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A spectral-like turbulence-resolving scheme for fine sediment transport in the bottom boundary layer

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ABSTRACT

A hybrid spectral-compact finite difference scheme for turbulent-resolving simulation of fine sediment transport in the bottom boundary layer is presented. The numerical approach extends an earlier pseudo-spectral model for direct numerical simulation (DNS) of turbulent flows with a sixth-order compact finite difference scheme in the wall-normal direction on Chebyshev grid points. The compact finite difference scheme allows easy implementation of flow-dependent properties (e.g., viscosity, diffusivity and settling velocity) and more flexible boundary conditions while still maintain spectral-like numerical accuracy. The numerical model is verified with analytical solutions of flow velocity and particle concentration of two simple Newtonian rheological closures under laminar condition. Prior laboratory and DNS data of turbulent channel flow are also used to validate the code. Several numerical simulations were carried out in a turbulent channel flow setting to investigate the interplay between the two turbulence modulation mechanisms induced by the presence of sediment, namely sediment-induced density stratification and enhanced viscosity due to rheological stress. We demonstrate that at the Reynolds number, Richardson number, and non-dimensional settling velocity used here, the flow remains turbulent but sediment-induced density stratification already causes noticeable damping of turbulence (drag reduction). By further introducing a Newtonian rheological stress into the system, flow turbulence is further damped by the increased effective viscosity, which can trigger laminarization.

1. Introduction

Understanding the deposition, resuspension and transport of fine sediment in fluvial, estuarine and coastal environments is vital to the prediction of a variety of geosciences and engineering problems. For example, to maintain the navigation of waterways, dredging is routinely carried out in numerous inlets and estuaries throughout the world. The dispersal and the fate of these dredged sediments, sometimes contaminated, also raise concerns. Through flocculation, fine sediment transport becomes the vehicle for the transport of carbon, nutrients and pollutants (Santschi et al., 2005). The timing and amount of fine sediments resuspended by tidal currents and waves from the benthic zone are therefore critical to the geo-chemistry and biological response of an ecosystem.

There are several main challenges in modeling fine sediment transport in the bottom boundary layer due to the co-existence and the strong coupling of several mechanisms. The presence of fine sediments can attenuate flow turbulence via sediment-induced density stratification, enhance mean flow (i.e., drag reduction), and in turn suppress sediment suspension (Winterwerp, 2001; Cantero et al., 2009, 2012; Ozdemir et al., 2010). When sediment concentration becomes large, inter-particle (or inter-floc) interactions give rise to rheological stresses that can be parameterized with an enhanced viscosity through a Newtonian (Einstein, 1906; Krieger, 1972; Krieger and Dougherty, 1959), shear thinning (Stickel and Powell, 2005), or yield behavior (Kessel and Kranenburg, 1996; Liu and Mei, 1990). It is well established from experimental and field observations that transport of fine sediment (i.e., mud) often experiences a transition between turbulent and laminar states (Kessel and Kranenburg, 1996; Sahin et al., 2012; Traykovski, 2010). Such a transition has critical implications to large-scale fine sediment transport and hydrodynamic modeling. For instance, Winterwerp (2001) demonstrated that the transition between turbulent and laminar conditions in a mud-laden tidal boundary layer is directly associated with the sediment carrying capacity. Cantero et al. (2012) linked the observed large turbidites with the sudden extinction of turbulence in turbidity currents. Under the dilute flow assumption without the consideration of rheological stress, the laminarization can be attributed to sediment-induced stable density stratification (Winterwerp, 2001; Cantero et al., 2009, 2012; Ozdemir et al., 2010). On the other hand, Kessel and

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Kranenburg (1996) modeled the observed turbulent–laminar transition of fluid mud on a sloping bed solely based on rheological stress. Essentially, they show that through both enhanced effective viscosity and yield stress (Liu and Mei, 1990), rheological stress can reduce the effective Reynolds number and trigger laminarization. In general, both sediment-induced density stratification and rheological stresses co-exist during fine sediment transport. We are motivated to develop a turbulence-resolving simulation model for fine sediment transport in order to investigate the interplay between these two mechanisms in determining the turbulent–laminar flow transition.

In the present turbulence-resolving simulation, our primary goal is to resolve a wide range of turbulent length scales. In fact, at low-to-moderate Reynolds numbers, we wish to resolve all the scales of turbulence. A 3D numerical scheme with high accuracy is therefore required. Pseudo-spectral methods are widely used in direct numerical simulations (DNS) of turbulent flows (Kim et al., 1987; Moser and Moin, 1987; Spalart, 1988; Zonta et al., 2012a, 2012b). By using information from the whole computational domain to calculate the derivatives, the pseudo-spectral method converges exponentially towards the exact solution. However, in the pseudo-spectral method, the differentiation matrix is dense (Cortese and Balachandar, 1995; Gottlieb and Orszag, 1987; Pedinotti et al., 1992). To accelerate the computation, eigen-decomposition method is commonly used for the dense matrices, where the eigen-decomposition of the differentiation matrix is precomputed (Cortese and Balachandar, 1995). Due to this reason, the pseudo-spectral methods are not very flexible for practical sediment transport applications where the viscosity, diffusivity and settling velocity are generally flow-dependent variables and the use of more complicated boundary conditions is often necessary.

