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EVIDENCE OF AN UNPRODUCTIVE COASTAL FRONT IN BAÍA D'ABRA, AN EMBAYMENT ON THE SOUTH EAST OF MADEIRA ISLAND, PORTUGAL

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ABSTRACT

Five oceanographic cruises were carried out in Baía D'Abra, Madeira Island (27 July–22 September 1994) in collaboration with the Madeira Fisheries Directorate. The aim of the study was to investigate how the distribution of various plankton communities was determined by physical oceanographic variables (e.g., temperature, salinity, surface currents). Five sampling stations (A, B, C, D and E) were chosen on a linear transect extending 9 km offshore. Depths varied from 20 m at the inshore station (A) to 500 m at the offshore station (E). A Conductivity-Temperature-Depth (CTD - SBE seabird electronics) device was deployed at each station. A 335 μm net was used to collect plankton samples. The samples were analyzed at the Madeira Fisheries Laboratory and at the Plymouth Marine Laboratory (PML) facilities (UK). Results revealed retention of fish eggs in Baía D'Abra probably due to the formation of an anticyclonic eddy. The eddy formed a thermo-haline front with the offshore waters around station B where a surface convergence seemed to decreased mesozooplankton productivity. The overall pattern of biological productivity was low at the coastal front (B) and high at its margins (C or D). Six to 9 km offshore oceanic waters were stratified. Different plankton communities were characteristic of the inshore and offshore waters. Fish eggs were commonly found within the inshore stations suggesting that either the bay served as an 'ecological safe' place or that the eddy was responsible for such aggregations. Furthermore, biodiversity seemed to increase with distance offshore. Typical coastal taxa included fish eggs and *Noctiluca* sp. whereas siphonophora and chaetognaths constituted the main oceanic groups.

Coastal fronts and eddies are important coastal features often associated with high productivity regions. Classical studies of high productive coastal fronts include: Pingree et al. (1975) description of tidal fronts associated with a summer phytoplankton bloom and red tides in the approaches to the English Channel. Simpson and Pingree (1978) observed high chlorophyll region associated with internal wave activity. They explained this subsurface chlorophyll maximum in the pycnocline just behind the front as a result from vertical transport of nutrients across the pycnocline during the passage of internal waves. Thereafter, Le Fevre (1986) discussed all the efforts made in the English Channel shelf fronts and the different aspects of their biology. Alldredge and Hamner (1980) documented the formation of dense aggregations of zooplankton in the turbulent area downstream of a headland when tidal streaming was at its maximum, and Oliver Willis (1987) reported that high concentrations of coral eggs which formed at the topographic fronts, at certain stages of the tide, remained as coherent linear patches as they drifted away from the places where the fronts had formed. Wolanski and Hamner (1988) reviewed the distribution of zooplankton in relation to topographically controlled fronts formed by headlands, islands and reefs. They concluded that when a tidal current streams past one of these structures there might form a front (often called the dividing streamline) which separates the normal tidal flow from the more turbulent eddies on the downstream side of the object. If the water is fairly shallow the turbulent eddies interacted with the bottom giving rise to convergence and sinking at the front. As a result, surface dwelling planktonic organisms tend to aggregate there, especially those that are buoyant. In the vicinity of coral reefs, for instance, where many species of coral tend to spawn synchronously, very dense aggregations of buoyant coral eggs are formed at these coastal fronts, which can then be readily identified from the air. Coastal fronts are also known to accumulate pollutants. Tanabe et al. (1991) described elevated concentrations of organochlorines as well as higher concentrations of organisms and sediments in a surface convergence front off the Seto Inland Sea, Japan. Not withstanding the strong physical forcing that seems to occur in coastal fronts zooplankton organisms are behaviorally active and can swim. Franks (1992) for instance, modeled dense concentrations of organisms as a physiological response to the frontal environment. The model showed how patchiness arises at fronts through retention and accumulation zones as well as through active swimming of zooplankton (see also Franks and Walstad, 1997). Govoni (1993) reinforced even further this cross-frontal dynamics. He described the exchange of water across frontal zones and the consequent flux of biota. An important result was a shoreward, or offshore, transport of coastal populations of larval fishes. Pineda (1994) reinforced the nearshore transport of neustonic larvae with the investigation of internal tidal bores and the formation of warm-water fronts off Southern California. Pinca and Dallot (1997) associated this notion of heterogeneous hydrodynamic structure, i.e., coastal fronts and eddies, separating a coastal area from a central divergence zone, with differences in the mesozooplankton community composition. For instance a copepod, *Centropages typicus,* was the predominant species of the anticyclonic eddy area. Most recently Shanks et al. (2000), observed an upwelling front moving onshore. The shoreward-moving front concentrated and transported larvae. The data also demonstrated that a relaxing of the upwelling front could transport high concentrations of larvae shoreward over the inner shelf, the authors proposed this as an important mechanism promoting the shoreward migration of larval invertebrates and fish.

In view of the present knowledge in the biological productivity of coastal fronts, the main contributions of our investigation can be seen as: (1) to reinforce the notion that when strong hydrodynamic oceanographic phenomena occur in coastal headlands and islands, differentiation in zooplanktonic communities occur. Intrinsic planktonic communities can in fact characterize coastal, intermediate (or neritic) and oceanic waters; (2) to challenge prior notions that all coastal fronts must be productive. Surface convergence in shallow water, for example, can diminish residence time of planktonic organisms resulting in an unproductive coastal front with highly productive surroundings; (3) to reinforce the idea that embayments, headlands, peninsulas and islands can serve as important nursery grounds for fish and/or invertebrates to spawn.

Geographic Setting

Madeira Autonomous Archipelago is located off the north west coast of Africa (33°N, 17°W) and is administrated as part of the Portuguese EEZ (Economic Exclusive Zone). In spite of its prime location, with important fishery resources, very little of the local coastal dynamics have been studied. This is the first study that attempts to interpret the in situ oceanographic variables that seem to control the planktonic communities in a local embayment.

