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The role of periodically varying discharge on river plume structure and transport

Yeping Yuan[a,b,*], Alexander R. Horner-Devine[c], Margaret Avener[c,1], Shaun Bevan[c,2]

[a] Ocean College, Zhejiang University, Hangzhou 310058, China
[b] State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China
[c] Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195, USA

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ABSTRACT

We present results from laboratory experiments that simulate the effects of periodically varying discharge on buoyant coastal plumes. Freshwater is discharged into a two meter diameter tank filled with saltwater on a rotating table. The mean inflow rate, tank rotation period and density of the ambient salt water are varied to simulate a range of inflow Froude and Rossby numbers. The amplitude and the period of the inflow modulation are varied across a range that simulates variability due to tides and storms. Using the optical thickness method, we measure the width and depth of the plume, plume volume and freshwater retention rate in the plume. With constant discharge, freshwater is retained in a growing anticyclonic bulge circulation near the river mouth, as observed in previous studies. When the discharge is varied, the bulge geometry oscillates between a circular plume structure that extends mainly in the offshore direction, and a compressed plume structure that extends mainly in the alongshore direction. The oscillations result in periodic variations in the width and depth of the bulge and the incidence angle formed where the bulge flow re-attaches with the coastal wall. The oscillations are more pronounced for longer modulation periods, but are relatively insensitive to the modulation amplitude. A phase difference between the time varying transport within the bulge and bulge geometry determines the fraction of the bulge flow discharged into the coastal current. As a result, the modulation period determines the variations in amount of freshwater that returns to the bulge. Freshwater retention in the bulge is increased in longer modulation periods and more pronounced for larger modulation amplitudes.

1. Introduction

Coastal river plumes deliver nutrients and contaminants to the coastal ocean, impacting the productive and sensitive coastal ecosystem. In general, the river plume system is often described in terms of four dynamical regions, namely, source, near-field, mid-field and far-field regions (Garvine, 1984; Horner-Devine et al., 2015). The mid-field region is the transition from energetic jet-like near-field outflow into a geostrophic coastal current in the far-field region. Under sufficiently low wind conditions, river outflow leaving the near-field regions forms a two-part structure, with a bulge extending offshore just downstream (in the Kelvin wave sense) of the mouth, and a coastal current propagating in the downstream direction. The bulge is dominated by anticyclonic circulation (Northern Hemisphere) and grows indefinitely until altered by an external force such as an ambient current or wind. In the present study, we focus on this two-part structure under no wind condition, described as the prototypical plume in Horner-Devine et al. (2015). This structure has been observed in coastal discharges such as the Columbia River (Hickey et al., 1998; Horner-Devine et al., 2009), the Niagara River (Masse and Murphy, 1992; Horner-Devine et al., 2008), and the Hudson River (Chant et al., 2008), and has been seen in laboratory studies (Avicola and Huq, 2003a; Avicola and Huq, 2003b; Horner-Devine et al., 2006) and numerical models (Garvine, 2001; Fong and Geyer, 2002; Chen, 2014). It has also been described analytically (Nof and Pichevin, 2001). The buoyant water recirculating in the bulge can have residence times as long as 3 − 4 days (Horner-Devine, 2009), and the retention of nutrients in the bulge may support algal blooms and lead to low dissolved oxygen along the coast (Chant et al., 2008). For coastal discharges that exhibit this two-part structure, the rate at which buoyant water accumulates in the bulge, and the corresponding rate of transport away from the bulge, are key variables for understanding the role of the plume in the coastal ecosystem.

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* Corresponding author at: Ocean College, Zhejiang University, Hangzhou 310058, China.
E-mail addresses: yyping@zju.edu.cn (Y. Yuan), arhd@uw.edu (A.R. Horner-Devine), tue74176@temple.edu (M. Avener), shaun.bevan@hdrinc.com (S. Bevan).

[1] Current address: Department of Mathematics, Temple University, Philadelphia, PA 19122, USA.

[2] Current address: HDR, Inc.

