



Scientific Excellence • Resource Protection & Conservation • Benefits for Canadians
Excellence scientifique • Protection et conservation des ressources • Bénéfices aux Canadiens

Flushing of oyster (*Crassostrea virginica*) larvae from a small tidal bay.

DFO - Library / MPO - Bibliothèque



14005456

David A. Booth¹ and Thomas W. Sephton²

¹) Université du Québec à Rimouski
Département d'océanographie
310 allée des Ursulines
Rimouski, Québec, G5L 3A1.

²) Department of Fisheries and Oceans
Science Branch, Gulf Region
Gulf Fisheries Centre
P.O. Box 5030
Moncton, New Brunswick, E1C 9B6

December 1993

Canadian Technical Report of Fisheries and Aquatic Sciences No. 1945

SH
223
F56
No 1945

Fisheries
and Oceans

Pêches
et Océans

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of the Department of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in *Aquatic Sciences and Fisheries Abstracts* and indexed in the Department's annual index to scientific and technical publications.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and the Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page. Out-of-stock reports will be supplied for a fee by commercial agents.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques du ministère des Pêches et des Océans, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications complètes. Le titre exact paraît au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la revue *Résumés des sciences aquatiques et halieutiques*, et ils sont classés dans l'index annuel des publications scientifiques et techniques du Ministère.

Les numéros 1 à 456 de cette série ont été publiés à titre de rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre. Les rapports épuisés seront fournis contre rétribution par des agents commerciaux.

167100

**Canadian Technical Report of
Fisheries and Aquatic Sciences No. 1945**

December 1993

Flushing of oyster (*Crassostrea virginica*) larvae from a small tidal bay.

by



David A. Booth¹ and Thomas W. Sephton²

¹) Université du Québec à Rimouski
Département d'océanographie
310 allée des Ursulines
Rimouski, Québec, G5L 3A1.

²) Department of Fisheries and Oceans
Science Branch, Gulf Region
Gulf Fisheries Centre
P.O. Box 5030
Moncton, New Brunswick, E1C 9B6

SH
223
F56
No 1945

*Imprimé sur du
papier recyclé*



*Printed on
recycled paper*

© Minister of Supply and Services Canada 1993
Cat. no. Fs 97-6/1945E ISSN 0706-6457

Correct citation for this publication is:

Booth, D.A. and T.W. Sephton. 1993. Flushing of oyster (*Crassostrea virginica*) larvae from a small tidal bay. Can. Tech. Rep. Fish. Aquat. Sci. 1945: 21p.

TABLE OF CONTENTS

LIST OF FIGURES	iv
ABSTRACT	v
INTRODUCTION	1
MATERIALS AND METHODS	2
RESULTS	3
1) Physical Results	3
2) Biological Results	4
DISCUSSION	6
Conclusion	9
ACKNOWLEDGEMENTS	9
REFERENCES	10

LIST OF FIGURES

- Figure 1. Caraquet Bay. Letters A - D give positions of Aanderaa moorings, N and S designate the S4 moorings, W the water level recorder, and M the meteorological station. Paspbiac is shown by a P. The public bed area is indicated by hatching. Station 1 is in Rivière Caraquet, and station 2 is in the middle of the public bed area.12.
- Figure 2. A summary of drogued buoy observations, showing interpolated hourly displacements for the 3 hours midway between high and low water, for both the ebb and the flood.13.
- Figure 3. Trajectory of buoy group on day 211. Each cross represents a position fix of one buoy, except at deployment where they indicate the limits of the group.14.
- Figure 4. Temperature ($^{\circ}\text{C}$) at three moorings showing the event that took place between days 206 and 211.15.
- Figure 5. Salinity at three moorings showing the event that took place between days 206 and 211.16.
- Figure 6. Detail of differences in temperature and salinity between moorings A and C: a) temperature at A - temperature at C, b) salinity at C - salinity at A.17.
- Figure 7. Concentration of oyster larvae averaged over stations 2 - 10. Asterisks show the times of sampling, the arrows those sampling times near low water. The dotted line gives the curve for low water sampling.18.
- Figure 8. Bar graph of oyster larvae concentrations averaged over stations 2 - 10 showing the proportion of different stages.19.
- Figure 9. Larval concentrations for two times on day 206 to highlight the tidal variability: am = 08:00 - 12:42; pm = 14:10 - 16:32.20.
- Figure 10. Larval concentrations for two times on day 210 to highlight the tidal variability: am = 06:20 - 10:16; pm = 12:00 - 15:14.21.

ABSTRACT

Booth, D.A. and T.W. Sephton. 1993. Flushing of oyster (*Crassostrea virginica*) larvae from a small tidal bay. Can. Tech. Rep. Fish. Aquat. Sci. 1945: 21p.

Keywords: bays, oyster larvae, tidal flushing, passive transport, dispersion.

Caraquet Bay, a small tidal bay, supports a natural population of oysters (*Crassostrea virginica*). Results from a study undertaken during the larval period of 1988, which included measurements of current, stratification, and larval concentrations, indicate that flushing of larvae is not by diffusion alone. The larvae disappeared from the bay but returned in time for spatfall. The observed flushing and return of the larvae were associated with an oceanographic event outside the bay which increased the horizontal gradients of water density. It is argued that flushing is weak under normal conditions but that asymmetry between flood and ebb flows, and thus the flushing, is enhanced by density gradients. Passive transport of larvae is discussed in the context of flows over small scale topography.

RÉSUMÉ

Booth, D.A. and T.W. Sephton. 1993. Flushing of oyster (*Crassostrea virginica*) larvae from a small tidal bay. Can. Tech. Rep. Fish. Aquat. Sci. 1945: 21p.

Mots clés: baie, larves d'huîtres, la sortie de marée, transport passif, dispersion

La Baie de Caraquet, une petite baie affectée par les marées, abrite une population naturelle d'huîtres (*Crassostrea virginica*). Les résultats d'une étude effectuée pendant la période larvaire de 1988, prenant en considération des mesures de courants, stratifications, et concentrations de larves, ont indiqué que la sortie des larves de la baie n'était pas expliquée par diffusion seulement. Les larves ont disparu de la baie mais sont révenu à temps pour la chute du naissain. Le départ et le retour des larves étaient associés à un évènement océanographique observé à l'extérieur de la baie qui a augmenté les gradients horizontaux de la densité de l'eau. La sortie de masses d'eau est faible sous des conditions normales mais la symétrie entre les marées montantes et descendantes, donc la sortie de masses d'eau, est accentuée par des gradients de densités. Le transport passif des larves est discuté dans le contexte de mouvements de masses d'eau sur une petite échelle topographique.

INTRODUCTION

Caraquet Bay (47°48'N, 65°0'W) is a shallow, semi-enclosed estuarine bay situated on the south shore of Baie des Chaleurs (Fig.1). The bay supports the most northern commercial population of eastern (American) oyster (*Crassostrea virginica* Gmelin) (Sephton and Bryan 1989) and the collection and cultivation of oysters is a traditional occupation of the area.

Apart from the entrance channel, the water depth at low tide is about 2 m. The mean tidal range is 1.4 m and thus thorough flushing might be expected within a few tidal cycles. The oyster population, however, manages to sustain itself with natural recruitment: after a 3 - 4 week pelagic existence, metamorphosing larvae are present in the bay. Moreover, the bay is used as a site for spat collection for aquaculture, and this despite the fact that there are no other large oyster beds within 30 km of the bay. Sufficient larvae must therefore remain in the region of the bay. What happens to the larvae during their pelagic existence?

A related question concerns the interannual variability of spat density on the collectors. Densities vary by almost two orders of magnitude (P.Cormier, Caraquet, pers.comm.). Numerous factors influence the success of a collector. These include silt on the collector (Carricker 1986), wave generated turbulence (Medcof 1961, Abbe 1986), predation (Osman *et al.* 1989) and unfavourable environmental conditions (Kenny *et al.* 1990). Nevertheless, without sufficient larvae in the water, the spat density cannot be large.

Oyster larvae, particularly the later stages, are not altogether passive plankton. They are known to migrate vertically (Andrews 1983, Mann 1988). Horizontal drift by active selection of depth is therefore possible, although the stimulating factor, whether salinity or otherwise, is not known. Such a drift requires either a shear in the mean flow or an oscillatory vertical migration in phase with the tidal current. Neither mechanism is likely in the case of Caraquet Bay, a region of short horizontal scales in topography. We therefore use the working hypothesis of passive drift. The fate of the larvae during their pelagic existence then becomes a question of dispersion.

The horizontal excursion of the tide is of the same order as the dimensions of the bay, i.e. larger than the horizontal scale of the topography. Horizontal shear in the flow is thus crucial to the dispersion.

The study undertaken in 1988 to investigate the dispersion of oyster larvae was designed to highlight the spatial structure of both the larval distribution and the flow. Although a complete budget of oyster larvae would be an ideal aim, this was not attempted. The practical difficulties in obtaining numerous larval samples at regular intervals in the channel or in following a larval patch for many tidal cycles permitted neither a Eulerian nor a Lagrangian budget. We concentrated, therefore, on an attempt to identify the mechanisms of exchange to and from the bay.

Two main rivers enter the bay (Fig.1). Another small river enters on the south shore and various dykes from a peat bog discharge along the north shore. During summer months, the total river discharge is about $4 \text{ m}^3 \text{ s}^{-1}$. The dune that stretches across the mouth is

exposed at low water and a bank lies along the inner edge of the channel. The natural oyster bed, (the public bed), is situated in the inner part of the bay. Other privately leased areas near both the south and north shore are, however, seeded regularly with young oysters. Bottom sediments vary from sand to silt and eel grass is prolific at the head of the bay.