Ponta de São Lorenço is an inhabited peninsula of the SE tip of Madeira Island (see Fig. 1). Canary current is the dominant surface current and NE trades are the dominant

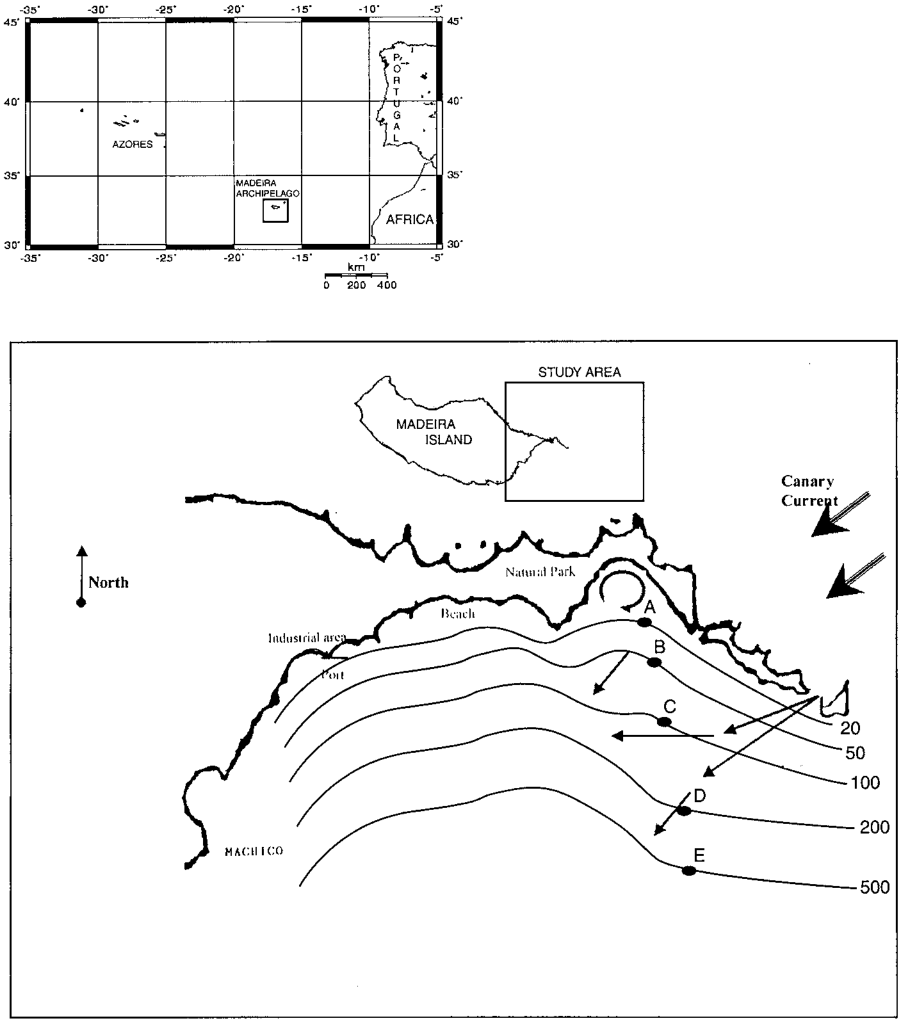


Figure 1. (A) Location of the Madeira Archipelago in relation to the Azores Archipelago, Portugal and the NW African coast. (B) Surface water circulation in Baía D'Abra– Península de São Lorenço (SE of Madeira Island) as observed in situ by Andrade (1994, pers. comm.) confirmed by 3.5 h of observations in our July cruise 1994. Drifting buoys were launched at 0.5 m depth. Isolines represent the bathymetry in the area based on the Portuguese Navy Navigational charts. Station locations are indicated with black dots.

wind regimes (see for example Tomczack and Godfrey, 1994). The land in the Peninsula de São Lorenço is dry (desert like) not inhabited and there are no river inputs into the bay, suggesting that most coastal productivity might originate elsewhere. In 1992 Madeira Fisheries Directorate designated the peninsula as the main stage for the first mariculture pilot project and we proposed this as the first study of the area prior to the installation of the cages. In order to study the circulation inside the bay, surface drifters were released over different tidal cycle circulation regimes. The arrows in Fig. 1 summarize the main circulation patterns at the surface in the peninsula as a result of the drifter's study that took place over a year prior to our study (Andrade, 1994, pers. comm.).

Materials and Methods

Five stations (A, B, C, D and E) were chosen on a linear transect extending 9 km offshore. Depths varied from 20 m at the inshore station A to 500 m at the offshore station E (Fig. 1). Four summer cruises were organized aboard RV Lobos in collaboration with the Madeira Fisheries Laboratory (Department of Fisheries Oceanography - DOP). Sampling began with wind direction, sea state, and secchi disc readings to measure light attenuation underwater. Conductivity, temperature, oxygen, and depth were automatically recorded with a CTD (from SBE Sea Bird Electronics) at each station. Surface temperatures were also taken with a thermometer for calibration. The plankton samples were collected by a 335 μm, conical net attached to a wire with a flowmeter in its mouth. A sampling bucket collected the filtered plankton at the cod end. After each oblique haul, plankton samples were labeled, fixed and preserved with buffered formalin (4%) diluted with seawater. The flowmeter was calibrated as described by Smith and Richardson (1977).

The laboratory analysis was undertaken at the facilities of the Madeira Fisheries Laboratory, Madeira and Plymouth Marine Laboratory (PML), UK. Detritus were removed from all samples. The total plankton 'biomass' was quantified using the method of volume-determination-by-displacement as described by Omori and Ikeda (1984). The samples were then fractionated into two equal aliquots using a 'Folsom' splitter. The fractionation was undertaken because the sub-samples were subsequently processed differently. Statistical analyses have shown that sub-sampling (two-stage sampling) is efficient when catch units are very large (Omori and Ikeda, l984). Because this study was concerned with higher taxonomic groups rather than individual species, catch units were large (300+ individuals per sample).

