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EFFECTS OF SELF-STRATIFICATION ON TURBIDITY CURRENTS: A LARGE EDDY SIMULATION APPROACH

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Summary. Turbidity currents are a subset of gravity-driven flows and can be categorized as non-conservative gravity current, as it's driving media (entrained sediment) is in a continuous flux with the bed through erosion and deposition. Thus, turbidity currents are one of the main methods of sediment transport and dispersal in the sub-marine environment. This exchange of sediment with the bed is an important balance that decides if the current is self-accelerating or decelerating. Thus any mechanism that affects the sediment exchange; affects the dynamics of the whole current. Turbulence modulation due to stable stratification is a well-known phenomenon but in this study we try to explore the effect of self stratification due to settling sediment particles on the over all dynamics of a Turbidity current, which is a relatively uncharted territory. Recently Direct Numerical Simulation (DNS) of a simplified formalism of turbidity currents (Turbidity current with a Roof) has helped us to characterize fascinating features like the break in flow symmetry due to presence of sediment, and the tendency for self-stratification and damping of near-bed turbulence. The simplified formalism of Turbidity Current with a Roof (TCR) allows for flows that (upon averaging over turbulence) are steady and uniform. DNS, however, has a major limitation in that the Reynolds numbers that can be simulated, which are orders of magnitude below that associated with field currents. Large Eddy Simulation (LES) offers an attractive alternative allowing much larger Reynolds numbers. The configuration of channel flows driven by pressure gradient (CDP) is similar to the TCR configuration, that is why DNS results of pressure driven channel flows are similar to those of TCR. First we briefly report on numerical experiments using DNS, designed to study the effect of varying shear Richardson number (Ri_τ, characterizing the degree of initial sediment concentration) on a CDP. Simultaneously we also report on numerical experiments simulated using LES with Dynamic Smagorinsky for the sub-grid scale (SGS), that are designed to study the effect of Reynolds number (characterizing the degree of turbulence) on the flow. Based on the observations made during the DNS simulations, we enlist three different dynamic regimes of flow recognized for the CDP configuration. LES results for shear Reynolds numbers ($Re_\tau = 180$) have been compared with DNS results and they show qualitative similarity. Based on the DNS simulations we briefly review the available SGS models and their appropriateness for doing LES of self stratified flows.

1 INTRODUCTION

Gravity currents are horizontal flows produced by the action of gravity on fluids with different densities, which can occur in naturally or through anthropogenic interventions. Examples include pyroclastic flows from volcanic eruptions, the disposal of residual brine from water desalination plants, desert dust storms, the discharge of a sediment-laden river into the ocean[1], snow avalanches[2], and contaminant and debris releases in urban areas, to name a few. An example relevant to Illinois is density currents observed in the Chicago River with important implications for water quality in Lake Michigan. In several geological, engineering and environmental phenomena, gravity currents are driven by a change of the bulk density produced by particles in suspension. These particles are kept in suspension by turbulent fluxes that balance out deposition, with turbulence-particle interaction and particle re-entrainment playing a major role. Submarine canyons, rivaling in size the Grand Canyon, have been carved out by turbidity currents capable of entraining sediment into suspension in a self-reinforcing cycle. This class of gravity currents is called non-conservative gravity currents (turbidity currents) due to its property of exchange (entrainment and deposition) of the disperse phase (particles) with the bed. Turbidity currents form deep ocean sedimentary deposits, which eventually evolve into oil reservoirs over geological time scales. Understanding the nature of these deposits has great implications in the exploration for hydrocarbon resources[3]. Deepwater sedimentation processes incurred from gravity flows are poorly understood and very difficult to measure in the laboratory and the field; as the phenomena are characterized by complex physical processes taking place over a very wide range of spatial and temporal scales. With the increase of computational power in the last two decades, high resolution numerical simulations have been increasingly used to shed light into several engineering and environmental problems related to gravity currents[4,5,6].

