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Horizontal Characteristics of Buoyant Plume off the Pearl River Estuary during Summer

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ABSTRACT

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Field measurements of salinity from 1978 to 1984 are used to investigate the horizontal structure of the Pearl River buoyant plume during high river discharge. According to the characteristics of horizontal salinity distribution in summer, buoyant plumes are classified into four types - offshore bugle spreading (Typel), west alongshore spreading (Typell), East offshore spreading (Type III), western and eastern alongshore spreading (Type IV). It is found that the plume shapes vary with time, presenting obvious monthly and annual variations and Typellalways occur in June, while in July the plume type has very high probability belong to Type III which controlled by river discharge and local wind.

ADDITIONAL INDEX WORDS: continental shelf; shape; South China Sea; river discharge; wind; buoyant plume; Pearl River Estuary

INTRODUCTION

Continental shelves associated with large river systems typically receive a large freshwater discharge and sediments influence coastal circulation, biogeochemistry, coastal sediment budgets and ocean pollutions. The distributions of the plume and sediments were controlled by fluvial, estuarine and marine processes, all of which are affected by the fresh water flow (GEYER et al., 2004). As relative indicators of the delivery and the ultimate fate of that sediment and other terrestrial matters, the study on the spreading of the buoyant plume is not only for coastal circulation, but also for coastal engineering environment, geomorphology and marine environment in shelf zone. The mechanism of freshwater discharged into the continental shelf has been studied intensively. Among these large river estuarine and shelf buoyant plumes, the Amazon, the Changjiang and the Mississippi have received the most study due to their large freshwater and sediments to the ocean. There are a series of previous studies conducted, based on a large amount of field data and numerical simulations (ZHU et al., 1997; LENTZ et al., 1995; WALKER et al., 1996; GEYER et al., 2000 and ESTOURNEAL, 1997). A variety of plume structures inside and outside the estuary were studied. It was found that plume dynamic processes were affected by various oceanic dynamic forces, river discharges and topography of the adjacent ocean. The Changjiang plume was confined to the south spreading along the coast and the northeast spreading dominated by summer monsoon wind, the cold eddy and the current of Yellow Sea (Pu et al., 2002). Two Rhone plumes response to opposing wind conditions have also been documented by ESTOURNEAL et al. (1997). The detailed plume morphology of Mississippi Plume was described by WALKER et al. (1996) using satellite data.

In the last decade, many models were developed to study the plume structures and the associated circulation under different forcing. CHAO (1988) used primitive ocean equations and idealised topography to describe the effects of wind and river discharge on buoyancy plumes. The dependence of three-dimensional plume characteristics on model parameters were investigated (KOURAFALOU *et al.* 1996; GARVINE *et al.* 1999). Recently, numerical models have been incorporated with realistic forces, including spatially and temporally varying winds and the river run-off, where the models were validated and verified using observations (KOURAFALOU, 1999).

The Pearl River ranks as the 13th largest river in the world with an annual discharge of 3.36 ×10¹¹ m³ and the Pearl River Estuary (PRE) is located midway along the northern boundary of the South China Sea (SCS) between the Taiwan Shoal and Hainan Island. Since the 1950s, fundamental research on the hydrographic features of the PRE, particularly the problems associated with tides and the mixing process between salt water and fresh water, were conducted. More recently, several studies have examined the buoyant plume during summer. MA et al (1990) pointed out the low-salinity water of PRE spread eastwards due to southeast monsoon, and spreads south-westward affected by other factors during summer. In the years of 1978 and 1979, the south-eastward spreading of low-salinity water reaches the shelf break, while westward expands to ~300km. XUE et al., (2001) study the mechanism of Pearl River plume based on numerical simulations and further suggest that the spreading path of low-salinity water of Pearl River is subject to the influence of wind, inshore surface heights and runoffs. Recently, the PRE plume in winter and its

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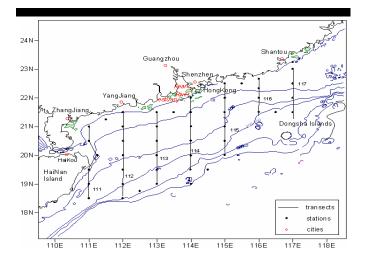


Figure 1. Topography of study area and locations of investigated transects.

estuary circulation were studied empirically and numerically (Wong *et al.*, 2004 and Dong *et al.*, 2004). The mechanism of biological or biogeochemical processes and sediment transport process near the PRE and the influences of the PRE plume on its processes were explored (YIN *et al.* 2004; CAI *et al.*, 2004; YING, 1999).