The physical data collected by the CTD were analyzed using the acquisition software (SBE, 1993). Standard algorithms were used for calculation of the different oceanographic variables, as described in Pond and Pickard (1983) and Fofonoff and Millard (1983). The variables calculated for this study were density $\theta_t = \rho$ (s,t,O) − 1000 [kg m^{-3}] and salinity S (‰). Temperature and pressure where directly measured.

Results

Secchi Depth.—The greatest secchi depths were recorded at the deepest stations in Baía D'Abra (Table 1). Nevertheless, whenever measured secchi depths were always deeper in stations A and C than they were at station B.

Temperature.—Figure 2A shows stratified offshore water (station D-6.2 km), with temperature decreasing with depth up to station C (3.5 km offshore), where a temperature gradient, i.e., front was detected. This temperature anomaly (22.30°C) had a horizontal span of 2 km and sunk from 16 m offshore to about 40 m inshore, around station B (2.45 km). Readings taken further inshore revealed a combination of complex water movements. Other interesting finding included the detection of a warmer ring, occurring between 0 to 12 m depth at station A. A thermal gradient between stations A and B inshore is evident form our results from the 8 September 1994 cruise.

Salinity.—Stratified waters were fond offshore (Fig. 2B). Saline waters 36.76‰ overlaid slightly less saline ones, i.e., 36.32‰, maybe due to strong surface evaporation. However, when approaching shore salinity gradients were again detected between stations B and C (2.5 to 3.5 km offshore). A frontal salinity gradient occurred between stations A and B.

Density.—The horizontal density (θ_t) gradients followed a pattern similar to that of temperature and salinity (Fig. 2C), whereby the denser and colder waters were found near the seabed offshore. Approaching the shore however, the 25.4475 isopycnal surface sunk

Table 1. Secchi depths in Baía D'Abra during the summer cruises.

Date Cruises	Station	Secchi depth (m)	Total depth (m)
27/7/94	A	17	20
	B	16	50
	C	20	100
	D	20	300
	E	22	500
19/8/94	A	20	20
	B	19.4	50
	C	24.5	100
	D	24	300
	E	23	500
22/8/94	A	20	20
	E	31	500
22/9/94	A	19	20
	E	26	500

from about 16 to 40 m between station B (2.5 km) and C (3.5 km), revealing the presence of a frontal gradient between the two stations.

SURFACE DRIFTERS.—Upon the initial cruise (27 July 1994), three surface (0.5 m) drifters were launched at station A (inshore). After a period of 3.5 h, two of the three buoys were retrieved near station B (to the SW). The buoy trajectories demonstrated an offshore transport from the coast, probably due to the formation of an eddy inside Baía D'Abra. The maintenance of the drifters at station B for some time also suggested the existence of a convergence zone.

TAXONOMIC GROUPING.—Identification of the samples was made for major taxonomic groups. The taxa were grouped as follows:

PHYTOPLANKTON.—*Dinoflagellates: Noctiluca* sp. (Raymont, 1983) was commonly encountered (as much as 93.3% of the whole sample). For this reason, its spatial and temporal distributions are shown separately. This was the first time that the *Noctiluca* sp. was identified in Madeiran waters; formerly, they were thought to be eggs of *Eucarida* (Amorim and Andrade, 1990).

ZOOPLANKTON TAXONOMY.—Historically very little has been done in the identifying the zooplankton communities around the Madeira Archipelago. Siphonophora *Abylopsis escholtzi* and *Muggiaea* sp. were commonly found around Madeiran (Raymont, 1983; Tregouboff and Rose, 1957). Other representative species observed in Madeira (Noronha, 1986) were: *Lensia subtilis*, *Chelophytes appendiculata*, *Endoxoides spiralis*, *Diphyes dispar*, *Diphyes bojani*, *Abylopsis eschscholtzi*, *Bassia bassensis.* Siphonophores were considered as varying between frequent and rare in an area 5 km offshore (Amorim and Andrade, 1990). Appendicularia such as the *Oikopleura* sp. (Raymont, 1983), were generally considered rare, although they were abundant during June 1989 (Amorim and Andrade, 1990). The Chaetognatha *Saggita* sp. (Raymont, 1983) were frequent in June and October 1989 and common in January 1990 and May 1989 (Amorim and Andrade, 1990). Polychaeta is a rare group in Madeira according to work from Amorim and Andrade (1990). The Cladocera *Evadne* sp. (Noronha, 1986; Raymont, 1983) exhibited irregular occurrence in Madeiran waters (Amorim and Andrade, 1990).