On the other hand, explicit finite difference and finite volume methods are the most widely used numerical methods due to their robustness in handling complex boundary conditions, flow properties and complicated geometries. However, these schemes only use neighboring points provided by the given stencil size, and converge slowly (algebraically) to the exact solution. To achieve the same accuracy as the pseudo-spectral method in a turbulence-resolving simulation, stringent grid refinement is required. With its spectral-like resolution, reasonable computational cost and its robustness in terms of boundary conditions, compact finite difference methods (Lele, 1992) nowadays are getting popular in CFD community (Shah et al., 2010; Hokpunna and Manhart, 2010; Boersma, 2011; Pereira et al., 2001; Shukla et al., 2007). In the high-order compact finite difference schemes, the first and higher derivatives are calculated implicitly with the information from all grid points of the computational domain. Compared to explicit finite difference schemes, the compact finite difference schemes provide significantly higher accuracy with the same stencil size (Lele, 1992).

The purpose of this study is to present a 3D turbulence-resolving numerical model for fine sediment transport in the bottom boundary layer based on a hybrid spectral and compact finite difference scheme. Model formulation for fine sediment transport appropriate for small Stokes number is discussed in Section 2. In Section 3, we discuss the numerical scheme of the present model, which extends the earlier pseudo-spectral scheme of Cortese and Balachandar (1995) with the implementation of a compact difference scheme in the wall-normal (vertical) direction. Section 4 presents model verifications and validations with prior DNS and laboratory data of steady channel flow. In Section 5, we present model results and discuss how Newtonian rheology with an enhanced viscosity can trigger laminarization of fine sediment in a turbulent boundary layer in conjunction with sediment-induced density stratification. Conclusions are summarized in Section 6.

2. Model formulation

In this study, we consider transport of fine sediment of Stokes number ($St=\tau_p/\tau_f$ with τ_p being the particle response time and τ_f the fluid time scale) smaller than unity in a turbulent channel flow (see Fig. 1). Ferry and Balachandar (2001) demonstrated that for particles with small Stokes number, the equilibrium approximation can be adopted, where sediment phase velocity $\tilde{\mathbf{u}}_s$ can be given explicitly as the sum of the fluid phase velocity $\tilde{\mathbf{u}}$, the settling velocity of sediment particle $\tilde{\mathbf{W}}_s$, and an inertial correction of $O(St)$ (see also Ferry and Balachandar, 2002 and a more recent review by Balachandar and Eaton, 2010)

$$\tilde{\mathbf{u}}_s=\tilde{\mathbf{u}}+\tilde{\mathbf{W}}_s-St(1-\beta)\frac{Du}{Dt}+H.O.T. \tag{1}$$

where $\beta=3/(2\gamma+1)$ redefines the particle-to-fluid density ratio with γ denoting the specific density of sediment. This model has been applied to study fine sediment transport in the bottom boundary layer (Cantero et al., 2008, 2009; Ozdemir et al., 2010). The key advantage of the equilibrium approximation is that the particle phase velocity can be explicitly calculated via the algebraic relationship shown in Eq. (1) instead of solving the full momentum equations of the particle phase. As shown by Cantero et al. (2009), by substituting Eq. (1) into the standard Eulerian–Eulerian two-phase equations for fluid and particle phases and making the Boussinesq approximation, the resulting governing equations for carrier fluid in channel flow become

$$\tilde{\nabla}\cdot\tilde{\mathbf{u}}=0 \tag{2}$$

$$\frac{\partial\tilde{\mathbf{u}}}{\partial\tilde{t}}+\tilde{\mathbf{u}}\cdot\tilde{\nabla}\tilde{\mathbf{u}}=-\frac{1}{\rho}\tilde{\nabla}\tilde{p}+\tilde{\nabla}\cdot[\nu(\tilde{\nabla}\tilde{\mathbf{u}}+\tilde{\nabla}\tilde{\mathbf{u}}^T)]+g\tilde{\phi}\mathbf{e_3}+gJ\mathbf{e_1}, \tag{3}$$

where $\tilde{p}$ is the flow pressure, ν is the effective kinematic viscosity of the fluid, ρ is the density of the carrier fluid and J is the slope of the channel. The sediment phase is calculated by the mass balance:

$$\frac{\partial\tilde{\phi}}{\partial\tilde{t}}+\tilde{\nabla}\cdot(\tilde{\mathbf{u}}_s\tilde{\phi})=\tilde{\nabla}\cdot(\kappa\tilde{\nabla}\tilde{\phi}), \tag{4}$$

where κ is the diffusion coefficient of the sediment phase and the particle phase velocity is computed by Eq. (1). Following previous fine sediment studies of Cantero et al. (2009) and Ozdemir et al. (2010), we neglect $O(St)$ terms in Eq. (1) in this study. In this set of simplified governing equations, which are appropriate for small Stokes number, the continuity and momentum equations of the carrier fluid phase are similar to the Navier–Stokes equations. If the effective kinematic viscosity of fluid is set to be constant (i.e., neglect the rheological effect), the only coupling term between the particle phase and the carrier fluid is the particle-induced density stratification. In Section 5, we will justify the small Stokes number assumption employed in the present investigation of fine sediment transport.

There have been many studies on the effective viscosity of fluid with the presence of (sediment) particles, in which the effective

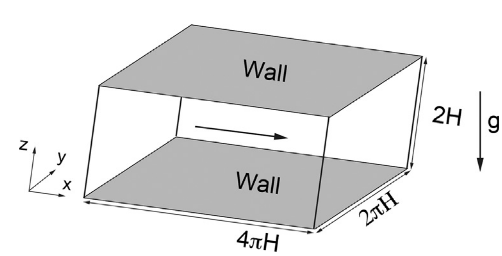

Fig. 1. A sketch of the model domain for channel flow. Periodic boundary conditions are implemented for the four sides of the box and no-slip wall boundary conditions are implemented for the top and bottom boundaries.