



Dynamic estuarine plumes and fronts: importance to small fish and plankton in coastal waters of NSW, Australia

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Abstract—In 1990, low density estuarine plumes in the vicinity of Botany Bay, Australia, extended up to 11 km across a narrow continental shelf (ca 25 km) on ebb tides. The shape and seaward extent of plumes varied according to a combination of state of the tide, freshwater input and the direction and intensity of coastal currents. Offshore plumes dissipated on the flood tide and fronts reformed at the entrance of Botany Bay. Major differences in the abundance and composition of ichthyoplankton and other zooplankton were found over a 400–800 m stretch of water encompassing waters of the plume, front and ocean on seven occasions. For example, highest abundances of the fishes Gobiidae, Sillaginidae, Gerreidae and Sparidae as well as barnacle larvae and fish eggs were found in plumes. Cross-shelf distribution patterns of zooplankton, therefore, are influenced by plumes. Distinct assemblages of plankters accumulated in fronts, e.g. fishes of the Mugilidae and Gonorynchidae and other zooplankters (e.g. *Jaxea* sp.). Accumulation in fronts was variable and may relate to variable convergence according to the tide. We argue that plumes provide a significant cue to larvae in coastal waters that an estuary is nearby. Moreover, although many larvae may be retained in the turbid waters of plumes associated with riverine input, larvae are potentially exported in surface waters on ebb tides.

INTRODUCTION

LARGE estuaries and enclosed bays are common along the coast of eastern Australia and generate conspicuous plumes, especially during ebb tides. Plumes often form significant intrusions into mainstream currents and are delineated by fronts (e.g. THORROLD and MCKINNON, 1992). In extreme cases riverine plumes may extend up to 90 km from the mainland, as observed for the Fitzroy River, in Queensland, during the 1991 floods (Larkum, personal communication). Clearly, these oceanographic features are capable of influencing the distribution of meroplankton and holoplankton, from reef, estuarine and oceanic environments, over broad spatial scales.

Estuarine and riverine plumes can influence ichthyoplankton distribution and transport. Studies have demonstrated that the composition of zooplankton communities often varies between water masses of the plume and oceanic waters (review: LE FEVRE, 1986). However, until recently, little attention has been given to the biology of estuarine fronts. Convergence zones are often sites of intense biological activity and typically manifest themselves at the surface as slicks and, for estuarine plumes, as turbidity fronts. The slicks

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of internal waves, Langmuir circulations, topographic and tidal fronts are known to affect the distribution, feeding and movement of plankton (KINGSFORD, 1990; KINGSFORD *et al.*, 1991). Of particular interest, regarding "Linear Oceanographic Features", is onshore movements and survivorship of small fish and invertebrates that are found as adults in coastal or reef environments. Estuarine plumes may attract or advect meroplankton into convergences of estuarine fronts. A consequence of aggregation may be that they are moved in the direction of coastal environments. Recent studies have demonstrated that plankters accumulate in estuarine fronts at times and not at others (DUSTAN and PICKNEY, 1989; GOVONI *et al.*, 1989; POWELL *et al.*, 1989; LOHRENZ *et al.*, 1990; GRIMES and FINUCANE, 1991). The dynamics of frontal regions and their effect on plankton requires more investigation.

The study of estuarine plumes and their associated frontal regions is useful for determining the potential importance of a number of different scenarios for meroplankters and holoplankters. Some meroplankters may exhibit behavioral mechanisms that facilitate their retention in estuaries early and/or late in their early life history (e.g. WEINSTEIN *et al.*, 1980; POLLOCK *et al.*, 1983; NORCROSS and SHAW, 1984; WHITFIELD, 1989; EPIFANIO, 1988), possibly avoiding density discontinuities such as fronts. Some estuarine organisms are spawned and spend their early life in waters over the continental shelf and must recruit to estuaries (e.g. VIEIRA, 1991). Ichthyoplankton may locate estuarine nursery grounds by responding to changes in turbidity (e.g. BLABER and BLABER, 1980). Moreover, the front may also be of ecological significance to meroplankton over the continental shelf that do not inhabit estuaries as adults (e.g. carangid and scombrid fish). For example, fronts may provide above average concentration of food for larvae (GOVONI *et al.*, 1989), but in one case no trophic advantage has been demonstrated (POWELL *et al.*, 1990).

The objective of this project was to describe the dynamics of estuarine plumes and fronts in a biological context. Specific aims were to: (1) describe the seaward extension and physical attributes of plumes under different conditions of tide and rainfall; and (2) estimate the abundances of ichthyoplankton and other zooplankters in and out of estuarine plumes in the immediate vicinity of the fronts (200–400 m).

METHODS

Study area

Botany Bay is partially flushed by the tide on the east coast of New South Wales, Australia. The bay is fed by two rivers, the Cooks River and Georges River (Fig. 1). Although considerable development by humans has taken place in the bay, stands of seagrass and mangroves are found in the upper reaches of the bay (MCGUINNESS, 1988). The maximum tidal range in Botany Bay is 2 m (F.I.A.M.S., 1990). This study was done in Botany Bay and up to 12 km offshore of Cape Banks.

