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Simulation of river plume behaviors in a tropical region: Case study of the Upper Gulf of Thailand

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ABSTRACT

River plumes are a general phenomenon in coastal regions. Most previous studies focus on river plumes in middle and high latitudes with few studies examining those in low latitude regions. Here, we apply a numerical model to the Upper Gulf of Thailand (UGoT) to examine a river plume in low latitudes. Consistent with observational data, the modeled plume has seasonal variation dependent on monsoon conditions. During southwesterly monsoons, the plume extends northeastward to the head of the gulf; during northeasterly monsoons, it extends southwestward to the mouth of the gulf. To examine the effects of latitude, wind and river discharge on the river plume, we designed several numerical experiments. Using a middle latitude for the UGoT, the bulge close to the river mouth becomes smaller, the downstream current flows closer to the coast, and the salinity in the northern UGoT becomes lower. The reduction in the size of the bulge is consistent with the relationship between the offshore distance of a bulge and the Coriolis parameter. Momentum balance of the coastal current is maintained by advection, the Coriolis force, pressure gradient and internal stresses in both low and middle latitudes, with the Coriolis force and pressure gradient enlarged in the middle latitude. The larger pressure gradient in the middle latitude is induced by more offshore freshwater flowing with the coastal current, which induces lower salinity. The influence of wind on the river plume not only has the advection effects of changing the surface current direction and increasing the surface current speed, but also decreases the current speed due to enhanced vertical mixing. Changes in river discharge influence stratification in the UGoT but have little effect on the behavior of the river plume.

1. Introduction

In coastal regions, the discharge of freshwater from rivers is one of the principle sources of buoyancy. Through formation of a river plume with a sharp density gradient between the buoyant freshwater and sea water, two notable characteristics emerge in the Northern hemisphere: an anticyclonic bulge in the vicinity of the river mouth and a downstream (in a Kelvin wave sense) coastal current (Chao and Boicourt, 1986). The behavior of the plume is influenced by a variety of factors, including wind (Fong, 1998; Dzwonkowski et al., 2014), the Coriolis force (Kasai et al., 2000; Fong and Geyer, 2002), ambient currents (Fong and Geyer, 2002), tides (Guo and Valle-Levinson, 2007; Horner-Devine et al., 2009), thermal stratification (Wang et al., 2008) and river discharge (Yankovsky et al., 2001; Wang et al., 2011; Dzwonkowski et al., 2014).

Most studies on river plumes are based on observations or model analysis conducted in middle or high latitude regions, such as the Chesapeake Bay (Pritchard, 1952, 1954; Guo and Valle-Levinson, 2007), Delaware Bay (Münchow and Garvine, 1993; Wong, 1994), the Columbia River (Horner-Devine et al., 2009), and the Yellow River (Wang et al., 2008, 2011). However, fewer studies examining river plume behaviors have been conducted in regions of low latitude. Low latitude regions have a small Coriolis parameter, enormous discharges of freshwater and distinctive wind patterns (Nittrouer and DeMaster, 1996). All of these factors make the behavior of river plumes in low latitudes significantly different from those in middle and high latitudes.

The main focus on tropical rivers has been on the Amazon River (Lentz and Limeburner, 1995; Lentz, 1995a, 1995b; Nittrouer and DeMaster, 1996), which discharges freshwater at the equator. Differing from river plumes in middle latitudes, which deflect to the right by the Coriolis force in the Northern Hemisphere, the Amazon River plume extends leftward to the north Brazilian shelf between the equator and 5°N under the superposition effects of the low latitude location, strong tides and easterly trade winds (Lentz, 1995a; Nittrouer and DeMaster, 1996). There are also other rivers in low latitude regions, not just around the equator, but between the equator and middle latitudes.

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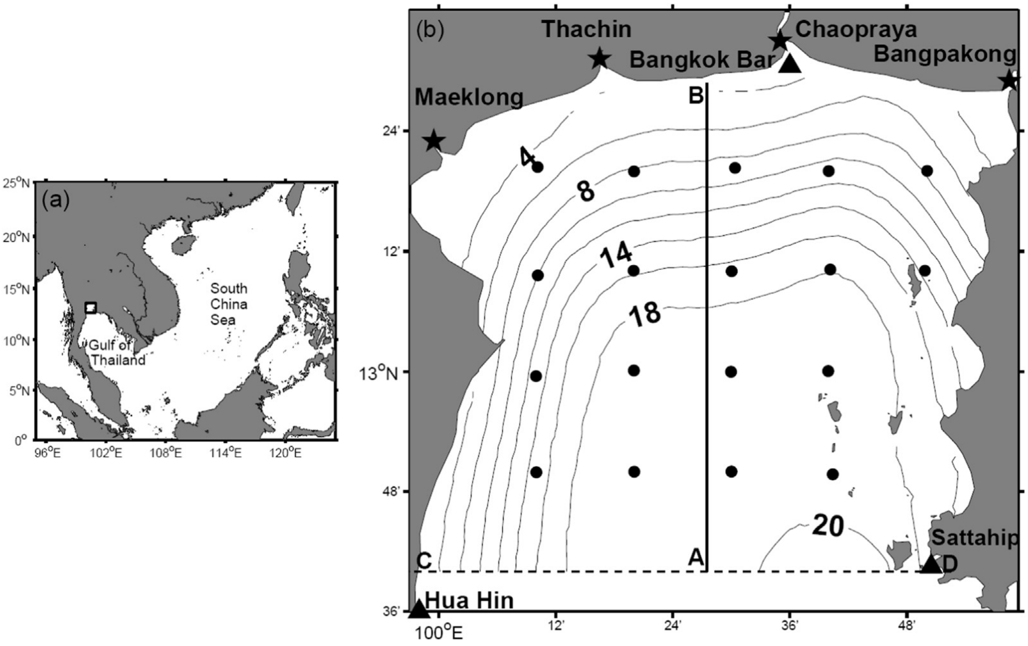

