

Numerical Study on River Plumes on a Southern Hemisphere Coast

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ABSTRACT

Coastal rivers often generate buoyant plumes at their mouth following high inflow rate events. This coastal water, especially in flooding season, collects freshwater runoff with a large number of sediments, which significantly affects the environment of the continent shelf. In the present study, the dynamics of a plume on a Southern Hemisphere coast has been studied using a 3D hydrodynamic model. It is found that a seaward bulge forms and tends to move leftwards. Based on the results of modeling simulations, the plume under relative small coastal current is classified as subcritical. And plume size increases in proportion to river discharge.

KEY WORDS: Plume; dynamics; Southern Hemisphere; numerical modeling; river discharge.

INTRODUCTION

The freshwater from the coastal rivers, accompanied by sediment and nutrients, runs into the continental shelf where the suspended material is deposited. The river flow plume, as shown in Fig. 1, is one of major visual phenomena in the process of the freshwater discharge. The water circulation and transport in the plume can influence the sediment dynamics, the coastal circulation, and the ambient ecosystem health.

Many studies have focused on the development of river plumes in the Northern Hemisphere. Boicourt (1973) viewed the freshwater discharged from the Chesapeake and Delaware Bays, and found that the freshwater left a distinct trace toward the right and formed the downstream current in the vicinity of the river mouth at the same time. Similar behavior has been observed in the laboratory by Stern et al. (1982). Later, a three-dimensional numerical model was first used as a powerful tool to simulate the evolution of the river plume by Chao and Boicourt (1986), and the results of simulations have shown that the plume spreads in the direction of Kelvin propagation with a bulge of anticyclonic surface flow.

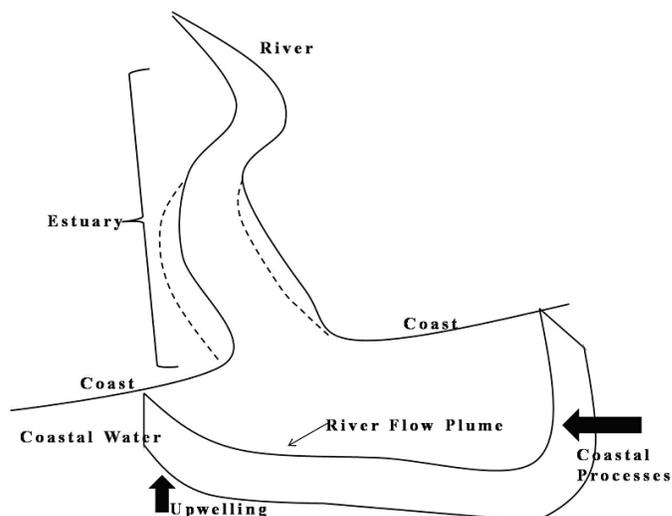


Fig. 1 Sketch of the dominant pathways of water in the estuary. Modified from Wolanski et al, (2007).

In recent years, more specific studies on the large river discharge in the Northern Hemisphere have examined river discharge and wind forcing on plumes, such as the plumes in the Columbia (Fulton, 2007), the Pearl River Estuary (Yin, et al., 2004; Ou et al., 2009), the western Gulf of Maine (Fong et al., 1997), the Rhone River (Naudin et al., 1997). Fulton (2007) analyzed the effects of the Columbia River plume's circulation on the Oregon shelf and demonstrated that alongshore and cross-shore momentum transports are greatly affected by river discharge. Ou et al. (2009) categorized the plume in the Pearl River Estuary into four major types, according to the different surface spread, and found that both the river discharge and the wind conditions are the vital factors affecting the plumes evolution. Fong et al. (1997) and Naudin et al. (1997) both found the winds also affected the plume's spread.

In order to analyze the plume behavior, previous studies have introduced several scaling analysis criteria to definite the surface shape

of the plume. Chao (1988) introduced the non-dimensional parameter λ_r , the ratio of width of the offshore bulge to the coastal current, to characterize the river plumes. When λ_r is greater (less) than 1.7, the river plume has defined as supercritical (subcritical). If λ_r was close to 1, the river plume might mix with high eddy viscosity diffusion (Kourafalou et al., 1996). Ou et al. (2009) analyze the surface spread of the river plume in virtue of λ_r and λ' , where λ refers to the ratio of the maximum length of spreading upwards to downwards. The Rossby number, R_o , has been used by Fong and Geyer (2002) to characterize the shape of the plume's bulge. For higher Rossby numbers, the bulge shape was more circular than low Rossby number plumes.

