Chapter 11

A transfer function for the quantitative reconstruction of oxygen contents in marine paleo-environments

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Abstract

We observed living (Rose Bengal stained) foraminifera in the Indian Ocean, Atlantic Ocean and Mediterranean Sea, and compared the distributional patterns with micro-profiled oxygen contents in the sediment column. Our data demonstrate that one group of species is apparently oxyphilic and that their abundances co-vary linearly with the oxygen content at the sediment-water interface. We developed a transfer function and tested this on a historic record from the Adriatic Sea. We show that application of this transfer function to benthic foraminiferal patterns in a core from the Adriatic Sea results in an accurate quantitative reconstruction of the oxygenation history over the past 160 years. The reconstructed record shows that the marine system rapidly became prone to hypoxia between AD 1890 and 1935. We suggest that this was due to the man-induced increased nutrient load of Po waters, related to the introduction of artificial fertiliser in the drainage area.

1. Introduction

For a better understanding of global change it is essential to quantitatively constrain ocean circulation and ventilation. In this respect, oxygen content patterns are helpful to determine present and past changes in the state of the oceans. Of all available proxies for oxygenation benthic foraminifera are still among the best (Sen Gupta and Marchain-Castillo, 1993; Kaiho, 1999). Foraminifera are uni-cellular protozoans that are abundant in marine waters. They play an important role in benthic ecosystems (Snider et al., 1984; Lee and Capriulo, 1990) and in some environments they even are the most abundant meiofaunal component (Shirayama and Hirokoshi, 1989). Although they often live in the sediment column down to a depth of more than 15 cm, densest populations occur at the sediment-water interface (Gooday, 1994; Jorissen et al., 1995; Van der Zwaan et al., 1999). It has been suggested that taxa occupy a distinct microhabitat (Corliss, 1985), but field observations indicate that various factors contribute to a dynamic distribution throughout the year (Barmawidjaja et al., 1992; Silva et al., 1996). Important among the ecological factors is certainly food, often regarded equal to the organic flux arriving at the sea floor (Gooday, 1994; Jorissen et al., 1995). Oxygen is considered to be a prime variable as well. Experimental research and field observations suggest, however, that it is not as important in limiting the distribution as previously thought, since many species seem to be facultative anaerobes or micro-aerophylic (Alve and Bernhard, 1995; Moodley et al., 1997; Jannink et al., 1998).

In an attempt to further assess the role of oxygen, we collected living (Rose Bengal stained) foraminifera from the Adriatic Sea, the Levantine Basin off Israel, the Atlantic Ocean off NW Africa and the Indian Ocean off Pakistan (Table 1). Pertinent data regarding to some of the sample localities and oceanographic conditions were published elsewhere earlier (Van der Linden and Van der Weijden, 1994; Reichart, 1997; Jorissen et al., 1998). We measured oxygen concentrations in the water column using CTD. Concentrations at the sediment-water interface were observed in water collected from the boxcores or with Niskin bottles. The oxygen concentrations were later determined by standard methods (Van der Linden and Van der Weijden, 1994). In the Mediterranean and Atlantic boxcores we additionally measured the oxygen concentrations in the sediment column by careful micro-profiling with oxygen-probes. Detailed geochemical data for sediments, bottom waters and pore waters were obtained for the Atlantic and Arabian Sea cores (Reichart, 1997; Jorissen et al., 1998). For the Indian Ocean boxcores, from which no oxygen probe measurements were available, Mn concentrations were used to establish the penetration level of free oxygen (Corliss and Emerson, 1990). In the case of the Indian Ocean and the Mediterranean Sea cores we analysed the foraminiferal assemblages from every 0.5 cm interval over the first 2 cm. In the Indian Ocean material we further analysed every cm-slice down to a depth of 5 cm, and sometimes to 10 cm. In the Atlantic Ocean boxcores we counted assemblages from every cm-slice, down to a depth of 5-10 cm.