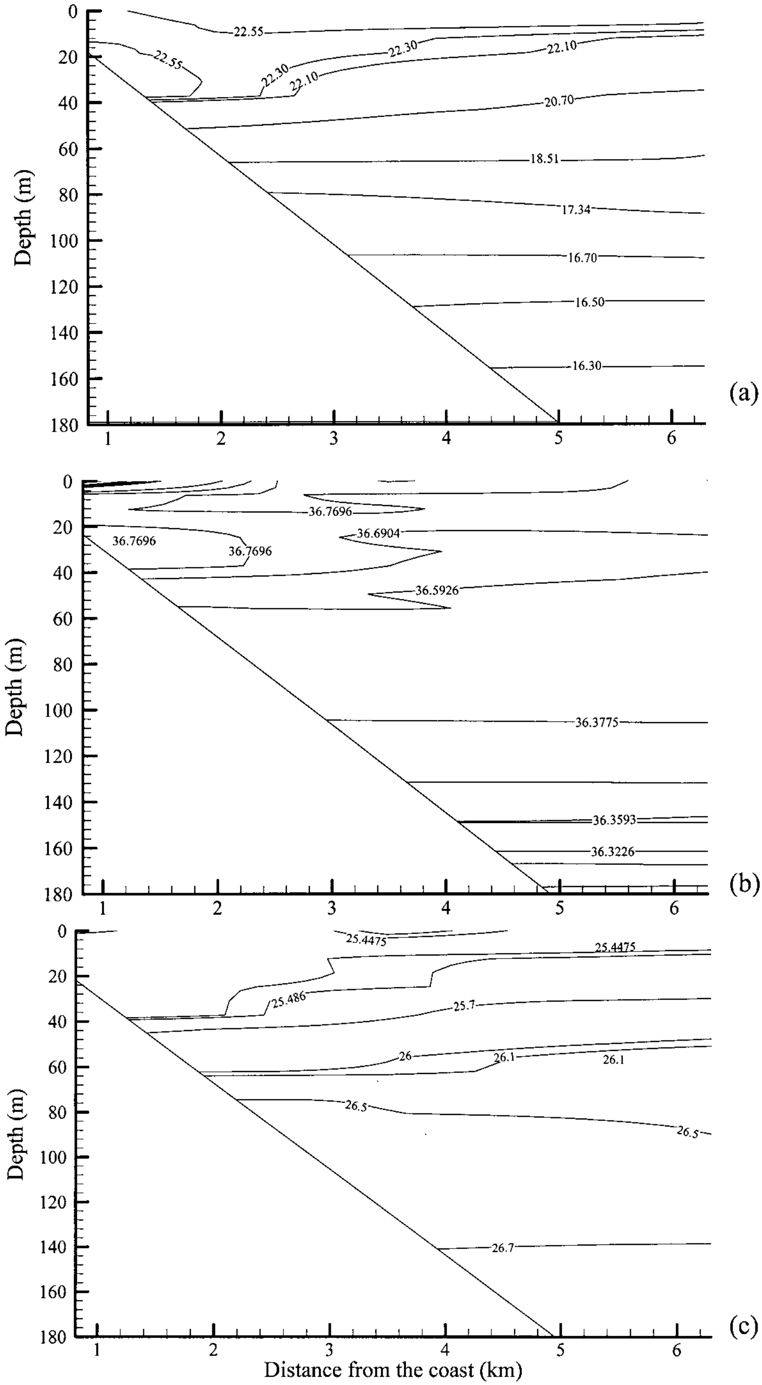


Figure 2. Vertical profiles of (a) temperature; (b) salinity and (c) density. Readings were taken at each station (A to D on the 8 September 1994). A thermo-haline gradient was detected around station B (2.45 km offshore). Density profiles confirm the present of a front in the area.

Copepoda was the most common of all zooplankton organisms historically seen in Madeiran waters. Vives (1970, 1972) studied the diversity of this group and found 34 different species originally identified by Noronha (1986). This group was considered dominant (Amorim and Andrade, 1990). Amphipoda was a relatively small component of the samples. Euphausiacea was not frequent during our summer sampling. Decapoda was mostly larvae from crabs and lobsters. Echinodermata were also mostly larval forms. Fish eggs and larvae were counted and grouped separately. Studies are being undertaken by the Madeira Fisheries Laboratory to evaluate the most important taxa of fish present in the plankton communities around Madeira. Dolioledea was a minor group in Madeiran waters (Raymont, 1983).

HORIZONTAL DISTRIBUTIONS OF MESOZOOPLANKTON.—Abundances of the plankton groups were quantified according to the number of individuals per 1000 m^3 for the total plankton volume and per 10 m^3 of water for the different taxa. Their horizontal distributions were plotted as abundances varied with distance offshore (Figs. 3A,B,4A,B,C). There was a decrease in the total zooplankton biomass from station A to station B on 19 August and 9 September 1994. This was followed by a subsequent increase at station C (Fig. 3A). The biomass decreased from station C to station D (8 September 1994) and E (19 August 1994). However, during 27 July 1994, sampling revealed a greater volume of plankton in station B than A. During 22 August 1994, plankton biomass decreased with distance offshore. The general pattern of total plankton volume showed maximum values at stations A and C, decreasing to station E (lowest biomass occurring at station B) (see Fig 3A). The largest volume was registered at station A on 22 August 1994 (42.3 ml 1000 m^{-3}), whereas the lowest was registered at station B on 8 August 1994 (8.6 ml 1000 m^{-3}).

Due to the bloom of the genus *Noctiluca* sp., its geographic variation is shown separately in order to detect any major patchiness of the minor groups (Fig. 3B). The *Noctiluca* sp. population decreased from the 27 July 1994 to 22 September 1994, when its distribution became fairly uniform at stations A and E. It decreased sharply from station A to stations B and C during all cruises. An increase of the biomass was observed on stations D or E depending on the time of the cruise. However, on 8 September 1994, *Noctiluca* sp. decreased from station C to D (refer to Fig. 3B).

After removing *Noctiluca* sp. the most predominant zooplankton organisms also showed interesting horizontal distributions. On the 27 July 1994 cruise (Fig. 4A). Most fish eggs (27.33 ind.10 m^{-3} of water) occurred near the shore (station A) inside Baía D'Abra. The copepods were the dominant group at station E offshore. The diversity increased from station A to E, with increasing distance offshore. Oceanic waters were composed of more groups; i.e., copepods, ostracods and siphonophores, than inshore waters. A decrease in zooplankton biomass at station B and C was also apparent. The most representative coastal groups were cladocera, copepods and fish eggs.

On the 19 August 1994 cruise (Fig. 4B), similar patterns reoccurred. Fish eggs were mostly found in inshore waters. Cladocerans, decapods and fish eggs dominated coastal waters whereas offshore waters were dominated by copepods, and cladocerans. Doliolideans were mainly a neritic group and station D was the most productive. Nevertheless, biomass decrease significantly from station A to B subsequently increasing to stations C and D.