There were a few studies on the horizontal salinity distribution outside the PRE (MA et al., 1990; LI et al., 1987), but there is a limited understanding about the distribution of buoyant plume and its associated dynamics. In the present study, the spatial characteristics of PRE buoyant plume on the northern shelf of SCS during summer will be investigated and analysed, with inter-decadal monthly field data obtained by South China Sea Branch from 1978 to 1984 (MA et al.1990).

THE STUDY AREA AND OBSERVATION DATA

The study area includes the PRE and its adjacent continental shelf with an ENE–WSW orientation and 150–300 km wide, as shown in Figure 1. Hong Kong, Guangzhou and many industrial towns, the most rapid developing region in China, lie on the shores. The northern continental shelf of SCS is greatly influenced by the large Pearl River freshwater discharge and a buoyant plume typically forms in the wet season.

A continuous hydrologic survey in the northern SCS was carried out by South China Sea Branch, China (MA et al., 1990) from 1978 to 1984. The measured transections and stations are shown in Figure 1. The survey conducted monthly from 1978 to 1981 and bimonthly from 1982 to 1984. The regular measurements collected a comprehensive database which provided useful information for the ocean resources exploitation, the ocean engineering, the navigation, the ocean environment study and other ocean research. The measured parameters included the water depth, the salinity, the temperature, the wind, the PH value and the wave height. In the monitoring time, the Pearl River discharged a large freshwater into the northern SCS. The seasonal discharge variation of the Pearl River is significant, 78% of total Pearl River discharge occurs in the flood season between April/September (Luo et al., 2002).

The northern continental shelf of SCS is a micro-tidal region and the mean tidal range is small and just with 0.85-0.95m

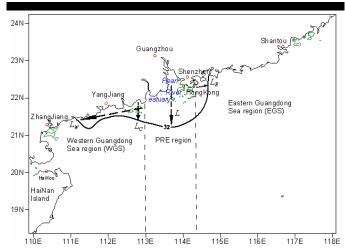


Figure 2. The classification of sea area and the definition of parameters.

outside PRE (ZHAO, 1990). Tide and tidal current in PRE are influenced by the topography and the river discharge (MAO et al., 2004). The surface current system in the SCS is largely dominated by the South Asian Monsoon. During summer, an anti-cyclonic circulation is formed by the prevailing southwest monsoon. The South China Sea Warm Current (flowing north-eastward throughout the year) and the Guangdong Coastal Current (flowing north-eastward during summer) (XUE et al., 2001; SU et al., 2004) also attributed significantly to the hydrodynamics in the study area. The prevailing wind of the northern of SCS in summer is SW wind, but there are other dominant winds with local variations as well. The local wind field changes affect the surface circulation directly, making surface circulation in summer flow not only north-eastward but also south-westward caused by other factors (MA et al., 1990).

DATA ANALYSIS

As a large amount of low-salinity water from PRE floating over the high-salinity, continental shelf water always displays tongue-like spreading offshore and coastal spreading in summer, the shape and behaviour of the buoyant plume off the PRE vary with time and may be affected by river discharge, bathymetry, tides, Coriolis force, wind and mixing processes. In order to emphasise both the coastal plume directions and offshore bulge, the study area is partitioned into three regions (Figure 2) - PRE region (113°E~114°20′E), Western Guangdong sea region (WGS) (between 113°E and the eastern of HanNan Island) and Eastern Guangdong sea region (EGS).

