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Morphology of the Zambezi River Plume on the Sofala Bank, Mozambique

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Abstract — Hydrographic data collected in the vicinity of the Zambezi River plume between 2004 and 2007 is discussed alongside historical data to infer the plume morphology. Our strategy involved the establishment of 73 CTD stations. Satellite-derived wind speed data and river discharge measurements at an upriver gauging station were also analysed. The plume dispersion patterns indicated a tendency in its progressive propagation to move both equatorward and poleward. This tendency was not explored in previous studies and places the Zambezi River plume in a short list of plumes across the globe that propagate in a direction opposite to Kelvin or shelf waves. Visual inspection of the salinity profiles revealed that the Zambezi plume is super-critical, indicative of a faster freshwater inflow compared to the phase speed of long internal waves. The plume's vertical structure was found to be surface-advected when the freshwater discharge measured at Tete was less than 2000 m^3s^{-1}, and bottom-advected under larger discharges. A clear distinction was found between the plumes of the Zambezi and Licungo Rivers, characterised by a seaward bending of the salinity contours as the Zambezi freshwater flows downstream past the mouth of the Licungo River.

INTRODUCTION

Freshwater discharges from river basins into the ocean have an important influence on the dynamics of many coastal regions. In these regions, the input of freshwater generates a distinct physical regime, characterised by a surface layer of less saline water flowing over the denser ambient seawater. Following plume generation, a vast range of dissolved and suspended materials reach the ocean with various consequences. The most profound of these occur within the region of freshwater influence and vary from the physical alteration of the coastline, to changes in productivity and the availability of biological resources. For example, evidence of seaward extension of the Zambezi Delta in geological timescales caused primarily by high sediment flux is presented in Walford *et al.* (2005),

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and the impact of the Zambezi freshwater on secondary production, in particular the shrimp fisheries in the adjacent coastal sea, is discussed by Mann and Lazier (2013). An accurate description of the dispersion of plume waters as well as of the plume structure is needed to elucidate these changes.

River plumes are often used as indicators of the spread of materials transported by rivers (e.g. nutrients, pollutants, sediments) to the ocean. For instance, Brakel (1984) analyzed satellite images and found distinctive patches of sediment dispersal in the Malindi Bay in Kenya, indicating a northward transport of the largest sediment plumes, promoted by the prevailing southern monsoon. A typical pattern in a positively buoyant plume is one in which a layer of freshwater spreads over the ambient waters. Within an estuary and near a river mouth, transport in the primary direction is dominated by advection of the river's momentum and depends largely on the volume, timing and intensity of the river discharge (Fong & Stacey, 2003; Nezlin *et al.*, 2005).

Despite numerous studies conducted along the Sofala Bank in recent years, as well as the proposed linkages between Zambezi River discharge and local secondary production, dispersal patterns of freshwater outflow from the Zambezi River have not been elucidated. However, a concise review of the coastal features along the coast of Mozambique has been provided by Lutjeharms (2006), and includes evidence that the seaward intrusion of freshwater from the Zambezi River can reach up to 50 km offshore, and is confined to a water depth of 15-30 m. The mean outflow of the Zambezi is 3000 m^3s^{-1} (Gammelsrød, 1992) and its freshwater discharge is believed to influence not only the near-shore hydrodynamics and ecosystems, but also the offshore mesoscale circulation. This is particularly noticeable when freshwater runoff dominates the water masses within the continental shelf (Schumann, 1998; Sætre & da Silva, 1984).

The Zambezi River plume is documented in this paper, based on data published in a number of reports as well as in situ data collected, to describe its patterns of dispersion.

METHODS

Study Site

The Zambezi River meets the Indian Ocean on the Sofala Bank (Fig. 1). The connection is made through a relatively large delta, characterised by weak navigability due to obstruction by grass and reeds. The course of the Zambezi River is marked by a number of artificial lakes impounded by dams (Kariba and Cahora Bassa), which are mostly used for power generation rather than water retention during the wet season. Despite regulation of the river flow at the dams, the historical flood seasonality in the lower Zambezi remains undisturbed, with annual floods occurring during the rainy season. However, the current maximum extent of the flooded area is reported to be less than half what it was before the dams were constructed (Scodanibbio & Mañez, 2005). According to Beilfuss and dos Santos (2001), rainfall in the Zambezi river basin is strongly influenced by the movement of the Intertropical Convergence Zone, and in the delta region, this movement translates into a rainy season 4-6 months long between October and April. This region is also highly susceptible to torrential rain from tropical cyclones and depressions that can occur between November and April (Mavume *et al.*, 2009). During the dry season, tidal influence is still noticed 80 km upriver, as noted during field work in September 2009 in this study.