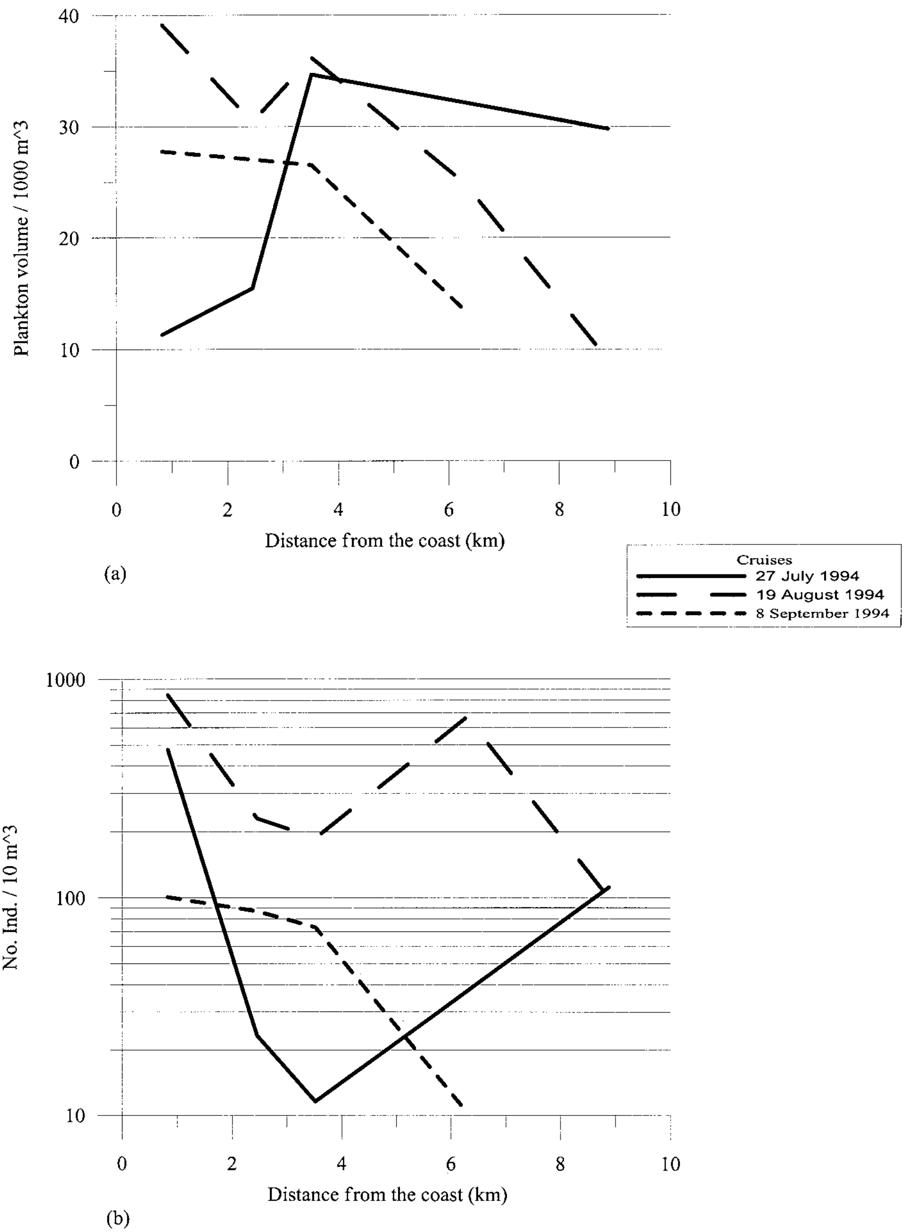


Figure 3. (A) Total plankton volume varying with distance offshore. Individual lines represent individual cruises (see legend for cruise date). Distances offshore for stations were: A-825 m, B-2.4 km, C-3.5 km, D-6.29 km and E-8.8 km.. Consistent low biomass was observed around station B; (B) Mesodistribution of *Noctiluca* sp. throughout summer 1994. The number of individuals is shown in a logarithmic scale to emphasize differences in biomass.