Non-dimensional parameters has been derived and used to classify the various plumes in the study. The salinity isohaline of 32 psu is determined to be the offshore boundary of the buoyant plume, where L is defined as the maximum distance between the boundary salinity isohaline and the river mouth in the PRE region, L_E refers to the maximum length between the boundary salinity isohaline and the coastal line in EGS region, L_W is defined as the maximum extent in the WGS region, and L_C is defined as the maximum width (taken as distance from coast to the plume boundary or as width between the plume boundaries), as shown in Figure 2. The non-dimensional parameters of $\lambda = L/L_C$ and $\lambda_I = L_E/L_W$ can be employed to characterise the plume's shape. The parameters of the plume in

summer from 1978 to 1984 are summarised in Table 1. Although the spreading processes and the seaward limit of the buoyant plume vary with time, the buoyant plumes off PRE can be classified into four types using the parameters such as λ and λ_1 : Offshore Bugle Spreading (Type I), West Alongshore

Spreading (Type II), East Offshore Spreading (Type III), Western and Eastern Alongshore Spreading(Type IV), and the details are summarised as follows.

Table 1 Characteristic parameters of the surface salinity of buoyant plume outside PRE in summer								
Time	Total area km²	$rac{L}{ ext{km}}$	$L_{E} top km$	$L_{\!\scriptscriptstyle W} \ _{\!\scriptscriptstyle m km}$	$L_{C} top km$	λ	λ_1	Plume type
Jun. 1978	51386	155	0	332	176.0	0.9	0.0	II
Jun. 1979	28234	66	51	184	110.0	0.6	0.3	II
Jun. 1980	30493	122	102	133	33.0	3.7	0.8	II
Jun. 1981	30493	22	0	245	132.0	0.2	0.0	II
Jun. 1982	38398	111	102	184	88.0	1.3	0.6	II
Jun. 1983	51951	133	296	56	110.0	1.2	5.3	IV
Jun. 1984	44610	122	286	128	55.0	2.2	2.2	IV
Jul. 1978	61550	161	286	133	143.0	1.1	2.2	III
Jul.1979	74538	149	286	245	176.0	0.8	1.2	III
Jul.1980	23717	116	31	56	33.0	3.5	0.6	1
Jul.1981	53080	122	275	82	132.0	0.9	3.4	III
Aug.1978	18070	33	0	112	93.5	0.4	0.0	II
Aug.1979	50821	122	296	102	132.0	0.9	2.9	III
Aug.1980	25411	89	214	5	99.0	0.9	42.8	III
Aug.1981	37834	133	296	92	93.5	1.4	3.2	IV
Aug.1982	26540	55	194	87	88.0	0.6	2.2	IV
Aug.1983	19199	55	41	107	71.5	0.8	0.4	II
Aug.1984	15246	89	41	41	44.0	2.0	1.0	I

Typel- Offshore Bugle Spreading

For this plume type, low-salinity water extends seaward but the westward extent (L_W) and eastward spreading (L_E) of low-salinity water are small. As an example, surface salinity fields of July, 1980 is shown in Figure 3. Low-salinity water confines to the nearshore zone of WGS and the maximum westward spreading reach 56km and the upstream extension only reaches 31km where it's close to Hong Kong sea area but the offshore extension is about 116km. Then the plume structure shows that the extent of offshore spreading L is larger than the extent of westward L_W and eastward L_W , and the downstream extent L_W is always larger than the upstream extent L_W , that is to say $\lambda > 1.7$ and $\lambda_1 < 1$ (Table 1), which means that Typelplume is also a supercritical plume simulated by CHAO (1988).

Typell-WGS Alongshore Spreading

For Type II plume, the westward extent L_W is longer than the eastward extent L_E ($\lambda_1 < 1$) and $L < L_W$. The low-salinity water of PRE extended progressively westward, while the upstream extension is restricted. From 1978 to 1984, this buoyant plume

type is most visual in summer especially in June. Figure 4 shows the salinity isohalines of this type during summers. All the buoyant plumes shape of Type II shows typical westwardly spreading which can be sub-divided into extreme spreading and non-extreme spreading. The extreme westward extension characterises in that the low-salinity water from Pearl River estuary all spread towards the western coastal sea area of Guangdong, while eastern extension is practically nil. For example, in June 1981 the low-salinity water was carried from the mouth of PRE to the eastern sea area of Hainan Island but the eastward extension was prevented entirely and the low salinity water didn't even get to Hong Kong sea area. The most common situation of this type is that small portion of low-salinity water bypass Hong Kong and was carried to EGS region, where L_E is short and mostly less than 105km, while a larger portion was carried seaward and westward, which is shown in Figure 4.