2. In-sediment distribution patterns

We used the Average Living Depth (ALD; Jorissen et al., 1995) as measure to evaluate how the

	Station	Depth (m)	Oxygen content (μmol/L)	Oxyphilic taxa
Indian Ocean (geographical co-ordinates of stations see Jannink et al., 1998	451 478 455 477 476 454 475 453 452	495 556 998 1000 1226 1254 1472 1555 2001	9.5 11.5 9.7 16.3 18.7 34.1 42.9 42.3 95.2	miliolids, *Gavellinopsis, Cibicides wuellerstorfi*
Atlantic Ocean (geographical co-ordinates of stations see Jorissen et al., 1998	1 2 3 7 **8** 9 10 11 15 17ᵉ 20b 21 22	507 1407 2075 **3010** **2530** 2002 1525 1200 1000 1890 1200 750 765	74,1 182,1 171,8 **219,1** **191,5** 161,6 140,1 220,1 145,9 119,2 129,9	*Cibicides kullenbergi, Cibicides wuellerstorfi, Cibicides ungerianus, Lenticulina, Hoeglundina elegans, Rosalina, Gavellinopsis, Sphaeroidina bulloides, Planulina ariminensis*, miliolids
Adriatic Sea (co-ordinates: - **108** : 44"45.4' N, 12"45.0' E - **203**: 44"34.0' N, 12"48.0' E)	Station 108 Aug 96 [*] Nov 96 **Jan 97** May 97 Jul 97 Sep 97 Station 203 Aug 96 [*] Nov 96 **Jan 97** **May 97** Jul 97 Sep 97	32 36	155[*] 51 **264** 213 115 86 236[*] 73 **249** **296** 165 175	*Ammonia beccarii, Amphicoryna scalaris, Buccella granulata, Lenticulina, Reussella, Rosalina*, miliolids [*] Not included in fig. 2: for this month only whole cm. samples available
Levantine (co-ordinates: - **S1**: 32".22.53' N, 34".48.36' E; - **S3**: 32".26.58' N, 34".42.84' E)	Station Lev 1 Aug 96 Dec 96 Feb 97 May 97 Jun 97 Sept 97 Nov 97 Jan 98 May 98 Station Lev 3 Aug 96 Oct 96 Dec 96 May 97 Sept 97 Jan 98 May 98	40 120	206 207 195 179 119 194 163 237 229 199 238 225 213 243 233 185	*Ammonia beccarii, Amphicoryna scalaris, Anomalina globulosa, Buccella granulata, Lenticulina, Elphidium crispum/ advenum/ macellum, Reussella, Rosalina*, miliolids

Table 11-I: Data on stations and oxyphilic taxa. Upon arrival on board all collected samples were immediately stored in ethanol and Rose Bengal. For this study the >150 mm size fractions were employed. Only vividly stained foraminifers, regarded as living at the time of collection, were picked and stored in slides. The criteria for distinction between living and dead are well standardised between the various laboratories. Samples printed in bold (Jan 97 station 108; Jan 97 and May 97 station 203; stations 7 and 8 Atlantic) are considered to be not representative due to unusual circumstances at time of sampling. Only species categorised as oxyphilic (thus if present at a station showing most abundant occurrences in topmost cm layers) are listed in the last column.
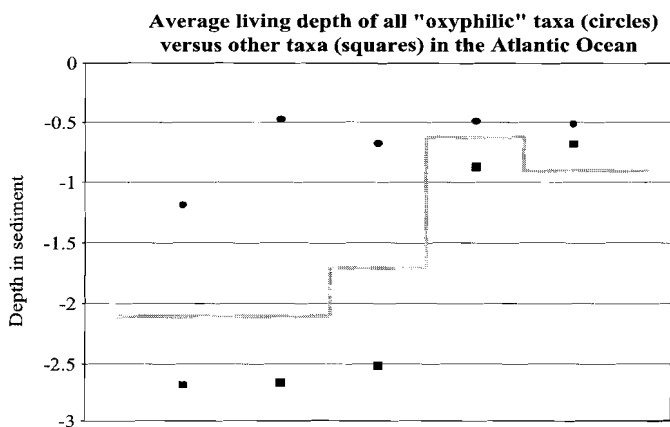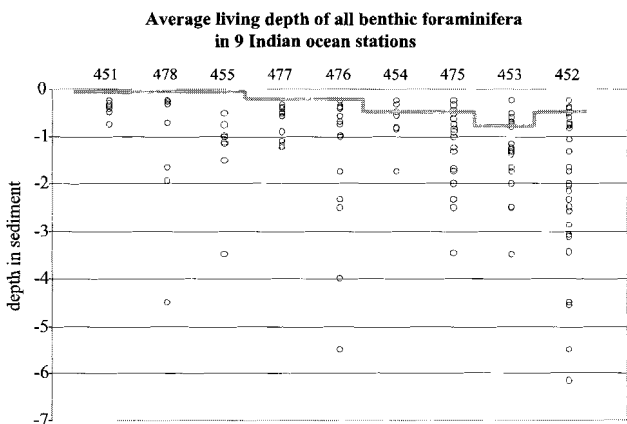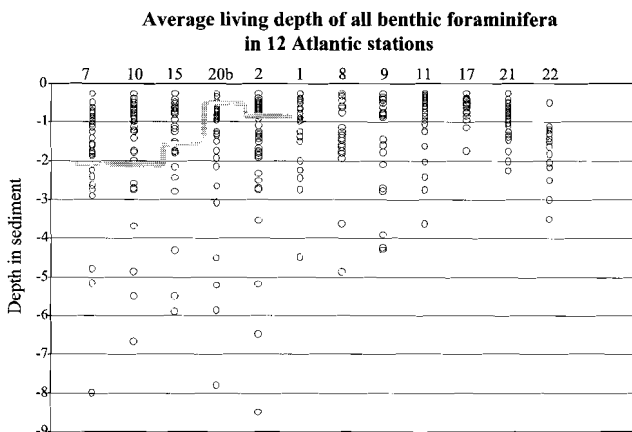
**Average living depth of all benthic foraminifera
in 12 Atlantic stations**

