The Mystery of Accelerating Turbidity Currents: The Curious Case of the Congo Canyon

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Motivated by the remarkably large propagation distances observed in turbidity currents near the mouth of the Congo River in Africa, a new model is proposed for their dynamics. It assumes that the erosion of solid particles from the bed underneath the current increases the density of the current such that the vortex rotational rate increases over the case of no erosion. If the rate of increase of vortex rotation is sufficient, the entrainment rate of fluid above the current is inhibited. As a consequence, the turbidity current propagates much farther than would be expected without the dynamic effect of acceleration.

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Key Points:

- A new model accounts for the effect of bed erosion on the rotational acceleration of entraining vortices in turbidity currents.
- Acceleration effects reduce the entrainment of clear water from above the current.
- This may explain the surprising speed and propagation distance observed in the Congo Canyon

Abstract

Motivated by the remarkably large propagation distances observed in turbidity currents near the mouth of the Congo River in Africa, a new model is proposed for their dynamics. It assumes that the erosion of solid particles from the bed underneath the current increases the density of the current such that the vortex rotational rate increases over the case of no erosion. If the rate of increase of vortex rotation is sufficient, the entrainment rate of fluid above the current is inhibited. As a consequence, the turbidity current propagates much farther than would be expected without the dynamic effect of acceleration.

Plain Language Summary

Turbidity currents are underwater avalanches of suspended sediment. The largest known ones are found in the Congo Canyon off of the mouth of the Congo River in Africa. These currents propagate much farther and faster than can be explained by conventional theories of turbulence. A new theory is proposed, in which the turbidity current propagates much farther by virtue of entraining less clear water above it due to erosion of sediment beneath it. The erosion increases the average density of the current, which increases the rotation rate of the vortices. This rotational acceleration reduces the entrainment rate through a dynamic effect.

1 Introduction

Originally discovered after the sequential failure of transatlantic cables, turbidity currents play a central role in the transport of sediment in the continental shelf and out into intro-continental basins, abyssal plains, and deep lakes. Turbidity currents are a type of two-phase, density currents. In other contexts, lahars, powder snow avalanches, pyroclastic, and lava flows also obey similar physics (Meiberg et al. 2013).

These currents can be highly destructive. For example, Mt. Rainier in Washington state is regarded by the US Geological Survey as the most dangerous volcano in the US, primarily because of the threat of fast-moving lahars to descend from the mountain into densely populated valleys near Seattle and Tacoma. Such flows need not be triggered by any volcanic eruption. A simple slope failure can suffice. Avalanches kill on average about 28 people every year in the U.S. (Duffin 2020)

The strongest known turbidity currents are in the Congo Canyon off the west coast of equatorial Africa (Cooper 2013), transporting sediment a great distance. Conventional values of turbulent entrainment rates suggest that these currents should more promptly slow down and stop due to entrainment of ambient fluid (McElwaine 2019). It appears that some unknown physics is inhibiting the turbulent entrainment.

2 Background

After some triggering event such as a slope failure, a mass of sediment descends a submarine slope. The mixture is more dense than the surrounding pure fluid, so it forms a density current flowing down the slope. Baroclinic torques generate vorticity, and the flow is certainly turbulent at typical Reynolds numbers of roughly 10^6 or greater. The turbulent eddies entrain pure upper fluid, tending to dilute the mixture and reduce the density contrast. If the bed underneath the turbidity current is erodible, the current may incorporate additional sediment, tending to increase the density contrast. So there are two opposing effects that compete to alter the density difference.

The most important dimensionless parameter in buoyant flows is the Richardson number, the ratio of potential to kinetic energy. It is defined as follows:

$$Ri = g'\delta/W^2, \tag{1}$$

where

$$g' = g\,\Delta\rho/\rho \tag{2}$$

is the reduced acceleration of gravity, $\Delta\rho$ is the density difference between the current and the ambient fluid, ρ is the density, and g is the acceleration of gravity. The characteristic thickness and speed of the current are δ and W respectively. The entrainment velocity of the ambient fluid from above the current is v_a, and the bed erosion rate from below is v_b. Figure 1 is a sketch.