Data sampling

The Mozambican National Institute of Fisheries Research (IIP) carried out an oceanographic cruise once every year between 2004 and 2007 on the Sofala Bank using vessels of the semi-industrial shrimp fishery fleet. Hydrographic measurements were collected at the stations illustrated in Figure 1 by deploying an enhanced Seabird CTD system with conductivity, temperature, depth, turbidity, dissolved oxygen and fluorescence sensors. The first measurement

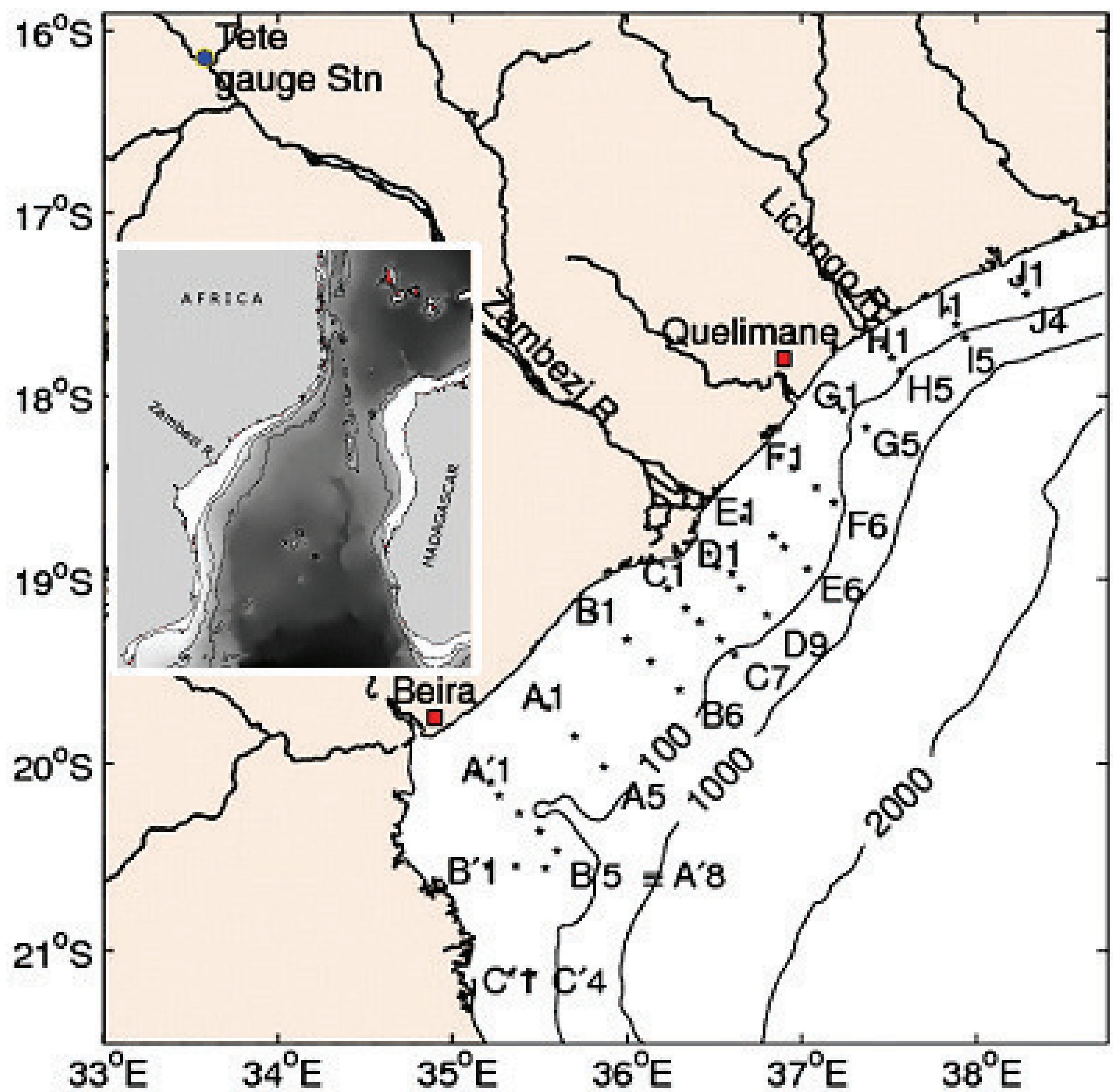

Figure 1. Hydrographic transects and stations in the vicinity of the Zambezi River delta.

was taken as close to the surface as possible at each station and subsequent readings were taken in profiling mode at an average of every two decibars. Calibration of salinity or temperature was performed prior to sailing and the post-processing and archiving was undertaken at the IIP headquarters in Maputo.