Figure 11-1: Average Living Depth of all living taxa (open circles) encountered in the Atlantic and Indian Ocean stations. Data from Jorissen et al. (1998) and Jannink et al. (1998). Grey line indicates the depth of penetration of free oxygen, in the Indian Ocean based on Mn profiles (see text). Vertical axes represent depth in the sediment column (cm). In fig. 1c (bottom panel) average living depth of all oxyphilic taxa is plotted against average living depth of all other calcareous taxa. Data are same as in topmost panel, first five stations.

**Average living depth of all benthic foraminifera
in 9 Indian ocean stations**

**Average living depth of all "oxyphilic" taxa (circles)
versus other taxa (squares) in the Atlantic Ocean**

foraminifera inhabit the sediment column. The ALD is a weighted average of the depth at which a taxon occurs in the total sediment column regarded. Although we studied quite different environments, the ALD data from all sites indicate that species are living so closely packed together that the individual distributional patterns must have considerable overlap. As an example we graphically summarized (fig. 1) the ALD patterns of all living taxa encountered at the Indian and Atlantic Ocean stations. Many species occur below the zone where free oxygen is available, suggesting that they are able to tolerate anoxic conditions at least temporarily. This is supported by earlier experimental evidence (Alve and Bernhard, 1995; Moodley et al., 1997).

After careful inspection of all our data, it appeared that some species are living consistently, although never exclusively, in the uppermost sediment layers of all localities studied. Among them are a number of fragile agglutinated taxa. Their chances to fossilise successfully are often poor (Murray and Alve, 1999). In order to arrive at proxies that have a general applicability even under fossil conditions with poor preservation, we removed all agglutinated taxa from the census counts. From the remaining calcareous taxa we further selected (see Table 1) only those that in all localities are most abundant in the topmost sediment layer. These apparently live as epifauna and most of them indeed meet the general morphological characteristics considered to be indicative for such species (Corliss, 1988). Their average ALD is consistently shallower than the level where free oxygen becomes absent (fig. 1c). We term this group 'oxyphilic', since one could suspect that the availability of oxygen is the reason for this shallow occurrence. Further evidence supports this notion. Some species (*Cibicides wuellerstorfi, Planulina ariminensis*) were earlier described as living preferentially at or above the sediment–water interface (Corliss and Fois, 1991; Linke and Lutze, 1992). Others, like *Sphaeroidina bulloides, Lenticulina* spp. and miliolids were reported to be infrequent under adverse oxygen conditions (Corliss, 1988; Den Dulk et al., 1998; Kaiho, 1999). From still other taxa, like *Ammonia, Rosalina, Gavellinopsis* and *Buccella*, the morphology indicates that infaunal behaviour, and thus tolerance to low oxygen contents, is unlikely. Moreover, specific species belonging to these genera were reported recently as preferring elevated microhabitats as well (Schönfeld, 1997; Debenay et al., 1998).

