parameterisation) and due to particle sinking [*Hunter et al.*, 1993; *Visser*, 1997; *Ross and Sharples*, 2004]:

$$z_{n+1} = z_n - \underbrace{w_p \Delta t}_{\text{sinking}} + \underbrace{K'(z_n)\Delta t}_{\text{deterministic term}} + \underbrace{R\left[\frac{2\,K\left(z_n + \frac{1}{2}\,K'(z_n)\Delta t\right)\,\Delta t}{r}\right]^{1/2}}_{\text{random term}} \quad (1)$$

z_n in equation (1) denotes the vertical position of the particle after n iterations, w_p is the vertical sinking/swimming velocity, K is the turbulent eddy diffusivity with the abbreviation $K' = \mathrm{d}K/\mathrm{d}z$, Δt is the time step for the iteration and R is a random process of zero mean and variance r (e.g., $r = 1/3$ for $R \in [-1, 1]$). For the experiments, 1000 particles are released into the water column at a depth of $z_0 = -10$ m with a total mixed layer thickness of $H = 30$ m and traced according to equation (1). The surface boundary is reflecting according to

$$z_{n+1} \rightarrow -z_{n+1}, \text{ if } z_{n+1} > 0 \quad (2)$$

Once a particle passes out of the mixed layer the time is recorded and the experiment continues until all particles have left the mixed layer. The results presented in the next section display the mean travel time of a particle from $z_0 = -10$ m to the base of the SML for a total of 2500 different combinations of sinking/swimming velocity w_p and eddy diffusivity K.

[5] The model results are compared to a solution to the inverse Fokker-Planck equation [*Lande and Wood*, 1987]

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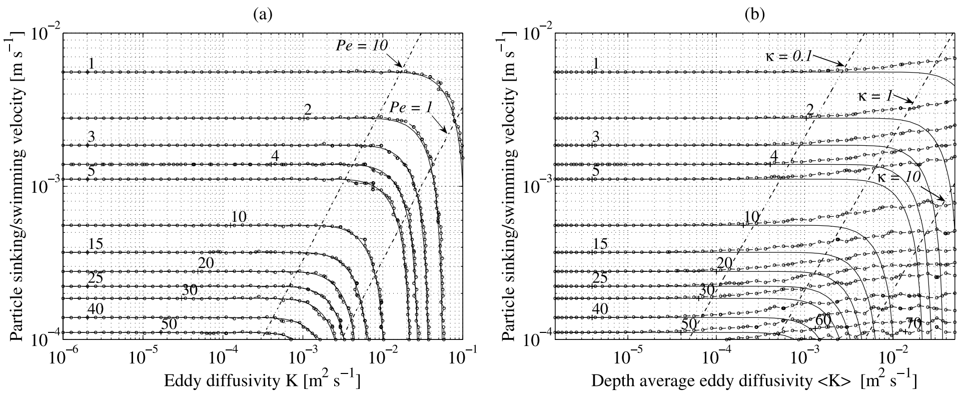

Figure 1. (a) Results for the homogeneous SML, and (b) for the inhomogeneous SML using equation (6) with $K_{bg} = 10^{-6}$ m^{2}s^{-1}. The solid lines represent the predicted times (in hours) from equation (3) using $z_0 = -10$ m and $H = 30$ m (in Figure 1b only plotted for reference). The dashed lines with open circles show the average times obtained from the random walk using 1000 particles with $\Delta t = 5$ s. The dash-dotted lines in Figure 1a show the values of the Péclet number. In Figure 1b the dash-dotted lines are isolines of $\kappa = K'_{max}/w_p$. The abscissa is $\langle K \rangle = K_{bg} + 0.5K_m$.

which allows analytic predictions for the time T that a particle sinking (or swimming) at a speed w_p ($w_p > 0$) would require to traverse a mixed layer of thickness H with homogeneous diffusivity K starting from an initial depth z_0 where $-H < z_0 \leq 0$:

$$T(z_0) = \frac{H + z_0}{w_p} - \frac{K}{w_p^2}\left[e^{z_0 w_p/K} - e^{-H w_p/K}\right] \qquad (3)$$

3. Results

3.1. Scenario 1: Homogeneous Turbulence

[6] In this first set of experiments the turbulence in the SML is considered to be homogeneous and isotropic. This is a very common approach [e.g., *Woods and Onken*, 1982; *MacIntyre et al.*, 1995; *Huisman and Sommeijer*, 2002] in which the stratified ocean is modelled as a two-layer water column with a constant diffusivity K_1 in the surface layer and a lower diffusivity K_2 in the layer representing the thermocline below. It has been shown that this approach cannot be used in conjunction with a random walk model as the discrete step in K between the two regions will inevitably lead to artificial accumulations of neutrally buoyant particles at the interface between the two layers [*Visser*, 1997] and therefore violate the well-mixed condition established by *Thomson* [1987]. In the experiments for this scenario, these problems are avoided as the particle tracking is only applied to particles within the SML and the particles are discarded as soon as they exit the mixed layer. A further reason why this scenario is considered is its applicability to relevant laboratory measurements [*Ruiz et al.*, 2004] where the turbulence is also assumed to be homogeneous over the experimental domain.