In the late 1970s, three cruises were conducted on board the R/V Dr F. Nansen to survey the fish resources and fishing potential along the Mozambican coast. Data from these cruises included the physical properties of the water (IMR, 1977, 1978a, b) and these were also used to analyse plume patterns in the present study.

Ancillary data

Freshwater discharge from the Zambezi River is measured on a regular basis by the Mozambique National Water Directorate at an upriver station located about 440 km from the river mouth (Figure 2). Monthly-mean wind data for 2000-2008 were extracted from the QuikSCAT dataset in a 2° x 2° box centred at the river mouth. South-easterly winds predominate in this region throughout the year (Nehama, 2012), with a significant change to near easterlies from August to December. No information regarding sea or land breezes is available for this region due to a lack of observations by the national meteorological service.

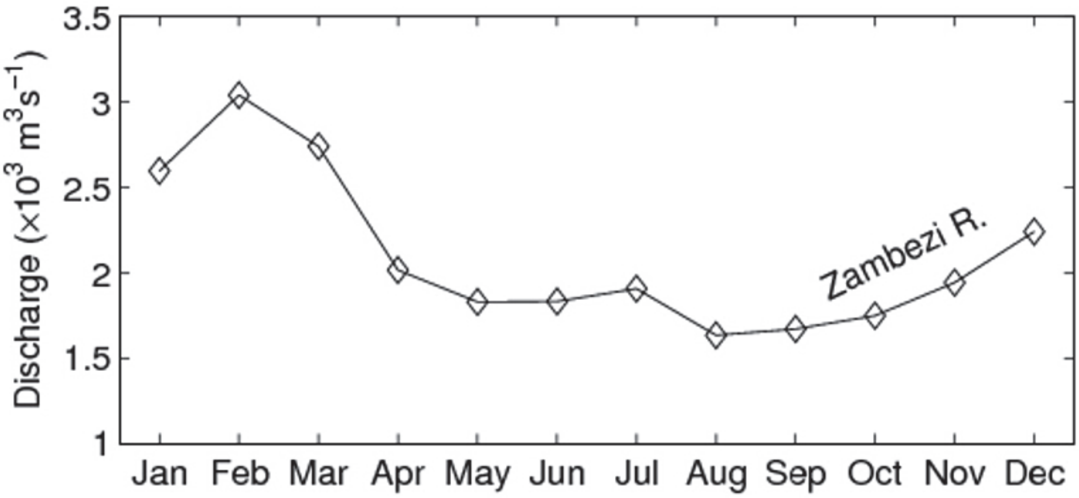

Figure 2. Seasonal variation in Zambezi River discharge based on 1976-2007 data from the Mozambique National Water Directorate.

RESULTS

Plume morphology from historical records

Surface salinity data collected in late September 1977 (IMR, 1977) clearly showed a tongue of less saline water leaving the delta and moving polewards (southwards). During these times, the ship drift indicated a weak equatorward surface current in the near-shore region, and a strong poleward current at the shelf break. Similar patterns were observed in January 1978, a few weeks prior to peak river discharges (IMR, 1978a). A striking seaward bending of isohalines was evident in front of the delta, as well as the occurrence of minimum surface salinity directly offshore of Beira where the shelf has its maximum extension. Vertical salinity profiles taken along the central line of