MATERIALS AND METHODS

Oceanographic instruments were deployed in the bay for a period of six weeks in 1988. Instrumentation included 7 current meters, an Aanderaa meteorological station at Oyster Point, and an Aanderaa water level recorder (WLR7) with a 70 m transducer at Caraquet Harbour (Fig.1). Four subsurface moorings, A - D (Fig.1), supported Aanderaa current meters at a depth of 3 m below low water. In addition, mooring B in the channel had a second Aanderaa meter at 1 m above the bottom in a low-water depth of 5.5 m. Meters on moorings A and B were of the type RCM7, others being the older RCM4s version. In addition, two InterOcean S4 electromagnetic current meters were installed on frames at 1 m from the bottom at sites S and N. All instruments, except the S4 at N, were deployed by 3 July 1988. The remaining S4 was installed on 28 July. Recovery began on 15 August.

The current meters were cleaned by diver at the end of July, but rotors on the meters in the channel were fouled with weed on recovery. Fouling also affected some conductivity cells and reduced the observed salinities. Affected data were discarded.

Lagrangian currents were measured with small drifting buoys, each with a narrow mast and a simple windowblind drogue (Booth 1981) of dimensions 0.8 m * 0.6 m. The drogue was centred at a depth 0.5 m. Based on frontal areas, slippage due to wind drag was $4 \cdot 10^{-3}$ * surface wind velocity. Groups of up to 20 buoys were followed by boat. At intervals of about 1 hour, positions of the buoys were measured with a microwave Motorola MiniRanger system on the boat. The buoys were tracked during a complete semidiurnal tidal cycle on two occasions, 6 July and 29 July, and for periods of between 2 and 10 hours on 8 other occasions between 5 July and 4 August.

Temperature and salinity measurements were made with an Applied Microsystem STD12, equipped with a shallow water pressure transducer. Uppermost samples were recorded with the sensors at about 0.3 m below the surface. The grid of 12 stations (Fig.1) was covered daily during the later stages of larval development.

At each station, a 750 l integrated plankton sample was collected by raising and lowering a submersible bilge pump from 0.2 m above the bottom to the surface during a 10 minute interval. At stations 8, 11 and, 12 (Fig.1), samples were collected from two standard layers, the upper one between the surface and a depth of 2 m, the lower one between depths of 3 m and 5 m. Larvae were concentrated by filtering

through a 100 μm Nitex mesh screen and were then preserved. Larval concentrations were sampled on the following days of the year: 189, 194-196, 201-203, and 206-215, with two circuits of the grid (with the exception of station 12) on all sampling days from day 206 except on days 209 and 215. A full circuit of the station grid took 3 - 4 h. Replication was omitted in an attempt to minimize the time per circuit. Sampling took place at various stages of the tide. Samples with large concentrations (> 250 larvae m^{-3}) were subsampled. All larvae in each sample were then identified and enumerated based on descriptions given by Drinnan and Stallworthy (1979).

RESULTS

1) Physical Results

Tidal currents in the channel reached 0.8 m s^{-1} during spring tides and 0.4 m s^{-1} during neaps. At the moorings both inside and outside the bay, tidal currents were generally less than 0.3 m s^{-1} .

River flow at Burnsville on Rivière Caraquet (data supplied by Environment Canada) 10 km from the estuary decreased from $2.8 \text{ m}^3\text{s}^{-1}$ on day 195 to $1.5 \text{ m}^3\text{s}^{-1}$ on day 200, and remained between 1.3 and $1.5 \text{ m}^3\text{s}^{-1}$ until day 213. Freshet values are ten times these values. Based on catchment areas (Anon. 1976), the total flow into the bay, including the contribution from the area downstream of Burnsville, was 1.9 times the value at Burnsville. A flow at Burnsville of $1.4 \text{ m}^3\text{s}^{-1}$ thus represents about 0.4% of the mean tidal prism per tidal period.

The wind remained light to moderate throughout the survey. During the period of biological interest between days 201 and 215, the maximum daily wind speeds decreased from 7 m s^{-1} to 4 m s^{-1} on day 211 and then increased again to 9 m s^{-1} .

The water column in the bay was generally well mixed except within the estuarine plume where a thin upper layer was often indicated by a vertical shear in the drift of weed and debris. The water column in the channel was also occasionally stratified. Haloclines with differences of 2 were recorded at station 11 on days 209, 211, and 212. The deepest halocline observed occurred at a depth of 2 m. The Aanderaa current meters in the channel, all below this depth, recorded net flows of about 0.02 m s^{-1} into the bay, but this speed is close to the accuracy limit. Salinities in the bulk of the bay ranged from 24 to 27, the highest salinity occurring in the northeast corner, presumably in part because of some flow over the dune at high water. Near-bottom salinities at station 3 were only 1 or 2 units lower than those in the northeast corner. Temperatures at mooring S tended to be 1 - 2 $^{\circ}\text{C}$ higher than those at mooring A in the channel and reached 24 $^{\circ}\text{C}$ by early August.

The current measurements (Sephton and Booth 1992) are summarised by plotting interpolated vectors of buoys and near-surface current meters for mid-flood and mid-ebb flows (Fig.2). Currents were strong in the channel, weak in the Maisonnnette corner of the bay. Intersecting vectors are of buoys tracked on different days. In general the flow appears symmetric. Asymmetric features included a weak seaward drift, an eddy to the north of the channel, and large net displacements observed on day 211 (29 July).

The oscillatory pattern of flow was supported by visual observations of the water surface and in particular the river plume emanating from Rivière Caraquet. At high water, the plume was restricted to the river mouth. As the ebb progresses, the plume advanced down the bay along the south shore and into the channel. A slick often coincided with the inner edge of the channel. On the flood tide, the plume was pushed back into the bay. On one occasion, a temporary V shaped front was observed at the inner end of the channel. At times several slicks existed in the bay.

Buoy results of day 211 are of particular interest as shown in Figure 3. A group of 20 buoys was deployed near the mouth of Rivière du Nord 2 h after high water. The first tidal range of the day was 1.5 m, the second 0.6 m. The group drifted seawards and into the channel, where it migrated to a convergence at its inner edge. The group elongated, but soon after the start of the flood tide, the buoys diverted abruptly across the edge of the channel. Light winds of $2 - 3 \text{ m s}^{-1}$ could not account for the net drift, which in this case was comparable to the tidal excursion.

Three days beforehand (day 208), two groups of 10 buoys released in the channel 1 h after low water also crossed the edge into the shallow region, where they displayed anticyclonic eddy motion (Sephton and Booth 1992). These groups, initially 0.3 km apart across the channel, were 7 h later separated by 1.3 km.

Buoys released just outside the bay also displayed eddy motion as well as stretching and fragmentation of the group (Sephton and Booth 1992).

Tidal variations of both temperature and salinity were large. At mooring S in the bay, variations at 1 m above the bottom reached 5°C and 5 respectively. In the channel at moorings A and B, variations were as large as 5°C and 2 respectively. At moorings C and D, the tidal variations were smaller.

On days 206 and 207, midway between neap and spring tides and in the middle of the period of biological interest, a change occurred by which the tidal variations of temperature (Fig.4) and salinity (Fig.5) suddenly increased. The average salinity also increased and the average temperature decreased. The event was observed at the moorings in the channel and outside the bay. It was not immediately evident inside the bay, although salinities rose at a rate of about 0.2 day^{-1} during the following week with a corresponding decrease in temperature. The event took place at mooring C one day earlier than at the moorings in the channel or further east at D, and generated an increase in horizontal gradients (Fig.6).

2) Biological Results

Between days 201 and 214, oyster larvae concentrations, averaged over stations 2 - 10 inside the bay, peaked three times (Figs.7,8). (Due to large variability, station 11 was omitted from these averages.) On day 203 large numbers of young larvae appeared in the samples. The maximum average concentration was over 10^3 m^{-3} . Except for day 214, samples were taken near low water or during the smaller of the two daily tides. Concentrations were generally higher at high water than at an adjacent low water, and sometimes differed by a factor of two (e.g. days 206, 207, 210). Such variations suggest that the horizontal scale of the larvae distribution was smaller than the tidal excursion. Care therefore must be exercised when considering a time series to avoid aliasing of the tidal signal. Taking the values for low water only, the series shows a decrease from a peak on day 203 to about 250 larvae m^{-3} on day 207 and then to a very small value on day 208 followed by a peak on day 210. The larvae thus virtually disappeared from the bay samples. On day 210, samples in the bay had a large proportion of mature larvae. These returned in time for the set. A second decrease after day 210 was followed by another peak of 400 larvae m^{-3} on day 215 when a second cohort of larvae appeared.

Concentrations of the different stages (early hinge and incipient umbo, early umbo, late umbo, and mature larvae) (Fig.8) indicated that larval development was not synchronous. Spawning, which was monitored before the field study, occurred during the first two weeks of July. The total larval development time was about 22 days with mature larvae of the first cohort ready to set by late July.

Concentrations for grids 6 h apart clearly show tidal variations (Figs.9,10). Although distortion of the distribution by variations in concentration during the 3 or 4 hour period required to cover the grid, plus the lack of replication limit the interpretation, high concentrations near the time of high water tended to occur in the northern half of the bay.

At station 11 (in the channel), there were no significant differences ($F=0.02$, $df=1,34$, $P=0.8867$) in the larval concentrations at the two layers sampled. Mean and standard deviations for the upper and lower layers were $134.2 \pm 140.3 \text{ m}^{-3}$ and $104 \pm 123.3 \text{ m}^{-3}$ respectively even though concentrations ranged from 0 to 350 m^{-3} . Neither the total concentration nor the concentration of the different development stages displayed a consistent pattern, even when the state of the tide was taken into consideration. The average concentration of mature larvae was slightly higher in the upper layer ($121 \pm 23 \text{ m}^{-3}$) than in the lower layer ($70 \pm 14 \text{ m}^{-3}$), but the difference was not significant ($F=0.16$, $df=1,34$, $P=0.6915$). There were no significant differences ($P>0.05$) among any of the other stages. At station 8 likewise, there was no significant differences between concentrations in the two sampled layers ($F=0.20$, $df=1,29$, $P=0.6619$).