Physical oceanography

The shape of estuarine plumes were described from twice daily flights of the *Beachwatch* helicopter; service of the Environmental Protection Authority of the New South Wales

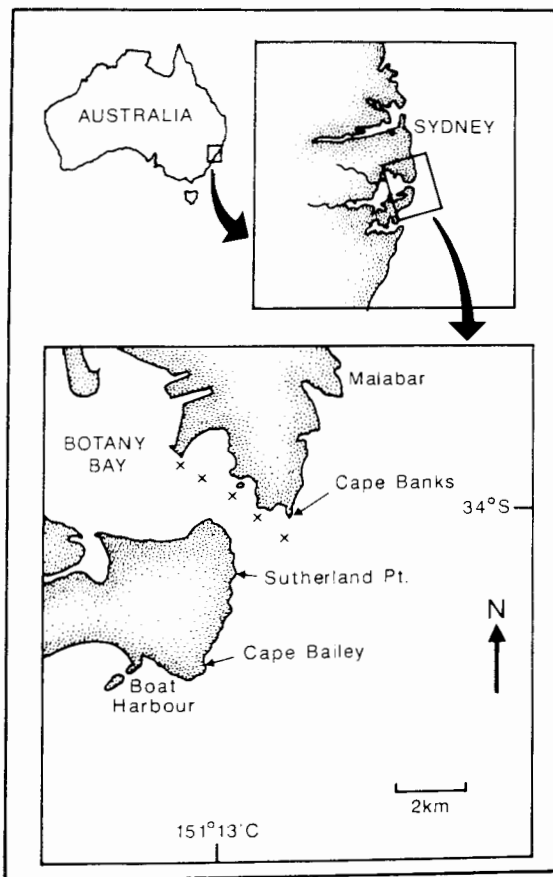


Fig. 1. Map of the study area showing the rivers feeding Botany Bay (N-S), Cooks River, Georges River. Crosses = CTD sampling stations.

State Government. The shape of fronts were drawn by eye on to a gridded map of the study area; exact positions on the map were determined by an electronic position finder. Where the shape of plumes is illustrated at ebb-low and flood-high tides, data were collected on the same day.

Conductivity, temperature and depth information were collected using a *Yeo-kal* CTD along a transect extending from the breakwater (half way into Botany Bay) and 6 km seaward of that point (Fig. 1). CTD drops were made at nine sites sampled at 700–900 m intervals. Transect points beyond the five indicated on the map (usually four) were positioned according to the location of plumes, those in the vicinity of the front (three CTD drops) were made 150–200 m in the plume and on the ocean side as well as in the front. Fronts at the time of sampling (11 September and 17 October 1990) were 4–5 km from the breakwater. Data on seawater density are presented as values of Sigma-t (kg m^{-3}). Vertical profiles of sigma-t across the front were contoured using Golden Graphics System software (SURFER). The program creates a regularly spaced grid for the data using the Kriging method (RIPLEY, 1981).

Plankton sampling and sampling designs

Ichthyoplankton and small fish are used as general terms to describe the early life history stages of fish. Not all fish were larvae, as some pre-settlement "reef" and "benthic" fish were juveniles (see KINGSFORD, 1988). Zooplankton, other than fish, were identified according to DAKIN and COLEFAX (1940).

A 15 × 3 m purse seine net (0.28 mm mesh), of similar design to that of KINGSFORD and CHOAT (1985), was used to sample plankton and fish. Based on the volume of a cylinder the seine was estimated to sample 45 m³ of seawater.

Ichthyoplankton and other zooplankton were sampled in waters of the plume (*ca* 200–400 m from front), front and ocean (*ca* 200–400 m from front) [Factor: PFO] on three separate days (Factor: Day) using the purse seine; 9 February–25 April 1990. Three replicate seines were taken in each water mass. This entire procedure was repeated in the presence and absence of a slick in fronts (Factor: Hyd = Hydrology). On some days turbidity fronts had a conspicuous organic slick associated with them and on other days the front was visible only as an abrupt transition in turbidity (Treatments of Hyd: slick, no slick). Sampling was haphazard with respect to state of the tide and was outside the entrance to Botany Bay. Additional sampling was carried out on one day (25 April 1990) in the presence of a slick in waters of the plume, front and ocean. These data were not analyzed using ANOVA, but are discussed in the text.

We used analyses of variance to assess the variation in larval fish density among water masses, the presence and absence of slicks and days. The factors PFO and HYD were treated as fixed factors (abbreviations see above). Days were nested in HYD and treated as a random factor [Day(HYD)]. Seines were replicates in which total counts of fish were made. If the factor HYD was not significant at $p = 0.25$ the data were pooled (according to UNDERWOOD, 1981) and the analysis repeated as a two-way ANOVA.

Similar analyses of variance of other zooplankton groups were conducted, except that an additional factor "Seine" was incorporated into the model. This was because two subsamples of zooplankton were analyzed from each seine. Seine was treated as a random factor, nested and in all other factors {SEN[P*D(H)]}, subsamples were replicates. For all analyses data were $\ln(x + 1)$ transformed to avoid heterogeneous variances.

Canonical discriminant analyses (CDAs) were done (SYSTAT; WILKINSON, 1990) to identify differences in faunal composition between waters of the plume, front and ocean for ichthyoplankton and zooplankton. Transformations [$\ln(x + 1)$] were used to "normalize" the data. Groups of fish were analyzed using PCA (SYSTAT) and were selected for the CDA based on the 12 highest "component loadings". Component loadings (from PCA) indicated the species that contributed most to variation in the data set, and therefore the like candidates for CDA to identify differences in faunal composition between waters of the plume, front and ocean. In a separate analysis (CDA), eight groups of zooplankters with high variation in abundance among water masses were chosen for CDA.

RESULTS

Physical oceanography

The extent to which plumes and fronts intruded into mainstream coastal currents varied considerably with state of the tide (Fig. 2). Estuarine plumes extended a considerable distance from the mouth of Botany Bay on ebb-low tide, while on flood-high tides fronts