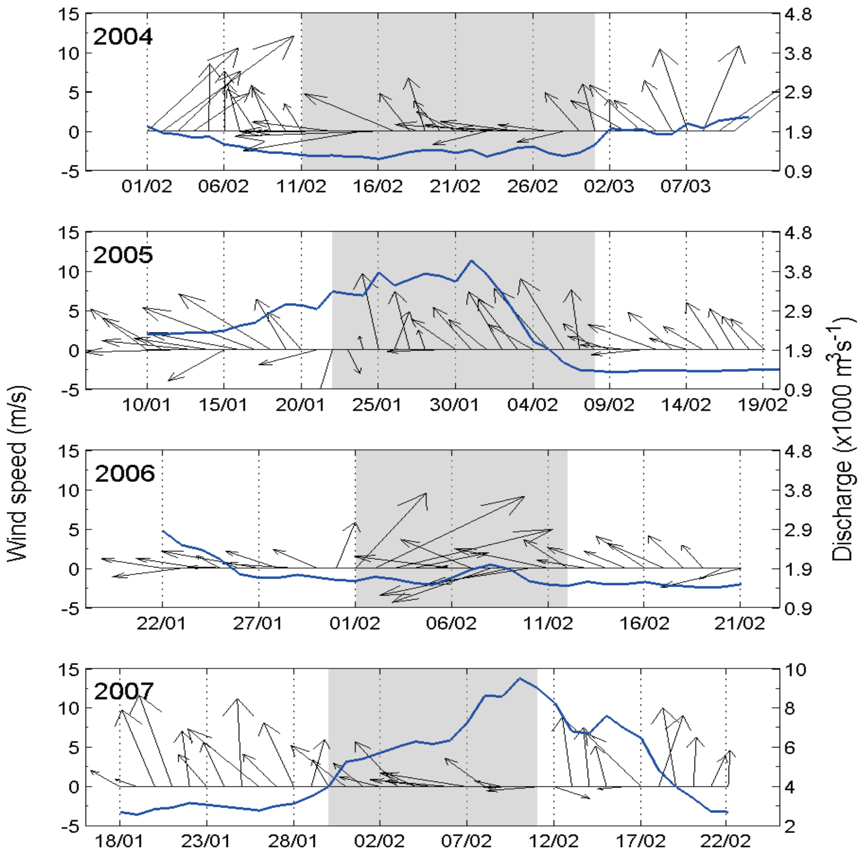

Figure 3. Zambezi River discharge data (solid line) derived from the Tete gauge station and QuikSCAT wind data (arrow vectors) for 2004-2007. Shaded areas correspond to periods of plume observation.

the delta revealed a stratified water column, a feature that was less noticeable in the south where the water column consisted mainly of denser ambient water.

In early May 1978, shortly after peak river discharge, the horizontal salinity profile pointed to an equatorward movement of plume waters (IMR, 1978b). The salinity contours of 20.0-34.5 bent landwards in the region north of Quelimane, indicating a limit in the direct influence of freshwater from the Zambezi River; this was in agreement with the observations of Siddorn *et al.* (2001). The plume waters in May 1978 occupied the entire water column down to 50 metres in transects located near the delta, as noted by the authors of the cruise report. There were clear rise and recession periods, with respective maximum and minimum monthly mean discharges of 3039 and 1633 m^3s^{-1}.

River discharge and wind conditions

Zambezi River discharge data during the hydrographic surveys in 2004-2007 (Fig. 3) revealed that river discharges were lower than the annual mean discharge (3000 m^3/s) in 2004 and 2006, and higher in 2005 and 2007. Daily readings varied a great deal during the

