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A model for thin layer formation by delayed particle settling at sharp density gradients

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ABSTRACT

Thin layers – regions where plankton or particles accumulate vertically on scales of a few meters or less – are common in coastal waters, and have important implications for both trophic dynamics and carbon cycling. These features can form by a variety of biological and physical mechanisms, including localized growth, shear-thinning, and directed swimming. An additional mechanism may result in the formation of thin layers of marine aggregates, which have been shown to decrease their settling velocity when passing through sharp density gradients, a behavior termed delayed settling. Here, we apply a simple vertical advection-diffusion model to predict the properties of aggregate thin layers formed by this process. We assume a constant vertical flux of particles from the surface, which is parameterized by observations from laboratory experiments with marine aggregates. The formation, maintenance, and shape of the layers are described in relation to non-dimensional numbers that depend on environmental conditions and particle settling properties. In particular, model results demonstrate layer intensity and sharpness both increase with higher Péclet number (Pe), that is, under conditions with weaker mixing relative to layer formation. Similarly, more intense and sharper layers are found when the delayed settling behavior of aggregates is characterized by a lower velocity minimum. The model also predicts layers that are vertically asymmetric and highly "peaky" when compared with a Gaussian distribution, features often seen in thin layers in natural environments. Lastly, by comparing model predictions with observations of thin layers in the field, we are able to gain some insight into the applicability of delayed settling as a thin layer formation mechanism in different environmental conditions.

1. Introduction

In the past few decades, planktonic thin layers have been shown to be common in coastal waters (Durham and Stocker, 2012). These layers – with a vertical extent on the order of meters – can represent enhanced concentration of phytoplankton (Cheriton et al., 2009; Rines et al., 2002), zooplankton (McManus et al., 2003), or aggregates (MacIntyre et al., 1995; Alldredge et al., 2002). Although thin vertically, these features can extend horizontally for kms and persist for days (McManus et al., 2003). Furthermore, thin layers represent hot spots for grazing, aggregate formation, carbon remineralization, and other important ecological processes (Alldredge et al., 2002; Benoit-Bird et al., 2009; Menden-Deuer and Fredrickson, 2010; Möller et al., 2012). Given their role in planktonic ecosystems, it is critical to determine what controls the occurrence and formation of thin layers. Although recent advances in imaging systems and other technologies have made it more feasible to observe thin layers in the field (e.g., Jackson and Checkley, 2011), there are still sampling limitations that prevent us from addressing mechanistic questions involving layer formation in natural environments. Mathematical models, coupled with lab and field observations, thus provide a way to investigate these important unanswered questions.

Several potential mechanisms have been proposed for thin layer formation. Thin layers can be formed by biological mechanisms including enhanced localized growth, directed swimming, or interactions between swimming and shear (Cheriton et al., 2009; Durham et al., 2009). Physical mechanisms can also lead to thin layer formation in many cases. Shearing of a horizontal plankton patch can result in vertically thin layers that tilt across isopycnals (Franks, 1995; Birch et al., 2008). Horizontal intrusions of water with enhanced plankton concentrations can also lead to vertical peaks in plankton abundance (Cheriton et al., 2010). Lastly, changes in particle buoyancy or settling velocity may also lead to the formation of thin layers (Stacey et al., 2007). Particularly for passively sinking particles such as aggregates – for which mechanisms involving growth and swimming are not applicable – a decrease in settling velocity when passing through sharp

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density gradients has been suggested as an important mechanism for layer formation (Alldredge and Crocker, 1995; MacIntyre et al., 1995; Alldredge et al., 2002). This is further supported by recent laboratory observations of marine aggregates exhibiting this temporarily decreased settling velocity at sharp density transitions – a phenomenon termed delayed settling (Prairie et al., 2013, 2015). Here we present a model of thin layer formation by delayed settling of particles at sharp density gradients, and investigate the implications of this layer formation mechanism for different environmental conditions.

Theoretical and experimental studies of delayed settling at sharp density gradients have shown that two mechanisms can cause a particle to temporarily slow down when settling through the density transition. A particle can entrain lighter fluid from above (Abaid et al., 2004; Camassa et al., 2009), resulting in a brief decrease in its settling velocity. Additionally, since marine aggregates are porous, particles encountering a sharp density gradient may initially be too buoyant to settle through until their density increases through diffusion sufficiently enough for them to continue to sink. This mechanism has been defined as diffusion-limited retention (Kindler et al., 2010; Camassa et al., 2013). Aggregates can exhibit delayed settling at sharp density gradients by both entrainment and diffusion-limited retention, as demonstrated by experimental studies that observed the settling of marine aggregates through salinity gradients (Prairie et al., 2013, 2015). Although recent progress has been made in understanding delayed particle settling at the individual scale, it is important to investigate how this small-scale process can affect larger-scale ecosystem processes through layer formation (Prairie et al., 2012).