Based on the spatfall monitoring data, (P.Cormier, Caraquet, pers. comm.), the set on collectors installed inside the bay was reported to be excellent (more than 10^4 spat per collector).

DISCUSSION

By active vertical movement through a shear in horizontal flow, mature larvae can bias their drift (Seliger *et al.* 1982, Andrews 1983, Abbe 1986, Mann 1988). In the case of Caraquet Bay, the water column in the channel was weakly stratified. The current meters recorded a weak subsurface inflow, but there was no evidence that mature larvae preferred the lower layer. Furthermore, the sudden changes observed in larval concentration occurred for all stages of larval development. The proportion of different stages in the samples did not vary greatly from one day to the next (Fig.8) as would be expected if mature larvae were making use of the shear. It is worth noting that the tidal excursion extends well beyond the limits of the entrance channel. If anywhere, the mechanism of active transport might be important under the estuarine plume in the inner part of the bay. For flushing of the bay however, the present results support neither estuarine retention nor tidal synchronization of vertical migration. A mechanism based on biological response appears inadequate for the major events of the larval time series (Fig.7). We consider therefore the transport of passive larvae.

In the simplest scenario, flushing the bay is by diffusive processes, including those that can be evaluated in terms of shear in the mean flow. Changes in larval concentration in the bay, however, were erratic (Fig.8) and the distribution of larvae did not expand as a diffusing cloud. Distributions near the end of the pelagic period (Figs.9,10) were no larger than earlier distributions and little larger than the bed of oysters itself. Diffusive processes, therefore, do not describe the observed flushing. Transport by advective processes must be considered.

Tidal flushing of a shallow bay depends on the difference between the flow fields of the ebb and the flood (Wolanski and Imberger 1987). Inside a bay with a constricted entrance, the flood flow forms a jet. The ebb flow, on the other hand, resembles a potential flow around a sink (Fischer *et al.* 1979). This asymmetry depends on topography which has the effect of guiding the flow (Wolanski and Imberger 1987). In the case of Caraquet Bay, the channel plus the passage inside Caraquet Island is longer than the tidal excursion. The buoy results (Fig.2) indicated a general symmetry between the flood and ebb flows. Topography appears to guide the flow between the channel and the inner part of the bay. This suggestion is supported by the distributions of mature larvae for which large concentrations tended to occur in the channel and in the inner part of the bay, but not in the northeast corner.

An exchange budget for tidal flushing is governed by eddies that form at the sides of tidal jets. An analysis such as that of Kashiwai (1984) would suggest that, in a bay with dimensions of Caraquet Bay, the residual eddy should be well developed. The analysis is for flat bottomed basins, and topographic guiding limits its application. Nevertheless, eddy motion was observed both inside and outside the bay (Sephton and Booth 1992). The sand spit that forms Oyster Point and the side channel just inside the sand bar may also indicate eddy motion.

Accepting for argument sake the presence of tidal eddies both inside and outside the bay, we have a flow field similar to that of the Aref-blinking-vortex (Khakhar *et al.* 1986) in which adjacent and oppositely rotating vortices alternatively turn on and off. Dispersion within this flow depends on the interval time, the distance between vortex centres, and the vortex strength. Under certain conditions, particle displacements become chaotic with a dramatic increase in dispersion of a marked patch. Such dispersion by chaotic stirring in the presence of coastal eddies is feasible (Zimmerman 1986, Geyer and Signell 1992). This is shown by convolutions made up of stretching and folding that occur near the entrance of a basin in the numerical model of Awaji *et al.* (1980). If, however, we use typical dimensions of the bay, the vortex strength, as estimated from buoy observations of day 208, is an order of magnitude smaller than that required to generate chaotic dispersion. Thus we suggest that, as a result of topographic guiding, the tidal eddies are by themselves not responsible for the flushing of larvae from the bay.

Between days 207 and 211, larvae in the bay disappeared and reappeared in time to settle (Fig.8). During the same period, enhanced tidal variations in temperature and salinity were observed, first at the outermost mooring, a day later in the channel. The associated change in mean temperature and salinity (Fig.5) and the enhanced horizontal gradients (Fig.6) suggest an intrusion of deep water. At a depth of 8 m near Paspbiac on the north shore of Baie des Chaleurs (Fig.1), a sudden rise and subsequent fall in temperature was observed during the same period (Gregory *et al.* 1989). Since the temperature in Baie des Chaleurs during this season varies between 18 °C at the surface and 0 °C at 50 m with strong gradients in the upper 30 m (Boudreault 1967), the event was probably a baroclinic adjustment throughout the Baie. Based on the frequency of step-like changes in the temperature records from Paspbiac, an event such as that observed appears likely during the 3 to 4 week pelagic existence of the oyster larvae.

On a large scale, Baie des Chaleurs is expected to respond to both local winds and those over the Gulf of St. Lawrence (Koutitonsky and Bugden 1991). No local wind event was observed. Weather charts provided by Environment Canada show that, apart from weak troughs that occurred to the south on days 204 and 207, high atmospheric pressure persisted over the Gulf between days 203 and 213. Another factor of influence, however, may be the vacillating near-surface Gaspé current that penetrates the plateau east of the Baie des Chaleurs (Koutitonsky and Bugden 1991).

At the local scale, it is clear that exchanges of larvae in and out of the Caraquet Bay occurred during the period of enhanced horizontal gradients of water density. Under conditions of sheared flow, intrusive or interleaving flows can result. The frequent presence of slicks in the bay including some along the inner edge of the channel indicate such flows. A temporary V shaped front (for other examples see: Largier 1992, Booth 1987) confirmed the sinking of dense flood water under the estuarine plume. Such a flow is likely to cause flushing (Largier and Taljaard 1991).

On two occasions during this period of enhanced density gradients, drifting buoys crossed the edge of the channel and drifted into the northeastern corner of the bay. The flood flow can be considered as leaky in that some restricted flow occurs over the edge of the channel. Thus the fate of a marked particle depends on its position in the channel. This

position sensitivity was also demonstrated not only by an increasing separation between buoy groups but also, at a scale of a few meters, by the elongation of a group at the edge of the channel, presumably a result of drift through a lateral shear in the flow. By encouraging sheared flow and perhaps vertical motion, any lateral gradient in density would enhance this sensitivity. The consequence is likely to be added asymmetry between the flood and ebb flows.

Large concentrations of larvae were found in the shallow region just north of the channel on days 206 (Fig.9) and 207 (not shown). On both days, these large concentrations disappeared within a few hours. Thus the exchange that was responsible for the flushing of larvae does appear to have been across the edge of the channel. On the other hand, when the larvae returned four days later, the larvae were concentrated in the eastern part of the bay (Fig.10).

Another way of visualising the shallow northeastern region is in terms of a trap (Okubo 1973). By temporarily storing water and later releasing it back into the main tidal flow, the region causes a phase lag in the tidal displacement and thus a longitudinal dispersion in the channel (Dronkers 1988). Exchange between the channel is governed not only by the tide and wind stress but also by lateral density gradients. Furthermore, wind and density gradients are likely to be the major factors influencing the movement of water in the shallow northeast corner of the bay. The behaviour of the trap, therefore, depends on local conditions, but the sudden appearance of dense water in the channel must be expected to cause an initial exchange.

A second trap, particularly for the oyster larvae themselves, may be the dense beds of eel grass at the head of the bay. Larval concentrations in the area were frequently lower than the mean value for the bay, particularly during the period between days 203 and 210. Unless the larvae somehow time their release, the eel grass does not appear to act as a trap for refuge.

Spatfall monitoring data collected from 1974 to 1991 (P.Cormier, Caraquet, unpublished data) indicate that spatfall varies from less than 10^3 per collector to over 10^4 per collector, 1988 being a year of high spatfall. Thus despite the flushing event observed, the collectors were a success. It is noteworthy, however, that variations in larval concentration both from day to day and particularly from station to station within the bay were greater than the interannual difference in spatfall.

The implication of the work is that flushing of larvae by hydrodynamic means overrides mechanisms that rely on an active larval response. There are two simple explanations, the first being the variability in oceanographic conditions on a time scale shorter than the period of pelagic existence. The second relates to the time response for vertical migration by the larvae. A biological response that is long in comparison to the time for exchange between different hydrodynamic regimes must limit the effect.

Typical vertical speeds of 1 mm s^{-1} (Mann 1988) give a time to migrate from top to bottom in the channel of almost 1.5 h. Apart from times of slack water, this is about the time required for the water to travel from one end of the entrance channel to the other. This

rules out tidally synchronized migration. Drift by larvae that seek a particular layer must also be limited if only because conditions at either end of the channel are different. Furthermore, the tidal asymmetry responsible for exchange is in both the vertical and horizontal planes. For an exchange across the edge of the channel into the area of the bay that may behave as a trap, the transit time is in the order of minutes, a scale too short for vertical migration to play a role.

In general, therefore, flushing by passive transport is likely to dominate over the transport resulting from a biological response to vertical shear in areas where 1) the oceanographic conditions vary rapidly or 2) the horizontal scale of the flow field is small compared to the tidal excursion or the horizontal distance travelled by the larvae during their vertical migration.

Conclusion

A baroclinic adjustment of Baie des Chaleurs can cause a change in oceanographic conditions of the coastal region outside Caraquet Bay thus creating horizontal density gradients. These enhance conditions for flushing through the entrance channel of the bay and in particular across the edge of the channel. The conditions include a Lagrangian sensitivity to position and interleaving flows. The result is an asymmetry between the flood and the ebb flows. The coincidence of an oceanographic event and the observed flushing of larvae suggested that the flushing was caused by density gradients in this manner.

No evidence was found for active migration of larvae. Relying on passive transport alone, the variations in tidal flows in and out of the bay are probably sufficient to explain the interannual variation in spatfall. The small horizontal scale of the larval distribution and the variation in larval concentration from day to day support such a conclusion. In small bays such as Caraquet Bay, where conditions vary rapidly and where the horizontal scale of the flow is small compared to either the tidal excursion or the horizontal distance travelled during vertical migration of larvae, the passive transport of larvae is likely to override drift caused by a biological response.