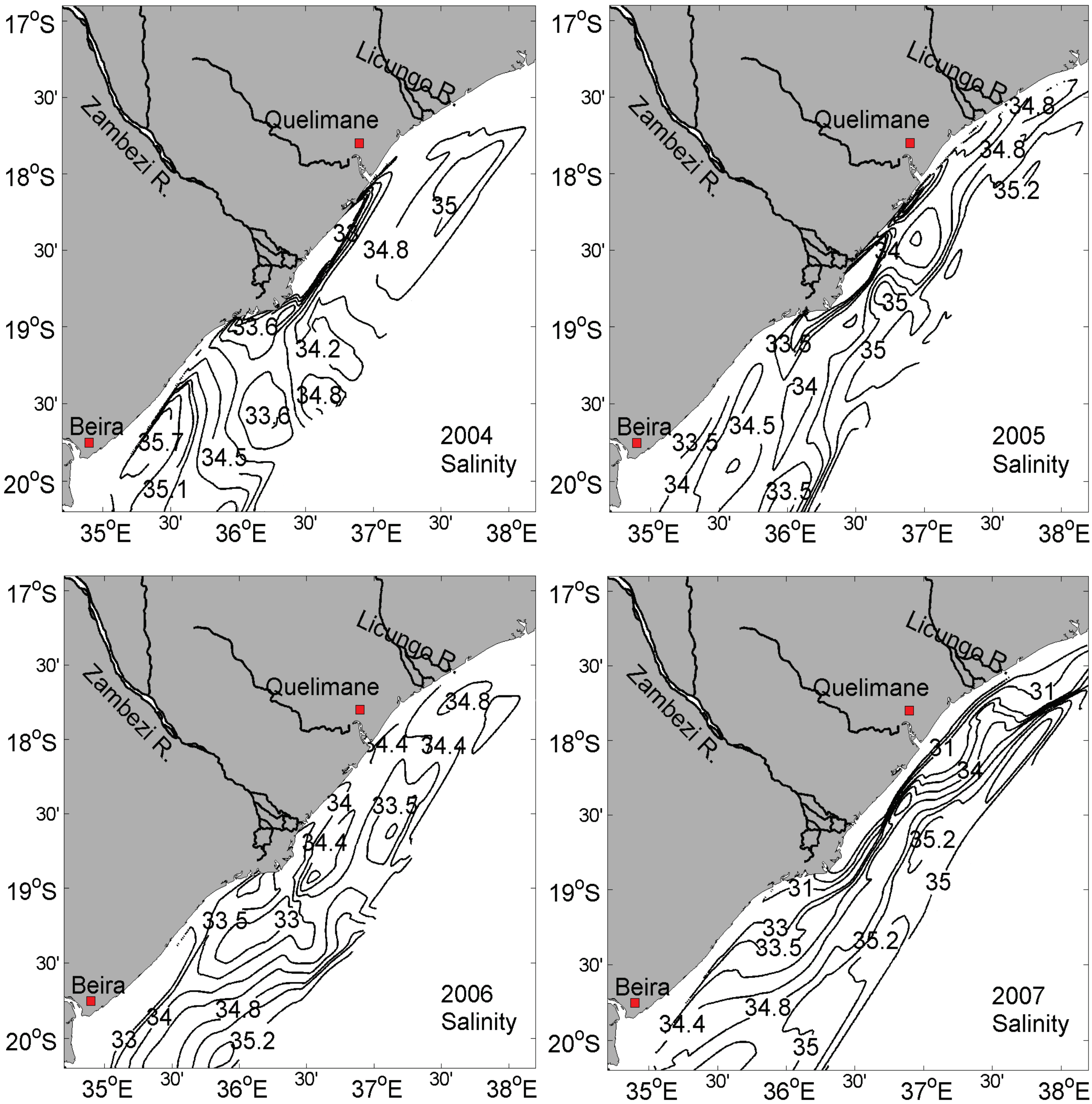

Figure 4. Near-surface salinity derived from CTD data collected in 2004-2007.

sampling period and, during peak discharges, the Zambezi distributaries overspilled their banks forming a broad channel to the ocean, particularly during spring tides (Beilfuss and dos Santos, 2001). Winds were very weak in 2004, moderate in 2005 and 2006, and moderate to strong in 2007. Their direction also varied considerably prior to, during and between plume observations. There was no predominant wind direction in 2004 but winds were mostly south-easterly in 2005, 2006 and 2007. During peak river discharges (January-March), easterly winds, followed by south-easterly winds, were most evident.

The plume observed in 2004

Hydrographic data recorded in 2004 is presented in Figures 4 and 5. The horizontal salinity and temperature profiles both reveal a feature representing plume waters (with a salinity and temperature of around 33.6 and 29.2°C respectively), apparently spreading southwards to 20°S. A re-circulating bulge was not evident in either the horizontal or the vertical salinity profiles. The plume occupied the surface layers at all stations located in the region immediately in front of the delta (Transect D), spreading from the coast to the position of the 100-1000 m isobaths. This

