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Cruise observation and numerical modeling of turbulent mixing in the Pearl River estuary in summer

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ABSTRACT

The turbulent mixing in the Pearl River estuary and plume area is analyzed by using cruise data and simulation results of the Regional Ocean Model System (ROMS). The cruise observations reveal that strong mixing appeared in the bottom layer on larger ebb in the estuary. Modeling simulations are consistent with the observation results, and suggest that inside the estuary and in the near-shore water, the mixing is stronger on ebb than on flood. The mixing generation mechanism analysis based on modeling data reveals that bottom stress is responsible for the generation of turbulence in the estuary, for the re-circulating plume area, internal shear instability plays an important role in the mixing, and wind may induce the surface mixing in the plume far-field. The estuary mixing is controlled by the tidal strength, and in the re-circulating plume bulge, the wind stirring may reinforce the internal shear instability mixing.

1. Introduction

1.1. Estuary and plume mixing

The river water carries abundant inland nutrients and micro-elements that may enhance primary productions in the estuary and near-shore areas. Due to their importance in coastal ecological environments, the estuary and plume waters have been investigated for decades by using cruise survey data, theoretical analysis, and numerical modeling, as well as physical model experiments in the laboratory. Turbulent mixing is one of the most important dynamical characteristics of estuary and near-shore waters, and plays a vital role in the dispersion of terrestrial water enriched with nutrients, micro-elements, sediments, pollutants, etc. in ambient coastal waters.

In the estuary and near-shore waters, the turbulent mixing is mainly generated by bottom stress, internal shear instability, and wind effect (Kay and Jay, 2003; MacDonald and Geyer, 2004; MacDonald and Horner-Devine, 2008; Ralston et al., 2010). The estuary and plume circulations and stratification may greatly affect the mixing status. In strongly stratified estuaries, observations and modeling results revealed that the mixing is stronger on ebb than on flood and primarily interfacial, and the interfacial mixing is driven by the shear stress between an active surface layer and an inactive salt-wedge layer, as demonstrated by a supercritical internal Froude number on ebb (Kay and Jay, 2003; MacDonald and Horner-Devine, 2008; Ralston et al., 2010; Jay and Smith, 1990). For partially or weakly stratified estuaries, the turbulent mixing is forced by the bottom stress and strengthens on flood (Peters, 1999; Stacey et al., 1999; Trowbridge et al., 1999; MacCready and Geyer, 2001; Chant et al., 2007). The extended salinity intrusion may cause higher salt flux during peak ebb although mixing is lower on ebb for a partially stratified estuary (MacCready and Geyer, 2001). The bottom stress may be enhanced near irregular topography and sills. It was found that in the Merrimack River estuary, a highly stratified salt wedge type, the mixing induced by bottom stress exceeds that induced by the internal shear, and is a main source of turbulence (Ralston et al., 2010).

1.2. The Pearl River plume

Although there are a number of studies on estuary and plume water mixing, different rivers have their own characteristics. As the third largest in China, the Pearl River flows into the northern South China Sea (SCS) through eight gates, namely, Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen, and Yamen (Dong et al., 2004). The Pearl River discharge reaches up to 20,000 $m^3\ s^{-1}$ in summer due to high precipitation upstream, and

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decreases to 3600 $m^3 s^{-1}$ in winter under dry condition. The Pearl River plume exhibits two basic flow patterns: in summer with the southwesterly monsoon, the low-salinity Pearl River plume water spreads eastward; in winter under the northwesterly monsoonal wind, the low salinity plume water turns westward along the Guangdong coast (Ma et al., 1990). The spreading path of low-salinity water of the Pearl River depends on winds, inshore sea surface heights, and runoffs (Xue et al., 2001).

Some basic characteristics of the Pearl River plume that were investigated in Pan et al. (2014) revealed the role that wind and tidal forcing play in determining plume dynamical properties. As with other plumes, the Pearl River plume also consists of a plume near-field and a far-field (Horner-Devine et al., 2009; Jay et al., 2009). The Pearl River plume anatomy, however, changes with wind patterns. Under the southeasterly (SE) wind, the plume has a near-field of a tidal plume and a re-circulating bulge and a far-field of westward, alongshore currents, while under a strong southwesterly (SW) wind, the re-circulating plume disappears, and the plume system consists of only a tidal plume in the near-field and a far-field plume extending eastward. Numerical modeling results suggested that the advection is enhanced during spring tides under both SE and SW winds in the tidal plume region. Thus, the Froude number is higher in the spring tide than in neap tide, and therefore, the spring tide facilitates a supercritical tidal plume, which is consistent with observation results (Pan et al., 2014).

In the flow field, the near-shore water is controlled by the plume near-field circulation, while the offshore current is forced eastward by the SCS Warm Current which flows eastward year-round in the northern SCS (Gu et al., 2012; Pan et al., 2014). Under the SE wind, corresponding to the re-circulating plume bulge, a sub-tidal, anti-cyclonic circulation appears outside of the estuary mouth. Under the SW wind, the re-circulating bulge disappears, and the surface water flows eastward driven by the SCS Warm Current. In the bottom layer, the current is mainly determined by the year-round SCS Warm Current in the offshore region. Wind has less influence on the bottom current, but may reduce the northeastward current velocity when the SE wind prevails. When under the SW wind, strong salt water intrusion is observed in the lower estuary. The SE wind weakens the surface outflow and causes the river water to pile at the up-end of the estuary, and the associated pressure gradient subsequently drives a seaward bottom flow which can decrease the bottom intrusion of the density gradient current (Pan et al., 2014). Thus, under the SE wind, the salt intrusion is weaker than that under the SW wind, and this asymmetry may affect the density structure in the estuary.

