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Effect of waves on the dispersal of the Pearl River plume in winter

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ABSTRACT

Waves, by enhancing surface wind stress and bottom stress, increasing water mixing, and creating water currents, play an important role in modifying the dispersal of river plumes. In this study, we used the COAWST modeling system to study the effects of waves on the dispersal of the Pearl River plume during winter. The waves help retain freshwater in the nearshore western shore and simultaneously displace the river plume further downstream in a down-wave direction. We distinguish the wave effects by analyzing their four components and the associated changes in freshwater transport. Among the four wave effects, the wave-induced enhancement of bottom stress is the most important process influencing the Pearl River plume along the western shore, followed by the enhancement of surface stress and the 3D wave forces. While for the mainstem of the estuary, enhancement of surface wind stress and bottom stress, the 3D wave forces are all important in altering the freshwater transport and saltier water intrusion.

1. Introduction

A river plume transports river-borne materials from the land to the ocean. Its dispersal largely determines the fate of these materials and greatly influences the coastal ocean circulation and ecosystem. Several factors, including river discharge, tides, earth's rotation, winds, waves, and internal processes, such as stratified-shear mixing, frontal dynamics, and geostrophic transport, influence river plume dispersal (Horner-Devine et al., 2015). Among the external forcings, the effects of river discharge, tides, earth's rotation, and winds on river plume dynamics have been intensively studied (Chao, 1988a, 1988b, 1990; Fong and Geyer, 2001; Lentz, 2004; Choi and Wilkin, 2006; Guo and Valle-Levinson, 2007; Jurisa and Chant, 2012; Moffat and Lentz, 2012; Cole and Hetland, 2016; Jiang and Xia, 2016). In contrast, the effects of waves are less well understood, although Horner-Devine et al. (2015) emphasized their important role in the mixing and transport of river plumes.

The structure and extent of a river plume is determined by the mixing and advective transport processes that occur as the freshwater empties into an estuarine embayment or the coastal ocean (Hetland, 2005; Hetland, 2010; Horner-Devine et al., 2015). Surface waves affect river plumes through four physical mechanisms: wave-enhanced surface wind stress, wave-enhanced bottom shear stress, wave-enhanced water mixing, and excessive momentum fluxes, hereinafter referred to as the 3D wave forces (Rong et al., 2014). Surface wind stresses are influenced by the wave-related sea state, with surface roughness increased by waves, scaling with either wave steepness (Hsu, 1974), or wave age (Donelan, 1990). Through bottom boundary dynamics, wave–current interactions increase the bottom friction felt by ocean currents (Madsen, 1994). Surface gravity waves affect the water surface boundary layer through wave–current interactions (e.g., Langmuir circulation), Stokes shear instabilities, and wave breaking (Sullivan and Mcwilliams, 2010). The enhanced turbulent kinetic energy due to these processes increases the water surface mixing, which penetrates downwards into the water column (Burchard, 2001). The variations in wave height and direction generate excessive momentum fluxes, which, mathematically, can be expressed either in a gradient stress tensor (Mellor, 2003, 2008) or in a vortex form formalism (McWilliams et al., 2004) and physically, can generate water level setup/setdown (Longuet-Higgins and Stewart, 1962) and water currents (Longuet-Higgins, 1970). Among the four physical mechanisms by which waves can influence river plume dispersal, the effects on the bottom and surface boundary layers are related to the elevated roughness and enhanced mixing, whereas changes in water currents and in the advective transport process of river plumes are due to the wave-induced Stokes drift and 3D wave forces induced Eulerian current. In the Coupled-

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Ocean-Atmosphere-Wave-Sediment Transport (COAWST) (Warner et al., 2010) modeling system, which is adopted here, the wave-induced current is a Lagrangian one, a summation of Stokes drift and Eulerian current (Kumar et al., 2012).

Despite the potential importance of wave effects in determining river plume dynamics (Horner-Devine et al., 2015), this topic is not well investigated. Gerbi et al. (2013) studied the effect of wave breaking on the river plume dynamics by incorporating surface wave breaking into the turbulence closure model. Rong et al. (2014) investigated the effect of current–wave interactions on the Mississippi–Atchafalaya river plume in the Texas–Louisiana shelf. Delpey et al. (2014) studied the effects of waves on the river plume dispersal in a small estuarine bay. Most recently, Akan et al. (2017) studied the impact of wave–current interactions on the Columbia River plume dynamics.

In this work, we investigated the effect of waves on the dispersal of the Pearl River plume within the South China Sea. The Pearl River plume features distinct seasonal variations under different river discharge and wind forcings (Dong et al., 2004). The effects of varying river discharge, tides and winds on the plume's dynamics have been intensively studied (Wong et al., 2004; Zu and Gan, 2007; Pan et al., 2014; Lai et al., 2015, 2016; Chen et al., 2016) whereas the effects of waves remain poorly understood. In this study, we investigated the effects of waves on the plume dynamics in the winter season, from November to February, when river discharge is smallest and the winds are strong and downwelling-favorable. Because of the stronger winds, the wave effects are expected to be more significant in the winter than in the summer, from May to September, when the winds are milder and upwelling-favorable. These conditions differentiate our study from Gerbi et al. (2013), whose focus was on the wave mixing effect under upwelling-favorable winds. It is also different from the studies by Gerbi et al. (2013), by Rong et al. (2014) and by Akan et al. (2017), who investigated river plumes within the continental shelf, because the wintertime Pearl River plume is already fully developed inside the Pearl River Estuary (Dong et al., 2004; Zu and Gan, 2007). This means that the wintertime Pearl River plume is more constrained by the geometry and bathymetry inside the estuary relative to the river plumes considered in the other studies.