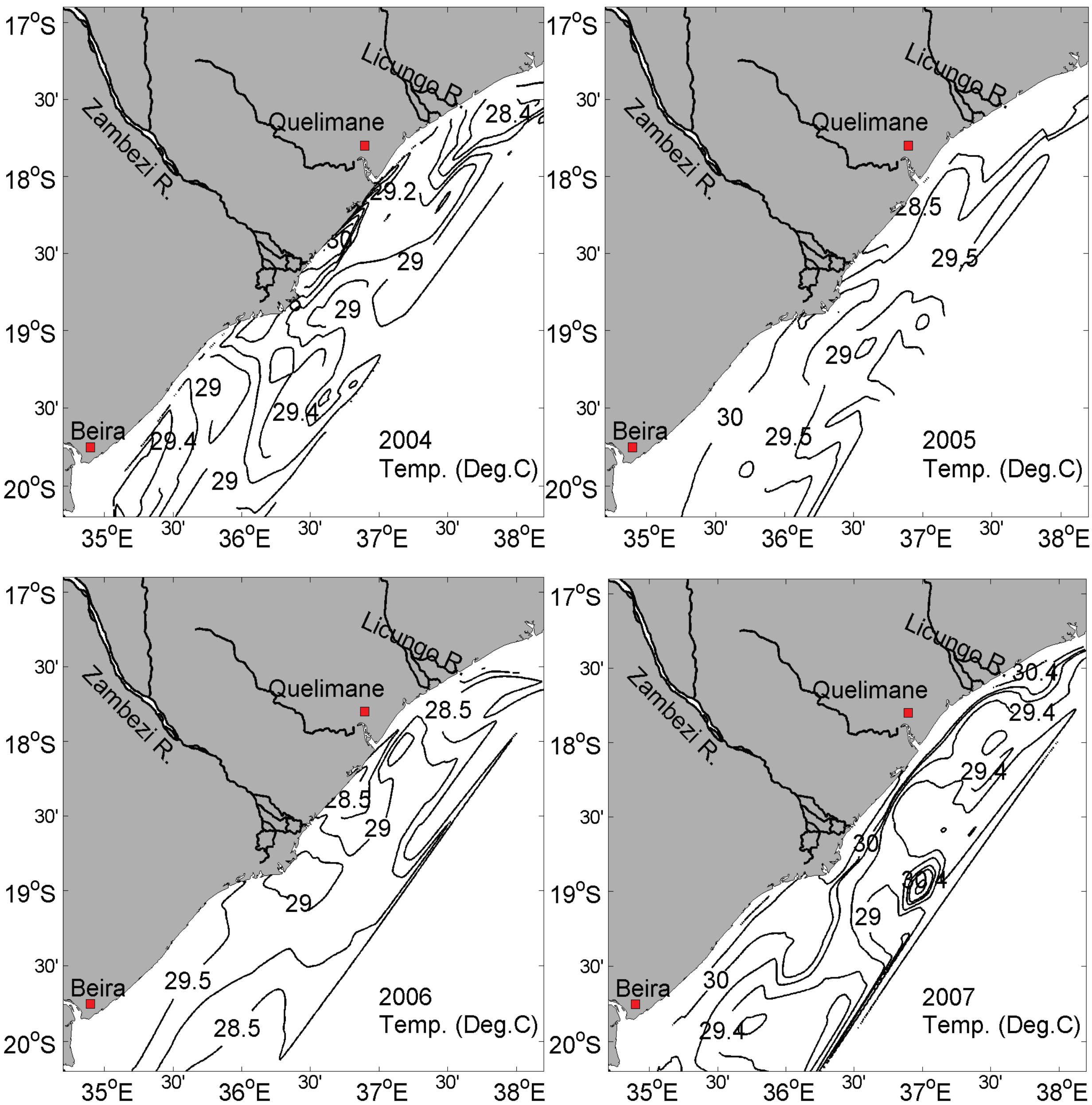

Figure 5. Near-surface temperatures derived from CTD data collected in 2004-2007.

pool of estuarine water of low salinity and high temperature followed the downstream coast, consistent with the theory of a density-driven coastal current (Garvine, 1999).

Vertical profiles at Transect I (Fig. 6), located about 200 km north of the river mouth, corroborated these findings.

The plume observed in 2005

The horizontal plume structure was similar to that observed in 2004 (Figs 4 and 5), except for the greater extent in southward movement by the plume waters. The salinity profile manifested a seaward bending in the isohalines and a second bulge near the mouth of the Licungo River. The extent of the offshore plume displayed in the vertical salinity profile (Fig. 6) was considerably smaller at the periphery of the Zambezi River mouth (Transect D) compared to the plume observed in 2004. The 2005 plume maintained contact with the seabed near the river mouth but elevated elsewhere. The coastal northward current attained its maximum depth at about 25 km from the coast (Transect I).

The plume observed in 2006

Low salinity (<35.0) waters were found almost throughout the study area in 2006 (Figs 4 and 5). The lowest salinities did not occur in the vicinity of the Zambezi mouth, but further south at the coast, directly offshore from Beira where other rivers might have contributed to the freshwater input. The equatorward movement of the Zambezi plume waters near the coast was not as marked in 2006, but rather offshore, suggesting their movement away from the coast. In spite of