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Buoyant coastal plumes can assume a wide range of geometries, varying predominantly in the aspect ratio (or, the bulge asymmetry), which is defined as the ratio between the cross-shore and alongshore bulge scales (L_{cross} and L_{along}, respectively). Horner-Devine et al. (2006) suggested that the aspect ratio is controlled by the ratio of inertial radius ($L_i = U/f$) and Rossby radius ($L_b = (2Q_{\text{in}}g'/f^3)^{1/4}$), where f is the Coriolis parameter, Q_{in} is the volumetric discharge rate, $g' = (\rho_0 - \rho_i)/\rho_0$ is the reduced gravity, ρ_0 is the density of the ambient salt water and ρ_i is the density of the freshwater inflow. High values of L_i/L_b indicate that the plume has a relatively higher initial offshore momentum, thus the bulge circulation movies offshore; while the bulge is held close to the wall when L_i/L_b is low. Plumes have been classified according to this aspect ratio in varying schemes by Garvine (1995), Yankovsky and Chapman (1997), Horner-Devine et al. (2006, 2015). In all of the above classification schemes the aspect ratio depends primarily on f, Q_{in}, and g'.

All of the above studies considered only constant discharge plumes. In reality, the flow rates of coastal discharges often change over time due to external forcing by tides, storms, and synoptic or seasonal variation in runoff. If all other parameters remain the same, high discharge creates a bulge that extends in the offshore direction (i.e., high aspect ratio), and is nearly perpendicular to the coastal wall when the flow reattaches at the downstream side of the bulge. Low discharge creates a bulge that extends preferentially in the alongshore direction (i.e., low aspect ratio), reattaching to the wall at a smaller angle. We refer to the configurations observed for high and low discharge plumes as circular and compressed plume structures, respectively. Conceptual pictures of these two plume types are shown in Fig. 1, where θ represents the angle of the bulge at the reattachment point, called as incidence angle (Avicola and Huq, 2003b, Horner-Devine et al., 2006; Chen, 2014). Here $\theta = 0$ indicates perpendicular reattachment. The case with $\theta < 0$ corresponds to the situation where the plume bulge has already became unstable and will eventually detach from the coast (Yankovsky et al., 2001), which is not considered in the present analysis. For positive θ, larger θ represents a plume in which the bulge is held closer to the wall (compressed plume structure) while smaller θ represents a plume in which the bulge is more offshore (circular plume structure). If the plume structure responds immediately to changes in discharge, then the variable discharge plume is expected to oscillate between a structure resembling that in Fig. 1c when Q_{in} is highest and one resembling that in Fig. 1b when Q_{in} is lowest.

Yankovsky et al. (2001) used a numerical model to investigate the impact of variable discharge on plume dynamics when the discharge varied at both the inertial period (12 h; i.e., $\tau_{\text{mod}} = 0.5\tau_{\text{rot}}$, where τ_{rot} is the earth's rotation period) and at a subinertial period of 10 days (i.e., $\tau_{\text{mod}} = 10\tau_{\text{rot}}$). At the inertial period, they saw no significant change in the structure of the bulge compared to constant discharge conditions. At the subinertial period, the bulge became distorted with its deepest point moving downstream and the lightest water pushed offshore. In some cases, particularly in the presence of an ambient coastal current, the bulge detached entirely and propagated downstream as an anticyclone. They compared their model to observations of this behavior both at the mouth of the Columbia River and south of the Hudson River estuary. They did not report on the freshwater retention in the bulge or the rate of transport away from the bulge using their numerical model.

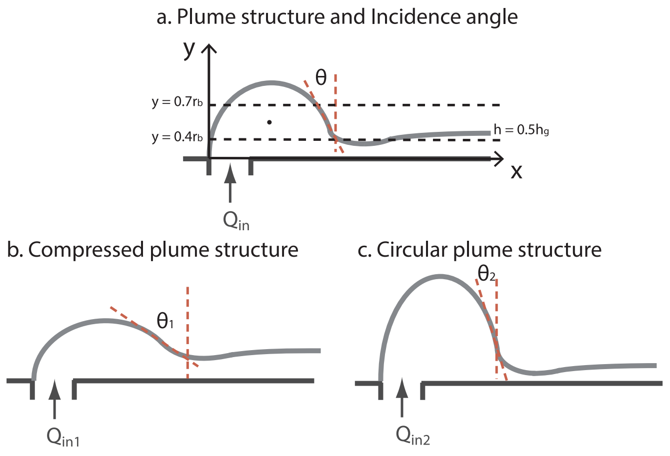

Fig. 1. Schematic of a) the typical plume structure and the definition of the incidence angle, b) inertial plume structure with high incidence angle, c) rotational plume structure with low incidence angle. Inflow discharge $Q_{\text{in1}} < Q_{\text{in}} < Q_{\text{in2}}$.