ACKNOWLEDGEMENTS

The field work was undertaken by Clair Bryan and Roger Pigeon. We thank them and their assistants including Danny Boulanger. We also thank all those at Caraquet who made our visit exceptional, especially Jean-André Blanchard and Paul Cormier.

REFERENCES

- Abbe G.R. 1986. A review of some factors that limit oyster recruitment in Chesapeake Bay. *Am. malaco. Bull. spec. ed.* 3: 59-70.
- Andrews J.D. 1983. Transport of Bivalve larvae in James River, Virginia. *J. Shellfish Res.* 3: 29-40.
- Anon. 1976. Potential impact of the St. Anne du Bocage sewage treatment plant. MacLaren Atlantic Ltd., Halifax.
- Awaji T., N. Imasato and H. Kunishi. 1980. Tidal exchange through a strait: a numerical experiment using a simple model basin. *J. phys. Oceanogr.* 10: 1499-1508.
- Booth D.A. 1981. On the use of drogues for measuring subsurface ocean currents. *Dt. hydrogr. Z.* 34: 284-294.
- Booth D.A. 1987. Some consequences of a flood tide front in Loch Creran. *Estuar. coast. Shelf Sci.* 24: 363-375.
- Boudreault F.R. 1967. Observations d'océanographie physique dans la Baie-des-Chaleurs, mai-novembre 1959-1960. *Cah. Inf. Stn. biol. mar. Grande-Rivière*, 39.
- Carricker M.R. 1986. Influence of suspended particles on the biology of oyster larvae in estuaries. *Am. malaco. Bull. spec. ed.* 3: 41-49.
- Drinnan R.E. and W.B. Stallworthy. 1979. Oyster larval populations and assessment of spatfall, Bideford River, PEI., 1958. *Can. Fish. Mar. Serv. Sci. tech. Rept.* 792: 1-32.
- Dronkers J. 1988. Inshore/offshore water exchange in shallow coastal systems. pp: 3-39. *In: Jansson B.-O. (ed). Coastal Offshore Ecosystem Interactions. Lecture Notes on Coastal and Estuarine Studies*, 22, Springer-Verlag, Berlin.
- Fischer H.B., E.J. List, R.C.Y. Koh, J. Imberger and N.H. Brooks. 1979. Mixing in inland and coastal waters. Academic Press, New York. 483pp.
- Geyer W.R. and R.P. Signell. 1992. A reassessment of the role of tidal dispersion in estuaries and bays. *Estuaries* 15: 97-108.
- Gregory D.N., E. Verge and P. Langville. 1989. Long term monitoring program 1988, Scotia-Fundy and Gulf of St. Lawrence. *Can. Data Rept. hydrogr. Ocean Sci.* 74: 233.
- Kashiwai M. 1984. Tidal residual circulation produced by a tidal vortex. Part 1: Life history of a tidal vortex. *J. oceanogr. Soc. Japan* 40: 279-294.

- Kenny P.D., W.K. Micherer and D.M. Allen. 1990. Spatial and temporal patterns of oyster settlement in a high salinity estuary. *J. Shellfish Res.* 9: 329-339.
- Khakhar D.V., H. Rising and J.M. Ottino. 1986. Analysis of chaotic mixing in two model systems. *J. Fluid Mech.* 172: 419-451.
- Koutitonsky V.G. and G.L. Bugden. 1991. The physical oceanography of the Gulf of St. Lawrence: a review with emphasis on the synoptic variability of the motion. pp 57-90. *In: Theriault J.-C. (ed). The Gulf of St. Lawrence: small ocean or big estuary. Can. spec. Publ. Fish. aquat. Sci.* 113.
- Largier J.L. 1992. Tidal intrusion fronts. *Estuaries* 15: 26-39.
- Largier J.L. and S. Taljaard. 1991. The dynamics of tidal intrusion, retention, and removal of seawater in a bar-built estuary. *Estuar. coast. Shelf Sci.* 33: 325-338.
- Mann R. 1988. Distribution of bivalve larvae at a frontal system in the James River, Virginia. *Mar. Ecol.- Prog. Ser.* 50: 29-44.
- Medcof J.C. 1961. Oyster farming in the Maritimes. *Bull. Fish. Res. Bd. Can.* 131: 158pp.
- Okubo A. 1973. Effect of shoreline irregularities on streamwise dispersion in estuaries and other embayments. *Neth. J. Sea Res.* 6: 213-224.
- Osman R.W., R.B. Whitlatch and R.N. Zajac. 1989. Effects of resident species on the recruitment into a community: larval settlement versus post-settlement mortality in the oyster *Crassostrea virginica*. *Mar. Ecol.- Prog. Ser.* 54: 61-73.
- Seliger H.H., J.A. Boggs, R.B. Rivkin, W.H. Biggley and K.R.H. Aspden. 1982. The transport of oyster larvae in an estuary. *Mar. Biol.* 71: 57-72.
- Sephton T.W. and C.F. Bryan. 1989. Changes in the abundance and distribution of the principal American oyster public fishing grounds in the southern Gulf of St. Lawrence, Canada. *J. Shellfish Res.* 8: 375-385.
- Sephton T.W. and D.A. Booth. 1992. Physical oceanographic and biological data from the study of the flushing of oyster (*Crassostrea virginica*) larvae from Caraquet Bay, New Brunswick. *Can. manusc. Rept. Fish. aquat. Sci.* 2162: 61pp.
- Wolanski E. and J. Imberger. 1987. Friction-controlled selective withdrawal near inlets. *Estuar. coast. Shelf Sci.* 24: 327-333.
- Zimmerman J.T.F. 1986. The tidal whirlpool: a review of horizontal dispersion by tidal and residual currents. *Neth. J. Sea Res.* 20: 133-154.

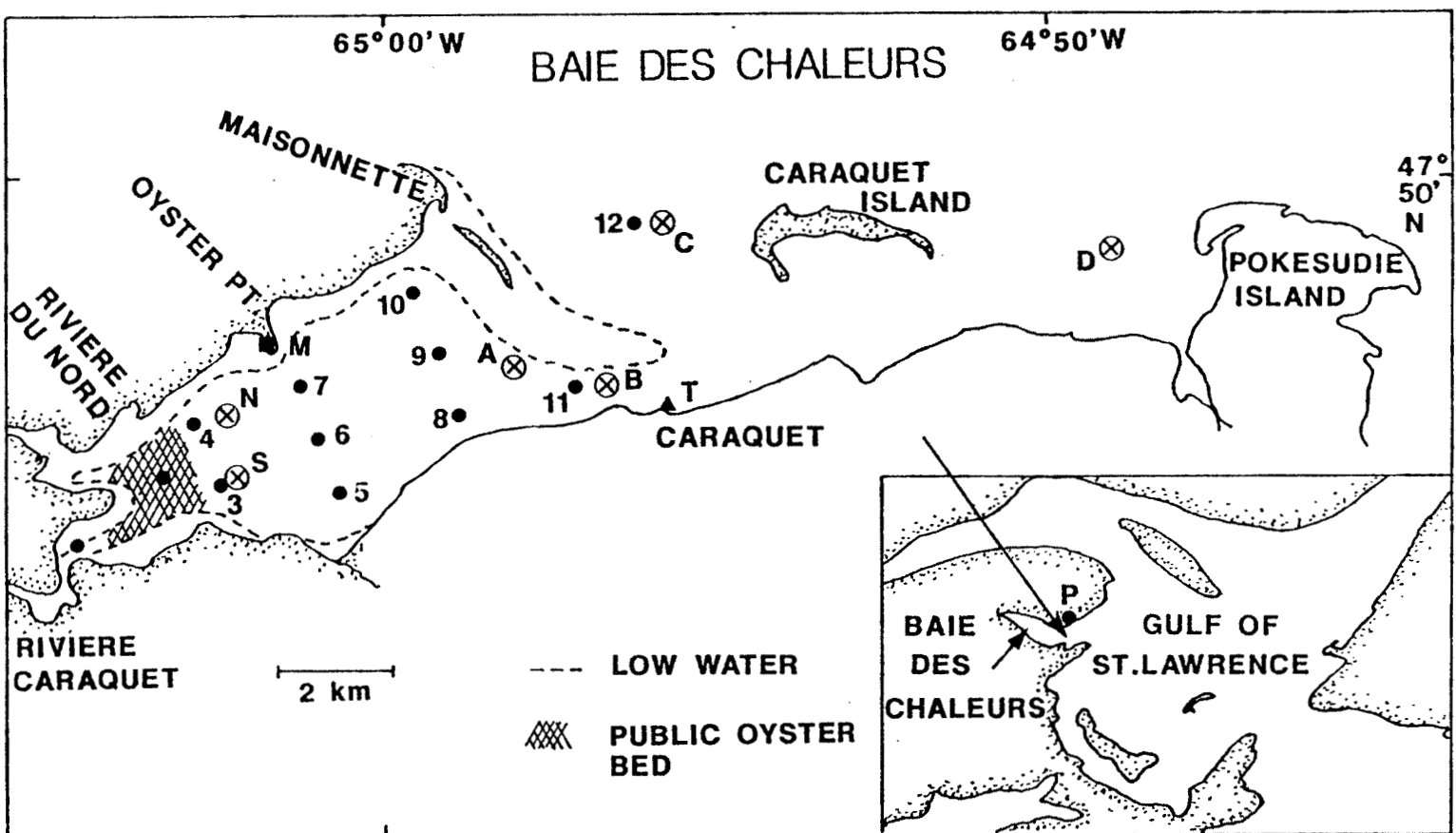


Figure 1. Caraquet Bay. Letters A - D give positions of Aanderaa moorings, N and S designate the S4 moorings, W the water level recorder, and M the meteorological station. Paspbiac is shown by a P. The public bed area is indicated by hatching. Station 1 is in Riviere Caraquet, and station 2 is in the middle of the public bed area.

