Ocean Modelling 63 (2013) 30–39

Contents lists available at SciVerse ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Non-hydrostatic modeling of cohesive sediment transport associated with a subglacial buoyant jet in glacial fjords: A process-oriented approach

Julio Salcedo-Castro [a,*], Daniel Bourgault [b,1], Samuel J. Bentley [c,2], Brad deYoung [d,3]

[a] Instituto de la Patagonia, Universidad de Magallanes, Avenida Manuel Bulnes # 01895, Punta Arenas, Chile
[b] Institut des sciences de la mer de Rimouski, Université du Québec à Rimouski, 310 allée des Ursulines, Rimouski, Québec, Canada
[c] Department of Geology and Geophysics, Louisiana State University, E-235 Howe-Russell, Baton Rouge, LA 70803, USA
[d] Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, Canada NL A1B 3X7

ARTICLE INFO

Article history:
Received 13 July 2012
Received in revised form 30 November 2012
Accepted 1 December 2012
Available online 5 January 2013

Keywords:
Glacier
Convective sedimentation
Plume
Flocculation
Buoyancy
Non hydrostatic model
Sediment dynamics
Fjord

ABSTRACT

Fine sediment transport produced by a subglacial freshwater discharge is simulated with a 2D non-hydrostatic model. The circulation pattern revealed a buoyant jet issuing from the aperture representing the subglacial tunnel, a vertically buoyant plume and a surface gravity current forming part of an estuarine circulation. Momentum-dominated experiments are more sensitive to the presence of suspended sediment in the discharge. At low concentrations, the sediment stays in the vertical plume and surface gravity current, and its concentration is progressively decreased by mixing but no settling is observed through the water column. At high concentrations, the sediment settles in the far field and is transported back to the near field by the landward estuarine current. Sediment settled from the surface layer through convective sedimentation, a process that was more effective than flocculation to transport sediment vertically, and showed vertical velocities faster than 1.0×10^{-2} m s^{-1}. Implications of these results are discussed.

1. Introduction

Approximately one-tenth of the world coastlines are active glacimarine environments or environments where sediment is deposited after being discharged from glacier ice (Curran et al., 2004). Some of these glacimarine environments are glacial fjords (ice fields or glaciers in the hinterland), characterized by high inorganic sedimentation rates, with sediment discharges coming primarily from a single source (Syvitski and Murray, 1981; Curran et al., 2004).

Especially in temperate glacial fjords, during the melting season the estuarine circulation can be idealized as a subglacial buoyant jet which transforms into a buoyant wall plume rising along the glacier face, and a gravity current at the surface or mid-depth (Syvitski, 1989; Powell, 1990; Russell and Arnott, 2003; Salcedo-Castro et al., 2011). The vertical plume has a typical horizontal length scale $L \sim 1$ m, that is much smaller than the vertical scale of the plume which is roughly the fjord depth, i.e. $H \sim 100$ m. The freshwater forcing in glacial fjords is, therefore, highly non-hydrostatic because $H/L \gg 1$ (Marshall et al., 1997).

The behavior of the buoyant jet depends on the balance between the buoyancy flux, given by the density difference between the plume (ρ_0) and the ambient fluid (ρ_a), and the momentum flux, represented by the initial jet velocity u_0. This balance between buoyancy and momentum is represented by the Froude number (Syvitski, 1989; Powell, 1990; Russell and Arnott, 2003; Salcedo-Castro et al., 2011):

$$\mathrm{Fr} = \frac{u_0}{\left(g\,d\left(\frac{\rho_a - \rho_0}{\rho_0}\right)\right)^{1/2}}, \tag{1}$$

where d is the opening size, and g is the gravitational acceleration. Thus subglacial discharges can be buoyancy-dominated (Fr < 1) or momentum-dominated (Fr $\geqslant$ 1) (Syvitski, 1989; Powell, 1990; Salcedo-Castro et al., 2011).

The study of buoyant jets began with the classical work of Albertson et al. (1950), Abramovic (1963), and Abraham (1969). Along with these studies, the study on buoyant plane jets was undertaken by others (Anwar, 1973; Kotsovinos, 1976; Kotsovinos, 1977; Kotsovinos and List, 1977).

The first experimental and theoretical investigations about buoyant jets in confined depth (Jirka and Harleman, 1973; Jirka,

* Corresponding author. Tel.: +56 (61) 207080.
E-mail address: j.salcedo@mun.ca (J. Salcedo-Castro).
[1] Tel.: +1 (418) 723 1986.
[2] Tel.: +1 (225) 578 5735.
[3] Tel.: +1 (709) 864 8738.

1463-5003/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ocemod.2012.12.005

1982; Jirka and Harleman, 1979; Lee and Jirka, 1981) stated that the structure and dilution of a buoyant jet can be defined as function of three dimensionless parameters: the Froude number Fr, the relative depth H/d (where H is the total depth) and the vertical angle of discharge (θ). Jirka and Harleman, 1973 also showed that the jet stability depended on these three parameters, where a stable jet was defined as not showing re-entrainment and recirculation cells. This dependence of the structure, stability and mixing of a buoyant jets on Fr and H/d has been observed in horizontal buoyant jets (Jirka and Harleman, 1973; Jirka, 1982; Sobey et al., 1988) and vertical buoyant jets (Jirka and Harleman, 1979; Lee and Jirka, 1981; Wright et al., 1991; Kuang and Lee, 2001, 2006).

Syvitski (1989) has pointed out that the presence of a suspended sediment load increases the initial momentum and velocity of a buoyant jet but a significant settling velocity of particles will produce a more rapid decaying of the jet velocity than that observed in a jet containing only dissolved matter. Thus it is expected that the suspended sediment will affect the buoyant discharges differently, depending on whether they are buoyancy or momentum dominated. Studies of sedimentation in glacial fjords have, however, been primarily focused on bulk sediment, so little is known about fine, cohesive, sediment transport in spite of its predominance in these systems (Syvitski, 1989; Curran et al., 2004).