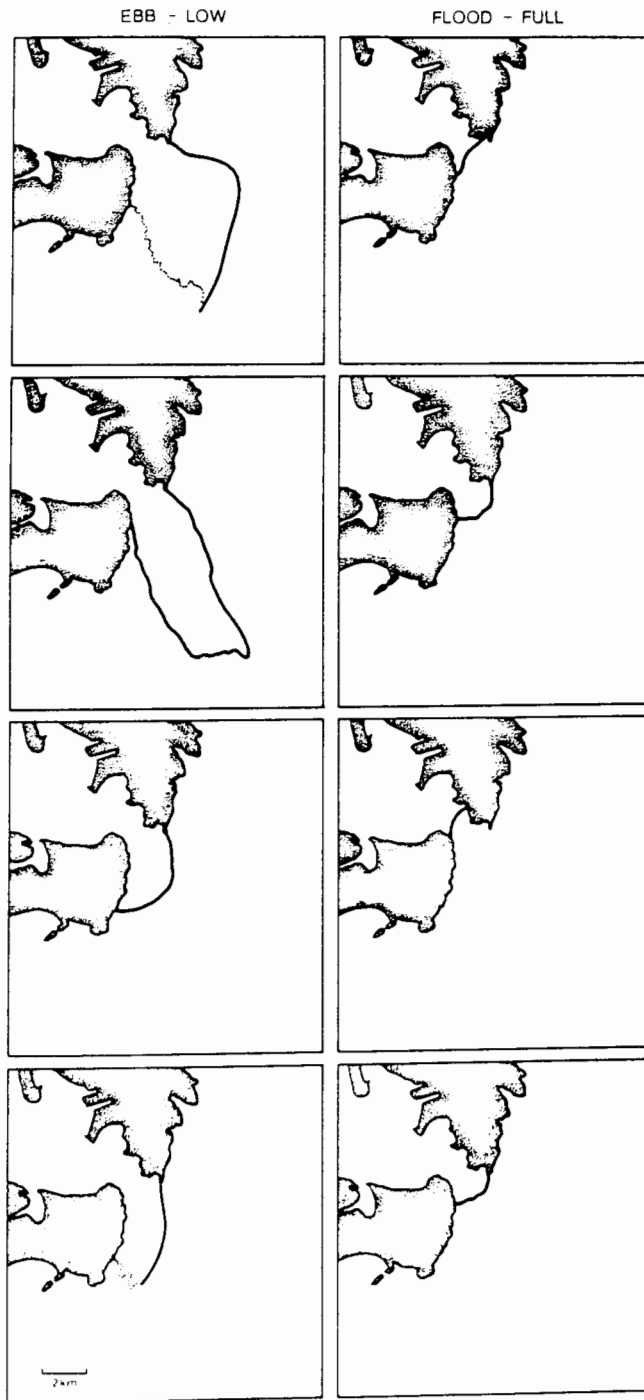


Fig. 2. Orientation of plumes at two states of the tide on 4 days.

were observed close to Botany Bay heads. The edge of plumes were clearly demarcated from coastal waters by a turbidity front. Turbid waters of the plume that extended far from shore on the ebb appeared to dissipate with the incoming tide and a new front formed near the entrance.

The mainstream flow of coastal waters influenced which side of the plume had the clearest frontal margin and influenced the shape of plumes. Currents varied among times, on some occasions southerly currents swept the plume in a northerly direction; conversely, currents from the north swept plumes in a southerly direction (Figs 2 and 3). Weak mainstream currents resulted in plumes extending into waters over the shelf with little North–South deviation (e.g. Fig. 2, 10 October 1990; Fig. 3). Although mainstream currents typically flow from North to South, reversals are common (GRIFFIN and MIDDLETON, 1991).

The maximum distances fronts extended from the shore varied among months (Table 1). Although the distances that fronts extended from shore appeared to relate to local rainfall, this was not significantly related to average monthly rainfall (Table 1; $r = 0.38$, $n = 19$, NS). Short, intense pulses of rainfall often resulted in very turbid plumes which were conspicuous for a number of days after the event of rain. In addition to rain, the intensity of local mainstream currents influenced the shape of plumes and the maximum distance they extended from shore. The maximum distance a plume extended from shore was 11 km over a continental shelf that is only 25 km wide. In some months plumes extended a maximum of 2 km from the shore, particularly in 1992 during an extended dry spell.

Vertical profiles of water density (σ_t) demonstrated that plumes were a shallow wedge of low density water (2–8 m deep) flowing over higher density coastal waters (Fig. 4). The intensity of the low density surface layer varied between times. On 11 September the low salinity layer appeared to commence a seaward movement toward the end of high tide. On ebb tide 2 h later a low density layer extended seaward, but an oceanic intrusion (@3–4 km) suggested upwelling into the plume. A fast moving, seaward flowing, 1–2 m deep low density layer was particularly clear on the 17 October ebb tide. Depressed isopycnals 20–30 m below the frontal margin may be the result of the plume flowing perpendicular to and interacting with strong longshore coastal currents, thus creating downward disturbance. On the 17 October flood tide, the wedge of low density water retreated and deepened within the bay as ocean waters flowed into the bay. σ_t values indicated the presence of a density gradient or cline extending from the surface frontal region back into the bay on ebb and flood tides.

Biology of estuarine fronts

Major differences in the abundance of total ichthyoplankton were found over a 400–800 m stretch of water encompassing waters of the plume, front and ocean (Days 1–3, Fig. 5). Rank abundance among water masses varied with days of sampling; as indicated by a significant interaction between the day and concentrations of fish in waters of the plume, front and ocean (PFO*DAY, Table 2). This pattern is clearly shown in Fig. 5 where total fish were most abundant in the plume on some days and the front on other days, regardless of whether a slick was present or not (Factor HYD was not significant at $p = 0.25$ and data were pooled in a modified ANOVA model; Table 2). Abundance of fish was generally low on the ocean side.