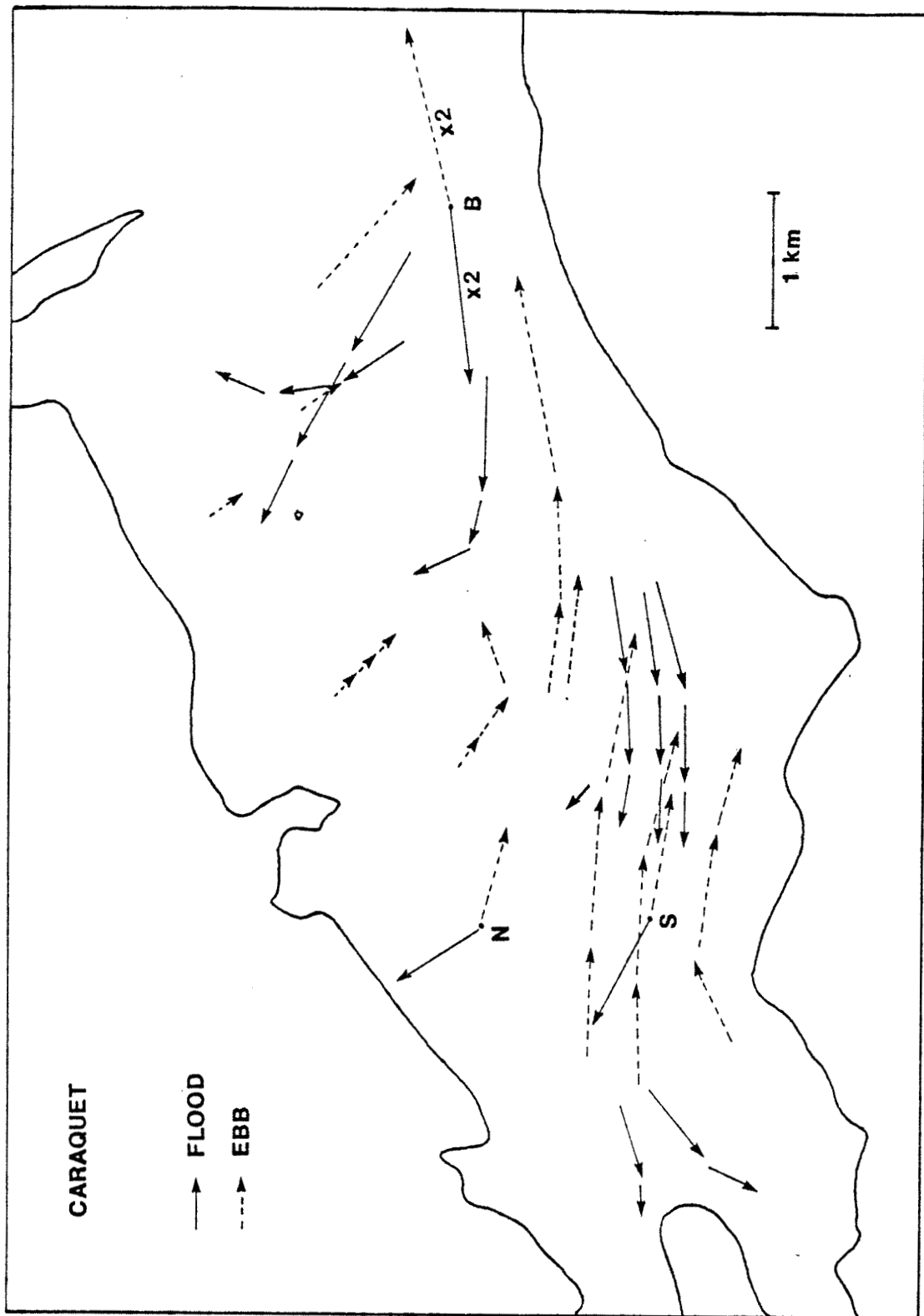


Figure 2. A summary of drogued buoy observations, showing interpolated hourly displacements for the 3 hours midway between high and low water, for both the ebb and the flood. Peak tidal velocities for average tides at moorings S,N and B have been added. Note the change in scale for mooring B.

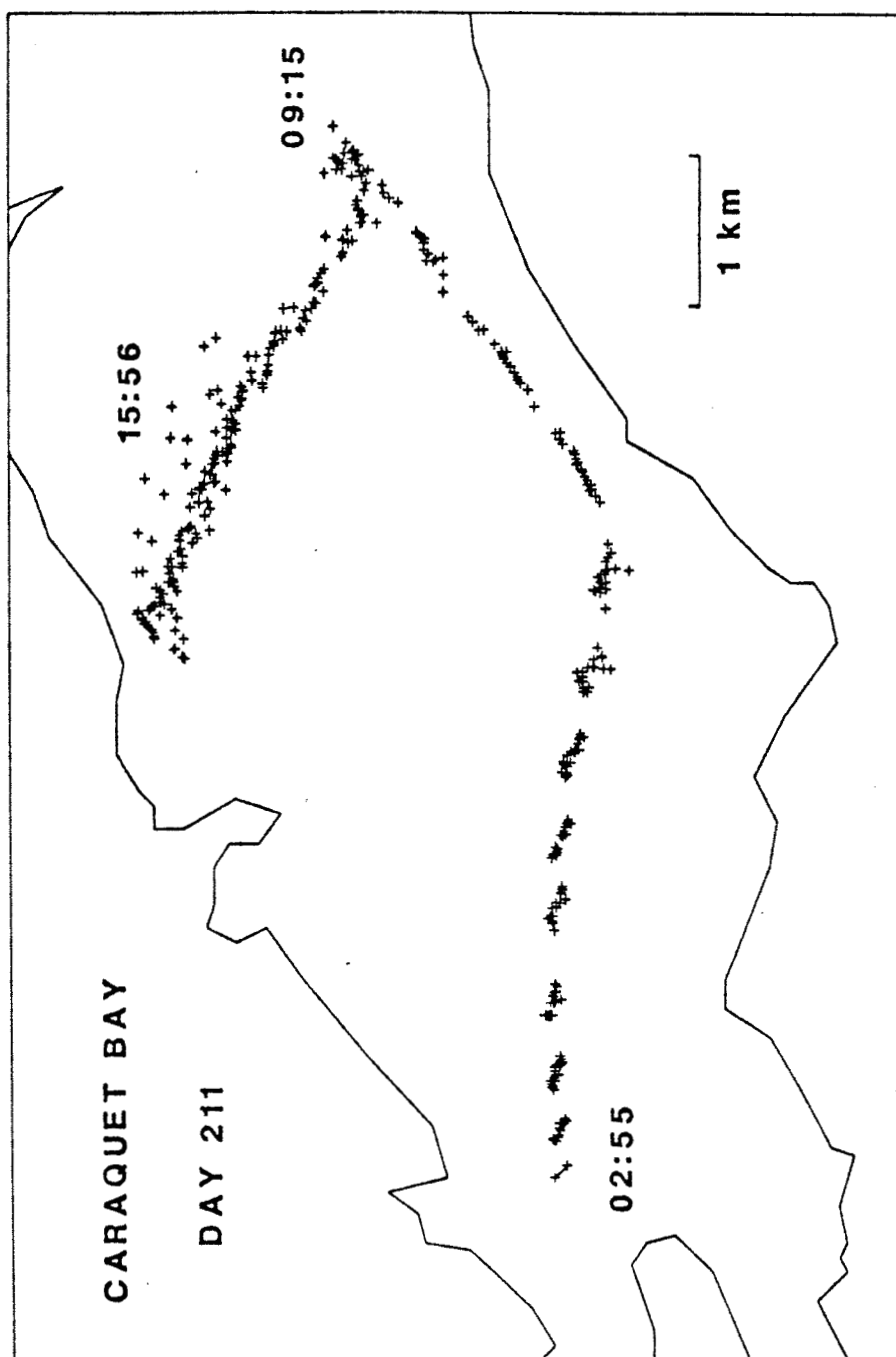


Figure 3. Trajectory of buoy group on day 211. Each cross represents a position fix of one buoy, except at deployment where they indicate the limits of the group. Observed tidal elevations: 06:50, 1.1 m; 14.50, -0.8 m; 19.30 0.2 m; (times in UTC).