We plotted the abundance of 'oxyphilic' taxa in the Adriatic Sea and the Levantine Basin versus the in-sediment oxygen contents (fig. 2). Only from these areas we have enough data to compose time series. From these time series it is obvious that the group indeed tracks the oxygen gradient in the sediment column, being only abundant in the topmost sediment layers where and when oxygen is available. Given our data we estimate that it takes some two months before the foraminiferal density patterns have adjusted to changing oxygen conditions. This lag results for a short time in the presence of the 'oxyphilic' group deeper in the sediment when the redox front has already moved upwards. In this context it is worthwhile to recall evidence (Alve and Bernhard, 1995; Moodley et al., 1997), also pertaining to species belonging to this group, which suggests that adult specimens can survive experimental anoxia for at least 60 days. Since we consider here the larger size fraction, the retarded response can be explained by survival of adults although these probably are not able to reproduce anymore. From our data it is also evident that the primary production and organic flux to the sediment have no strong correlation with the occurrence of the taxa considered; the periods of their highest density coincide with the times of deepest oxygen penetration.
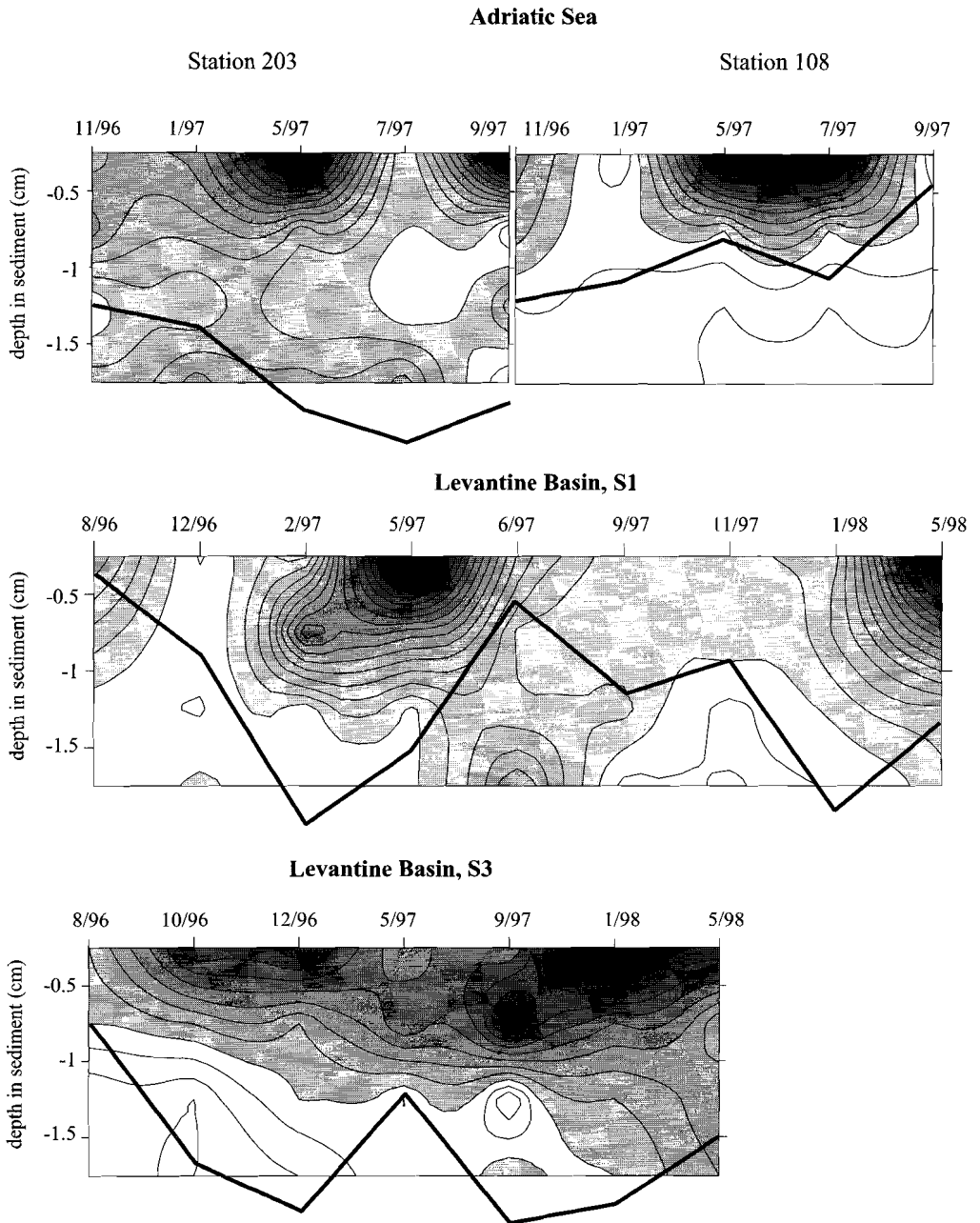
Adriatic Sea

