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Response of salinity distribution around the Yellow River mouth to abrupt changes in river discharge

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ABSTRACT

To investigate how salinity changes with abrupt increases and decreases in river discharge, three surveys were conducted along six sections around the Yellow River mouth before, during and after a water regulation event during which the river discharge was increased from $\sim$200 to $>$3000 m^3 s^{-1} for the first 3 days, was maintained at $>$3000 m^3 s^{-1} for the next 9 days and was decreased to $<$1000 m^3 s^{-1} for the final 4 days. The mean salinity in the Yellow River estuary area during the event varied $\sim$1.21, which is much larger than its seasonal variation ($\sim$0.50) and interannual variation ($\sim$0.05). Before the event, a small plume was observed near the river mouth. During the event, the plume extended over 24 km offshore in the surface layer in the direction of river water outflow. After the event, the plume diminished in size but remained larger than before the event. The downstream propagation of the plume (as in a Kelvin wave sense) was apparent in the bottom layer during the second survey and in both the surface and bottom layers during the third survey. The plume sizes predicted by the formulas from theoretical studies are larger than those we observed, indicating that factors neglected by theoretical studies such as the temporal variation in river discharge and vertical mixing in the sea could be very important for plume evolution. In addition to the horizontal variation of the plume, we also observed the penetration of freshwater from the surface layer into the bottom layer. A comparison of two vertical processes, wind mixing and tidal mixing, suggests that the impact of wind mixing may be comparable with that of tidal mixing in the area close to the river mouth and may be dominant over offshore areas. The change in Kelvin number indicates an alteration of plume dynamics due to the abrupt change in river discharge during the water regulation event.

1. Introduction

River plumes are a general phenomenon in coastal water. They are affected by many factors, including the inertial effect at the river mouth, Coriolis force, winds (Fong, 1998; García Berdeal et al., 2002; Choi and Wilkin, 2007), ambient currents (Fong and Geyer, 2002; Xing and Davies, 2002), tidal currents (Isobe, 2005; Guo and Valle-Levinson, 2007), local topography (Kourafalou, 2001; Xing and Davies, 2002), stratification (Kourafalou, 1999; Wang et al., 2008) and river discharge (Pullen and Allen, 2000; Kourafalou, 2001; Yankovsky et al., 2001; Choi and Wilkin, 2007). The competition of these factors results in a variety of behaviors and time scales in river plumes.

Among the factors affecting river plumes, the river discharge and its temporal variation are particularly important. River discharge varies over many time scales. The longer time scales can be interannual or seasonal, whereas shorter time scales can last only several days, such as during a flood. Hereafter, we refer these short time scales as abrupt changes in river discharge.

Compared to the interannual or seasonal variations in river discharge, it is difficult to understand the influence of abrupt changes in river discharge on salinity distributions from field observations. Interannual and seasonal variation in salinity can be monitored by monthly or seasonal routine hydrographic surveys. However, the variation in salinity with an abrupt change in river discharge is difficult to capture with such routine surveys. In addition, an abrupt change in river discharge is often caused by a heavy precipitation event accompanied by bad weather conditions. The strong winds that coincide with bad weather conditions

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not only limit a field survey but also strongly affect the evolution of a plume.

The Yellow River (see Fig. 1 for the position) is one of largest rivers in the eastern Asian marginal seas. During the past several decades, its annual discharge has decreased gradually, partly due to climate change and partly due to human use (Wang et al., 2006), resulting in an unbalanced relationship between water and sediment inside the river and an increase in the salinity of the Bohai Sea (Wu et al., 2004). During 2002–2004, the Yellow River Conservancy Commission (YRCC) carried out a series of water regulation experiments to reshape the coordinative relationship between water and sediment by artificially releasing a large amount of water in a short time. Usually, a water regulation event last for only two weeks but the river discharge during the event accounted for greater than 20% of the annual discharge. Since 2005, water regulation events have been conducted regularly at the beginning of every flood season.

The salinity around the Yellow River mouth is expected to change dramatically with a large river discharge during a water regulation event, but the changes have not been well documented. With an interest in sediment transport, Wang et al. (2005) have reported that the plume near the river mouth containing high sediment moved rapidly during the water regulation event in 2005. Using a numerical model, Mao et al. (2008) have suggested that the variations in Yellow River runoff, including runoff during water regulation events, are important to the salinity not only in the area around the river mouth but also in the entire Bohai Sea. Based on a box model, Zhao et al. (2010) have examined the effects of water regulation events on the mean salinity of the Laizhou Bay, a semi-enclosed bay located southwest of the river mouth (see Fig. 1 for its position).

Treating the water regulation event as an opportunity to observe the response of a plume to an abrupt increase and decrease in river discharge, we carried out three surveys and measured the salinity and temperature around the Yellow River mouth before, during and after the water regulation event in 2009. After describing our observations in Section 2, we report the salinity distributions from our three surveys in Section 3 and discuss them in Section 4. Our conclusions are presented in Section 5.