The spreading range of low-salinity water changes with time, the farthest of which flows to the eastern Hainan Island ($L_W > 240 \, \mathrm{km}$), while the nearest one only bypassing the YangJiang ($L_W \approx 130 \, \mathrm{km}$). In the meantime, the low-salinity water edge changes, approximately spreading parallel to the western coast of Guangdong. Comparing L and L_C , there is $\lambda < 1.7$, the plume is clearly subcritical. It might be due to the increased landward

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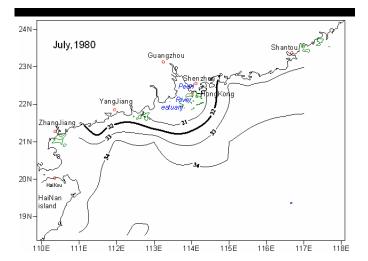


Figure 3. Type I- offshore bugle spreading which shows the surface salinity of July, 1980

friction force or the strengthened horizontal and vertical eddy diffusion (CHAO et al., 1988).

Type III - EGS Offshore Spreading

The dominant characteristic of this type is that the low-salinity water from Pearl River estuary was carried offshore and eastward to EGS, as it is shown in Figure 5. The low salinity water spread offshore but not alongshore eastward and there are some ambient waters between the coast and the plume boundary, which is the most distinctive characteristic totally different from type II. In this plume type, the eastward extent L_E is larger than the westward extent $L_W(\lambda_1 > 1)$, but L_W may also reach a large value, e.g., in July 1978, $L_W = 245$ km. Basically, for Type III, low-salinity water began to move offshore near DaYa Bay to the eastern continental shelf rather than spread alongshore towards Shantou nearshore region, which always accompanied with the upwelling current along the EGS coast. As shown in Figure 5, the low-salinity water spreading pattern of July, 1978 turns out to be offshore movement and spread eastward out of this study domain, while the plume boundary can be found at the continental shelf break at Dongsha Islands (Hong et al., 1999). It is also determined that Type III plumes are typically subcritical, as $\lambda < 1$.

Type IV- Symmetrical Alongshore Spreading

When the low salinity water extended progressively alongshore westward and eastward with limited spreading in the offshore direction, the low salinity water confined in the coastal zone is defined as Type IV buoyant plume, as indicated in Figure 6. It can be seen that the surface salinity distribution is nearly symmetrical on the axis of Pearl River Estuary in June, 1984. The low-salinity water spreads alongshore both sides and the farthest end of eastward movement reaches Shantou, while the westward comes to the west of Yangjiang. In general, the edge of Type IV is more complicated and changeable. However, the seaward limit, L, of Type IV is various. It is also found that $\lambda_1 > 1$, but the

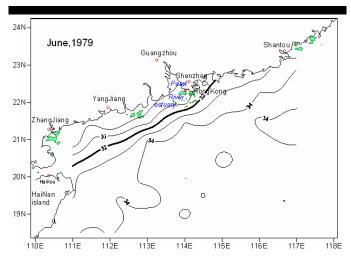


Figure 4. Typell- WGS alongshore spreading which shows the surface salinity of June, 1979

salinity increases from the coast to the open sea and the low salinity water is coastally trapped. This characteristic is the main difference from that of Type III plume. For Type IV plume, the EGS upwelling current disappears along the coast.

THE SEASONAL AND ANNUAL VARIATIONS

Obviously, the seasonal variation of river discharge affects the seasonal change of PRE plume (DONG *et al.* 2004). In flood season, huge quantities of fresh water pour into PRE and spreads outward on the surface of sea waters and the buoyant plume can spread eastward to Shantou and westward to the Hainan Island (Figure $4\sim5$). In dry season, runoffs are so small that the low-salinity water solely confines near the estuary.