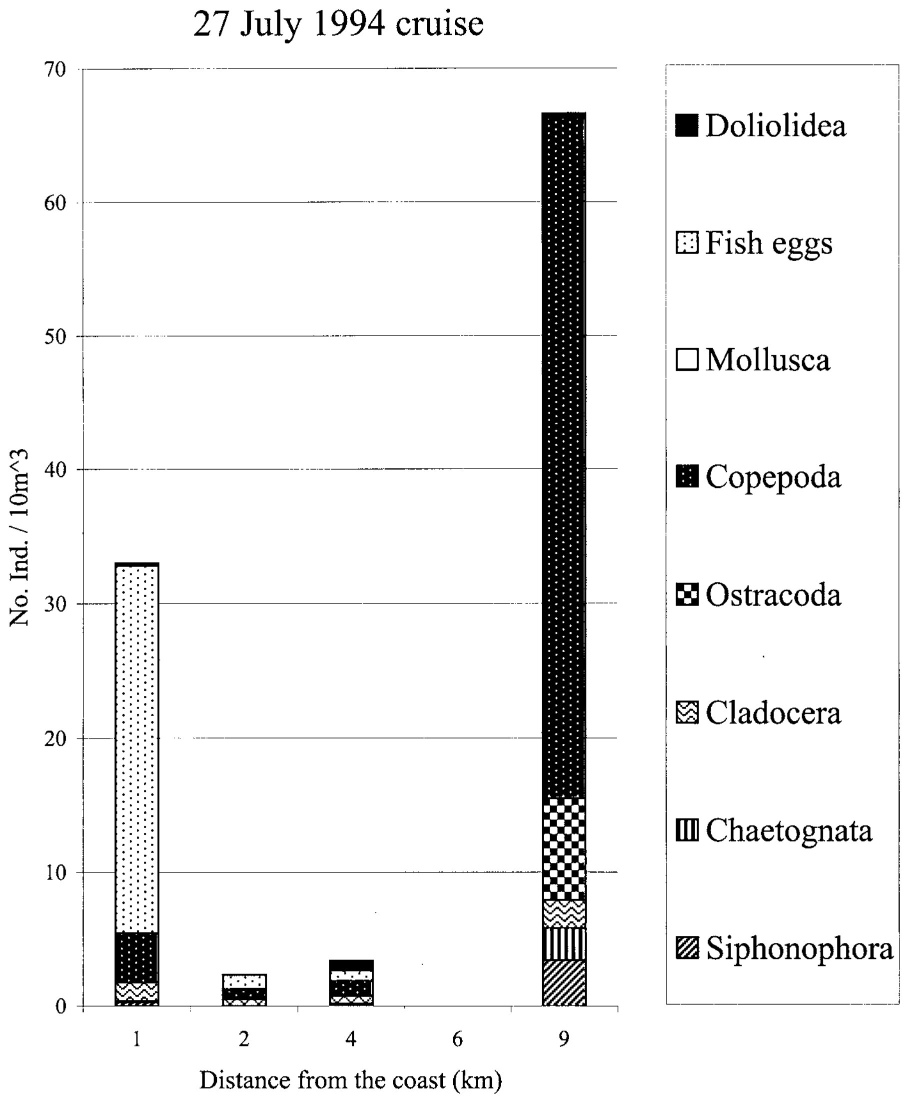
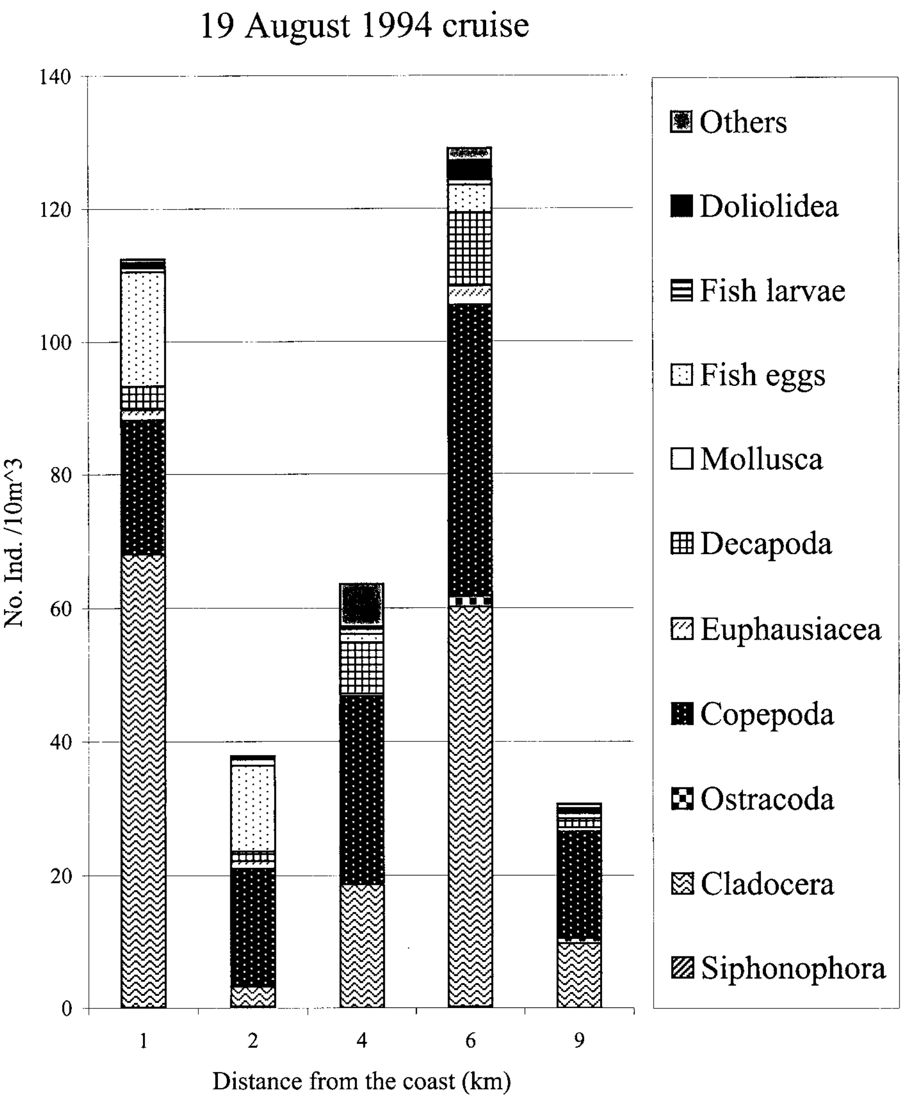


Figure 4. Horizontal distribution of the main zooplankton groups. Sampling took place at stations A, B, C and E (a) 27 July 1994 cruise; (b, *see page 1066*) 19 August 1994 cruise; (c, *see page 1067*) 8 September 1994 cruise. Consistent low biomass at station B was observed.

A significant decrease in the number of individuals also occurred from station A to B in the 8 September 1994 cruise rising again to station C (Fig. 4C). Near the coast, the most important groups were copepods and fish eggs.