Since the rivers with larger discharge like Amazon River and Mississippi River attract the most attention, main studying on plumes has focused on the Northern Hemisphere coast. Few studies, however, have looked at the river plumes in the Southern Hemisphere. It is of great importance to obtain a better understanding of river plume hydrodynamics, especially in flood season, as the river plume has significant impacts on the aquatic environment and human health in Australian coast waters (Wolanski et al., 2007). In the present study, a 3D hydrodynamic model is applied to examine the behavior of the river plume in the Southern Hemisphere. The Mike3, as one product of DHI package, operates three-dimensional, primitive equation model, which is applicable to simulations of flows in coastal areas and seas (DHI, 2003).

MODEL SET-UP

The model domain is determined to be a rectangular basin with a flat bottom of 50 m depth implicitly with the river mouth indicated by point A, as shown in Fig. 2 and Fig. 3. Freshwater is discharge into this model domain that is full of ocean water via the river mouth. The horizontal grid resolution is 3 km both in the cross-shore and alongshore direction; vertical grid resolution is 1 m, and simulation period lasts 26 days with stepped in 30-s steps.

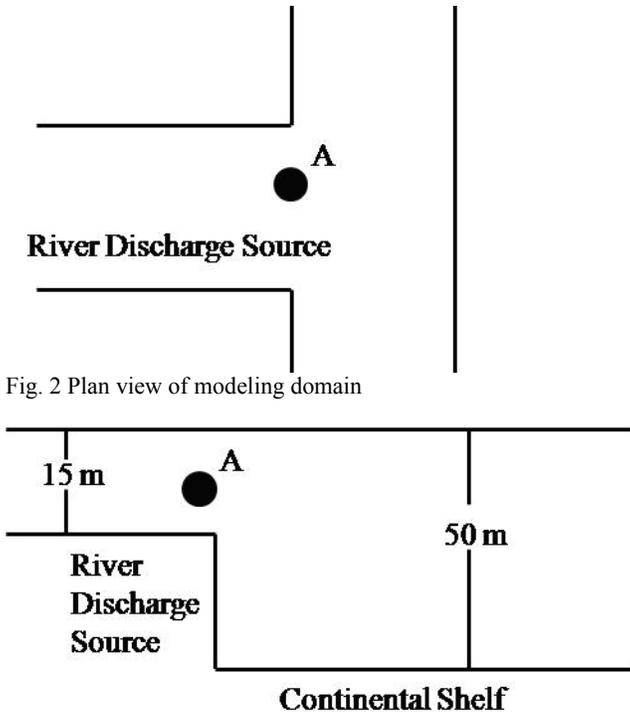


Fig. 2 Plan view of modeling domain

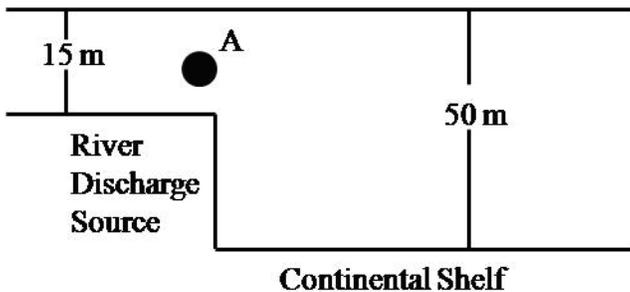


Fig. 3 Cross-section view at river mouth

The river inflow is of uniform density and discharges with uniform velocity. In this study, the influence of tides and wind are ignored, and the temperatures of both the river discharge and ambient coastal water remain unchanged at 17°C, while the salinity is the time dependent variable. The salinity values of ambient coastal and the river inflow are set as 32 and 20 psu respectively. Correspondingly, the salinity isohaline of 30 psu is chosen to be the offshore boundary of the river plume. Four plume dimension parameters are illustrated in Fig. 4, where L and L_c represent the width of the bulge area and upstream current respectively, and L_u is defined as the length of the upper part of the bulge, while L_d describes the length of the lower part of the bulge.