Four types of PRE buoyant plume have been revealed and the monthly change of plume structure and range were explored. It was more probability to come into being Type II in June which the plume spread westward, while in July the extension of low-salinity water has a very high probability of belonging to Type III which the main spreading of freshwater turns eastward. Yet, the spreading direction of low-salinity water in August is changeable in that it includes four types of spreading patterns (Table 1). It can be found that the PRE plume variation is affected by winds and there exists a causal relationship between the spreading type of PRE plume and wind of the northern SCS. During June, the easterly wind is always the dominant wind which pushed the plume toward the southwest side of the PRE estuary and surface plume morphology presents Type II. Southwest wind events occur most frequently in July. The strong southwest winds can cause a surface transport directly to the east and form the Type III.

The annual change of the buoyant plume refers to the variations of spreading area and path in the same month from 1978 to 1984. Table 1 shows that the annual change of spreading area of June and August is obvious. There are two peak values in the spreading area of plume and the maximal spreading area in 1979 could be five times as much as the minimal area of August, 1980. The maximal spreading area exceeds 74,000 km² and the minimal value is observed in August, 1984 with plume area of ~15,000km². It is evident that the monthly and annual variations

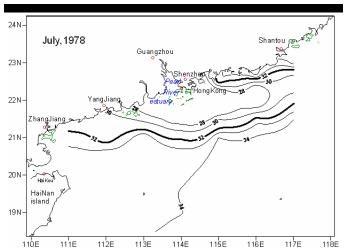


Figure 5. Type **III---**EGSA offshore spreading, which shows the surface salinity of July, 1978

of spreading area were caused by Pearl River discharge. Comparison can be made between the monthly average discharge and spreading area of plume. The Pearl River discharge is in close positive correlation with the spreading area of plume.

CONCLUSION

Field measurements from 1978 to 1984 off the PRE on the northern shelf of SCS are used to investigate surface salinity distribution and to classify the morphology of the buoyant plume outside PRE. The morphology of buoyant plume outside PRE present four types during summer. Type I referred to offshore bugle spreading which low-salinity water extended seaward but the westward and eastward spreading extents of low-salinity water were limited. This type may be controlled by Coriolis force and affected by relative weak environmental force and the mechanism has studied based on numerical simulations (CHAO, 1988; KOURAFALOU et al., 1996). Typell refer to the westward alongshore spreading which the low-salinity water of PRE extended progressively westward, while the upstream extension was restricted. Type III point to eastward offshore spreading which low-salinity water was carried offshore and eastward. And Type IV referred to western and eastern alongshore spreading which low saline water is coastal trapped and extended both eastward and westward.

The PRE buoyant plume varies with time, presenting obvious monthly and annual variations. In general, Type II which the plume spread westward always occur in June, while in July the eastward extension of low-salinity water has very high probability belong to Type III. All the spreadings of the PRE buoyant plume in summer companied with a large amount of sediment directly influence the marine environment and the human activities in the spreading area, especially the coastal zone near PRE. Since the sediments from the Pearl River carried by the buoyant plume and its westerly alongshore current didn't take into account, it is inevitable that the harbour and the human-made deep channel near YangJiang failed, which was caused by an amount of fine sediments during the flood time in 2005 but the PRE buoyant plume structures respond to forcing conditions rapidly, at last which environmental factor controlled these plume

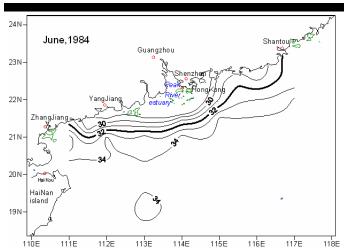


Figure 5. Type IV--- symmetrical alongshore spreading, which shows the surface salinity of June, 1984

structures? The mechanism of plume off PRE which are associated with river discharge, winds, shelf circulations and tidal mixing will be carried out in the future.

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