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Fjord water circulation patterns and dysoxic/anoxic conditions in a Mediterranean semi-enclosed embayment in the Amvrakikos Gulf, Greece

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ABSTRACT

Oceanographic research in the Amvrakikos Gulf in Western Greece, a semi-enclosed embayment isolated from the Ionian Sea by a narrow, shallow sill, has shown that it is characterised by a fjord-like oceanographic regime. The Gulf is characterised by a well-stratified two layer structure in the water column made up of a surface layer and a bottom layer that are separated by a strong pycnocline. At the entrance over the sill, there is a brackish water outflow in the surface water and a saline water inflow in the near-bed region. This morphology and water circulation pattern makes the Amvrakikos Gulf the only Mediterranean Sea fjord. The investigations have also shown that the surface layer is well oxygenated, whereas in the pycnocline, the dissolved oxygen (DO) declines sharply and finally attains a value of zero, thus dividing the water column into oxic, dysoxic and anoxic environments. At the dysoxic/anoxic interface, at a depth of approximately 35 m, a sharp redox cline develops with Eh values between 0 and 120 mV occurring above and values between 0 and −250 mV occurring below, where oxic and anoxic biochemical processes prevail, respectively. On the seafloor underneath the anoxic waters, a black silt layer and a white mat cover resembling Beggiatoa-like cells are formed. The dysoxic/anoxic conditions appeared during the last 20 to 30 years and have been caused by the excessive use of fertilisers, the increase in animal stocks, intensive fish farming and domestic effluents. The inflicted dysoxia/anoxia has resulted in habitat loss on the seafloor over an area that makes up just over 50% of the total Gulf area and approximately 28% of the total water volume.

Furthermore, anoxia is also considered to have been responsible for the sudden fish mortality which occurred in aquaculture rafts in the Gulf in February 2008. Therefore, anoxic conditions can be considered to be a potential hazard to the ecosystem and to the present thriving fishing and mariculture industry in the Gulf.

1. Introduction

Coastal embayments are highly diverse environments with a varying spectrum of physical isolation from the open sea and water circulation patterns. These embayments mainly include estuaries, lagoons, rias and fjords.

Coastal embayments are characterised by high productivity and are very important nursery grounds for several commercial fish species (Valiela, 1991). The contribution of these areas to the overall fish and shellfish landings is considerable. Both extensive and intensive aquaculture activities are also carried out in these protected areas (Valiela, 1991). However, coastal embayments are characterised by high anthropogenic inputs from urban, industrial and agricultural activities. Therefore, they are very vulnerable to pollution, and some of these areas tend to become either dysoxic or anoxic. Since 1969, the number of areas in the marine environment characterised by these conditions has spread exponentially around the world, which has serious consequences for ecosystem functioning (Diaz and Rosenberg, 2008).

The purpose of the present paper is to examine the oceanographic regime, the water circulation patterns, the water oxygen efficiency and the prevailing environmental seafloor conditions in one of the largest semi-enclosed embayments in the Mediterranean Sea: the Amvrakikos Gulf in the Ionian Sea, Northwestern Greece (Fig. 1a,c). The Amvrakikos Gulf is well known for shrimp fishing and for an extensive aquaculture industry that has developed over the last 20 years.