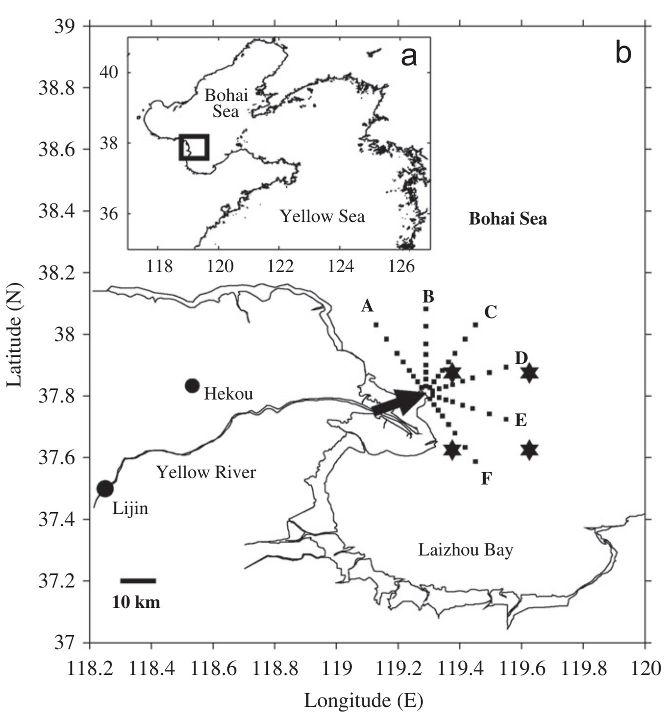

Fig. 1. (a) Location of the survey area and (b) the positions of the six sections, represented by characters A–F. The arrow denotes the outflow direction of the Yellow River water. Squares denote stations for salinity and water temperature measurements. Stars denote grid points for wind data from QuikSCAT.

2. Field observations

For the water regulation event of the Yellow River in summer of 2009, the river runoff recorded at Station Lijin (see Fig. 1b for its position), the nearest hydrological station to the river mouth ($\sim$100 km away), increased from 230 $m^3 s^{-1}$ on June 22 to 3170 $m^3 s^{-1}$ on June 24. After a runoff larger than 3000 $m^3 s^{-1}$ was maintained for 9 days, the runoff decreased from 3135 $m^3 s^{-1}$ on July 3 to less than 1000 $m^3 s^{-1}$ on July 7 (Fig. 2). Corresponding with the variation in river discharge, we carried out three surveys on June 19, July 1 and July 19, which were before, during and after the water regulation event, respectively (Fig. 2). The distance between Lijin Station and the Yellow River mouth may have caused a time lag of $\sim$10 h between the record of river discharge and its arrival time at the Yellow River mouth during the water regulation event. Because our goal was to observe the subtidal movement of the plume, this time lag was neglected.

Six sections were arranged over a semicircle centered at the river mouth. Each section consisted of eight stations (Fig. 1) that were relatively denser near the river mouth. Three fishing boats were employed, with each covering two sections. The boats started at the same time and finished all the sections within $\sim$10 h. The water temperature and salinity were measured by conductivity–temperature–depth profilers (CTDs).

A large amount of river sediment always flows into the sea during a regulation event and causes a change in bathymetry around the river mouth (Wang et al., 2005). We also found slight changes in water depth at some stations during our survey period. However, such changes in bathymetry had essentially no influence on the plume observations because the maximum difference in water depth was less than 10% of the whole depth.

In addition to the *in-situ* hydrographic data, daily satellite wind data from QuikSCAT Level 3 Daily, Gridded Ocean wind Vectors (see Fig. 1 for data positions; data were available from http://podaac.jpl.nasa.gov/DATA_PRODUCT/OVW/index.html#quikscat) and daily precipitation data observed at the Hekou weather station (see Fig. 1b for its position), which is the nearest weather station to the study area, were also used in this study.

3. Results

3.1. Variability in the horizontal distribution of salinity

The first survey was carried out on June 19, 2009, when the river discharge was low (173 $m^3 s^{-1}$). Before the water regulation event, low salinity water was concentrated in the northern region of the Yellow River mouth in only the surface layer (Fig. 3a). Because the salinity was relatively high, water with salinity lower than 26, which will be used to define the plume front in the second and third surveys, was rarely identified in the results of the first survey.

The second survey was on July 1, 2009, when the river discharge was high (3600 $m^3 s^{-1}$) and a high river discharge had been maintained for several days (Fig. 2). During the water regulation event, the surface salinity at most of the stations decreased dramatically, and low salinity water spread offshore far from the river mouth (Fig. 3d). The low salinity water in the