Station 203   Station 108

Figure 11-2: Time series of the distribution of oxyphilic taxa in the topmost 2 cm of two Adriatic Sea and two Levantine permanent stations. Level of penetration of free oxygen was measured with microprobes and is indicated by bold line. Contoured foraminiferal densities in the Adriatic Sea vary between 0 and 40 specimens/50cc. Densities in the Levantine station S1 vary between 7 and 220 specimens/50cc, those of Levantine station S3 between 0 and 15 specimens/50 cc.

3. Paleo-oxygenation: transfer function and application

In fig. 3 we plotted the relative proportion of the oxyphilic taxa in the calcareous assemblage, versus the oxygen content at the sediment-water interface. The correlation between oxygen and the oxyphilic species is statistically significant, but we identified five deviating samples. Samples taken in January or May from the Adriatic Sea are from periods of sudden change; well-mixed conditions and the onset of spring production led to sudden oxygen supersaturation even at the sediment-water interface. Samples from stations 7 and 8 in the Atlantic Ocean were taken after an upwelling event; given the exceptionally high abundance of *Globobulimina* specimens, the sediment oxygen demand at these stations was clearly out of balance with the rather well-ventilated bottom water. The deviating faunal composition in these five samples is likely to be attributable to a time lag between changes in oxygen contents and the subsequent faunal response (see also fig. 2 for time lag).

The observation that the oxyphilic taxa are favouring the oxic microhabitat, provides no explanation why their total abundance is positively correlated with the oxygen contents as measured at the sediment-water interface. Oxygen is limiting foraminiferal distribution only at the lowest concentrations (Alve and Bernhard, 1995; Moodley et al., 1997); there is no evidence that it directly regulates population density at higher oxygen contents. Our data indicate that the foraminiferal microhabitat expands with deeper oxygen penetration (fig. 1c). It can be assumed that in general the volume of aerated sediment correlates rather well with the bottom water oxygen contents. Increasing oxygenation will thus lead to larger volume of inhabitable sediment for the oxyphilic group and subsequent increase of their population size. Since that is a universal relationship, the observed regression probably is structural and valid also for other areas and different time slices

The regression (O_2 [μmol/l]= 7.23 + 5.62 * {% oxyphilic}, R^2= 0.66) as given in fig. 3 leads to the possibility to reconstruct average paleo-oxygenation at the sediment-water interface if the

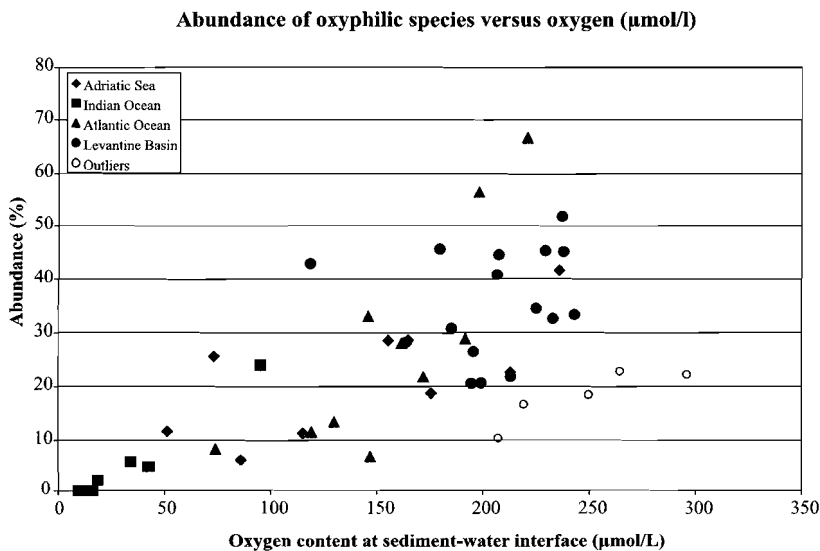**Abundance of oxyphilic species versus oxygen (µmol/l)**

