Ocean Modelling 113 (2017) 66–84

Contents lists available at ScienceDirect

Ocean Modelling

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

Flow splitting in numerical simulations of oceanic dense-water outflows

Gustavo M. Marques[a,*], Mathew G. Wells[b], Laurie Padman[c], Tamay M. Özgökmen[d]

[a] Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, New Jersey, USA
[b] Department of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, Canada
[c] Earth and Space Research, Corvallis, Oregon, USA
[d] Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

ARTICLE INFO

Article history:
Received 12 September 2016
Revised 11 March 2017
Accepted 19 March 2017
Available online 25 March 2017

Keywords:
Intermediate and bottom water formation
Internal hydraulic jump
Overflows
Gravity currents

ABSTRACT

Flow splitting occurs when part of a gravity current becomes neutrally buoyant and separates from the bottom-trapped plume as an interflow. This phenomenon has been previously observed in laboratory experiments, small-scale water bodies (e.g., lakes) and numerical studies of small-scale systems. Here, the potential for flow splitting in oceanic gravity currents is investigated using high-resolution ($\Delta x = \Delta z = 5$ m) two-dimensional numerical simulations of gravity flows into linearly stratified environments. The model is configured to solve the non-hydrostatic Boussinesq equations without rotation. A set of experiments is conducted by varying the initial buoyancy number $B_0 = Q_0 N^3/g'^2$ (where Q_0 is the volume flux of the dense water flow per unit width, N is the ambient stratification and g' is the reduced gravity), the bottom slope (α) and the turbulent Prandtl number (Pr). Regardless of α or Pr, when $B_0 \leq 0.002$ the outflow always reaches the deep ocean forming an underflow. Similarly, when $B_0 \geq 0.13$ the outflow always equilibrates at intermediate depths, forming an interflow. However, when $B_0 \sim 0.016$, flow splitting always occurs when $Pr \geq 10$, while interflows always occur for $Pr = 1$. An important characteristic of simulations that result in flow splitting is the development of Holmboe-like interfacial instabilities and flow transition from a supercritical condition, where the Froude number (Fr) is greater than one, to a slower and more uniform subcritical condition ($Fr < 1$). This transition is associated with an internal hydraulic jump and consequent mixing enhancement. Although our experiments do not take into account three-dimensionality and rotation, which are likely to influence mixing and the transition between flow regimes, a comparison between our results and oceanic observations suggests that flow splitting may occur in dense-water outflows with weak ambient stratification, such as Antarctic outflows.

1. Introduction

Oceanic outflows are large-scale density-driven currents generated either at high latitudes, where water density increases due to cooling and brine rejection from growing sea ice, or in subtropical marginal seas, where water density increases due to evaporation. These outflows have been widely studied (Legg et al., 2009; Price and Baringer, 1994), since they play an important role in establishing the large-scale circulation. In general, high latitude outflows, e.g. Denmark Strait outflow (Girton and Sanford, 2003), Faroe Bank Channel outflow (Mauritzen et al., 2005) and Antarctic outflows (Foldvik et al., 2004; Gordon et al., 2004; Muench et al., 2009), sink to the bottom of their respective basins, while outflows located closer to the equator, e.g., Mediterranea Sea outflow (Baringer and Price, 1997; Price et al., 1993) and Red Sea outflow (Matt and Johns, 2007; Peters et al., 2005), equilibrate at intermediate depths.

There is no clear observational evidence that major oceanic outflows, such as those discussed by Price and Baringer (1994) and Legg et al. (2009), can vertically split into two or more branches as a consequence of mixing and affect intermediate and deep layers simultaneously.[1] Nevertheless, flow splitting in smaller scale density-driven currents has been observed in lakes (De Cesare et al., 2006), in a Mediterranean reservoir (Cortés et al., 2014a) and in the Arctic Ocean (Aagaard et al., 1985). Given the difficulties in measuring oceanic outflows, especially at high latitudes,

---

* Corresponding author.
E-mail address: gmarques@princeton.edu (G.M. Marques).

[1] The Mediterranean outflow splits into two cores after the flow begin to descend into the Gulf of Cadiz, but this is a consequence of topographic steering (Baringer and Price, 1997). In the present work, focus is given to flow splitting induced by mixing rather than topographic effects.

http://dx.doi.org/10.1016/j.ocemod.2017.03.011
1463-5003/© 2017 Elsevier Ltd. All rights reserved.

and the fact that there are many processes acting in these flows concurrently (e.g., tides, hydraulic control, thermobaric effect and geostrophic eddies), it is possible that flow splitting could also take place in large-scale oceanic outflows but has not been identified. If that is the case, conceptual models developed to close the heat budget in the global overturning circulation (Hughes and Griffiths, 2006; Wåhlin and Cenedese, 2006; Wells and Wettlaufer, 2007) would have to be revisited, since they assume that large-scale high-latitude oceanic outflows only ventilate the abyssal ocean. Throughout this paper, we follow the terminology used by limnologists and classify the different flow regimes as interflow, underflow or split flow.

Much of what is known about dense outflows comes from numerous laboratory experiments of bottom gravity currents (Baines, 2001, 2005; Cenedese et al., 2004; Cenedese and Adduce, 2008; Cortés et al., 2014b; Ellison and Turner, 1959; Lane-Serff and Baines, 1998; Mitsudera and Baines, 1992; Monaghan, 2007; Simpson, 1999; Wells and Wettlaufer, 2007; Wells and Nadarajah, 2009). Ellison and Turner (1959) proposed a theory for the bulk properties of a density gravity current flowing into homogeneous ambient water. They showed that the entrainment velocity of the plume (W_e) could be represented as the product of the mean fluid velocity (U) and an entrainment parameter (E) that is an empirical function of the Richardson number (Ri) for the layer. Cenedese et al. (2004) added the effects of a rotating tank and found the development of three flow regimes (laminar, waves and eddies), where each of them has different mixing characteristics. In a follow-up study, Cenedese and Adduce (2008) showed that E also depends on the Reynolds number (Re), and not just on Ri as previously proposed by Ellison and Turner (1959).