1.3. Scope of this study

Compared with other major river systems, the Pearl River has been insufficiently investigated, and the plume dynamics have been poorly understood. There are still a lot of unclear issues, such as the mixing characteristics in the estuary and near-shore area. In this paper, we focus on clarifying the turbulent mixing in the estuary and plume waters, understanding driving mechanisms for the mixing, and exploring how the plume and estuary water mixing responds to tidal and wind forcing. This study is an extension and continuation of our previous investigation on the Pearl River plume, which focused more on the plume anatomy and circulation (Pan et al., 2014).

The remainder of the paper is organized as follows. Section 2 describes the cruse observation, and Section 3 presents the configuration of numerical modeling. The turbulent mixing is analyzed in Section 4, and mixing-driven mechanisms are investigated in Section 5 based on modeling results, followed by discussions on the effects of wind and tide on the mixing status in Section 6. The summary is given in Section 7.

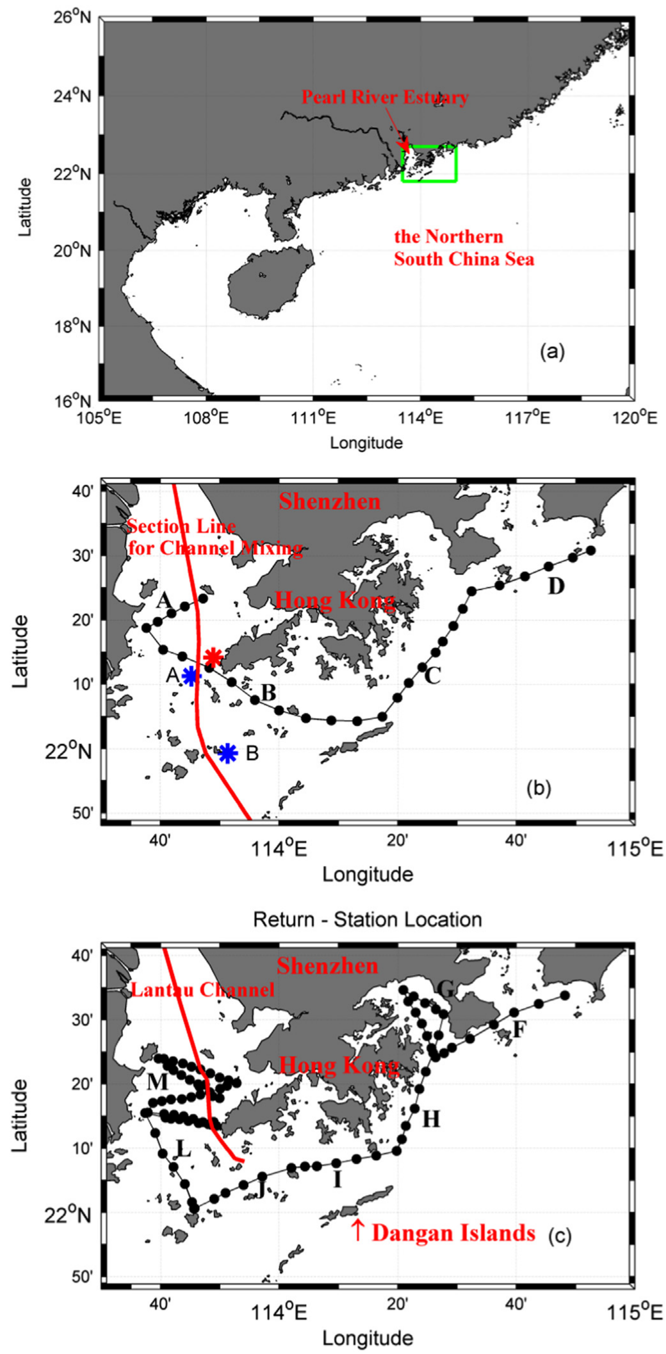

Fig. 1. The study area in a large context (a). Cruise transects and CTD sampling stations (solid dots) for outgoing (b) and returning (c) surveys of the 2012 cruise. The red asterisk and the red line in (b) shows the mooring observation location and section line for channel mixing (Fig. 6), respectively. The red line in (c) illustrates the Lantau Channel. Asterisks A and B in (b) denote the locations in the tidal plume and the plume re-circulating bulge, respectively, at which the mixing characteristics are analyzed. The green box in (a) specifies the spatial extent of (b) and (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Cruise observation

A sea cruise survey to collect in-situ data in the Pearl River estuary and the near-shore region had been implemented from 4 to 14 June 2012. Fig. 1a shows the location of the Pearl River estuary in a large context. Cruise transects and CTD cast stations are displayed in Fig. 1b and c. In the first half of the cruise period, the cruise sampled the water from the estuary east of Hong Kong