Bearing these characteristics in mind, we used the COAWST modeling system to examine the effect of waves on the Pearl River plume dynamics, especially on its freshwater transport. Our main objectives are to: 1) reveal the effects of waves on the dispersal of an estuarine river plume; 2) explore the processes and mechanisms responsible for these effects; 3) distinguish the roles of four different physical processes of the wave effects in affecting the river plume's dispersal and make a comparison to other systems.

This paper includes a description of the study area, followed by a brief introduction of how the COAWST modeling system is implemented in the study site. Using the COAWST model, we investigate the changes in the Pearl River plume dynamics caused by waves. To unveil the mechanisms behind these changes, we analyze the effects of waves on surface and bottom stresses, water mixing/stratification, circulation and freshwater transport. Several idealized numerical experiments were conducted to elucidate the effects of waves traveling in different directions. The roles played by different processes of the wave effects were distinguished through diagnostic model studies. Lastly, we contextualized our results by comparing them to other relevant studies.

2. Study site and implementation of COAWST

2.1. The Pearl River Estuary (PRE)

The Pearl River, located in southern China, is the second largest river in China in terms of river discharge. It transports large amounts of freshwater ($3260 \times 10^8\ m^3/a$), sediments ($8872 \times 10^4\ t/a$) and nutrients through three estuaries in the Pearl River Delta before flowing into the northern South China Sea (Hu et al., 2011). The PRE is the largest of the three estuaries (Fig. 1a) and receives, through four outlets, over half of the freshwater and sediment loads from the Pearl River (Huang and Zhang, 2004). The Humen, Jiaomen, Hongqili and Hengmen Outlets receive, respectively, 25.1%, 12.6%, 11.3%, and 14.5% of the total river discharge from the Pearl River based on statistics from 1960 to 2005. The fate of these river-borne sediments and nutrients is largely determined by the dispersal of the Pearl River plume.

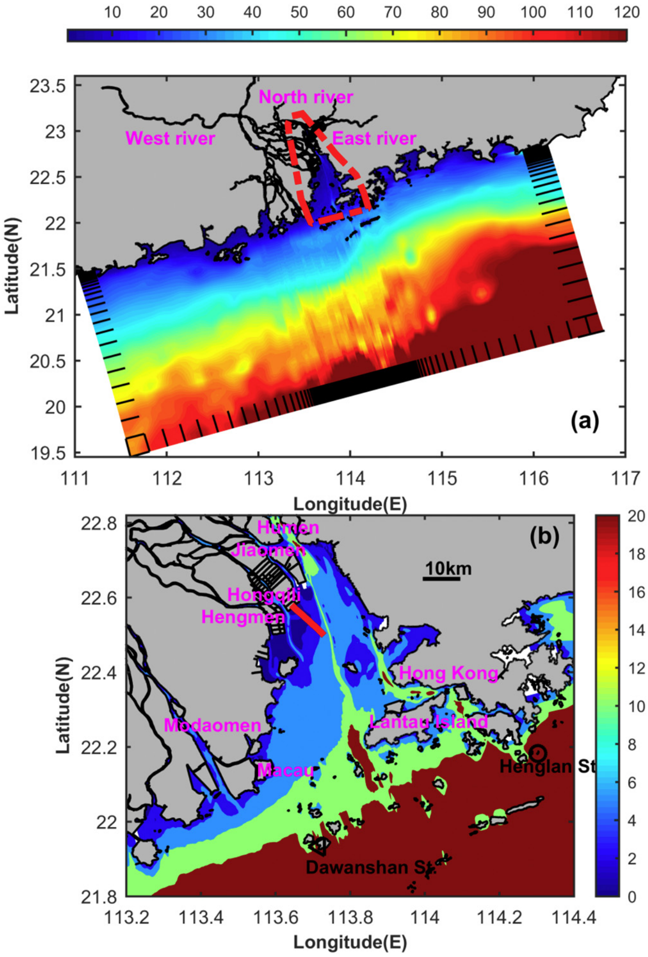

Fig. 1. a) The study site and model domain. The West, North, and East Rivers are three branches of the Pearl River, creating the Pearl River Network in the Pearl River Delta (PRD). The red dashed box is the region of the PRE. b) Bathymetry of the PRE. The two green stripes in the PRE show the locations of the West and East Channels; adjacent to the two channels are the West, Middle, and East Shoals. Sections and station for analysis. The red line shows the cross-section for identifying changes in freshwater thickness and seaward current on affecting the changes in freshwater transport. The triangle depicts the wave measurement station, while the circle denotes the wind station in Hong Kong. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The PRE (Fig. 1b) is funnel-shaped. Its width increases from 6 km at the Humen Outlet, the head of the estuary, to ~50 km at its mouth, between Hong Kong and Macau. The axial length of the estuary is approximately 70 km. Its bathymetry is complicated, and is characterized by two channels (West Channel and East Channel, with depth > 5 m) and three shoals (West Shoal, Middle Shoal, and East Shoal), each < 5 m deep. The West Shoal, a shallow region along the western shore, comprises several tidal flats and marshes formed by deposited river sediments. The West Channel is > 10 m deep, and the depth of the East Channel varies between 5 and 15 m. The tidal river extends ~50 km beyond the head of the estuary.