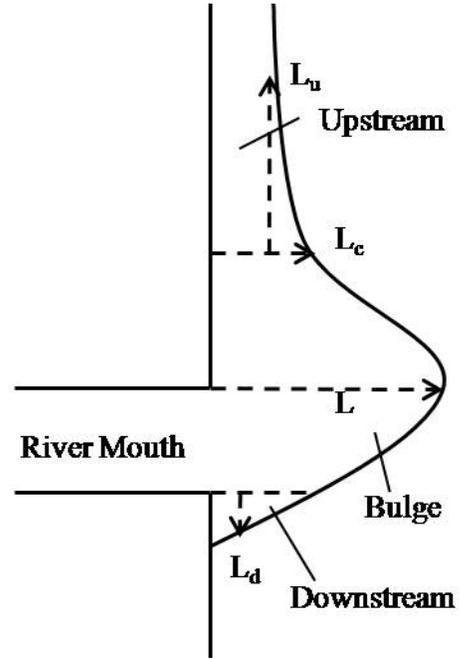


Fig. 4 Diagram of plume within a bulge and coastal current

Following previous studies (Chao 1988; Fong and Geyer 2002; Ou et al. 2009), the non-dimensional parameters, λ_r , λ and R_o are used to classify the river plume structure:

$$\lambda_r = \frac{L}{L_c}, \lambda = \frac{L_u}{L_d} \text{ and } R_o = \frac{u_i}{fL_i} \quad (1)$$

where u_i is the velocity of the river discharge; f is the Coriolis force parameter, and L_i is the width of the river mouth.

PLUME DYNAMICS

There are a great number of factors which significantly affect the evolution of the river plume, such as the bathymetry, the Coriolis force, the river discharge, winds, tides and other coastal processes. Some of them are discussed below.

Plume Characteristics

The spreading of the river plumes at different river discharge rates, within the first 14 days, is displayed in Fig. 5. It is important to note that the background current is only 0.01 m/s for all the plums

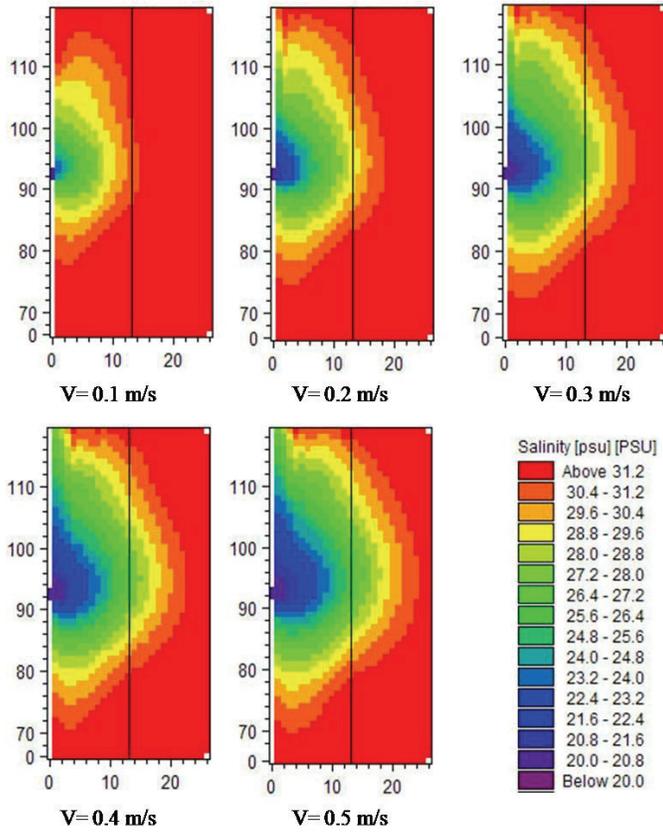


Fig. 5 The evolution of river plumes at river discharge rates

Generally, the inflowing buoyant is observed to form a bulge near the river mouth and develop an upstream current alongshore, as shown in Fig. 5. According to the definition in Fig. 4 and Eq. 1, the horizontal characteristics of the river plumes listed in Table 1 are analyzed.