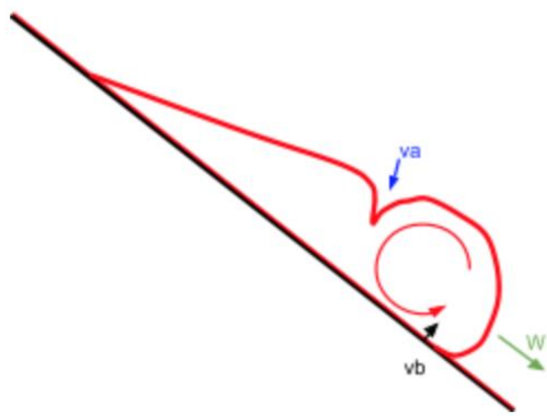

FIG. 1. Density current moves with speed W, eroding sediment at a speed v_b and entraining clear upper fluid at speed v_a

Buoyant flows tend to adjust themselves to achieve a Richardson number of approximately one, corresponding to an equipartition of energy between potential and kinetic. The flow does this by adjusting the speed, entraining fluid, and/or by shedding fluid (Turner 1973).

Entrainment plays the most important role in the dynamics of turbulent flows in general and of turbidity currents in particular. According to the entrainment hypothesis of Morton et al. (1956), the entrainment velocity is always proportional to the characteristic velocity of the flow, equivalent to saying that the entrainment velocity depends only on the largest eddy size. The hypothesis makes perfect sense when the largest eddy is the one doing the entraining.

However, the hypothesis fails when entrainment occurs by an eddy of size that is different from the largest. For example, in a stratified or compressible flow, the governing dimensionless parameter of Richardson or Mach number defines the size of the entraining eddy to be less than the largest. The entrainment hypothesis is no longer valid.

Just as the entrainment hypothesis fails when a smaller eddy does the entraining, it also fails under strong vortex acceleration. Here acceleration refers to acceleration of the rotational rate of turbulent eddies. First observed in the turbulent jet (Breidenthal 1986, Keto et al. 1987, and Zhang & Johari 1996), the theory was extended to all canonical turbulent flows (Breidenthal 2008). Counter-intuitively, the normalized entrainment rate decreases in all accelerating flows, except Rayleigh-Taylor.

In particular, acceleration effects can play a large role in buoyant flows. The first known example is the heated jet, a laboratory simulation of buoyancy-addition in cumulus clouds due to latent heat from phase change (Bhat & Narasimha 1996). They observed the spreading angle of an upward-moving vertical jet decrease as heat was added to it.

Note that the entrainment rate is reduced even when the rotation rate of the large eddy is still decreasing in time. What matters is the rate of decrease with respect to that of the unaccelerated flow.

A second example is a volcanic tunneling eruption (Bergantz & Breidenthal 2001). Based on the ultimate surface deposits, it appears that a magma chamber under a certain volcano initially contained magma A. At a later time, a second, distinct magma B containing more water in solution entered the chamber, and a volcanic eruption ensued. Remarkably, almost pure magma B erupted out of the volcano before magma A was deposited on top of the magma B deposit. Magma B somehow tunneled through the magma chamber without entraining much of the resident magma A. Vesiculation bubbles from water coming out of solution in magma B reduced its average density as it rose through the magma chamber. The entrainment rate was reduced by the resulting buoyancy change, due to acceleration effects. Magma B was able to tunnel through magma A with little entrainment or mixing.

Compared to the ordinary buoyant plume, the increasing buoyancy from the latent heat release generates additional baroclinic torques. Their induced velocities conspire to narrow the width of the engulfment tongues into the plume. Since turbulent entrainment is dominated by these tongues (Roshko 1976), the entrainment in accelerating plumes is thereby reduced, in some cases dramatically (Bhat & Narasimha 1996, Breidenthal 2006). For example, inside of thunderstorms, pure sea-level air can be transported up to the stratosphere essentially without dilution.

3 Model

Turbidity currents are not subject to a phase change, but nonetheless have a potential source of additional buoyancy. Erosion of particles from the bed underneath a turbidity current tends to increase the (negative) buoyancy and hence g'. In turn, this tends to increase the Richardson number. In order to maintain Ri = 1, the speed W tends to increase over what it would otherwise be, according to Eq. (1).

Increasing speed has two consequences. First, this permits additional erosion and continued suspension of bed particles into the flow. Second, the turbulent entrainment rate of pure, upper fluid into the current tends to be inhibited by acceleration effects.