[7] If the eddy diffusivity K in equation (1) is thus considered to be constant with depth, the random walk simplifies to

$$z_{n+1} = z_n - w_p \Delta t + R\left[\frac{2\,K(z_n)\,\Delta t}{r}\right]^{1/2} \qquad (4)$$

It can be shown, that this random walk equation and the Fokker-Planck equation that can be used to derive equation (3) [*Lande and Wood*, 1987] are in fact equivalent [*Okubo*, 1980]. Not surprisingly, the results from this approach are therefore in excellent agreement with the predictions from equation (3) (Figure 1a). If we define the Péclet number Pe as

$$Pe = \frac{\text{mixing time scale}}{\text{sinking time scale}} = \frac{H^2/K}{H/w_p} = \frac{w_p H}{K} \qquad (5)$$

we notice that turbulence starts to reduce the residence time of our plankton particles from about $Pe = 10$ onward. For $Pe = 1$ turbulence has already halved the residence time in the SML.

3.2. Scenario 2: Inhomogeneous Turbulence

[8] Now let us consider a more realistic scenario in which the turbulent intensity is allowed to decrease toward the surface and the bottom of the mixed layer, that is, toward the surface where the proximity of the boundary reduces the sizes of turbulent eddies, and toward the top of the thermocline where the increased water column stability reduces turbulent mixing. In order to simulate this situation the turbulent diffusivity within the mixed layer ($0 \geq z \geq -H$) is modelled using a simple cosine of the form

$$K(z) = K_{bg} + \frac{K_m}{2}\left[1 - \cos\left(\frac{2\pi z}{H}\right)\right] \qquad (6)$$

K_{bg} is a background diffusivity which quantifies the amount of turbulent mixing in the thermocline and near the surface, and K_m is the maximum diffusivity at the centre of the mixed layer (Figure 2a). The time step in equation (1) is chosen according to Equation 8 from *Ross and Sharples* [2004] to yield an error of less than 1% at all times. The advantage of equation (6) is that it yields $K' = 0$ at the surface which is a requirement if the reflecting boundary condition for the particles [equation (2)] is to function correctly [*Ross and Sharples*, 2004].

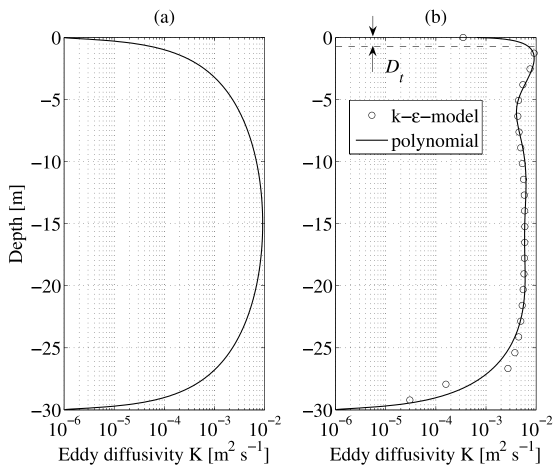

Figure 2. (a) Diffusivity profile from equation (6) with $K_{bg} = 10^{-6}$ m^2 s^{-1} and $K_m = 0.9 \cdot 10^{-2}$ m^2 s^{-1}. (b) Diffusivity profile from the k-ϵ-turbulence closure model from an experiment with surface winds of 45 km h^{-1} (circles). The solid line shows the fitted polynomial that is used for the random walk. D_t denotes the thickness of the miniature mixed layer at the surface (see text).

[9] The results for this inhomogeneous scenario are very different from the homogeneous case (Figure 1b). An increase in turbulent mixing intensity now leads to an increase in the residence time of particles in the mixed layer, retarding their sinking/downward swimming. It should be stressed, that this increased residence time is not due to a physiological response of the phytoplankton cell but a purely physical mechanism. The velocity difference between the particle and the surrounding fluid is always $-w_p$. The increased residence time is rather due to the deterministic term in equation (1) which can be thought of as a representation of the higher probability for turbulence to displace away from the smaller length scales, that is, the boundaries [*Visser*, 1997]. It is particularly for the high turbulence conditions, that is, for large values of K_m, that K' may become large enough at the base of the SML that it partly compensates the smaller sinking/swimming velocities. If we plot the isolines of the ratio $\kappa = K'_{\max}/w_p$ we notice that the residence time already starts to increase from $\kappa \approx 0.1$ onward (Figure 1b). For $\kappa = 10$ the increase is about 30–40%.