But there are still many aspects of these problems to understand and explore, especially in the field of non-conservative gravity currents; unlike in channel flow, where the turbulence field is basically set by the continuous phase flow, in gravity-driven two phase flows the turbulence field may, indeed, be affected and modified by the presence of the disperse phase. In this situation, characterization of turbulence and turbulence modulation by the disperse phase are of paramount importance and more so in the case of turbidity currents; where the disperse phase is non-conservative. In these cases the mechanism of entrainment and deposition of disperse phase (sediment for turbidity currents) becomes integral to the resilience of the current. Hence forth in this paper we will refer to the disperse phase as sediment; as it is the kind of non-conservative gravity current which has been focused on in this paper. Similar to turbidity currents, rivers also carry huge amount of sediment in suspension. And if the concentration of sediment is high enough; they will show properties similar to turbidity currents; like stable stratification due to suspended sediment[7]. And like in the case of turbidity currents; at sufficiently high concentration it will have an effect on the regime of the flow[8]. In turbidity currents, gravity pulls suspended sediment downslope, and suspended sediment then pulls water with it. So one can see that turbidity currents are driven by suspended sediment, and change in flow regime from turbulent to laminar will severely affect it[3].

Interest in the deposition mechanism of the turbidity currents is largely due to its correlation to presence of Hydrocarbons[9]. The deposits under consideration are called turbidites. Turbidites are usually emplaced in layers and the layer of our interest is also called the massive layer, i.e. either lacking or highly deficient in depositional structure. Mechanisms of formation of most of the layers of a turbidite are well understood and broadly accepted but the mechanisms for the emplacement of massive turbidites are more speculative. Several mechanisms[10] offered to explain massive units but none of them hold water. An alternative mechanism[3] had been put forward and the proposed mechanism was found to be valid for bulk Reynolds number $Re_b = 2000 \sim 8000$ using DNS[3,11]. But the Reynolds numbers at which the mechanism was validated are relatively low compared to the ones encountered in the field. So, the primary motivation of this study was to check the Reynolds invariance of the proposed mechanism by simulating Turbidity Current with a Roof (TCR) at higher Reynolds number. DNS at higher Reynolds number are very computationally intensive so for this study we have used LES. Historically, LES have been found to capture most of the important features of a flow and at relatively much less computational cost than DNS[12]. LES results have been compared with DNS results for $Re_\tau = 180$ (Re_τ, characterizes the degree of turbulence intensity).

For the purpose of the study a simplified formalism of turbidity current, Turbidity Current with a Roof (TCR) has been used and the formalism used is in agreement with the one used by Cantero et al.[3,11]. The phenomena we are studying can also occur in rivers which have enough suspended sediment to cause self-stratification[8]. So, another simplified formalism (similar to TCR) called Channel flows Driven by Pressure gradient (CDP), which is analogous to a river flow was used to study the effect of self-stratification on pressure driven channel flows[13]. In this paper we also briefly discuss about DNS simulations of CDP for different shear Richardson number (Ri_τ, which is analogous to initial sediment concentration) but constant Re_τ and particle settling velocity ($\tilde{V}$). As the effect of self-stratification on the flow for CDP and TCR are similar in characteristics; from a brief discussion of the dynamic flow regimes of CDP we will draw few generic insights about the appropriateness of the available SGS models for LES of self-stratified flows.

2 MATHEMATICAL FORMULATION

2.1 TCR using Large Eddy Simulation

Turbidity currents generally dont have a distinct upper boundary. On the contrary, they entrain ambient water across a more diffusive upper boundary. Thus turbidity currents tend to thicken in the downstream direction due to the water they entrain. The TCR model places a roof above the bed, thus preventing ambient water entrainment and thus creating a channel flow. This assumption might not be true for head of the current[6] but is perfectly valid for the body of the current. The channel is submerged in water, and both ends are open to this ambient water (Fig. 1). The flow within the channel is driven purely by the presence of sediment in the water. The channel is assumed to be adjusted so that the flow and sediment transport entering the channel equal that exiting the channel (cyclic boundary conditions). The TCR model thus retains a key element of turbidity currents, i.e., that they are sediment driven. The TCR configuration doesnt have inflows or outflows; this simplifies the implementation of LES. A problem with a similar configuration (but with stable stratification instead of self-stratification) was studied by Armenio and Sarkar[14] and our LES formulation is similar. Only difference is, in our case we have used Dynamic Smagornisky[15,16] to model the sub-grid scale stresses whereas they had used the MIxed model[14]. The dimensionless form of the Navier-Stokes, continuity and the advection-diffusion (for sediment) equations are filtered (for LES, variables have bar on top), giving us our set of governing equations.