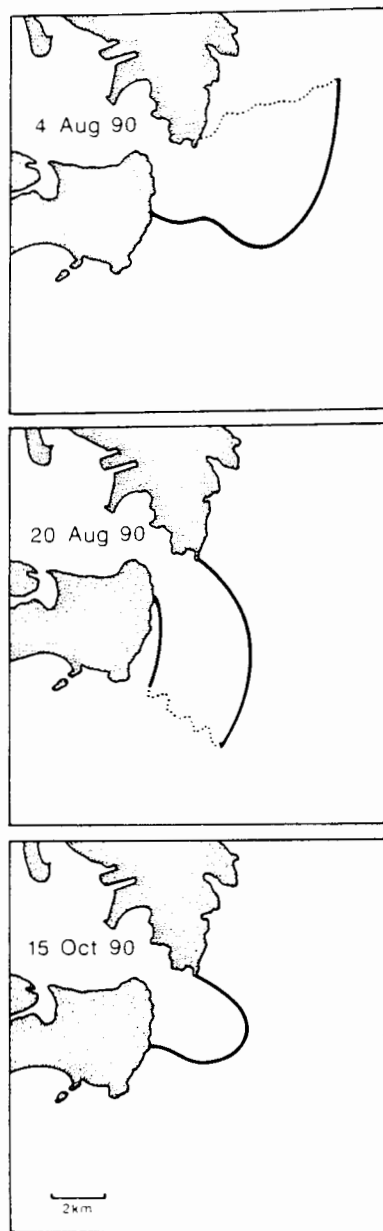


Fig. 3. Orientation of plumes on the ebb-low tide under different conditions of coastal currents. (Direction of current flow): 4 August 1990 (N); 20 August 1990 (S); 15 October 1990 (no current).

Major differences in taxonomic composition were found between waters of the plume, front and ocean (Fig. 6, Table 3). Seventy-four percent of the seines ($n = 54$) were correctly predicted to have come from the water mass from which they were collected, according to canonical discriminant analysis (Fig. 6). Faunal associations were strongest in

Table 1. The maximum distances (km) estuarine plumes extended from the coast of New South Wales over a period of 12 months. Distances were measured from Cape Banks (Fig. 1) in an easterly direction. Rainfall = total mm of rain recorded by the Bureau of Meteorology of NSW, data from Observatory Hill in Sydney. ND = no data

Month		Distance from shore (km)	Rainfall (mm)
February	1990	6.3	631
March		4.6	162
April		3.2	320
May		7.5	131
June		5.0	45
July		2.0	67
August		8.0	205
September		6.0	205
October		9.0	47
November		4.0	36
December		2.4	44
January	1991	2.0	41
February		2.7	42
March		3.4	24.4
April		3.2	25.6
May		ND	93
June		11	372
July		8.8	106.2
August		4	4
September		ND	20
October		ND	8
November		ND	33
December		2.5	192.6

the plume and front. Waters of the plume contained the majority of the following families (% of total in plume, Table 3), Gobiidae (96%), Sillaginidae (82%), Gerreidae (74%), Sparidae (74%) and low numbers of Ambassidae (82%), Triglidae/Platycephalidae (74%). Blenniidae (99%) were primarily found in the plume, as well as in fronts (% of total catch in plume and front). Reef and estuarine fish such as girellids and mullids, however, were mostly in frontal waters. The consistently low numbers of estuarine fish and some reef fish (Table 3) in oceanic waters suggested that fronts mark an important oceanographic transition through which few of them venture. The taxonomic composition of fish in the front was often different to that of the plume or the ocean (Fig. 6). Very high concentrations (% in front, Table 3) of gonorynchids (91%) and mugilids (90%) were found in the front at times. Rarer pelagic species, such as carangids were also most commonly found in the front. Although cheilodactylids were found in the plume, front and ocean, the greatest number of individuals was found in fronts. Waters of the ocean contained relatively low numbers of a variety of groups, the following ranked highest: cheilodactylids, mullids, pomacentrids, gonorynchids, sparids, mugilids, gerreids and carangids (Table 3).

Very high concentrations of small fish were found in the front on one additional sampling time in the presence of a slick (25 April 1990); gonorynchids [No. per 45 m³ Plume, Front, Ocean (SE)] [14(3), 183(70), 25(11)], mullids [9(6), 144(56), 10(5)] and poma-

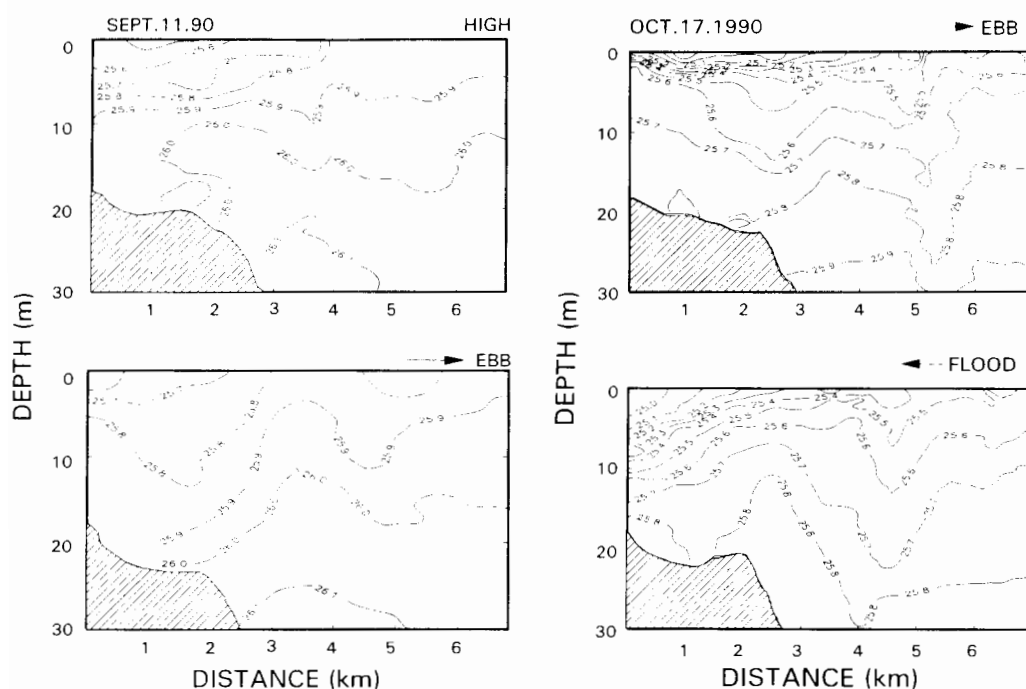


Fig. 4. Vertical profiles of Sigma- t along sampling transects made at two states of the tide on two days. 11 September 1990, weak turbidity plume; 17 October 1990, strong turbidity plume. Distance = km from a breakwater in the middle of Botany Bay (see Fig. 1).

centrids [6(6),13(7),0] as well as pomatomids [3(1),6(3),0]. Cheilodactylids were most abundant in the plume at this time [15(5),1(1),0] and very low numbers of other groups were captured.