Acceleration effects are quantified by a dimensionless acceleration parameter

$$\alpha = -d\tau_v/dt,$$

where τ_v is the vortex rotation period [10]. For an unforced turbulent flow, the vortex rotation period is essentially equal to the chronological age of the vortex, and α is just equal to its unforced value α^*

$$\alpha = \alpha^* < 0.$$

There may be acceleration effects even if the vortex rotation period is constant or increases only slowly in time. An example is the exponential jet, where the vortex rotation period is constant and equal to the e-folding time scale of the forcing (Zhang & Johari 1996). The spreading angle is reduced by about 20% compared to the unforced jet.

The rate of bed erosion is a very strong function of the flow speed (Bagnold 1936, Sekine & Nishimori 2008). This is necessary for an erosion feedback mechanism to increase the buoyancy.

According to this model of turbidity currents, sediment can propagate much further over an erodible bed than a non-erodible one. The increased exchange of momentum with the erodible bed is predicted to be more than counterbalanced by the reduced exchange of momentum with the fluid above via entrainment.

In the extreme limit of precisely zero entrainment rate, a turbidity current flowing down a constant slope of uniform, erodible bed particles would never stop. Its thickness would remain constant forever, as it is accelerated hydraulically. In general, to the extent that acceleration effects reduce the entrainment rate, the current would travel farther than otherwise.

The model is based on the fact that acceleration only affects the entrainment rate when the change in vortex rotation rate is appreciable during one vortex rotation, the time scale of importance to the dynamics of the vortex. So a turbidity current would only experience reduced entrainment from acceleration effects if the buoyancy continually increases. Once the normalized rate of increase in buoyancy falls below some threshold value, the acceleration effects are anticipated to disappear. The physics would revert back to the non-accelerating case, as observed in the turbulent jet (Zhang & Johari 1996).

Ambient fluid above the turbidity current is entrained at a rate v_a. In the limit of vanishing entrainment rate, the thickness of the turbidity current is approximately a constant, 0. The vortex rotation period is

$$\tau_v = \delta_0/W = (\tau_0 - \alpha t) = \sqrt{(\delta_0/g')}.$$

Thus

$$W = \delta_0/(\tau_0 - \alpha t) \quad (3)$$

and

$$g' = \delta_0/(\tau_0 - \alpha t)^2. \quad (4)$$

If the Richardson number is unity, the time rate of change of g' due to erosion is

$$dg'/dt = 2\alpha\delta_0/(\tau_0 - \alpha t)^2 = 2\alpha W^3/\delta_0^2. \quad (5)$$

The bed erosion rate v_b is approximately proportional to the cube of the friction velocity Bagnold 1936, Sekine & Nishimori 2008), in accord with eq. (5).

According to this model, a turbidity current under the right conditions might approach an acceleration regime of vanishing entrainment. The velocity and the buoyant force would increase rapidly in time, according to Eq. (3) and (4). Even if the limit of vanishing entrainment is not reached, acceleration effects may partially inhibit entrainment, thereby increasing the speed and the propagation distance over that of a non-eroding density current.

A competing explanation is that the internal stratification within the turbidity current is responsible for inhibiting the entrainment. The particle concentration and/or size is greater near the bottom of the current, so that the flow is somewhat stratified (Paull et al. 2018). Stratification is of course well known to inhibit turbulent entrainment (Turner 1973).

Parker et al. (1986) proposed a four-layer turbulence model that considers the energy of the flow under certain closure assumptions. Their model predicts the conditions under which the current will become "self-accelerating" in a linear sense. The present work suggests a physical mechanism for this transition, the dynamic effect of rotational acceleration on entrainment.

4 Conclusions

A new model for the dynamics of turbidity currents is proposed. In analogy with phase change in clouds and in vesiculating magmas, the bed erosion under a turbidity current may increase the buoyant force sufficiently rapidly to induce acceleration effects such that the rate of entrainment rate of upper fluid into the current would be reduced. Ironically, bed erosion would increase the propagation distance of a turbidity current. Further work will attempt to model the physics numerically. Simple lab experiments with and without an erodible bed will also address the issue.

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This theoretical manuscript contains no new experimental data.

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