$$\frac{\partial \bar{\tilde{u}}_i}{\partial \tilde{t}} + \frac{\partial}{\partial \tilde{x}_j}\left(\bar{\tilde{u}}_i \bar{\tilde{u}}_j\right) = -\frac{\partial \bar{\tilde{p}}}{\partial \tilde{x}_i} + \frac{1}{Re_\tau}\frac{\partial^2 \bar{\tilde{u}}_i}{\partial \tilde{x}_j \partial \tilde{x}_j} + \bar{\tilde{C}}_g - \frac{\partial \tilde{\tau}_{i,j,sgs}}{\partial \tilde{x}_j} \tag{1}$$

$$\frac{\partial \bar{\tilde{u}}_i}{\partial \tilde{x}_i} = 0 \tag{2}$$

$$\frac{\partial \bar{\tilde{c}}}{\partial \tilde{t}} + \frac{\partial}{\partial \tilde{x}_j}\left(\overline{\left(\tilde{u}_j + \tilde{V}\right)\tilde{c}}\right) = \frac{1}{Re_\tau Sc}\frac{\partial^2 \bar{\tilde{c}}}{\partial \tilde{x}_j \partial \tilde{x}_j} - \frac{\partial \tilde{\lambda}_{j,sgs}}{\partial \tilde{x}_j} \tag{3}$$

where $\tilde{u}$ is the dimensionless fluid velocity, $\tilde{c}$ is the dimensionless volumetric concentration of sediment, $\tilde{V} = (\tilde{V}\sin(\theta), 0, -\tilde{V}\cos(\theta))$ is the dimensionless settling velocity of sediment and $\tilde{C}_g = (\tilde{c}, 0, -\tilde{c}''/\tan(\theta))$ ($\tan\theta$ is the slope of the channel). Here $c'' = c - c^*$ where c^* is the concentration averaged in the plane tangential to the walls. $\hat{p}$ is the pressure field that remains after removing the hydrostatic component[11]. The sediment particles are assumed to be small enough for an Eulerian representation to be employed. The flow is also assumed to be sufficiently dilute so that particle-particle interaction can be neglected, and that Boussinesq approximation can be employed. Velocity is scaled using the average shear velocity $u_{*,avg}$ and length using the half channel height h.Time and pressure scales are derived using the above scales and fluid density (ρ_f). The dimensionless numbers in equations 1- 3 are the shear Reynolds number (Re_τ) and the Schmidt number (Sc). Another dimensionless parameter which characterizes the initial sediment concentration is shear Richardson number (Ri_τ).

$$Re_\tau = \frac{u_{*,avg}h}{\nu} \qquad Ri_\tau = \frac{gRhc^{(v)}}{u^2{}_{*,avg}} \quad and \quad Sc = \frac{\nu}{\kappa} \tag{4}$$

Here ν is the kinematic viscosity of the fluid, g is the magnitude of gravitational acceleration, $R = \frac{\rho_s}{\rho_f} - 1$ with ρ_s being the sediment particle density, $c^{(v)}$ the volume averaged concentration, and κ is the diffusivity of the sediment particles. More details about the parameters can be found in the study by Cantero et al.[11]. In equations (1) and (3) we have terms in the extreme right, which are generated due to the use of a spatial filter on the dimensionless governing equations. The SGS stress and sediment flux are defined by $\tau_{i,j,sgs} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j$ and $\lambda_{j,sgs} = \overline{u_j c} - \bar{c}\bar{u}_j$ respectively.