Fig. 1. (a) Location and (b) bathymetry (m) of model domain in the Upper Gulf of Thailand (UGoT). Stars indicate the positions of the river mouths of the Maeklong, Thachin, Chaopraya, and Bangpakong, respectively. Solid circles show the stations where observational data are available for 2014 and 2015. Triangles indicate observation stations for tidal harmonic constants, namely Hua Hin, Sattahip and Bangkok Bar, respectively. Section AB is indicated by the solid line. Line CD shows the position of the open boundary of the model.

They may not be subject to persistent large river inflows and easterly trade winds, but have seasonal variations in river discharge and wind patterns such as those in middle latitude regions. Here, we examine the behavior of a river plume in a tropical region, the Upper Gulf of Thailand (UGoT, Fig. 1), which has seasonal variations in river discharge and is subject to monsoons.

The UGoT, which is a semi-enclosed shallow sea located in a tropical region at about 13°N, has characteristics of estuarine-like systems due to large freshwater discharges. The sea is surrounded by land on the eastern, northern and western sides and is connected to the main Gulf of Thailand at its southern boundary (Fig. 1a). The maximum depth is approximately 20 m in the southeastern part of the UGoT. Four rivers, namely, the Maeklong, Thachin, Chaopraya and Bangpakong from west to east (Fig. 1b), discharge freshwater into the gulf. The seasonal variation in discharges of these rivers is apparent, with smaller discharges from December to May and larger discharges from June to November. The UGoT is also subject to monsoons with dry northeasterly winds from November to January and wet southwesterly winds from May to September.

A study on the seasonal variation of water column conditions in the UGoT (Buranapratheprat et al., 2008) revealed that strong stratification develops in September and October when river discharge is large and heat flux is moderate, while the water column becomes well mixed in December and January due to surface heat loss, lower discharge from rivers and strong inputs of wind stress. Using a three-dimensional model, Buranapratheprat et al. (2009) showed that monsoons determine seasonal circulation in the UGoT, which is clockwise during southwesterly monsoons and counter-clockwise during northeasterly monsoons. However, they did not pay special attention to the dynamics of river plumes in the UGoT. Using a numerical model, Saramul and Ezer (2014) evaluated dynamics in the UGoT, which are influenced by surface heat flux, river runoff, and low latitude. They found that the extension of river plumes differs under different monsoon conditions. The larger Coriolis parameter in middle latitudes in their model likely pushes the plume farther along the west coast and makes the plume near the river mouth less axisymmetric. However, the larger Coriolis parameter cannot lead the plume to turn more to the right, for which they did not give an explanation. Due to insufficient information on the river plume in the UGoT, as well as the potential contribution of river water-induced stratification to the generation of hypoxia (Green et al., 2006), which could have severe consequences on the coastal ecosystems in the UGoT, it is necessary to enhance our understanding of the distribution of the river plume in the UGoT and its contribution to stratification. In this study, our objective is to investigate the dynamics responsible for the river plume and stratification in the UGoT, including the influences of low latitude, wind and river discharge, through three-dimensional numerical modeling.

In Section 2, we briefly introduce *in situ* data collected in the UGoT and model configuration. After comparison of the model results with observational data, the modeled behaviors of the river plume and the induced stratification in the UGoT under monsoons will be described in Section 3. In Section 4, we examine the influences of low latitude, wind and river discharge on the river plume in the UGoT through a series of numerical experiments. The study is summarized in Section 5.

2. Observational data and model description

Water temperature and salinity data were collected at 0.1 m intervals through the entire depth at 18 stations (black points, Fig. 1b) once in August, September, November and December 2014 and in February, April and June 2015 in the UGoT. Using these observational data, we determined seasonal variations in the horizontal and vertical distributions of water temperature and salinity, thereby identifying the presence of a river plume.

In order to understand the distribution and controlling factors of the observed river plume, we developed a numerical model for the UGoT. The model is based on the Princeton Ocean Model (POM), which is a three-dimensional, primitive equation, sigma-coordinate model (Blumberg and Mellor, 1987; Mellor, 2003). The vertical diffusivity coefficients are calculated by a second momentum turbulent closure scheme (Mellor and Yamada, 1982), and the horizontal diffusivity coefficients are parameterized by the Smagorinsky formulation (Smagorinsky, 1963). The model domain and bathymetry are shown in Fig. 1b. Spatial resolution is ~1 km in the horizontal direction and 21 sigma layers in the vertical direction, with higher resolution in the surface and bottom layers than in the middle layer.

For external forcing, we consider monthly heat flux (Fig. 2a), monthly river discharges (Fig. 2b), and monthly wind stresses (Fig. 2c), all of which represent climatologic conditions and are from Buranapratheprat et al. (2008). The net heat flux is the sum of the sensible heat flux, latent heat flux, long wave radiation and short wave radiation, and has small seasonal variation with a maximum value in