The intent of the work presented here is to examine the effects of variable discharge on a buoyant coastal discharge in a laboratory setting, at both inertial and subinertial periods. We explore a wide parameter space by varying f (given by $4\pi/\tau_{\text{rot}}$ in the laboratory), g', and Q_{in}, as well as τ_{mod} and ΔQ_{in}, where ΔQ_{in} is the amplitude and τ_{mod} is the period of the discharge variation, respectively. We categorize each run by the inflow Froude number ($Fr_{\text{in}} = U_{\text{in}}/\sqrt{g'h_{\text{in}}}$) and inflow Rossby number ($Ro_{\text{in}} = U_{\text{in}}/(fw_{\text{in}})$), where h_{in} and w_{in} are the inflow depth and width, respectively, and $U_{\text{in}} = Q_{\text{in}}/(h_{\text{in}}w_{\text{in}})$. Variable discharge runs are also characterized by a dimensionless modulation period, $\tau_{\text{mod}}/\tau_{\text{rot}}$, which compares the timescale of changes in discharge to the timescale of rotation. Using the optical thickness method (Holford and Dalziel, 1996; Cenedese and Dalziel, 1998), we directly measure the quantity and distribution of buoyant fluid in the bulge, and compare the rate of accumulation under conditions of variable discharge to that when discharge is constant.

We anticipate that discharge modulation may result in deformation of the bulge geometry, which modifies the flux of freshwater from the bulge to the coastal current according to the incidence angle theory introduced by Whitehead (1985) and later developed by Avicola and Huq (2003b) and Chen (2014). This may increase or decrease the alongshore flux, depending on the phasing of the geometric changes and the freshwater transport within the bulge. While it is also possible that changes in discharge may influence near-field mixing and subsequent alongshore transport, the present experiments are designed primarily to test the bulge geometry hypothesis.

It should be noted that tidal variability can have additional effects that are not considered here. There is evidence that alongshore tidal currents can act to stabilize the bulge (Isobe, 2005) or enhance the alongshore freshwater transport (Chen, 2014), that the eddies produced by tidal currents can strengthen and hasten the formation of the bulge (Chao, 1990), and that the estuarine mixing induced by tides can contribute to the formation of a more bottom-advected plume (Guo and Valle-Levinson, 2007). Our objective is not to consider these effects exhaustively, but rather to use a simple model to consider in isolation the effects of variation in discharge on plume structure and dynamics.

2. Materials and methods

Experiments were carried out in the University of Washington's Harris Hydraulics Laboratory in an annular tank (inner radius = 22 cm, outer radius = 92 cm) atop a rotating table (Fig. 2). Details of the table can also be found in Horner-Devine et al. (2006). The table was filled to a depth of 20 cm with salt water, brought to the desired rotation rate for a given run, and left spinning at that rate for 60 min before the run to achieve solid body rotation, which is sufficiently larger than the homogeneous spin-up time scale $E^{-1/2}f^{-1}$ = 5 min (Yuan et al., 2011), where $E = \nu f^{-1}H^{-2}$ is the Ekman number, where ν is the water viscosity. During the run, a Plexiglas lid covered the tank to prevent unwanted evaporation and wind shear over the water surface.

Freshwater was stored in a plastic basin on the rotating table. The freshwater inflow was typically driven by a magnetic drive impeller pump or a gear pump. The voltage input to the pump was pulse-width modulated using a micro-controller, such that the resulting flow rate varied nearly sinusoidally. The inflow entered the tank at the surface of the ambient salt water through a 5 cm wide, 1 cm deep mouth in a