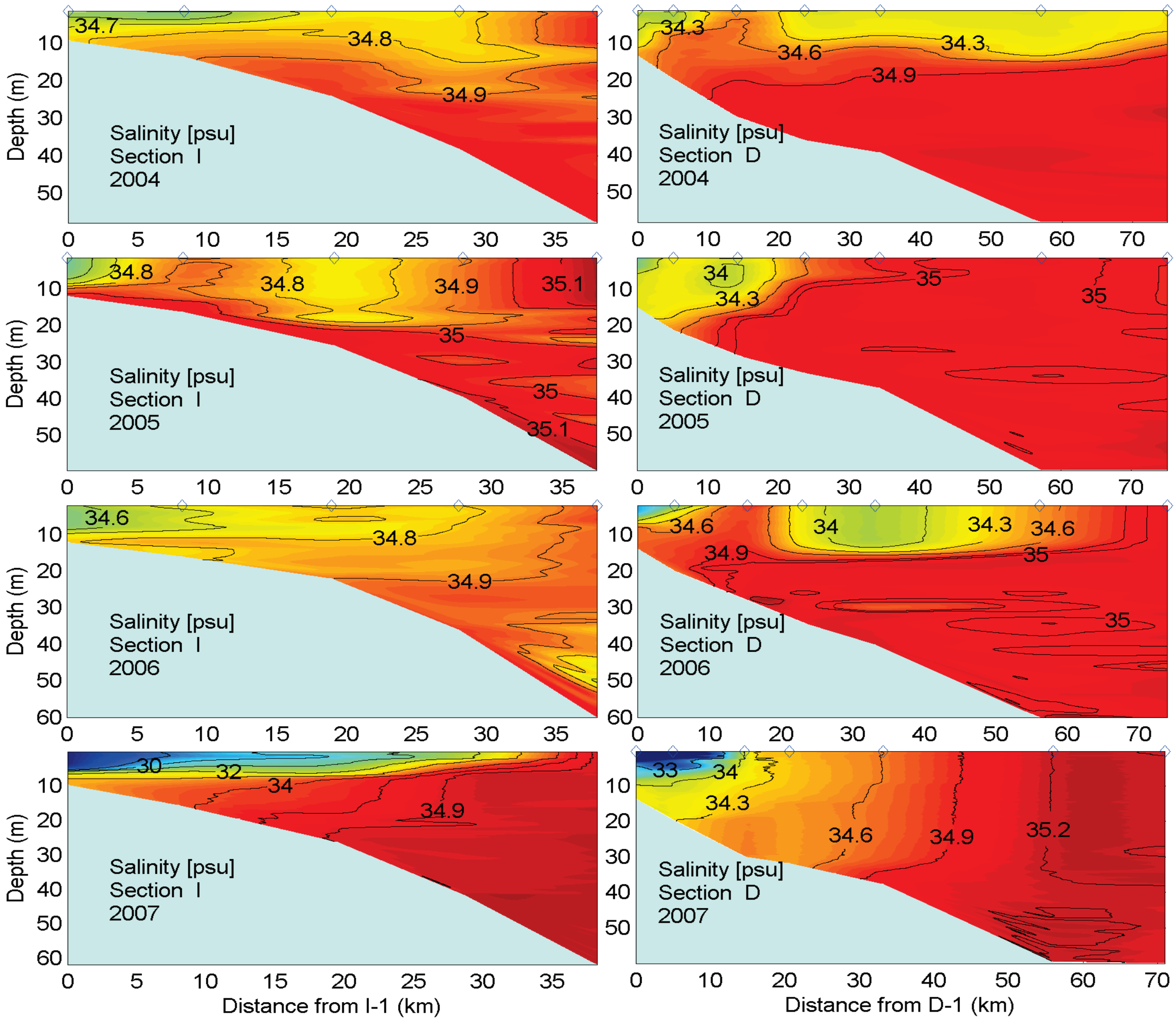

Figure 6. Vertical profiles of salinity recorded in Transects D (at the Zambezi River delta) and I (located north of the delta).

this behaviour, the 2006 turbidity profile (Nehama, 2012) has indicated that sediments were transported primarily equatorward.

Vertical profiles of the plume in 2006 (Fig. 6) indicated that low-salinity water was limited to the surface layer to a depth of 20 m near the river mouth (Transect D); such water occupied the entire water column at Transect I further north.

The plume observed in 2007

Less dense water of low salinity (<31.0) and high temperature bounded the coast from the delta to the area north of the Zambezi River (Figs 4 and 5), indicating the presence of a strong, buoyancy-driven flow along the coast, extending beyond the limits of the sampled area. The salinity and temperature profiles bent seaward near the mouths of the Cuacua (at Quelimane) and Licungo Rivers, increasing the width of the buoyancy-driven flow considerably. This was more evident at the Licungo River than the Cuacua River. In addition, a considerable amount of suspended sediment was present some distance from the coast directly offshore of this river mouth.

Vertical profiles of this plume revealed that it occupied the entire water column from the coast to a considerable distance offshore (Fig. 6). Its surface layer at coastal stations in all transects consisted of water with <33.0 in salinity and the 33.0 isohaline was located farther offshore in Transect I.