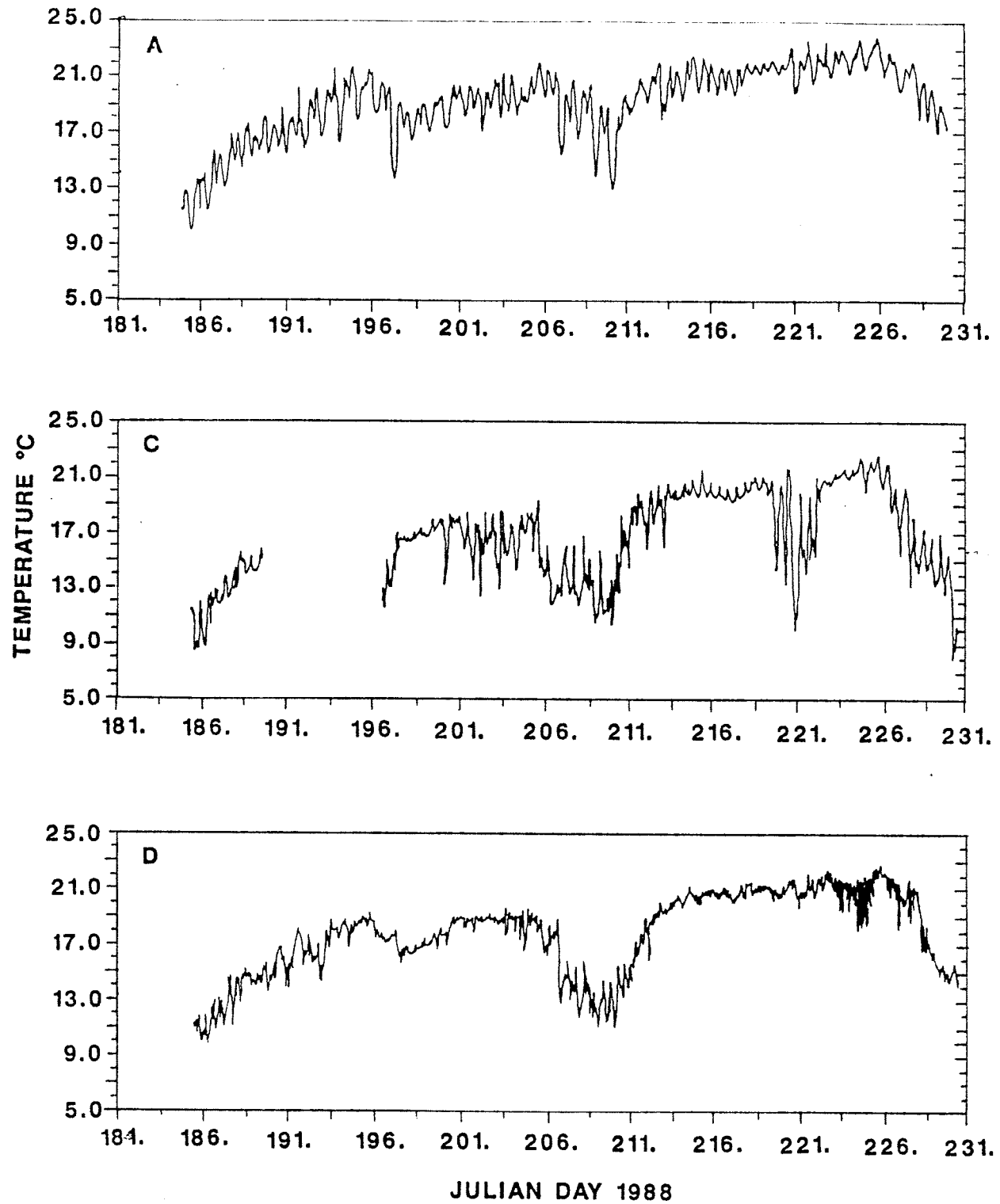


Figure 4. Temperature (°C) at three moorings showing the event that took place between days 206 and 211.

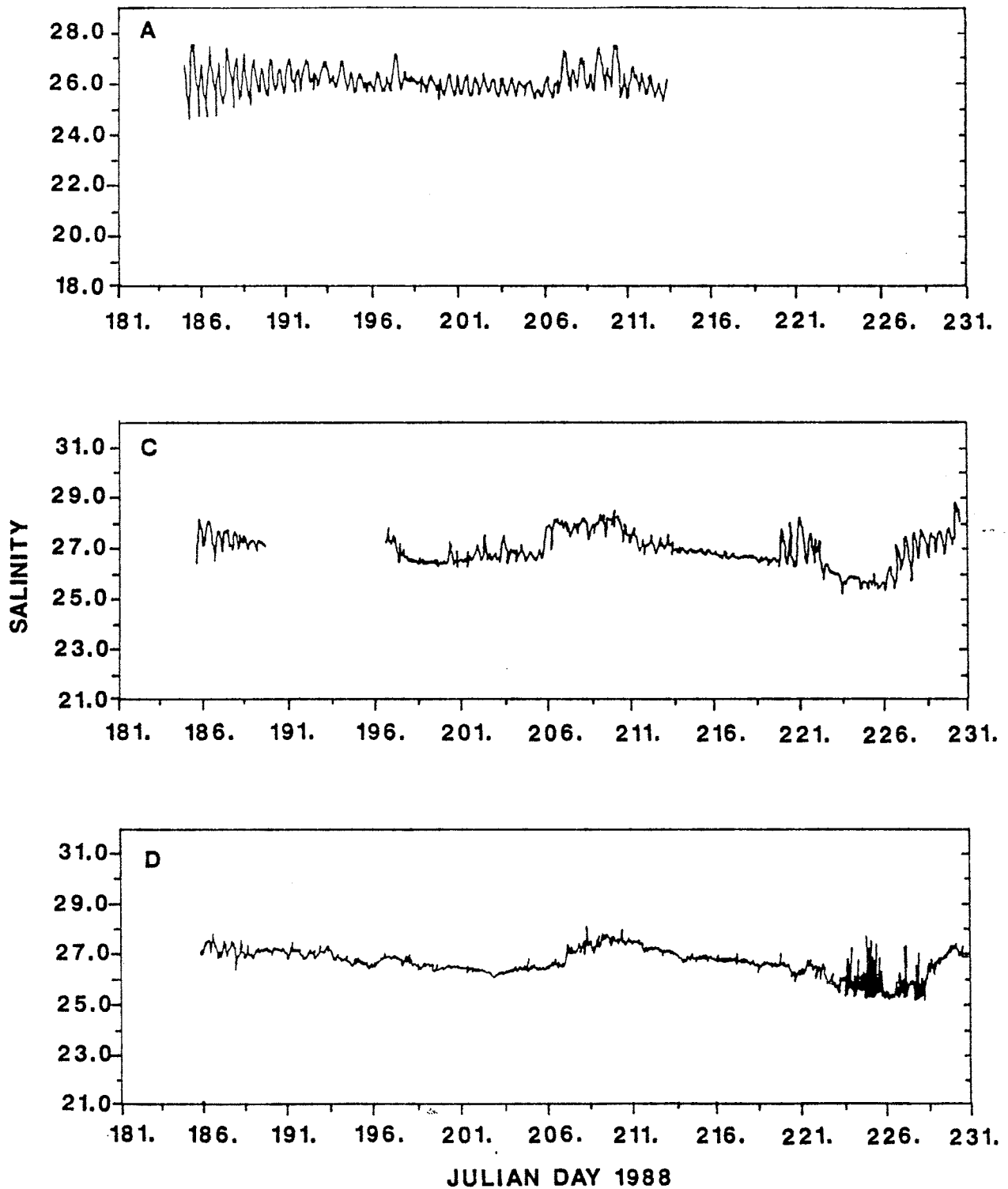


Figure 5. Salinity at three moorings showing the event that took place between days 206 and 211.

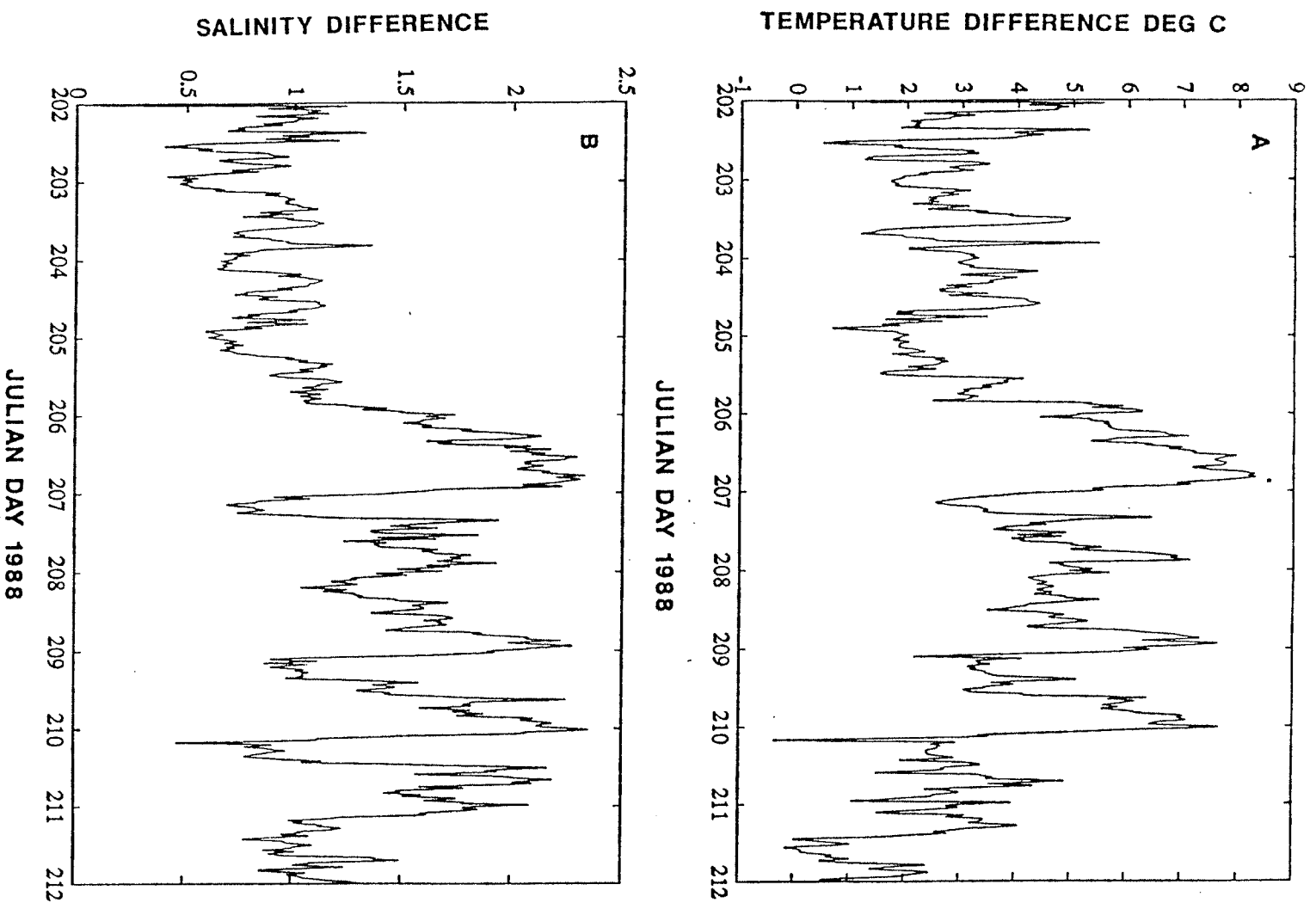


Figure 6. Detail of differences in temperature and salinity between moorings A and C:
a) temperature at A - temperature at C, b) salinity at C - salinity at A.