The computational domain is of height $2h$, length $L_x = 4\pi h$ and width $L_y = 2\pi h$. A no slip boundary condition is imposed at the top and bottom walls. Also, the sediment is assumed to be sufficiently fine so that the flow does not allow for net deposition; that is, any particle that settles is instantly re-entrained into suspension. In the direction tangential to the walls, periodic boundary conditions are applied for all variables. The boundary conditions are defined as

$$\tilde{u} = 0 \qquad at \qquad \tilde{z} = -1 \quad and \quad \tilde{z} = 1 \tag{5}$$

$$\tilde{c}\tilde{V} + \frac{1}{Re_\tau Sc}\frac{\partial \tilde{c}}{\partial \tilde{z}} = 0 \qquad at \qquad \tilde{z} = -1 \quad and \quad \tilde{z} = 1 \tag{6}$$

The sets of dimensionless governing equations are solved using a dealiased pseudospectral code. Fourier expansions are employed for the flow variables in the directions tangential to the walls ($x - y$), while in the inhomogeneous direction normal to the walls (z) a Chebyshev expansion is used. An operator splitting method is used to solve the momentum equation along with the incompressibility condition. A low-storage mixed third-order Runge-Kutta and Crank-Nicolson scheme is used for the temporal discretization of the advection- diffusion terms. The scheme is carried out in three stages with the pressure correction at the end of each stage. More details on the implementation of this numerical scheme can be found in the work of Cortese and Balachandar[17]. The computational grid resolution employed for the simulations are $(N_x, N_y, N_z) = (96, 96, 97)$.

2.2 CDP using Direct Numerical Simulation

The formalism for Channel flow Driven by a Pressure gradient (CDP) is similar to the TCR case. Only difference is the absence of a slope in the channel, thus the flow in the channel is driven by a constant pressure gradient. The dimensionless governing equations that describes the case is

$$\frac{\partial \tilde{u}_i}{\partial \tilde{t}} + u_j \frac{\partial \tilde{u}_i}{\partial \tilde{x}_j} = \tilde{G} - \frac{\partial \hat{p}}{\partial \tilde{x}_i} + \frac{1}{Re_\tau} \frac{\partial^2 \tilde{u}_i}{\partial \tilde{x}_j \partial \tilde{x}_j} + Ri_\tau \left(\tilde{c} - \tilde{c}^{(h)} \right) e_g \tag{7}$$

$$\frac{\partial \tilde{u}_i}{\partial \tilde{x}_i} = 0 \tag{8}$$

$$\frac{\partial \tilde{c}}{\partial \tilde{t}} + \left(\tilde{u}_j + \tilde{V} \right) \frac{\partial \tilde{c}}{\partial \tilde{x}_j} = \frac{1}{Re_\tau Sc} \frac{\partial^2 \tilde{c}}{\partial \tilde{x}_j \partial \tilde{x}_j} \tag{9}$$

where $\tilde{c}(h)$ is the horizontally-averaged concentration, $e_g = (0, 0, -1)$ is the unit gravity vector, $\tilde{V} = (0, 0, -\tilde{V})$ is the constant particle settling velocity and $\tilde{G} = (1, 0, 0)$ is the driving streamwise pressure gradient. Rest of the parameters are same as the TCR case. For the present case the computational domain is of height $2h$, length $L_x = 4\pi h$ and width $L_y = 4\pi h/3$.