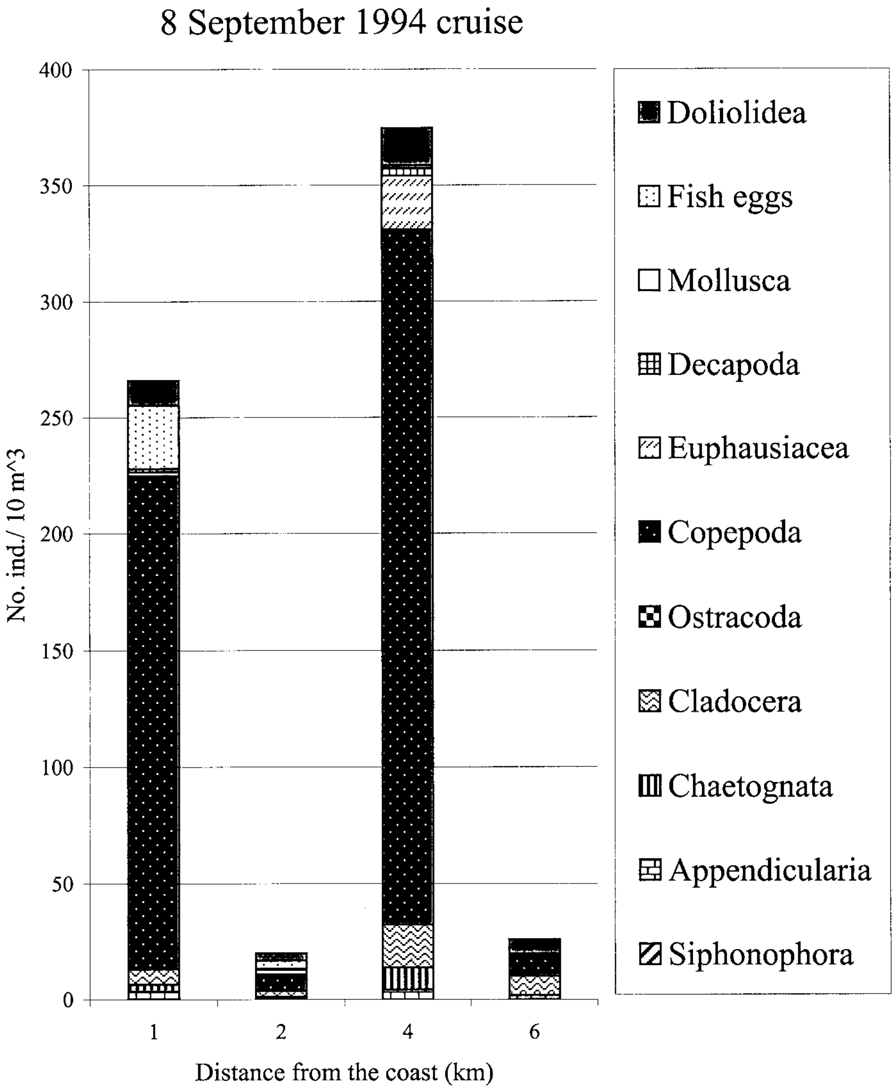
Discussion

Water Visibility.—At the oceanic stations D and E, the secchi depths were greater, with shallower secchi depths recorded at the inshore station B. For the purpose of this study, secchi disc readings were enough to show the variation of water visibility from coastal waters to oceanic. Future investigations should include the use of more sophisti-



cated instruments such as an irradiance meter, which also takes into account the downwelling light from the sun.

OCEANIC CIRCULATION.—The eddy formation near inside the bay observed by Andrade (1994 pers. comm.) supported by our own personal observations could explain the accumulation of ichthyoplankton (fish eggs and larvae) nearshore. In fact, Boehlert and Mundy (1993) discussed the available information on ichthyoplankton distributions at isolated seamounts and oceanic islands as they relate to spatial assemblages. Plankton patches that exist in embayments of oceanic islands are very much controlled by current-topography interactions, such as small eddy systems. Furthermore, an increasing number of studies agree that fish tend to seek ecological—'safe' sites to spawn (Leis, 1982, 1983; Leis et al., 1984; Frank and Leggett, 1983).



Wolanski and Hamner (1988), observed complex three-dimensional secondary flows around island headlands that resulted in physical and biological fronts. Their study has shown that topographically generated fronts affected the distribution of sediments, and aggregated eggs, larvae and plankton. This aggregation was also important in determining the distribution and density of benthic assemblages and of pelagic and secondary and tertiary predators. In our study area, Ponta de São Lorenço is historically known amongst Madeiran fishermen to be very fertile in pelagic and benthic species of fish and invertebrates. However, the island/headland effect was also aggravated by the large Peninsula of São Lorenço that served not only to stir the Canary Current flow but also to 'engulf' the agglomeration of planktonic organisms within the bay. Wolanski (1994), identified these currents within island embayments areas as''secondary currents', which were also observed in the Australian Great Barrier reef to cause the formation of rotating eddies.

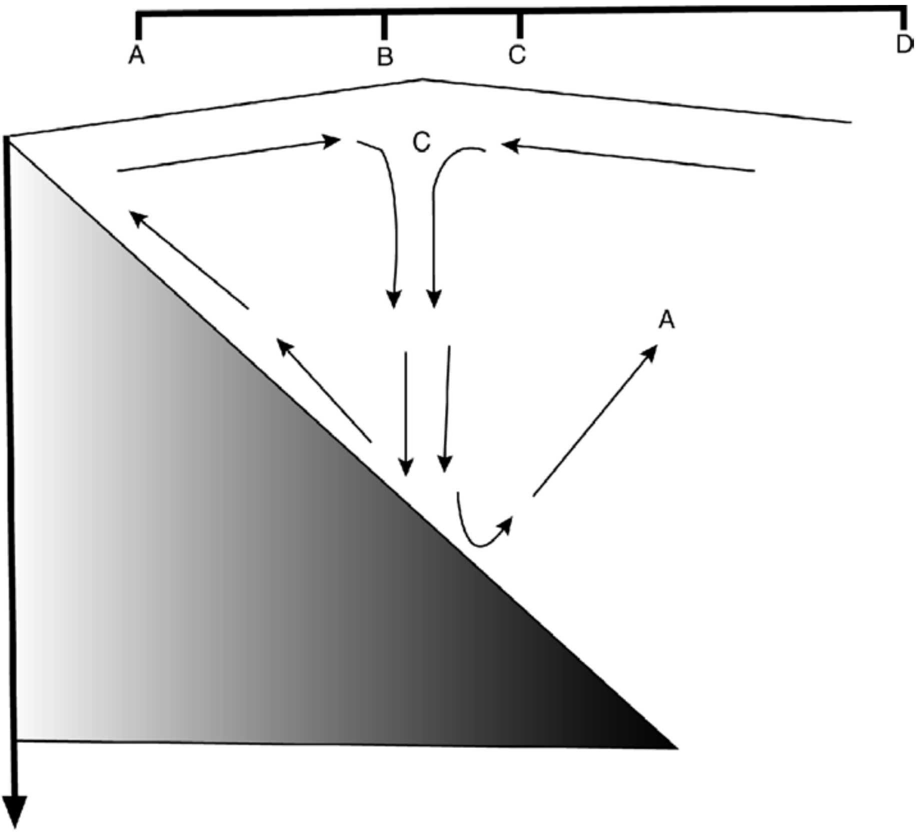


Figure 5. Empirical model suggesting the main processes controlling biological productivity in Baía D'Abra. The scale is hardly exaggerated.