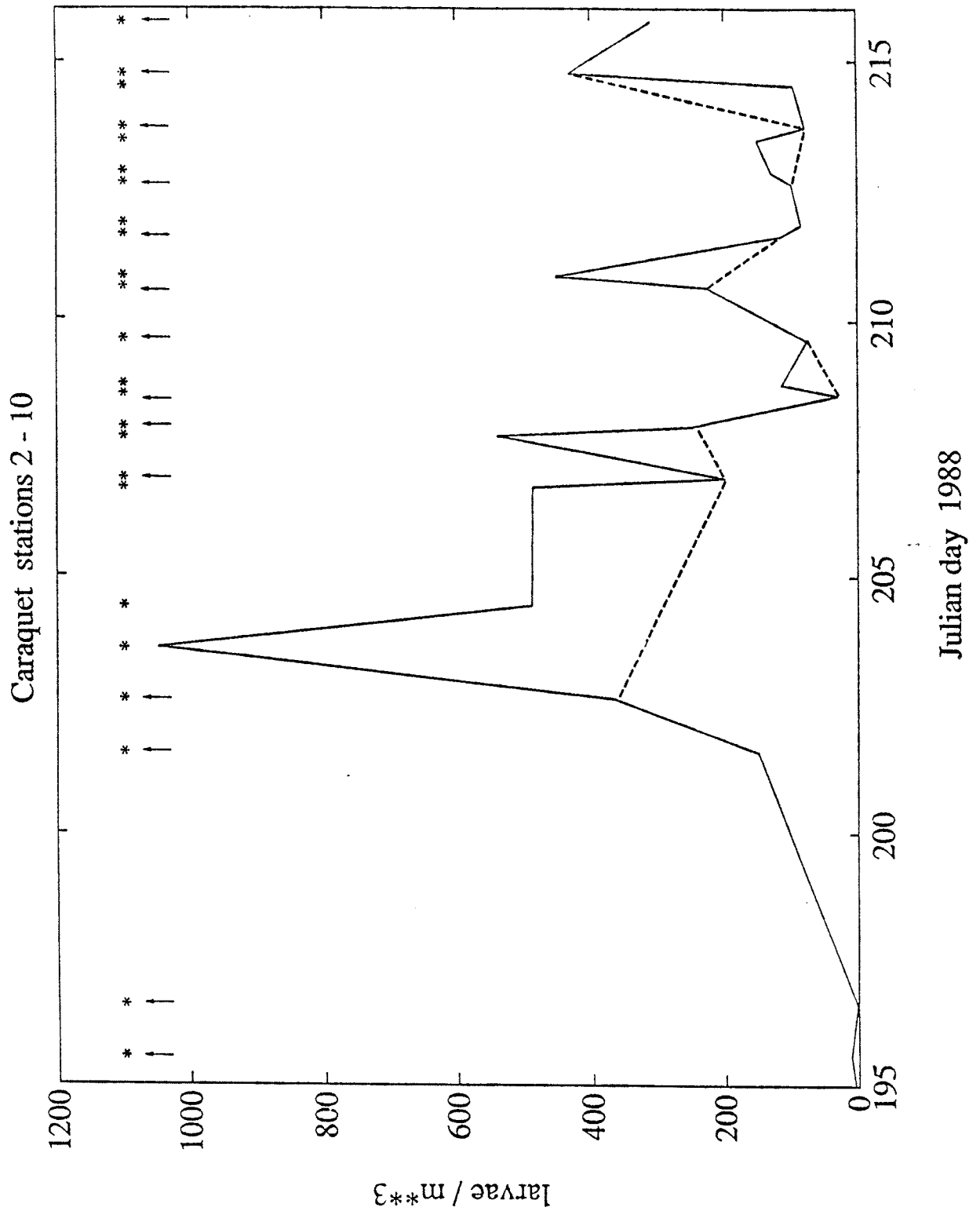
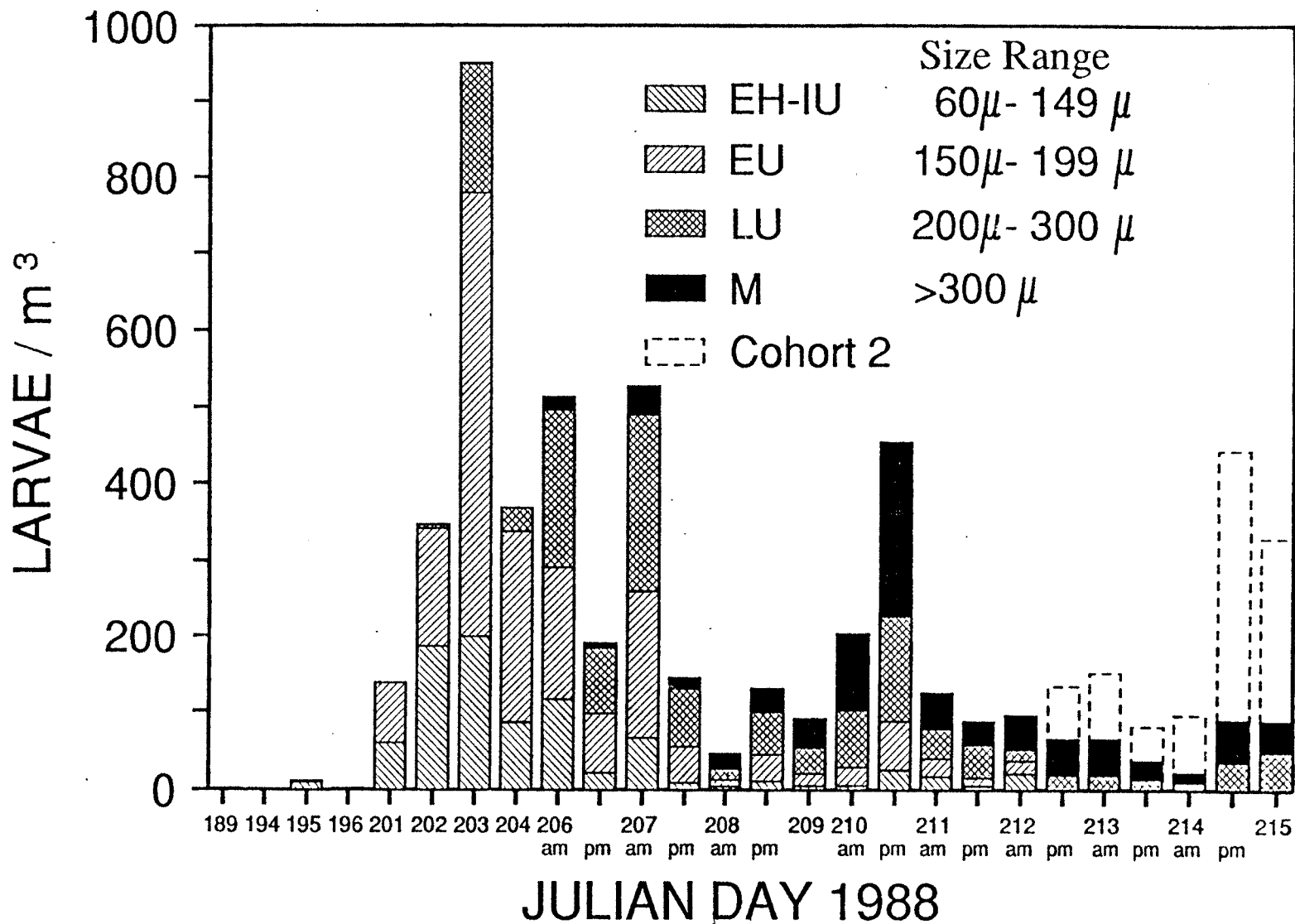


Figure 7. Concentration of oyster larvae averaged over stations 2 - 10. Asterisks show the times of sampling, the arrows those sampling times near low water. The dotted line gives the curve for low water sampling.

Figure 8. Bar graph of oyster larvae concentrations averaged over stations 2 - 10 showing the proportion of different stages.