Table. 1 Characteristic parameters of river plumes

V (m/s)	L (km)	L_c (km)	L_u (km)	L_d (km)	λ_r	λ	R_o
0.1	33	30	45	24	1.1	1.87	0.62
0.2	45	45	60	36	1	1.66	0.85
0.3	54	54	72	51	1	1.41	1.04
0.4	57	57	78	60	1	1.30	1.26

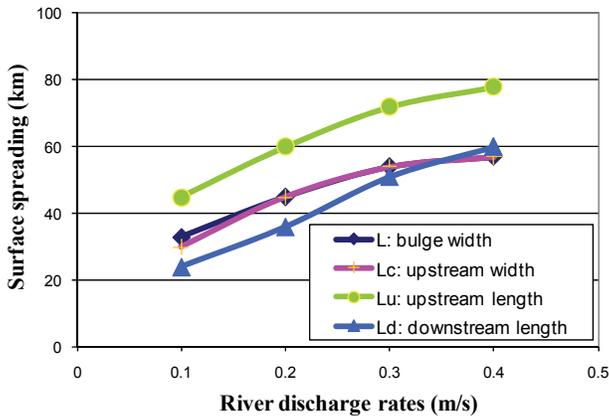


Fig. 6 Surface spreading of river plume at different river discharge rates

The Fig. 6 exhibits the surface spreading distance of different parts of the plume. It is easy to find every part of the plume becomes larger with increasing river discharge rate, especially the downstream region. On the other hand, the bulge and upstream almost keep the same width as each other, although the river discharge changed greatly.

For $\lambda_r \approx 1$, as shown in Fig. 7, the river plumes are typically subcritical; that is, the plume spreads alongshore more rather than offshore (Chao 1988). With the increasing velocity of river discharge, this development tendency still does not change. As suggested by Ou et al. (2009), when $\lambda > 1$, the river plumes are classified as upstream offshore plume with $L_d < L_u$ for all discharge rates. It can be seen when the river discharge increases, λ decreases, but is still greater than 1. Fong and Geyer (2002) indicates that shape of bulge is becoming more circular with higher R_o , such as higher river discharge rate. Basically, the outcomes by analysis of λ_r , λ and R_o agree well, and are also very close to the simulation results in Fig. 5

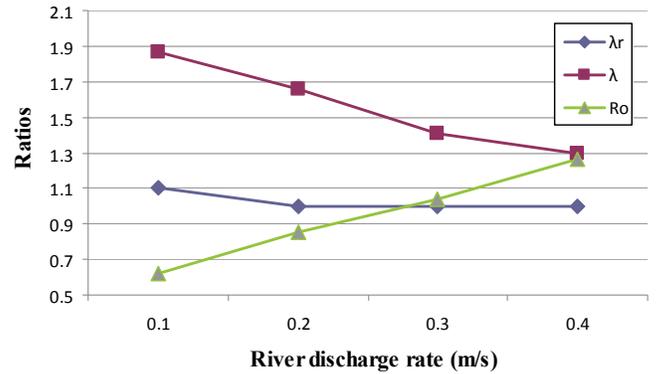


Fig. 7 Three types of ratios at different river discharge rates

The Influence of Coriolis Force

Many of the previous studies (e.g., Fong and Geyer 2002) have concluded that the buoyant discharge turned rightward in the Northern Hemisphere without other forces, due to the Coriolis force. In contrast, the river plumes observed in this study show that the river inflow turns leftward under anti-clockwise Coriolis force in the Southern Hemisphere, as shown in Fig. 8.