[10] Clearly, the profile from equation (6) is only an idealised approximation of an oceanic mixed layer. A k-ε-turbulence closure model [see *Sharples et al.*, 2006] has therefore been employed to obtain a more realistic representation. The model was set up with a 30 m mixed layer (no temperature stratification) separated from a homogeneous bottom layer by a thermocline of thickness 5 m and temperature change of 4°C. In 40 different experiments the model was forced with wind velocities ranging from 1 to 35 m s^{-1}. In general, the shape of the diffusivity profiles obtained from these experiments does not significantly deviate from the cosine of equation (6) but the profiles often exhibit an asymmetric bias of varying magnitude toward the surface (Figure 2b). In order to examine the effect of this bias on the previous findings, we extracted one of these asymmetric profiles as our working profile and fitted a 9th order polynomial to the discrete data points (Figure 2b) for use with the random walk. The polynomial has been conditioned to yield $K' = 0$ at the bottom of the SML. The strong decrease in K toward the surface has been shown to be unrealistic as a k-ε-model generally fails to represent wave induced near-surface turbulence and only considers the reduction in turbulent length scale producing a law-of-the-wall like behaviour [*Craig and Banner*, 1994]. For the present study a simple correction scheme has been applied which resolves the above issue and also prevents any inaccuracies in the random walk. We define a top boundary layer within the SML of thickness D_t which is fully mixed according to

$$z_{n+1} \rightarrow D_t R, \text{ if } z_{n+1} > -D_t \tag{7}$$

where R is a random process between 0 and -1. The size of D_t (in metres) has been modelled according to

$$D_t = 0.06 + 9.5 K_m^{4/7} \tag{8}$$

For most of the diffusivities from Figure 1 this yields D_t of the order of a few centimetres and only for very high diffusivities of $K_m \geq 10^{-2}$ m^2 s^{-1} which produce the strong gradients in the K profile, D_t becomes of the order of 1 m. Considering that the k-ε-model has to be forced with wind velocities exceeding 45 km h^{-1} in order to obtain a maximum diffusivity of $K_m = 10^{-2}$ m^2 s^{-1}, it appears justified to assume that in such conditions the top 75 centimetres of the water column will be homogeneously mixed by the surface waves. By eliminating the extreme gradients from the profile it is also possible to maintain a reasonable time step of $\Delta t = 0.5$ s in the random walk.

[11] If we now compare the results obtained from these experiments to those from the simple cosine function we find that they are essentially identical (Figure 3). The particular shape or symmetry of the diffusivity profile has thus no influence on the overall result (but see the comment on $K'_{\max}$ below).

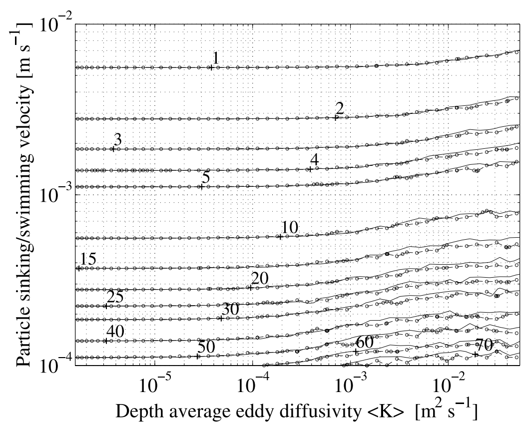

Figure 3. Comparing the residence times obtained with the asymmetric profile from the k-ε-model (solid line) with the results from the simple cosine of equation (6) (open circles). The time step for these experiments was 0.5 s. The depth average for the profile from Figure 2b is $\langle K \rangle \approx 0.54 K_m$.

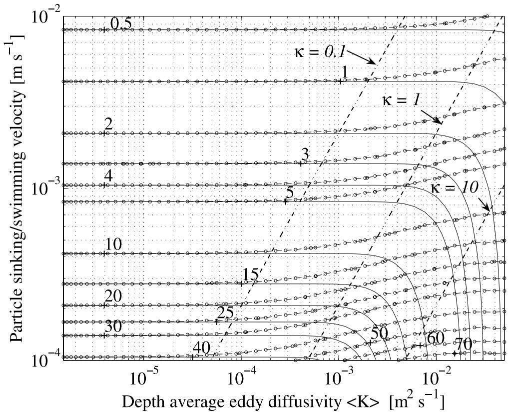

Figure 4. True residence times in hours for a 30 m SML using 10 000 particles and the profile from equation (6). The solid lines show the predictions from equation (3) for H = 30 m and $z_0 = -15$ m.