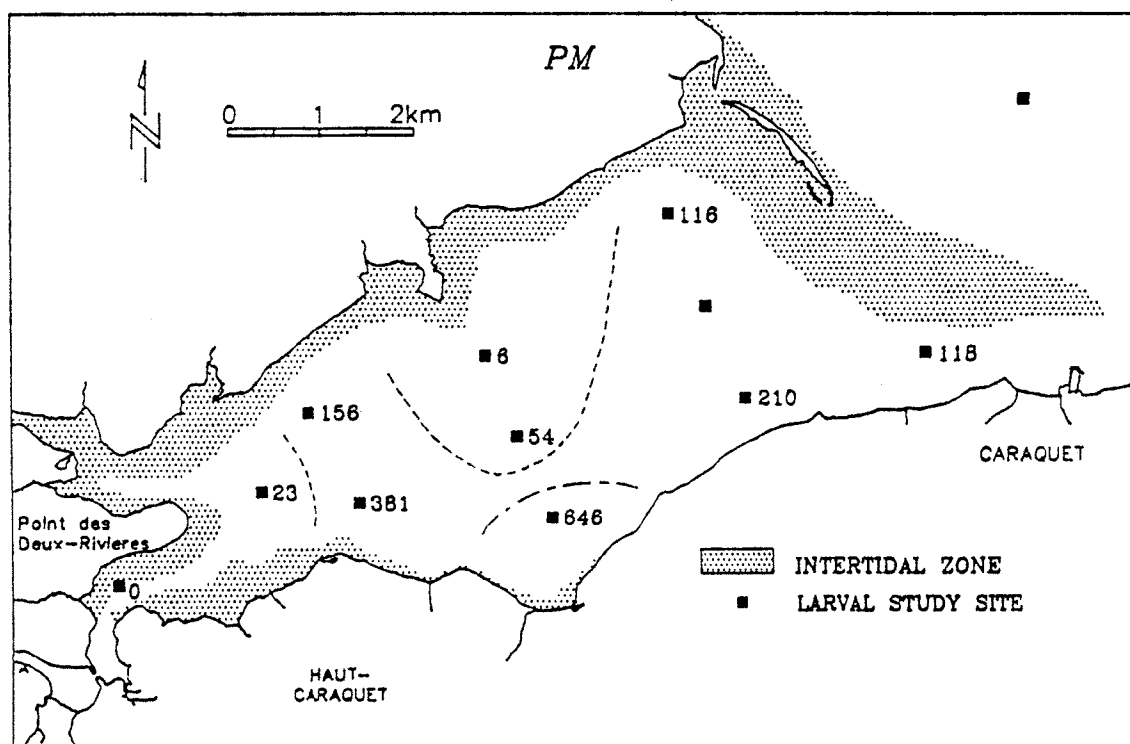
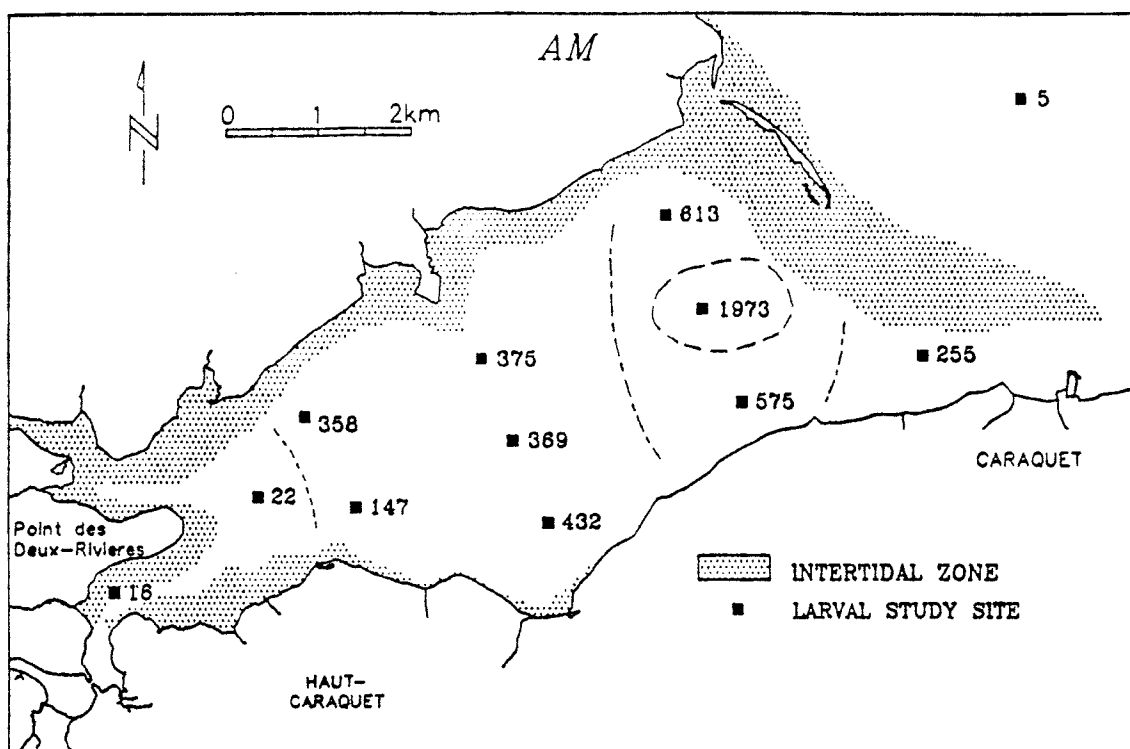


Figure 9. Larval concentrations for two times on day 206 to highlight the tidal variability: am = 08:00 - 12:42; pm = 14:10 - 16:32. Tides: 14:10 small high water. Contours— 1000 larvae m⁻³, --- 500 larvae m⁻³, - - - 100 larvae m⁻³.

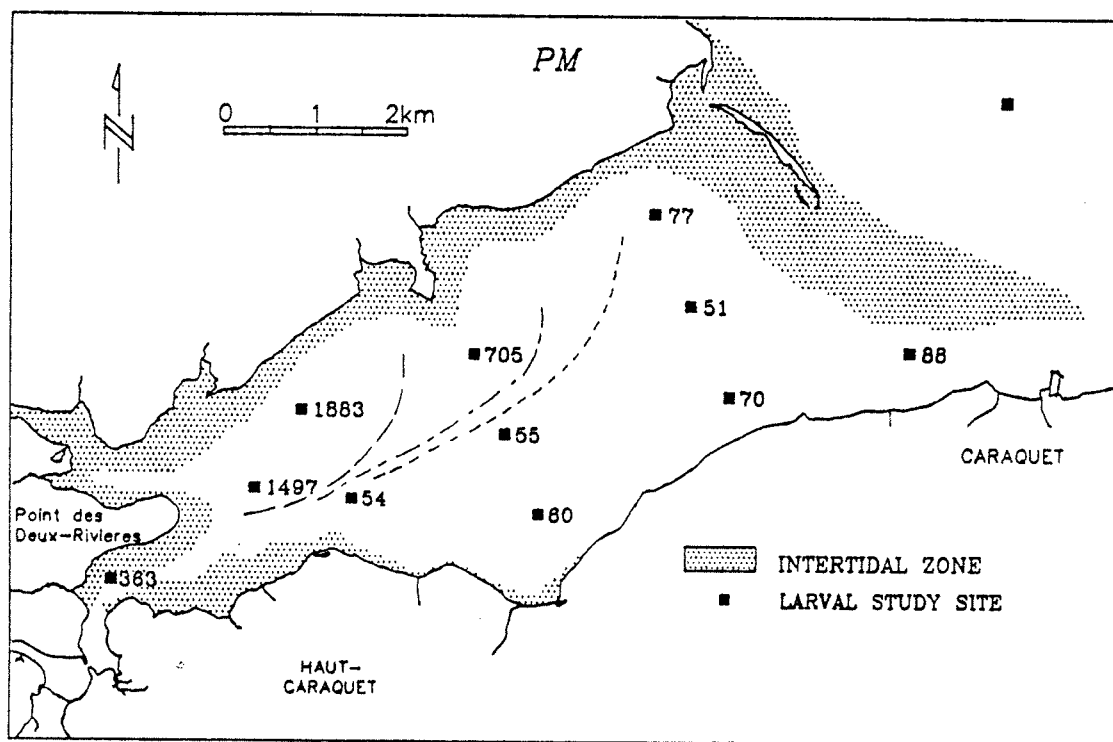
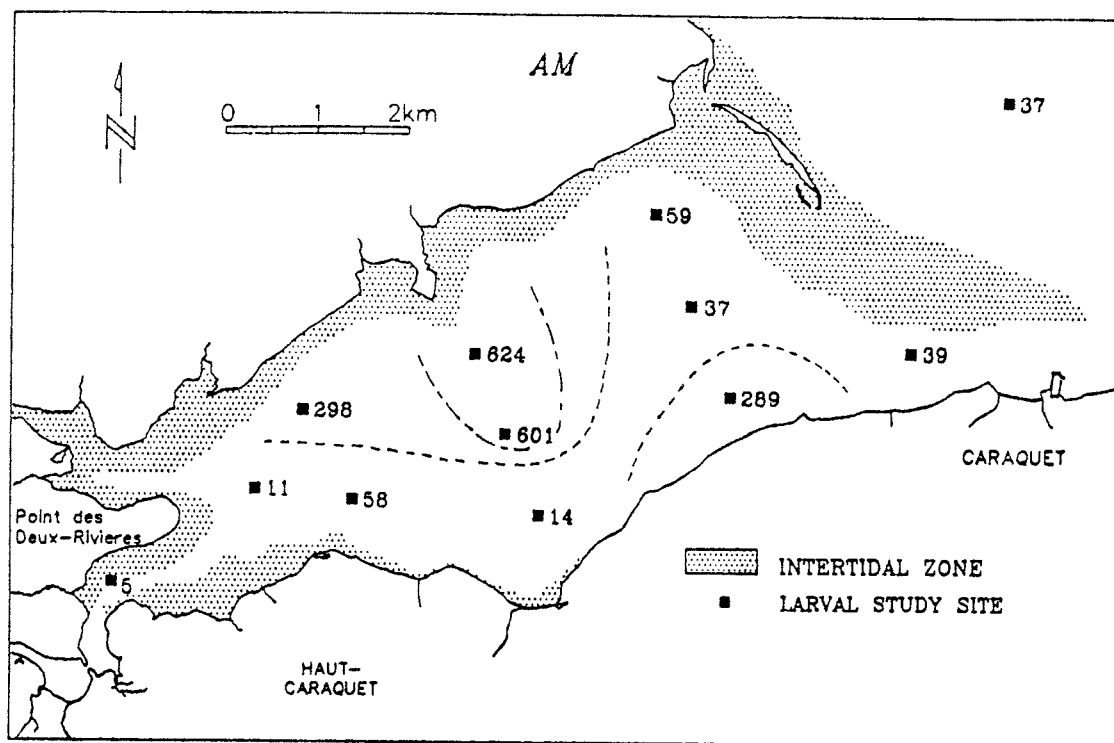


Figure 10. Larval concentrations for two times day 210 to highlight the tidal variability: am = 06:20 - 10:16; pm = 12:00 - 15:14. Tides: 13:40 low water. Contours —1000 larvae m⁻³, ---500 larvae m⁻³, - - - -100 larvae m⁻³.