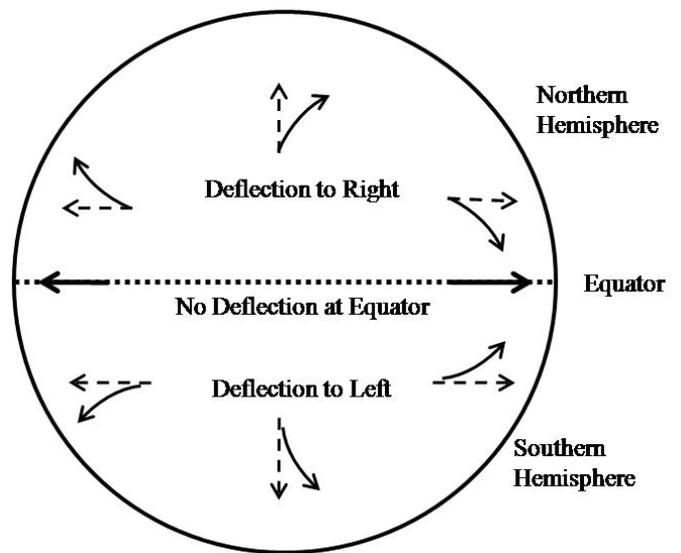


Fig. 8 Coriolis force

The bulge circulation driven by Coriolis force can be formed on the upper layer in the vicinity of the river mouth (Chao 1988). Additionally, a typical mid-latitude value for f is 10^{-4}s^{-1} on the earth; hence the Coriolis force acts similarly for the plumes located mid-latitude in the different hemisphere, except to change the inflowing water's direction.

The Influence of River Discharge

It is well documented that river discharge is one of the major forces to determine the plume size; that is, the plume size and the river discharge are well correlated (Walker 1996; Ou et al. 2009). The relationship has also been confirmed by analyzing the simulation results in this study.

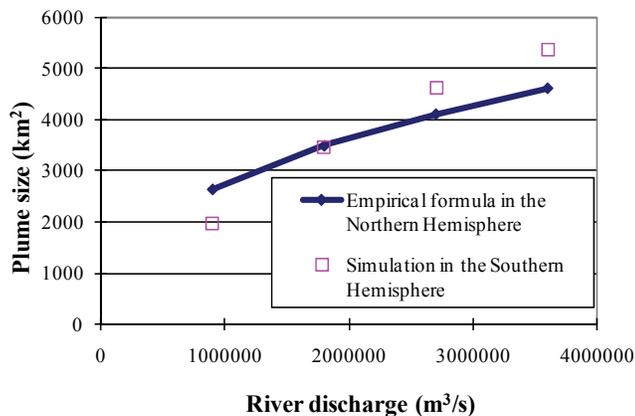


Fig. 9 The relationship between the river discharge and the river plume size

Fig. 9 shows the relationship of plume size from the numerical results and the river discharge, which is calculated using $Q \equiv \iint v dA$, where V refers to the river discharge rate and A refers to the size of the plume. On the other hand, the results from empirical formula $P \approx \alpha Q^{\beta/0.85}$ (Warrick and Fong, 2004), where the location-based parameter $\alpha=400$ and $\beta=0.3$ (Ou et al. 2009) in the Northern Hemisphere, are employed to compare with the numerical results.

With the contrast of the results from these two methods in Fig. 9, it is obvious that the plume size increases typically with the river discharge increasing. However, it has to be mentioned that the same amount of river discharge makes a greater contribution to the plume size in Southern Hemispheres than Northern Hemisphere. In addition, Fig. 7 shows that the increasing rivers discharge, on the one hand, give the same support to the areas of bulge and upstream offshore; on the other hand, it gives much more support to the extension of downstream region compared with the upstream.

Additionally, analysis of λ_r , λ and R_o above also indicates that river discharge affects the surface spreading of the plume. It is particular that for higher R_o discharge conditions, the higher river discharge makes the surface plume more symmetrical, which is similar to the Northern Hemisphere (Fong and Geyer 2002).

CONCLUSIONS AND FUTURE WORK

A numerical model has been used to investigate the dynamics of a river plume on a Southern Hemisphere coast. The dynamic influences of the

Coriolis force and the river discharge on the evolution of the buoyant plume have been discussed. The modeling simulation results have shown that these influences in the Southern Hemisphere are different to the Northern Hemisphere. As expected the anti-clockwise Coriolis force in the Southern Hemisphere drives the river inflow left in vicinity of the river mouth, and the river discharge is closely connected to the plume size; that is, the plume size increases with the river discharge. Compared with the same plume properties in the Northern Hemisphere, the river discharge gives larger contributions to increase the plume size in the Southern Hemisphere Based on the current conclusion, while there are some further work should be done. It plans to find another method to verify the results of numerical simulations such as mathematical calculation.

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