[12] If the experiments are performed with an initially uniform particle distribution we obtain a better estimate of the true residence times (Figure 4). For low turbulence, these times correspond to those predicted by equation (3) for $z_0 = -15$ m, that is, the particle ensemble behaves like its centre of mass. As turbulence increases, the relative increase in residence time is slightly larger than in Figure 1b. For a different SML depth H^*, the new residence times can be obtained simply by multiplying the results from Figure 4 by $H^*/30$ m (results not shown). This scaling only works, however, if the turbocline thickness remains the same, that is if $K'_{\max}$ is constant.

4. Discussion

[13] We have examined the issue of how turbulent mixing affects the sedimentation of planktonic particles (i.e., particles with negligible inertia) from an oceanic mixed layer. Previous studies have arrived at apparently contradictory results showing that both an increase and a decrease in particle residence time was possible. By using two very simple sets of experiments we have shown how these results can be obtained from the same turbulence model by only changing the implementation of the mixed layer slightly.

[14] In the first set of experiments, the water column was modelled by using the classical two-layer approach: the ocean is divided vertically into a surface layer of relatively high and vertically constant turbulence and a second sub-surface layer (representing the thermocline region) with a usually much lower but also vertically homogeneous turbulent intensity. This approach has been widely used in the marine literature due to its mathematical simplicity. For example, it allows for a stochastic solution to the sedimentation question [e.g., *Lande and Wood*, 1987]. This scenario also corresponds to the experimental setup of *Ruiz et al.* [2004] who measured the effect of turbulent mixing on the settling velocity of diatoms in a region of homogeneous turbulence inside a rotating Couette device and in a tank stirred by an oscillating grid. In good agreement with theoretical predictions [equation (3)] and the results from the present simulations (Figure 1a), *Ruiz et al.* [2004] found that turbulence strongly increases the downward flux of negatively buoyant plankton. This is partly due to the nature of the experiment: the particles sink and therefore always enter the turbulent eddies from above which then transport them downward as they spin. If we applied these results to a temperate shelf sea environment like the North Sea, however, where the SML is often only 20–30 m deep, we would have to conclude that moderate to strong surface winds would essentially flush all negatively buoyant phytoplankton cells from the SML within a few hours (Figure 1a), leaving behind only positively buoyant or motile species. Clearly, this is not the case. The findings from *Ruiz et al.* [2004] can thus only be applied if the turbulence is fully isotropic and homogeneous over the entire domain under consideration. Only then does turbulence increase the downward flux of particles.

[15] If we consider a more realistic scenario where turbulence is no longer homogeneous with depth, but where temperature stratification strongly inhibits vertical turbulent exchanges and the effective diffusivity therefore decreases toward the bottom of the SML, then the simple model from equation (3) can no longer be applied. Cells near the base of the SML have a higher probability of becoming displaced away from the thermocline (upward) than toward it (downward). This is due to the fact that the larger eddies that facilitate most of the vertical transport are located toward the centre of the mixed layer. This effect is expressed through the deterministic component in equation (1). As a result, higher turbulent intensities in the interior of the SML will thus always lead to an increase in the residence time of planktonic particles compared to quiescent conditions. This increase is most significant (25–50%) for moderate to high turbulence (i.e., low Péclet numbers) and stands in stark contrast to the findings from the homogeneous scenario which predicted a decrease in residence time of up to 90%. We could argue that most biologically sustainable scenarios generally have $Pe \lesssim 1$ as live phytoplankton would otherwise quickly sink out of the euphotic zone and become light limited. These sustainable scenarios are thus in the range of Péclet numbers for which turbulence has a significant effect on the residence time and turbulence may therefore play an integral role in the maintenance of these ecosystems. Detritus or motile species can easily have $Pe \gg 1$ however.

[16] A further result of the spatially varying diffusion is a bottom heavy distribution of the sinking particles in the SML. Because the SML is usually considered to be a homogeneous entity (e.g., for global plankton biomass estimates from satellite measurements of ocean colour) it may be worth pointing out that for some parts of the world's ocean this may only be a crude approximation, in particular, if there are different species with different sinking rates present.

[17] One last point to emphasise is that the previous results are only valid for particles with negligible inertia and sinking velocities small compared to the turbulent velocity scales. Many sediments have a non-negligible inertia which means that they are unable to follow the small scale velocity fluctuations of the flow and therefore diffuse less [see *Ross and Sharples*, 2004, and references therein]. Fast sinkers, on the other hand, simply fall through the turbulent structures (crossing-trajectories ef-

fect) [see *Csanady*, 1963] and will therefore also diffuse less. The effect this has on the residence times is presently unknown. Since the residence times are only affected at high diffusivities, however, it could be hypothesised that the heavy or fast sinking particles are less affected by turbulence and will have settling characteristics more similar to quiescent conditions.

[18] In summary, the long standing paradigm of marine ecology after which turbulence is required to keep plankton suspended in the SML seems indeed to be justified.

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