Figure 11-3: Relationship between oxyphilic taxa and oxygen concentration at the sediment water – interface.

abundance of the oxyphilic group is known. The relationship is statistically significant and that is remarkable if we take into account that samples are included from very different trophic regimes. In the NW Atlantic average primary production is between 65-235 $gC.m^{-2}.yr^{-1}$, in the Indian Ocean it is 200-400 $gC.m^{-2}. yr^{-1}$ and in the Levantine Basin it is only 35 $gC.m^{-2}.yr^{-1}$ (Oren, 1970; Codispoti, 1991; Jorissen et al., 1998). This further strengthens our argument that the distribution of the species mentioned is indeed to a large extent dependent on the availability of oxygen.

We applied the new proxy to a well-dated core located in the muddy zone in front of the Po River at 32 m water depth and covering the past 160 years (Barmawidjaja et al., 1995) . The resulting quantitative oxygenation curve (fig. 4) can be compared with historic data as far back as AD 1911 (Justic et al., 1987; Justic, 1991). There is a high similarity in trends of our reconstruction representing average oxygenation at the sediment-water interface and the calculated year-average trend based on historic data (Justic et al., 1987). The later is based on observations 2 m above sea bottom. The difference between the curves amounts to 80-100 μmol/l, a difference that we also observed in the field. In our Levantine data, the average difference between oxygenation at 0.5m above sea bottom and at the sediment-water interface amounted to 92 μmol/l. It is clear that since AD 1890 a steady deterioration took place. This is clearly related to the use of artificial fertilisers (Barmawidjaja et al., 1995; Justic, 1991). Our data show that since AD 1930 the environment has been forced close to hypoxia, as indeed has become evident (Justic et al., 1987); the total drop in average oxygenation amounts to 100 μmol/l. Following a short-term amelioration after World War II and since 1970, the

Oxygenation history since AD 1820
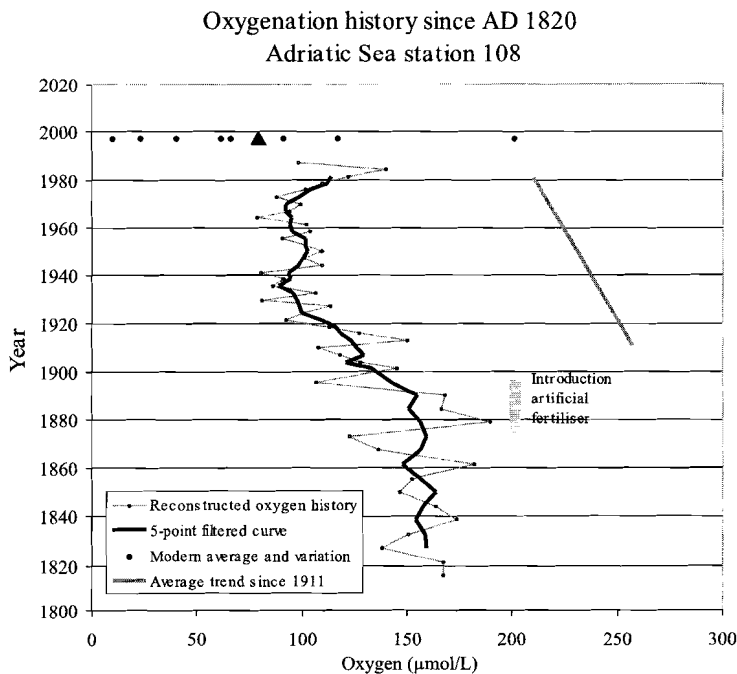### Adriatic Sea station 108

Figure 11-4: Oxygenation history covering the past 160 years of core 108, located in the northern Adriatic Sea just in front of the Po River (co-ordinates 44 45,4 N, 12 45,0 E). Oxygenation curve based on faunal data and datings of Barmawidjaja et al. (1995); historic trend in oxygenation is here represented by calculated fit of historic (1911-1982) oxygen data (see Justic et al., 1987, and Justic, 1992). Monthly variation of modern values (1998, own observations) is indicated by dots, their average by triangle.

last part of our reconstructed curve suggests again deterioration. This is confirmed by the modern values of which the average one fits our reconstruction very well, indicating that the proxy is a valuable tool for the accurate reconstruction of average oxygenation in paleoceanography.