Eddies with alternate their rotation, i.e., clockwise to anticlockwise, are often seen with the tidal currents. These secondary circulation patterns were also important in transporting sediments in and out of the bay. Notwithstanding the similarities between the circulation patterns, Wolanski and Hamner (1988) observed an aggregation of floating particles, including coral eggs along the convergence (downwelling) zones, whereas in the present study the convergence, around the location of station B, seems to cause a substantial decrease in the amount of biological material accumulated at the front (no slick). At the mesozooplanktonic level and in terms of '*Noctiluca* sp.,' the frontal area around station B is unproductive from July to September 1994. Horizontal cross sections of temperature, salinity and density in the onshore-offshore transect of stations showed a thermo-haline frontal system between stations B and C. Taking into account our ship time limitations with limited CTD observations (full spectrum of stations only measured on the 8 September cruise), future studies in this area should concentrate on the small-scale circulation patterns and the role of turbulence in the aggregation of mesoplanktonic organisms. Mooring systems fitted with ADCPs (Accustic Droppler Current Profiler) and automatic OPC (Optical Plankton Counters) would be a good consideration for long-term monitoring. If the frontal system is observed to be formed offshore, study of its physical and spatial evolution over time would be an important contribution to our observations.

In terms of the biological productivity this study confirms Parsons et al (1984) notion where intrinsic biota is present in coastal, neritic and oceanic waters. Pinca and Dallot (1997) also found a strong predominance of a species of copepod in an anticyclonic area, suggesting that if hydrographic conditions are persistent enough plankton communities might evolve to respond to the local oceanographic variables. Species that are dominant in frontal regions might not be so dominant in the immediate surroundings and vice versa. Another important consideration in studying coastal fronts, tidally or geomorphologically induced, is that fronts are very dynamic and they might be formed offshore subsequently moving inshore and change its intrinsic characteristics (biologically and/or physically) and/or eventually dissipate. Overtime, and considering the cross-frontal transport of behaviorally active planktonic organisms (Franks, 1992), fronts might loose their intrinsic high productive characteristic consistently acclaimed throughout the literature. Alternatively, frontal regions with convergence at the surface, downwelling in its center and upwelling in its sides, might reach 'too shallow waters' where it would become energetically too costly for an organism to sustain the pressure of the downwelling currents becoming therefore unproductive. Consequently in the organism perspective it would be ecologically more advantageous to depart from the front and inhabit its surroundings as a dominant species. In fact, one would go as far as to hypothesize that these fronts might be used by the behaviorally active organisms as mere transport corridors or pathways to 'ecologically safe' shore areas such as islands and headlands, where food is abundant and predation might be minimal.

In this study differences in the composition of mesozooplanktonic communities can be categorized as follows: nearshore waters (0–0.5 km offshore, station A), neritic waters (0.5–4 km offshore, stations B and C), and oceanic waters (4–9 km offshore, stations D and E). The nearshore waters (station A) were characterized by high density of fish eggs and *Noctiluca* sp. (Figs. 2B,3A,B,C) both positively buoyant organisms. However, on some occasions, copepods, cladocerans and some fish larvae were present in significant numbers. Although the taxonomic composition of nearshore waters varies among studies, there is evidence that such assemblages predictably occur near islands (e.g., Wolanski et al., 1984; Wolanski, 1994). Neritic waters (station B) in Baía D'Abra showed very low zooplankton densities. In fact, this was observed consistently among all planktonic groups. The exception was the phytoplankton group of *Noctiluca* sp.

At the oceanic station E, diversity was highest with exclusively oceanic groups, such as siphonophores, dolioledea and chaetognaths. Note that 'oceanic' in this context does not refer to an assemblage consisting only of oceanic species (as they probably all are), rather it refers to an assemblage containing taxa found at the greatest distance from the island in stratified deep oceanic waters. The vertical distribution at the oceanic station E needs further investigation. Other groups such as copepods, ostracods and cladocerans were also present in great abundance. During 19 and 22 August 1994, however, most ostracods were collected at station A. As it is typical of any initial investigation, the precise information of spatial, temporal, and biological dimensions of the eddy and frontal systems observed in Baía D'Abra requires further research. Future research should concentrate on species diversity as opposed to the general taxa, as well as in the long term monitoring of the spatial and temporal evolution of this front.

Conclusions

The general physical conditions that are though to control the dynamics of the local zooplankton communities are summarized in Figure 5.

An eddy is formed in Baía D'Abra, accumulating fish eggs. Convergence and downwelling seem to occur around station B where a thermo-haline unproductive front was detected. As a result of surface convergence and downwelling organisms were washed to the neighborhood areas increasing biological productivity at station A and further offshore around station C and/or D. Total plankton biomass generally decreased from stations A to B subsequently increasing to stations C and/or D.

A summer bloom of *Noctiluca* sp. was newly identified for Madeira. Its distribution revealed a decrease in its biomass from stations A to B and temporally from July to September. This group may be acting as an important source of food for zooplankton within the bay, with particular relevance to fish larvae.

Most fish eggs were found to be at the inshore stations A and B suggesting that the bay was either serving as an 'ecological safe place' or that the eddy was trapping the eggs inshore.

Diversity was found to increase offshore. At the deepest station E, most common taxa (oceanic) were siphonophora and chaetognatha. At the inshore station A (coastal) and at stations B and C (neritic), the most commonly found organisms were fish eggs and *Noctiluca* sp.

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