Abundance patterns of fish eggs, over a 400–800 m stretch of water encompassing waters of the plume, front and ocean revealed major differences in abundance (Fig. 7). Fish eggs were most abundant in fronts and/or in plumes. This would suggest that many fish spawn in Botany Bay and some eggs advected in mainstream currents in “ocean” waters may accumulate in fronts as well. Differences in rank abundance of fish eggs in waters of the plume, front and ocean, on different days, resulted in a significant PFO*Day interaction (Table 4). The presence or absence of a slick at the front had no significant predictable effect on the abundance pattern of eggs (Factor HYD was pooled because $p > 0.25$). Significant differences among individual seines [Factor: Sen(P*D); Table 4] indicated that fish eggs were patchily distributed within a water mass.

There were also major differences in taxonomic composition of zooplankton between waters of the plume, front and ocean (Times 1–3, Fig. 8). The primary differences in samples taken in the plume and the ocean were the high concentrations of fish eggs and barnacle larvae that were found in the plume, while abundance of the larvacean *Oikopleura* spp. was generally highest in the ocean. In addition, harpacticoid copepods were often captured in highest numbers in the plume (*Macrosetella gracilis*, 53% of the total number in all water masses were in the plume). Barnacle larvae were abundant on 3 of 6 sampling days and always ranked first in abundance in the plume, with a maximum

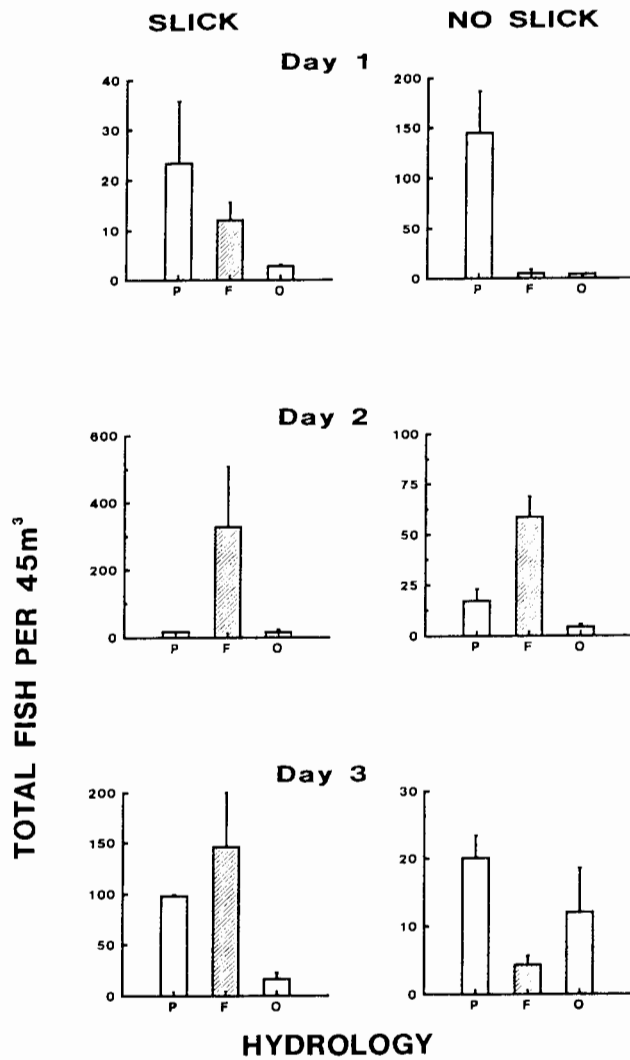


Fig. 5. Total abundance of fish sampled 200–400 m from the estuarine front in the plume (P), on the front (F) and 200–400 m on the ocean side (O); mean + 1SE.

mean concentration of $24 (\pm 9, SE) m^{-3}$. *Oikopleura* spp. were collected at concentrations of up to $145 (\pm 24, SE) m^{-3}$ in the ocean, while $2\text{--}60 m^{-3}$ was the range of mean concentrations found in the plume.

Samples collected from fronts were often similar to those from the ocean or plume indicating that taxa from either side of the front (plume and ocean) were well represented (Fig. 8). Any differences in the CDA that separated the front from other water masses were due to high numbers of the crustacean larva *Jaxea* sp. in the front ($37 \pm 8, SE) m^{-3}$, compared to waters of the plume (3.5 ± 1) and ocean (0). Furthermore, very high concentrations of fish eggs were often found in the front (56% of total, Fig. 7).

