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# On the modelling of shallow turbidity flows

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## ABSTRACT

In this study we investigate shallow turbidity density currents and underflows from mechanical point of view. We propose a simple hyperbolic model for such flows. On one hand, our model is based on very basic conservation principles. On the other hand, the turbulent nature of the flow is also taken into account through the energy dissipation mechanism. Moreover, the mixing with the pure water along with sediments entrainment and deposition processes are considered, which makes the problem dynamically interesting. One of the main advantages of our model is that it requires the specification of only two modeling parameters — the rate of turbulent dissipation and the rate of the pure water entrainment. Consequently, the resulting model turns out to be very simple and self-consistent. This model is validated against several experimental data and several special classes of solutions (such as travelling, self-similar and steady) are constructed. Unsteady simulations show that some special solutions are realized as asymptotic long time states of dynamic trajectories.

## 1. Introduction

Underwater turbidity currents are sediment-laden underflows that play an important rôle in the morphology of the continental shelves (more generally of ocean bottoms) and in the global sediment cycle going to the formation of hydrocarbon reservoirs. We refer to Ungarish (2009) for a self-contained and comprehensive account of the theory of gravity currents and intrusions. The presence and entrainment of sediments differentiates them from stratified flows due to, e.g. temperature or salinity differences. The main physical mechanisms include the deposition, erosion and dispersion of important amounts of heavy sediment particles. Turbidity currents are not to be confused with *debris flows*, which represent fast-moving masses of poorly sorted heterogeneous material where interactions among the material pieces ( ≈ particles) are important. Moreover, debris mix little with the ambient fluid. Debris flows have been a mainstream topic in the scientific literature due to their hazard they wreak in mountain regions (and not only).

The driving force is the gravity acceleration acting on dispersed sediment particles along steep and moderate bottom slopes. The initial perturbation is amplified by this acceleration, which in turn destabilizes the flow into shear instabilities that result in turbulent mixing and the transfer of mass and momentum. This gravity force creates the horizontal pressure gradient due to the increase of hydrostatic pressure resulting from the addition of particles. The heavy sediment particles are suspended in the mixing layer by fluid turbulence. The studied here processes are responsible of the transfer of littoral sediments to deep ocean regions. One should not disregard the destructive potential of gravity currents onto underwater structures such as pipelines, cables, etc. Turbidity currents in submarine canyons can attain surprisingly high velocities of the order of $8 \sim 14\,\mathrm{m/s}$ (Krause et al., 1970; Parker et al., 1986). These high velocities in the downstream direction result from the self-acceleration (and self-suspension) process from an appropriate initial perturbation, when more and more sediments are entrained by the flow from the bed, thus, increasing the rate of work performed by gravity (Parker et al., 1986). This process is sometimes referred to as the “ignition” (Garcia and Parker, 1993; Parker, 1982; Parker et al., 1986), which translates the energy imbalance property of such flows. One of important scientific questions is to determine the conditions necessarily to have an igniting flow. However, the self-acceleration stage cannot continue indefinitely. Most often the bed slope drops off (due to the bed morphology) or, simply, the sediment supply ceases. The mechanism of ignition was already described in Pantin (1979). However, the first laboratory demonstration of self-

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accelerated turbidity flows took 30 more years (Sequeiros et al., 2009).

Turbidity currents is a particular case of (continuously) stratified flows and they are fundamentally different from classical density underflows (Ellison and Turner, 1959). The main difference comes from the fact that the source of the density gradient, i.e. the suspended sediment, is not conservative. The suspended sediments are free to exchange with the core layer near the sea bed. The ambient still water is also entrained into this process. These exchanges are difficult to quantify and they constitute one of the main difficulties in the modeling of such flows (Pantin, 1979; Parker, 1982; Parker et al., 1986). In this respect turbidity currents are fundamentally non-conservative flows in their nature. Gravity flows may occur in the atmosphere[1] over topography, sub-aerial (e.g. avalanches, pyroclastic flows) and sub-aqueous environments (e.g. turbidity currents) over bathymetries. They may result also from anthropogenic activities such as when a dense buoyant industrial effluent or pollutant is released into a lake, river or ocean. In the present study we shall consider mainly sub-aqueous flows due to the abundance of available experimental data. We refer to Meiburg and Kneller (2010); Parsons et al. (2007) as general excellent reviews on this topic.

Perhaps, the first serious attempts to observe turbidity currents in natural environments were performed in late1960s at SCRIPPS Canyon offshore of LA JOLLA, CALIFORNIA. They were reported in Inman et al. (1976). However, the flows reported in that study were so violent that the instrumentation was lost during these density currents making the detailed analysis extremely difficult (Parsons et al., 2007). The exact time moment of these underwater events is unpredictable which make them difficult to monitor in natural environments. Most of our physical knowledge on underwater turbidity currents come from small scale laboratory experiments (Garcia and Parker, 1993; Kubo, 2004; Kubo and Nakajima, 2002; Middleton, 1967). The experiments are bound to use common liquids for practical reasons. In general, it is not possible to respect all scalings. To give an example, we can mention the issue with particle sizes and their settling velocity. Nevertheless, taking into account the difficulties in obtaining field data, laboratory experiments are the only source of quantitative data about turbidity currents. The mathematical modelling is needed to extrapolate these experimental results to the scales on which these processes occur in nature. Nonetheless, the experiments offer a great opportunity for the verification of numerical results.