For non-rotating gravity currents flowing down slopes and into linearly stratified environments, Mitsudera and Baines (1992) showed the development of a well-defined turbulent layer with up- and downslope streaming formed above the bottom current. These experiments also revealed the presence of cusp-shaped waves near the top of the slope, which were attributed to generation of Holmboe-like instabilities. Baines (2001) then proposed that these instabilities are responsible for the wisps of detrained fluid observed in laboratory experiments. These observations highlighted the different characteristics of the flow compared with experiments with homogeneous ambient stratification, and motivated additional laboratory experiments by Baines (2005, 2008). In the latter, ranges of ambient stratification frequencies (N) and slope angles (θ) were used and two main types of flow regimes emerged: 1) for sufficiently large θ, the flow was dominated by strong entrainment balanced by buoyancy force; and 2) for small θ, the flow detrained and the balance was mainly controlled by buoyancy force and bottom drag. Herein, we use $\alpha = \tan(\theta)$ to represent the slope of θ.

An additional flow regime, characterized by the splitting of the gravity current and the presence of both entrainment and detrainment, was also observed by Baines (2005, 2008) (Fig. 1), but it was not explored in detail and remains unexplained in continuously stratified environments. These different flow regimes were investigated in the context of a non-dimensional parameter, namely the initial buoyancy number (B_0):

$$B_0 = \frac{Q_0 N^3}{g_0'^2}, \tag{1}$$

where g_0' is the reduced gravity ($g_0' = g\frac{\Delta\rho}{\rho_0}$), Q_0 is the volume flux of the dense water per unit width at the top of the slope, g is the acceleration due to gravity, $\Delta\rho$ is the density difference between the outflow and the environmental fluid just above it, and ρ_0 is a reference density.

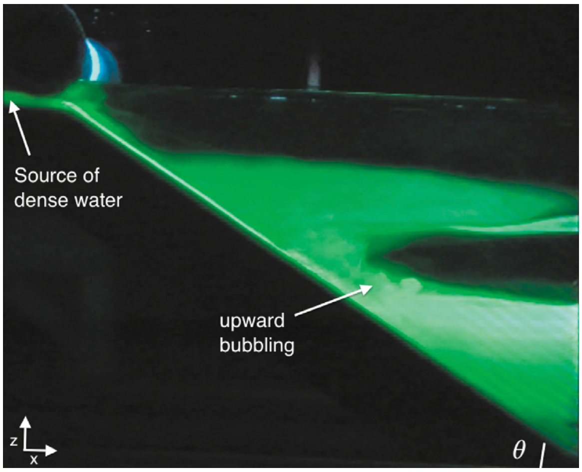

Fig. 1. An example of flow splitting observed in a non-rotating laboratory experiment where dense water flows down on a steep shelf slope ($\theta = 30\ ^{o}$) and into a linearly stratified ambient water (adapted from Baines, 2008). The fluid has been dyed with fluorescence and is illuminated by a thin laser beam that scans a central vertical section.

The flow splitting regime shown in Fig. 1 was observed in just two experiments with a very large angle ($\theta = 30^{o}$) and with intermediate values of B_0 (1.7 and 4.0×10^{-3}). It is characterized by the splitting of the main plume into two branches: a denser and less diluted plume at the bottom, and a less dense and more diluted plume located at intermediate depths.

Density flows can also be studied in numerical models. Guo et al. (2014) conducted numerical simulations of non-rotating laboratory-scale gravity currents descending a slope into a linearly stratified environment. Based on front positions, density and vertical velocity profiles, they showed that their simulations were in good agreement with laboratory experiments (Baines, 2001, 2005; Mitsudera and Baines, 1992). However, Guo et al. (2014) did not explore the flow splitting regime since their simulations were only run for a short time and just one of their experiments showed the beginning of a split scenario with blobs of dense water detaching from the main current (see their Figs. 3c and d). While there have been some numerical studies investigating flow splitting in two-layer systems (Cortés et al., 2015; Wobus et al., 2013), this type of flow has never been modeled in detail in a linearly stratified environment.

Additional insights can be gained from studies based on non-rotating laboratory experiments of dense water flowing down slopes into a two-layered ambient stratification (Cortés et al., 2014b; Monaghan, 2007; Wells and Wettlaufer, 2007). Three possible outcomes have been described for this setup (see Figs. 1a, b and c in Cortés et al., 2014b): 1) the flow separates from the bottom and forms an interflow; 2) the flow reaches the bottom of the domain and forms an underflow; or 3) the flow splits as it impinges into the single density step and forms two intrusions. The latter is the equivalent to the flow splitting in a linearly stratified environment shown in Fig. 1.

Motivated by observational evidence of flow splitting in a Mediterranean reservoir, Cortés et al. (2014b) conducted a series of laboratory experiments to investigate the splitting of a gravity current upon reaching a density interface. These authors proposed that flow splitting can be predicted based upon two non-dimensional parameters: the density Richardson number (Ri_ρ) and the densimetric Froude number (Fr). These numbers are defined as:

$$Ri_\rho = \frac{g_{12}' h_1}{B_f^{2/3}}, \tag{2}$$