Some taxa did not show clear faunal associations with the three water masses. Calanoid

Table 2. Results of ANOVA on total fish in plume, front and ocean waters. Data are $\ln(x + 1)$ transformed. Cochran's test (C) for homogeneity of variance were done on transformed data and were tested at $p = 0.05$. HYD = Hydrology (slick & no slick) was pooled in this analysis because it was not significant at $p = 0.25$. PFO = plume, front, ocean was treated as a fixed factor; DAY was treated as a random factor. NS = not significant at $p=0.05$, DF = degrees of freedom for F-test. Data are presented in Fig. 4

	Total fish C = 0.2, NS		F	p
	DF	MS		
PFO	2,10	11.1	2.21	NS
DAY	5,36	4.82	10.7	<0.001
PFO*DAY	10,36	3.8	8.44	<0.001
RES	36	0.45		

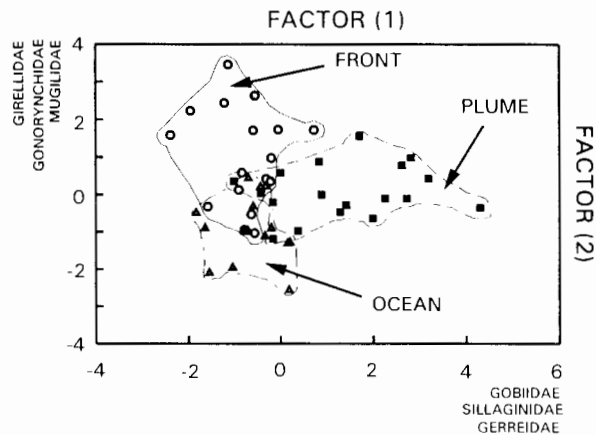


Fig. 6. Canonical discriminant analysis on the ichthyoplankton from waters of the plume, front and ocean. Multivariate test statistic: Pillai's Trace = 0.878, $df = 24,82$; $F = 2.673$; $p < 0.001$. Canonical loadings of fish groups (Factor 1, Factor 2): Gonorynchidae (-0.115, 0.278); Cheilodactylidae (0.041, 0.171); Girellidae (-0.162, 0.482); Monodactylidae (0.356, -0.062); Blenniidae (0.352, 0.274); Triglidae/Platycephalidae (0.392, -0.018); Gerreidae (0.385, 0.155); Sparidae (0.190, 0.358); Sillaginidae (0.481, -0.044); Mugilidae (-0.112, 0.572); Ambassidae (0.364, 0.011); Gobiidae (0.520, 0.083); highest loadings are indicated on the graph. Symbols: squares = plume, circles = front, triangles = ocean.

(*Temora* spp.) and cyclopoid copepods (*Oncaea* spp.; *O. venusta* and *O. mediterranea*) contributed little to canonical loadings which were used to distinguish samples from different water masses (Fig. 8). Rank abundance of copepods varied greatly from day to day in different water masses, which resulted in a significant PFO*Day interaction for total copepods (Table 4). Although the cladoceran *Penilia avirostris* was captured in concentrations of up to $1350 (\pm 100, SE) m^{-3}$ in the plume and had some influence in the canonical analysis (Fig. 8), rank abundance in plume, front and ocean, changed dramatically among days. On 2 of 6 days $< 2 m^{-3}$ *Penilia* were captured. On 2 of 6 sampling days concentrations

Table 3. Small fish captured during sampling on 6 days (if ≥ 2 individuals); main design. Families are classified according to the environment in which they are typically found as adults and juveniles. Reef fish = associated with rocky or coral reefs; Pelagic fish = fish that spend their entire lives in the pelagic environment; Estuarine Fish = fish that primarily live as adults and juveniles in estuaries; Benthic Fish = species associated with the substratum away from reefs and estuaries.

	PLUME	FRONT	OCEAN
<u>Reef Fish</u>			
Synodontidae	1	1	0
Cheilodactylidae	54	79	35
Enoplosidae	3	0	0
Pempheridae	4	0	0
Girellidae	2	19	0
Scorpididae	0	0	2
Mullidae	18	48	20
Pomacentridae	29	15	10
Monodactylidae	19	1	0
Labridae	12	1	0
Blenniidae	63	22	1
Tripterygiidae	1	4	0
<u>Pelagic Fish</u>			
Clupeidae	10	11	2
Carangidae	9	38	9
Pomatomidae	2	5	0
<u>Estuarine Fish</u>			
Gonorynchidae	45	936	42
Atherinidae	1	25	2
Ambassidae	18	2	2
Terapontidae	9	1	3
Gerreidae	173	28	8
Sparidae	129	45	1
Sillaginidae	47	4	6
Mugilidae	29	343	9
Creediidae	1	1	0
Gobiidae	255	7	3
Pleuronectidae	3	0	1
<u>Benthic Fish</u>			
Dactylopteridae	3	9	0
Triglidae and Platycephalidae	23	4	4

of 370–700 m⁻³ in the ocean were 9–18 times higher than those in the plume or front while on one day concentrations of 390 ± 50, 640 ± 30 and 510 ± 65 were measured in plume front and ocean respectively.

DISCUSSION

Estuarine plumes formed important physical oceanographic intrusions into mainstream currents off the coast of New South Wales, Australia, and were most turbid during times of heavy rainfall (personal observation). The distance that plumes extended from the shore