DISCUSSION

The Zambezi River plume, as it is known today, is characterised as an estuarine plume that turns northward and proceeds along the coast (Mann & Lazier, 2013; Hoguane, 1997; Siddorn *et al.*, 2001). Data presented here suggest that the above-mentioned northward and subsequent equator-ward flow of plume water might occur during high discharge periods, possibly only in years of extremely high discharge. During the present study, the average discharges were 1300, 2500, 1600, and 6000 m^3s^{-1} in consecutive years from 2004, and the transport of plume waters north-eastwards (equatorward) was only found in 2007.

In contrast to earlier publications describing only a northward density-driven flow, plumes in the present study were also found to advect polewards (southwards) in a number of years, including in historical data provided in the IMR (1977, 1978a, b) reports. The exception to this pattern was the plume event recorded in 2007 (Figs 4 and 5) which featured strong north-eastward transport and greatly reduced poleward transport of less dense water.

It must be noted that this poleward transport differs from the upstream (i.e. opposite to the Kelvin wave direction) intrusion of plume waters expected from a number of previous simulation-based studies. For instance, according to Chapman and Lentz's (1994) predictions, a coastally-trapped upstream flow attached to the coast, caused by "self-advection" of the plume, should be negligible in comparison with the downstream transport of plume waters. Garvine's (1999) findings, however, yield predictions similar to the findings of this study: he hypothesized that little or no upstream intrusion would occur over a flat bottom, but plume waters would significantly penetrate upstream over even a gentle slope in the absence of a background downstream flow.

The dynamic basis for such upstream propagation was analysed in numerical simulations of the Suo-Nada River plume (Seto Inland Sea, Japan) by Magome and Isobe (2003). Their results supported findings which suggested that a stretched vortex line served as the main driver for the upstream intrusion. According to their review, upstream intrusion of freshwater has been observed in only a few natural systems, viz. the Changjiang River (East China Sea), major Siberian rivers (Arctic), the Mississippi River and the Suo-Nada outlet (Seto Inland Sea, Japan). The results presented here justify the inclusion of the Zambezi River in this short list, although the model results and explanations obtained for other plumes (for instance, Chapman and Lentz, 1994; Garvine, 1999; Magome & Isobe, 2003) cannot be applied in this case, as they link the upstream flow with re-circulation in front of the bulge, which has not been observed in the Zambezi River plume system.

The plumes discussed here are characterised as being super-critical (having a speed of freshwater inflow which exceeds that of the long internal waves), following the characterisation scheme of Chao (1988) and Kourafalou *et al.* (1966), since the width of plumes delineated by the 34 or 35 isohaline (Figs and 4 and 5) decreases from the bulge region towards the downstream coast. Note that the portion of plume water that spreads upstream was ignored in this classification, and in some cases extends over a larger area (cf. data collected in 2006).

The plumes observed in 2005 and 2007 are classified as being bottom-advected with respect to their vertical structure directly offshore from the riverine sources, while those observed in 2004 and 2006 fall into the category of intermediate. The latter are predominantly vertically stratified, yet with a small degree of homogeneity near the river mouth. The bottom-advected plumes exhibit a higher tendency towards homogeneity throughout their cross-shore extension (Yankovsky & Chapman, 1997). The base of the Zambezi River plume (where it reaches the seabed) extends offshore up to 15-30 km in the region immediately seaward from the centre of the delta (Transect D; Fig. 6).

Freshwater discharges from the Pungoe and Licungo Rivers, located near Beira and north of Quelimane respectively, make an important contribution to overall buoyancy forcing along the coast. The vast majority of the data presented here displayed seaward bending in salinity contours in the vicinity of the Licungo River, which is indicative of a clear distinction between the Zambezi and the Licungo River plumes; this corroborates the observations of Siddorn *et al.* (2001). We also suggest that the Licungo River plume will limit equatorward spreading of the Zambezi River plume during periods of exceptionally low Zambezi discharge, and it will generate a protuberance in the course of the plume waters during periods of high discharge. On the other hand, no clear distinction was found between the Zambezi and Pungoe plumes, as they merge seamlessly in the shallows of the Sofala Bank.

CONCLUSIONS

This study thus describes the morphological features of Zambezi River plumes observed during single-cruise campaigns conducted between 2004 and 2007. It has shown that the Zambezi River plume is one of a small group of plume systems that penetrate large distances upstream, opposing the Kelvin waves. The downstream portion of the plume is, in general, attached to the shoreline, spreading offshore to the 50 m isobath within a super-critical structure. Plume waters occupy the entire water column at the coast, and the upper 10 to 20 m away from the coast. The plume's vertical structure is surface-advected under freshwater discharges weaker than 2000 m^3s^{-1}, and bottom-advected under larger discharges.

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