The gravity current can be divided geometrically into the flow *head, body* and *tail*. The head is shaped as an ellipse and, generally the head is higher than the flow body. In the present study we are mainly interested in the flow head modelling, where the most intensive mixing processes take place. Consequently, it influences the whole flow dynamics. The most advanced point of the flow head is called the front or nose.

The main difficulties in understanding the dynamics of gravity turbidity currents come from their genuinely turbulent nature. Moreover, the phenomenon is nonlinear, heterogeneous and unsteady. The flow complexity increases when the flow entrains more and more sediments in suspension. The literature devoted to the mathematical modeling of the density currents is abundant. First of all, we would like to mention the classical monographs on this subject (Liapidevskii and Teshukov, 2000; Townsend, 1980; Turner, 1973). The first and simplest models intended to explain the classical lock-exchange configurations was proposed in Huppert and Simpson (1980). These models are referred to as *integral, box* or 0D models, since all quantities are averaged in space. The modern approaches to the mathematical modeling of such flows were initiated in Pantin (1979); Parker (1982); Parker et al. (1986). A dense cloud 0D model for powder-snow avalanches including non-BOUSSINESQ and sediment entrainment effects along the avalanche path was proposed in Rastello and Hopfinger (2004). Powder-snow avalanches are large-scale, finite volume release turbidity currents (in the form of large scale suspension clouds) occurring on mountain slopes. These clouds sometimes reach 100 m in height and the front velocities of the order of 100 m/s. Without sediments (i.e. snow in the case of avalanches) distributed over the incline, the density current first accelerates and then decelerates without reaching important velocities. With sediments entrainment, the current can be maintained in the accelerating self-sustaining state during sufficient intervals of time to reach the velocities indicated above. In Hopfinger (1983) a fair correlation of the avalanche velocity with the snow cover was demonstrated. The measurements of an avalanche front velocity in the SION valley, SWITZERLAND demonstrate a constant increase of the front velocity with traveled distance (Dufour et al., 2001) (during the accelerating phase, of course). Thus, we come to the conclusion that the inclusion of sediments entrainment effect is of capital importance to predict the correct density current front velocity.

Some of recent studies devoted to the sediments transport within depth-averaged models include Benkhaldoun et al. (2009); Bradford and Katopodes (1999); Fernandez-Nieto et al. (2008); Khan et al. (2005); Morales de Luna et al. (2009). This list is far from being exhaustive. The shallow water approach assumes that vertical accelerations are negligible, so the pressure being essentially hydrostatic. The sediment concentration is a passive tracer with exchanges among different layers. The flow is fully turbulent, even if pure viscous effects are generally negligible. Moreover, the energy required to keep the sediments in the suspension cloud is a negligible portion of the total turbulent energy production (Parker et al., 1986). Thus, the base model has to be first REYNOLDS-averaged (Sreenivasan, 1999) before applying the long wave approximation. Several authors made an effort to take into account the turbulence modeling into the shallow water type models (Fe et al., 2008; 2009; Mei et al., 2003). Our approach to solve this issue will be detailed below. Nowadays, the multi-layer approaches to the density stratified flows become more and more popular (Audusse et al., 2010). Finally, some researchers chose a more CFD[2]-like approach to the simulation of density flows incorporating eventually the advanced turbulence modeling (Birman et al., 2005; Etienne et al., 2005; Özgökmen et al., 2006; 2007). Perhaps, the first Direct Numerical Simulation (DNS) of the gravity current dates back to the years of 2 000 Härtel et al. (2000). These simulations have an advantage of being depth-resolving and, thus, providing very a complete information about the flow structure in two or even three dimensions. However, due to the high computational complexity, only idealized academic configurations can be considered within reasonable CPU-time at the current state of technologies. Recently proposed three-dimensional (3D) turbidity-current models can be found in Huang et al. (2005); Imran et al. (2004); Kassem and Imran (2004). Moreover, the 3D DNS computations are often limited in the bulk REYNOLDS number.

In the present study we adopt a simplified (1.5D) approach along the lines of Choi and Garcia (2001); Liapidevskii (2004); Salaheldin et al. (2000) based on the EULERIAN formulation and depth-averaged formulations. A LAGRANGIAN simplified BANG1D model was proposed in Pratson et al. (2001). A simple 1.5D model was proposed in Johnson and Hogg (2013). The authors parametrized their model by making the entrainment velocity depending on the dimensionless RICHARDSON number. In the present study we close the model in an alternative way.

Very similar physical processes take place in powder-snow avalanches where the snow particles suspension flows down the mountains and the snow plays the rôle of sediments in underflows (Hopfinger, 1983). Consequently, very similar mathematical models appear in these two fields and to make the bibliography review more

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[1] For instance, downslope windstorms over topography in COLORADO (US) were observed and examined in Lilly (1978); Neiman et al. (1988).

[2] Computational Fluid Dynamics (CFD).