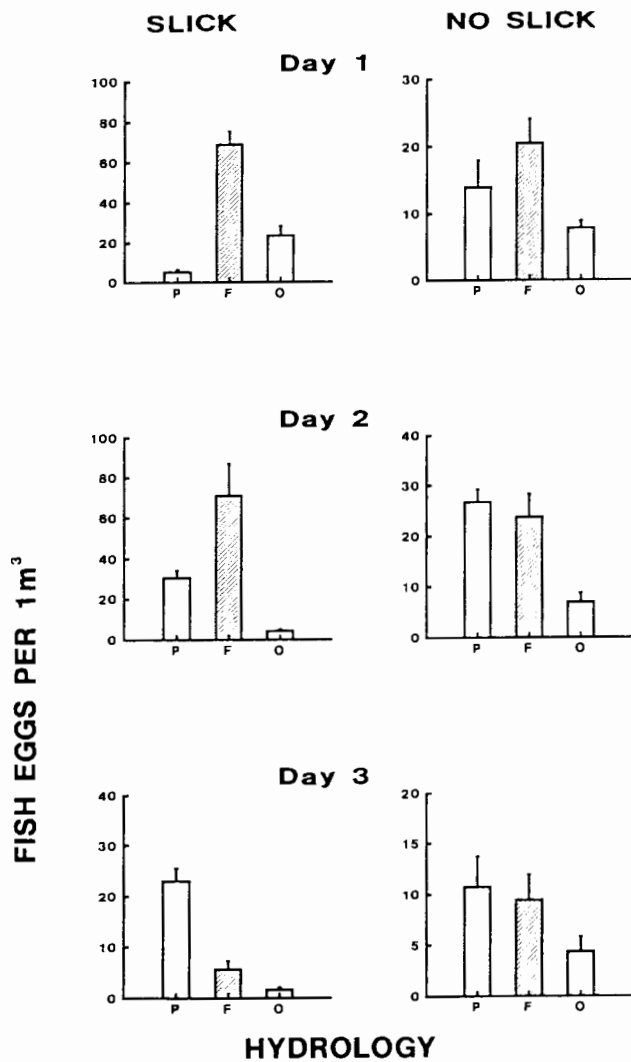


Fig. 7. Total abundance of fish eggs samples 200–400 m from the estuarine front in the plume (P), on the front (F) and 200–400 m on the ocean side (O); mean + 1SE.

appeared to vary according to a combination of state of the tide, input of freshwater, direction and strength of mainstream currents. Tidal amplitude and wind (MERTZ *et al.*, 1992) may also alter the shape of plumes. The movement of fronts varied markedly according to state of the tide (as may the sharpness of some fronts, YANAGI and TAMURU, 1990), with fronts traversing over 11 km of coastal waters on some occasions. Fronts extended their greatest distance from the shore on ebb tides, as a fast moving seaward flowing layer (as for LARGIER and TALJAARD, 1991). Freshwater input and state of the tide have been shown to influence the position of fronts in other parts of the world (YANAGI and TAKAHASHI, 1988; PINCKNEY and DUSTAN, 1990). Moreover, freshwater plumes may have important effects on local circulation patterns. For example, KOUTITONSKY *et al.* (1990)

Table 4. Results of ANOVA fish eggs and total copepods found in waters of the plume, front and ocean. Data are $\ln(x + 1)$ transformed. Cochran's test (C) for homogeneity of variance were done on transformed data and were tested at $p = 0.05$. HYD = Hydrology (slick and no slick) was pooled in these analyses because it was not significant at $p = 0.25$. PFO = plume, front, ocean was treated as a fixed factor; DAY and SEN = seine were random factors; NS not significant at $p = 0.05$.

Fish eggs C = 0.026, NS				
	DF	MS	F	P
PFO	2,10	13.19	3.25	NS
DAY	5,36	5.73	11.74	<0.001
H*P	10,36	4.04	8.29	<0.001
SEN(P*D)	36,54	0.49	3.39	<0.001
ERROR	54	0.14		

Total copepods C = 0.026, NS				
	DF	MS	F	P
PFO	2,10	4.62	1.6	NS
DAY	5,36	4.42	8.04	<0.001
H*P	10,36	2.91	66.5	<0.001
SEN(P*D)	36,54	0.74	24.43	<0.001
ERROR	54	0.04		

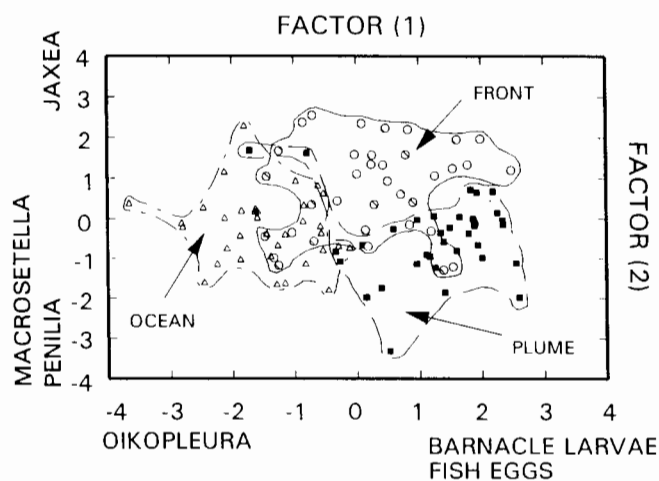


Fig. 8. Canonical discriminant analysis on the plankton fauna from waters of the plume, front and ocean. Multivariate test statistic: Pillai's Trace = 0.818, $df = 16,198$; $F = 8.571$; $p = <0.001$. Canonical loadings of plankton groups (Factor 1, Factor 2): *Temora* spp. (0.044, -0.069); *Oncaea* spp. (0.032, 0.099); *Macrosetella gracilis* (0.169, -0.292); *Oikopleura* spp. (-0.319, -0.117); *Penilia avirostris* (0.079, -0.209); barnacle larvae (0.282, -0.190); *Jaxea* sp. (0.129, 0.346); fish eggs (0.365, 0.549); highest loadings are indicated on the graph. Symbols: squares = plume, circles = front, triangles = ocean.

found that river run-off generated anticyclonic eddies beyond the immediate area of the run-off. Observations that flotsam and other material (e.g. drift algae, KINGSFORD, in press) accumulated in fronts on the ebb and flood tides suggested convergence at both states of the tide. Flotsam (including pollutants) commonly accumulates in the fronts of estuarine plumes (BROWN *et al.*, 1991) and other Linear Oceanographic Features (KINGSFORD, 1990).