Whereas suspended fine sand and coarse silt sink as single grains, the settling of finer silt and clay is affected by flocculation and the existence of aggregates (Syvitski, 1989; Curran et al., 2004). The flocculation rate is primarily dependent on sediment concentration (Mehta, 1986; Dyer, 1995; Hill et al., 1998; Hill et al., 2000; Shi and Zhou, 2004; Liu, 2005), but it is also influenced to a lesser extent by salinity, turbulence and other factors (Winterwerp, 2002; Dyer et al., 2002).

Field and laboratory studies of sedimentation from buoyant jets and plumes have been mainly focused on non-cohesive sediments, where sedimentation rate depends fundamentally on particles settling velocity (Carey et al., 1988; Sparks et al., 1991; Bursik, 1995; Ernst et al., 1996; Lane-Serff and Moran, 2005). Recently, Lane-Serff (2011) modeled the deposition of cohesive sediment from buoyant jets and found that the settling velocity decreased as the sediment load decreased. Lane-Serff also observed that the deposition rate was lower near the source but higher further away as more sediment remained in the current for longer distances.

Another process that has recently been shown to influence the sediment transport associated with buoyant plumes is the convective sedimentation (McCool and Parsons, 2004). This is produced when the stratification hinders the descent speed of the sediment and, as a result, sediment concentrates along the pycnocline, until the region becomes gravitationally unstable and the inhomogeneities in the density field turn into convective cells (Hoyal et al., 1999; Parsons and Garcia, 2001; McCool and Parsons, 2004). Laboratory observations by Green (1987) about this "sediment fingering" showed that this process can be important especially in conditions of high sediment concentration, small particles and weak stratification. Parsons et al. (2001) stated that this convection occurred even at sediment concentrations as low as 1 kg m^{-3}, and one consequence of the convective instability of the original hypopycnal plume was the generation of a bottom turbidity current, or hyperpycnal plume that moved at moderate speeds over the bottom.

There have been some modeling efforts to study the sedimentation process in glacial fjords. Mugford and Dowdeswell (2007) used a stratigraphic simulation model that could link the environmental and climatic conditions to the geological formation of distinctive glacimarine deposits in Kangerdlugssuaq Fjord (Greenland) and McBride Glacier (Alaska). More recently, Mugford and Dowdeswell (2011) used a jet model and could reproduce some important features of the sedimentation in McBride Glacier (Alaska).

Most models used in oceanography consider the hydrostatic assumption that is justified when horizontal length scales L of the motion are several orders of magnitude larger than vertical length scales H (Cushman-Roisin, 1994). Hydrostatic models, however, are not suitable to simulate highly non-hydrostatic processes such as convection and high-frequency gravity waves (Marshall et al., 1997), shelf/slope convection, and buoyancy driven coastal jets (Gallacher et al., 2001; Shaw and Chao, 2006). Here we carry out a numerical study of cohesive sediment transport associated with buoyant discharges in glacial fjords, using a non-hydrostatic model, more suitable to the nature of this processes. We hope to capture some basic understanding about the sediment transport in glacial fjords, using a simplified configuration that does not include ambient stratification, ocean currents, or ice processes.

2. Methods

2.1. Experimental setting

We used a non-hydrostatic model developed by Bourgault and Kelley (2004). This is a two-dimensional, laterally averaged model and uses a finite-difference scheme with a variable-mesh z-coordinate C-grid. The model details and experimental configuration used here are described in Bourgault and Kelley (2004) and Salcedo-Castro et al. (2011), respectively.

The module for sediment transport in the model includes an equation for the advection–diffusion of sediment concentration,

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + (w + w_s)\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(\kappa_e \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(\kappa_e \frac{\partial C}{\partial z}\right), \quad (2)$$

where $C(x,z,t)$ is the sediment concentration, $\kappa_e(x,z,t)$ is the coefficient of eddy diffusivity, and w_s is the sediment settling velocity.

The following expression is included to account for the modification of the equation of state for density by the presence of sediments (Wang et al., 2005):

$$\rho = \rho_w + \left(1 - \frac{\rho_w}{\rho_s}\right)C, \quad (3)$$

where ρ_w is the density of water, and ρ_s is the density of sediment. Also, the model includes the following bottom boundary condition to represent the processes of resuspension and deposition (Partheniades, 1965; Kuijper et al., 1989; Markofsky and Westrich, 2007):

$$\kappa_e \frac{\partial C}{\partial z} - w_s C = E_b, \quad (4)$$

where:

$$E_b = \begin{cases} E_0\left(\frac{|\tau_b|}{\tau_c} - 1\right) & \text{if } |\tau_b| > \tau_c \text{ (resuspension)}, \\ C_b w_s\left(1 - \frac{|\tau_b|}{\tau_c}\right) & \text{if } |\tau_b| \leqslant \tau_c \text{ (deposition)}. \end{cases} \quad (5)$$

Here, E_b is the bottom sediment flux, E_0 is the erosion coefficient, C_b is the sediment concentration at the bottom layer, and τ_c is the critical stress for resuspension and deposition. The choice of the values for the parameters used here is shown in Table 1, which was based on representative values for cohesive sediment (McAnally and Mehta, 2001; van Rijn, 2007).

Table 1
Parameters used for sediment transport in the model.

Parameter	Value
ρ_s (kg m^{-3})	2650
ρ_w (kg m^{-3})	1000
w_0 (m s^{-1})	0.00001
E_0 (kg m^{-2} s^{-1})	0.0001
τ_c (Pa)	0.3