3 RESULTS

The DNS simulations of CDP was conducted at $Re_\tau = 180$, which is same as the reynolds number in the study by Cantero et al.[13]. For our study we simulated different cases by varying the Ri_tau and $\tilde{V}$. Simulations were run till the flow in the channel attained a steady state, which usually took 15-30 days (wall clock time) running on 8 processors. In their study Cantero et al.[13] had only explored the effect of $\tilde{V}$ on the flow but in a way that is only half of the story, because Ri_τ also plays an important part in deciding the degree of stratification in the flow. Through our simulations it was observed that the effect of increasing the Ri_τ of a flow keeping $\tilde{V}$ constant is in a way similar to increasing $\tilde{V}$ and keeping Ri_τ constant. But then it was found that the relationship between the two parameters is not linear, that is the combination of Ri_τ and $\tilde{V}$ required to cause a stable stratification strong enough to completely dissipate turbulence doesn't scale linearly. Further details about general flow characteristics, turbulence properties etc. has not been dealt in this paper, rather we would like to discuss about the dynamic regimes of the flow. In the study we did a set of simulations in which $\tilde{V}$ was kept constant at 0.05 and Ri_τ was increased starting from 1.0. It was observed that at $Ri_\tau \approx 10.0$ the flow near the bottom boundary became laminar and almost all velocity fluctuations were dissipated. Similar characteristics of the flow was observed as we increased Ri_tau, only difference was the time it took for the stable stratification to dissipate all the turbulence near the bed but all of them attained almost similar velocity profiles at steady state. Strangely, it was observed that when Ri_τ was made 14.0 or more, the flow completely re-laminarized. Though this was not impossible but it was highly improbable because even if for a short time the Gradient Richardson number (Ri_g) near the top wall of the channel was high enough to dissipate all the turbulence, the flow over the course of time should regain its turbulent nature near the top boundary.

$$Ri_g = \frac{g_z R d\bar{c}/dz}{(d\bar{u}/dz)^2} \tag{10}$$

This is expected to happen due to a constant downward $\tilde{V}$ of the suspended sediment, which will eventually reduce the concentration of sediment at the top boundary thus reducing the Ri_g at the top. So, we came the conclusion that we might be failing to capture some important physics at play. But we were already doing DNS, that is we were already sufficiently resolving all the important turbulent length scales. But to be sure we again did the same simulation with a higher computational grid resolution (increase $N_x \times N_y \times N_z$ from $96 \times 96 \times 97$ to $150 \times 150 \times 151$) and this time we were able to resolve the flow correctly. Interestingly the flow initially (just after the start) became laminar, both at the top and bottom. This made the flow accelerate for a while but eventually when sediment concentration near the top wall reduced (due to constant downward motion of the sediment) the flow slowly retained its turbulent characteristics near the top wall. Throughout the process turbulence near the bottom boundary remained dissipated due to a strong stable stratification, which only got accentuated in time.

For the TCR cases LES model used (Dynamic Smagorinsky) was found to be sufficiently adept in capturing the physics involved in some of the initial cases simulated. It must be pointed out that the cases dealt with were for higher Re_τ but moderate Ri_τ and $\tilde{V}$. The results are similar to the ones observed earlier[11], but the intuition we get from our DNS simulations is for extreme cases (higher Ri_τ and $\tilde{V}$) our current LES models might not be sufficient to capture all the physics involved in the flow.

4 CONCLUSIONS

From the DNS simulations of the CDP configuration, we observe three distinctive dynamic flow regime for $Re_\tau = 180$ and $\tilde{V} = 0.05$. First, for $Ri_\tau < 10.0$ the flow in the channel is still turbulent, but we find that with increase of the initial concentration of sediment the flow becomes more and more skewed that is the mean velocity maxima gets more and more below the centerline of the channel. The second regime is when $10.0 \leq Ri_\tau < 14.0$, the flow in channel is mixed. Near the bottom boundary the flow almost relaminarizes but near the upper wall the flow is still turbulent. As the upper wall still produces turbulence, the flow till the mean velocity maxima is turbulent with a sharp reduction in turbulence intensity as one goes below it. The mean flow profile of the flow remains almost the same for increasing Ri_τ. The third dynamic regime we get when $Ri_\tau > 14.0$, initially the flow at both the top and bottom boundary relaminarizes. The flow throughout the domain is not perfectly laminar, but as the turbulence at the top and bottom boundaries is dissipated the flow shows some laminar characteristics like parabolic mean velocity profile and a linear viscous stress profile. The flow continues to accelerate and reaches mean velocity values higher than those attained earlier but then in time the sediment slowly shifts downward. This eventually results in the decrease of