Plumes and associated fronts clearly have the ability to influence small-scale distribution patterns of fish and plankton (<1 km). By moving across the continental shelf they may influence broader-scale patterns of plankton distribution. Species composition of ichthyoplankton and other zooplankters often varies with distance from the shore (e.g. SHERMAN *et al.*, 1984; KINGSFORD and CHOAT, 1989; SUTHERS and FRANK, 1991; LEIS, 1991), plumes and associated fronts may alter the nature of these over periods of time. Thus, plumes and fronts (as for other oceanographic features) should be considered in designs for ichthyoplankton surveys, or the interpretation of existing data. Fronts caused by differences in salinity, temperature and shear have been demonstrated to influence the distribution of zooplankters on a variety of spatial scales in many parts of the world (LE FEVRE, 1986; GOVONI *et al.*, 1989; GRIMES and FINUCANE, 1991; GOVONI and GRIMES, 1992). With the exception of DUSTAN and PINCKNEY (1989) and PINCKNEY and DUSTAN (1990), the dynamic nature of the position of fronts and the consequences to zooplankters has received little attention. Some of the differences we found in species composition of fish and other zooplankters in the plume, front and ocean may be conservative. The depth of the plume in the vicinity of the front (Fig. 4) suggests our 3 m deep purse seine may have included some fish and plankton from beneath the plume in "ocean" waters on occasions; especially when density differences throughout the water column were weak (e.g. 11 September 1990, Fig. 4), or when the plume was very thin (17 October, Fig. 4).

We observed major differences in the density of ichthyoplankters and other zooplankters in the vicinity of fronts at scales under 1 km (e.g. Gonorynchidae and Mugilidae, Table 3). The variable patterns of abundance that were found both within and among taxa in waters of the plume, front and ocean was not unexpected. A number of factors that could influence distribution patterns are as follows:

(1) fish probably respond to the presence of water masses in different ways according to concentrations of prey and predators in them. It has been argued that fish may stay in certain oceanographic features if concentrations of food are high (KINGSFORD, 1990), and the integrity of some oceanographic features may influence the chances small fish and other meroplankton have of survival (e.g. LASKER, 1975). However, the ability to demonstrate nutritional advantage in different water masses may prove difficult due to the dynamic nature of the frontal region (e.g. POWELL *et al.*, 1990).

(2) Fish were generally more abundant in waters of the plume or front, regardless of the presence-absence of slicks or the day of sampling. For estuarine fish and some reef fish, fronts may provide important oceanographic clues not to venture past the boundary of the front. For example, gobiids, sillaginids and gerreids (Table 3) were primarily found in waters of the bay rather than on the ocean side. It is also possible that some larvae are subducted down frontal edges to subsurface haloclines. If some taxa do spend their early life in mainstream currents before moving to estuarine nursery areas (e.g. ABLE *et al.*, 1989; POWELL *et al.*, 1989), fronts would provide an important cue to the location of estuaries and sheltered bays especially during ebb tides. This could explain the high densities of mugilid larvae that were found in fronts which were probably spawned from

adults in open coastal waters (KINGSFORD and TRICKLEBANK 1991; VIEIRA, 1991). Fish may respond to salinity, turbidity, or food gradients and follow the edge of fronts as they move. PINCKNEY and DUSTAN (1990) found "along front transport" during ebb tide in Charleston Harbour, South Carolina. The possibility that fish are transported toward the shore along the frontal edge on flood tides, and away from shore on the ebb requires more investigation.

(3) All samples were made in the vicinity of fronts found outside the heads of Botany Bay. Sampling, however, was not stratified according to state of the tide. The intensity of convergence at the front may change with the tide and may influence the degree to which plankters accumulate in fronts (GOVONI and GRIMES, 1992). For example, DUSTAN and PINCKNEY (1989) found that the aggregation of phytoplankton in fronts is weaker on the outgoing tide. Differences in the degree of aggregation we found in fronts may explain the different patterns of abundance we found among days of sampling. Moreover, observations from helicopter (Fig. 2) and boats indicated that turbid waters of the plume dissipated on the incoming tide. This phenomenon probably causes a rapid dilution of waters of the plume and a subsequent mixing of plankters and fish from water masses of the plume, front and ocean. An extension of this study would be the investigation of ichthyoplankters, other zooplankters and oceanography in the vicinity of fronts by stratifying sampling according to phase of the tide. It was interesting that fronts with slicks did not appear to influence the distribution of plankters to a greater or less extent than fronts without slicks. We assume that the physical distinction between these two conditions is the result of waters converging at different angles. The strength and direction of mainstream currents, which were observed to influence the direction of plumes (Fig. 3), may affect angles of convergence at fronts and the production of slicks. We also argue that the interaction of plumes and coastal current may influence the density (σ_t) of water below the front (e.g. Fig. 4), especially where the direction of plume movement is perpendicular to that of coastal currents potentially creating turbulence. Shear parallel to frontal interfaces has been found in other parts of the world (GOVONI and GRIMES, 1992), but no mention was made of turbulence effects below fronts.

The occurrence of a thin wedge of low density water near the surface which moves according to state of the tide, is of relevance to plankters throughout the water column. Low density waters may influence horizontal and vertical patterns of circulation and the related transport of plankters (EPIFANIO, 1988; KOUTITONSKY *et al.*, 1990; PICCOLO and PERILLO, 1990). Significant aggregation of plankton and particles can occur at the subsurface halocline, or pycnocline (e.g. NASH *et al.*, 1987). Moreover, larval fish and invertebrates may control their position in estuaries by vertical migration (review: NORCROSS and SHAW, 1984). Meroplanktonic fish and invertebrates that we found in plumes on ebb tides may be those that are temporarily or permanently lost from estuaries to coastal waters, primarily because the plume appears to dissipate outside of the bay as the flood tide commences. Large inputs of freshwater may represent significant transport of larvae to coastal waters and genetic exchange among estuaries.

In conclusion, the estuarine plume off Botany Bay is a significant intrusion into coastal waters. Plumes and fronts from the bay were dynamic in form according to tide, the input of freshwater and the intensity and direction of coastal currents. The distribution of meroplankters (including fish of estuarine, reef, benthic and pelagic origin) and holoplankters are greatly influenced by these oceanographic features. Some meroplankters, including fish and invertebrates, may behave in such a way that they are rarely advected

from the plume. Variable accumulation of plankton at fronts will result in a pulsing of biological activity in this region that is potentially important for trophic interactions among plankters and nekton. An exciting area of research is the importance that fronts and plumes have for transporting small fish and other plankters along the length of fronts, or as a consequence of the gross movement of the frontal edge.

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