Previous studies have modeled thin layer formation by balancing some convergent mechanism acting to accumulate particles with diffusion that acts to dissipate the layer (Stacey et al., 2007; Birch et al., 2008; Prairie et al., 2011). Some of these studies have examined particular mechanisms of layer formation, including formation by plankton motility (Stacey et al., 2007; Birch et al., 2009), shear (Birch et al., 2008), and depth-dependent changes in particle settling (Condie and Bormans, 1997). These models provide insight into the expected layer properties for a given formation mechanism. Here we similarly develop a model for thin layer formation specifically looking at the case of delayed particle settling at sharp density gradients. Previous modeling studies of layer formation due to buoyancy include Stacey et al. (2007), which balanced layer convergence with turbulent diffusion to determine the resulting layer thickness, and Birch et al. (2009), which used an advection-diffusion model to solve for the resulting layer profile vs. depth at steady-state. However, both of these models assumed a linear dependence of settling velocity on density that is inappropriate for the case of delayed settling in a stratified fluid, in which particles exhibit a settling velocity minimum at the depth of the density gradient. By contrast, we use profiles of settling velocity from a recent experimental study (Prairie et al., 2013) to formulate a dependence of settling velocity on depth that effectively describes delayed settling in a stratified water column. With this model, we are able to better predict the implications of delayed settling for thin layer formation, and subsequently for large-scale ecosystem functioning.

2. Methods

2.1. Model description

To model thin layer formation by delayed settling, we build upon previous advection-diffusion models of thin layer formation (Stacey et al., 2007; Birch et al., 2009; Prairie et al., 2011). Our model is described by the following differential equation:

$$\frac{\partial P}{\partial t}+\frac{\partial [wP]}{\partial z}=\frac{\partial}{\partial z}\kappa\frac{\partial P}{\partial z} \tag{1}$$

where $P(z)$ (units: #particles L^{-3}) is particle concentration, t (units: T) is time, z (units: L) is depth, $\kappa(z)$ (units: $L^2\ T^{-1}$) is a possibly depth-dependent vertical eddy diffusivity, and $w(z)$ (units: L T^{-1}) is the particle settling velocity, which is assumed to be identical for every particle in the model. In this model, the advection term (second term on the left hand side) represents the mechanism acting to accumulate particles – in this case vertically-varying particle settling velocity (formulated as in Birch et al. (2009)). This is counteracted by the term on the right hand side of the equation, vertical eddy diffusivity, which acts to disperse the particles. Specifically, it is the flux-conservative form of the advection term in Eq. (1) that permits focusing, or layer intensification, which is well-known mathematically for differential equations of this form (McLaughlin and Forest, 1999). We assume that (1) there is a constant advective flux of particles entering at the upper boundary of the domain, equal to $w_O P_O$, where w_O (units: L T^{-1}) and P_O (units: #particles L^{-3}) are the initial settling velocity and particle concentration respectively in the region of uniform density above the pycnocline, and (2) that the system has evolved to a steady state, in which the particle concentration depends only on z. Although not valid for rapidly evolving systems, the assumption is reasonable in the case of a longer-term bloom where aggregate formation results in a constant flux of settling particles. The steady-state assumption is examined in more detail later. Above and below the pycnocline, the concentration gradient, and consequently diffusive flux, are negligible, and the advective flux through the top of the domain must balance the flux through the bottom at steady state, implying the particle concentration below the pycnocline (P_f) is equal to:

$$P_f=\frac{w_0 P_0}{w_f} \tag{2}$$

where w_f (units: L T^{-1}) is the terminal settling velocity below the density gradient. We use this relationship to solve the model using the following boundary conditions in the lower limit of the domain:

$$P(\infty)=P_{f\,P'(\infty)=0} \tag{3}$$

To solve this model specifically for the case of delayed particle settling, an analytical function is needed for $w(z)$ that appropriately describes the settling velocity vs. depth profile of a particle passing through a sharp density gradient. Previous experimental and theoretical work with particles passing through sharp density gradients, which has included observations of particles ranging in size and shape and density gradients of different strengths, has demonstrated a settling velocity vs. depth profile with a strikingly consistent shape (Prairie et al., 2013, 2015; Camassa et al., 2013), characterized by asymmetry and a settling velocity minimum (Figs. 1A, 1B). To represent this profile, we use an empirical function for $w(z)$ that captures both the observed depth-dependence and asymmetry. The function is the sum of a hyperbolic tangent and the probability density function of a Gumbel distribution (Fig. 1C). The hyperbolic tangent captures the jump in terminal settling velocity above and below the settling velocity minimum associated with the change in ambient density. The Gumbel distribution captures the minimum settling velocity with asymmetrical shape; other more common distributions were not used because they were not asymmetrical (e.g., normal distribution) or did not have the entire real number line as a domain (e.g., lognormal distribution). The settling function is given by:

$$w(z)=w_0-\frac{w_0-w_f}{2}\left(1+tanh\frac{z-z_0}{\beta}\right)-e\left(w_0-\frac{w_0-w_f}{2}-w_G\right)e^{-\frac{z-z_0}{\beta}}e^{-e^{-\frac{z-z_0}{\beta}}}, \tag{4}$$

where w_O is the terminal settling velocity above the sharp density gradient, w_f is the terminal settling velocity below the sharp density gradient, β (units: L) is a length scale that relates to the thickness of the Gumbel distribution, w_G (units: L T^{-1}) is a settling velocity parameter that depends on the minimum settling velocity, w_{min} (but differs because the location of the minimum in the Gumbel distribution is not centered), and z_O (units: L) is a depth offset related to the location of