Ri_g near the top wall of the channel, thus decrease in the turbulence dissipation. And then finally at steady state the flow attains the characteristics of the steady state regime of $10.0 \leq Ri_\tau < 14.0$. The third dynamic regime is important because it gives us an insight into a different mechanism for reaching the steady state. Also in nature the flows usually don't have a no-slip top boundary, they usually have a slip (open-channel flow) boundary or a moving boundary (wind, another moving fluid layer or even a moving boat) which opens up more interesting avenues of research. More important is the fact that for simulating the third regime correctly we had to increase our computational grid resolution, this points towards Ri_τ dependent physics which for a particular $\tilde{V}$ and Re_τ is switched on when Ri_τ is greater than a certain value.

The above becomes more important in the context of LES. In our present LES simulations we find the Dynamic Smagorisnky model to be good enough for handling the moderate cases. But will our models be good enough to handle extreme cases in which even DNS only succeeded at a higher grid resolution. We think the reason for this behavior is non-resolution of the prevalent length scale at that particular set of conditions. Unlike the case of un-stratified flows in stratified flows there are two length scale which are important, the Ozmidov length scale[18]($l_o = (\epsilon/N^3)^{0.5}$) and the Kolmogorov length scale ($l_K = (\nu^3/\epsilon)^{0.25}$). Most of the time l_K is smaller than l_o thus a DNS simulation with the grid size based on l_K will be able to represent all the ingrained physics but if the level of stratification increases (will happen if the Ri_τ value is high enough) then l_o will become smaller than l_k, henceforth the governing length scale for DNS changes. Due to the change in the governing length scale to l_o (for $Ri_\tau \geq 14.0$) we had to increase the grid resolution of the DNS simulation. So, this highlights a need for us to be more cognizant while numerically simulating stratified flows. Especially in the case of LES and RANS modeling of flows, where we tend to approximate lot of the small scale physics; we should always be aware of the physics we might not be depicting correctly and the corresponding effects it might be having on the results of our simulations. It is also widely known that when $l_o < l_K$, homogenous turbulence transitions to internal waves[18]; but we are not sure what happens to these waves eventually and none of the existing LES or RANS models address this issue. From the DNS experiments it can be said that the existing LES models for doing scalar transport might not be perfectly suited for self-stratified flows. It is quite obvious that the physics of the flow depends a lot on the gradient Richardson number (Ri_τ) of the flow and due to self stratification effects it evolves over time, so we need a LES model which takes into account the buoyancy effects more explicitly. Most of the LES based studies of stratified flows are for the case in which stratification is imposed[14,19], these cases are less restrictive than a self-stratified case as in the later the stratification inducing agent is in continuous flux. This short paper, has been written as an extended abstract without any of the plots of the results discussed because the primary aim of this paper is to introduce the reader to the problems we are studying. It also lays down a few interesting things that can be further explored. This paper is aimed as an accompanying document to the poster to be presented at the conference.

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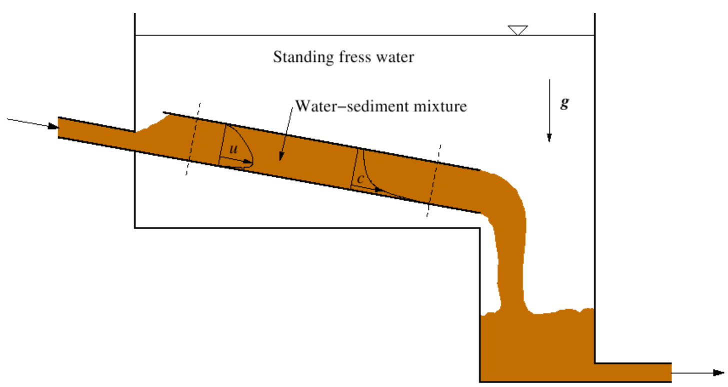

Figure 1: Channel configuration for Turbidity Current with a Roof