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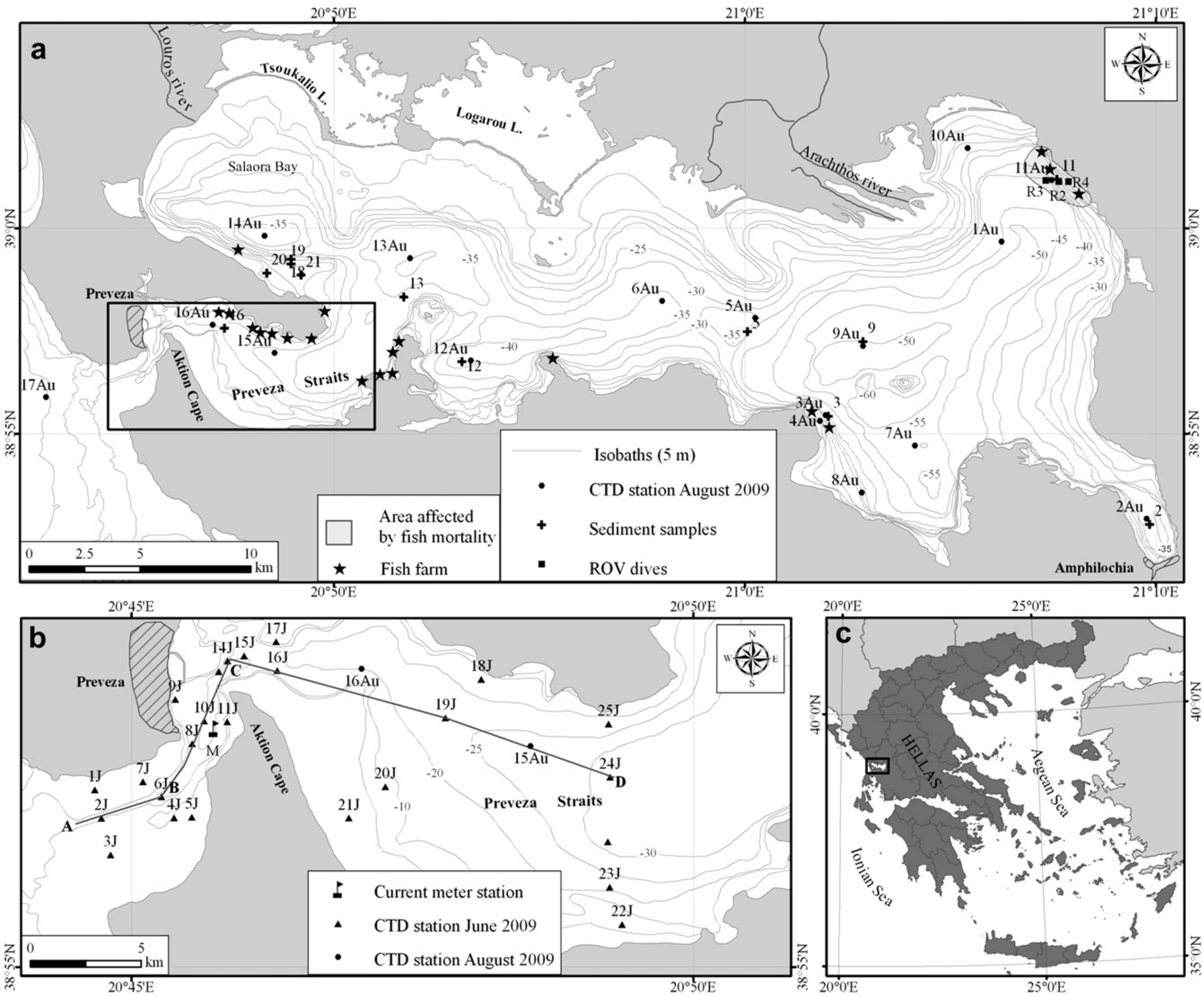

Fig. 1. (a) Bathymetric map of the Amvrakikos Gulf, the location of sampling stations and the location of the fish farms; (b) Bathymetric map of the Preveza Straits, which connects the Amvrakikos Gulf to the Ionian Sea. The location of the sampling stations and the position of the salinity and density sections (ABCD) along the Straits are shown in Fig. 5; and (c) Location of the study area in Western Greece.

This research was triggered by the sudden massive mortality of fish in aquaculture rafts in the north eastern part of the Gulf (Fig. 1a), which occurred in February 2008, during an extremely cold, wet and windy spell (Fisheries Commission). The study was carried out 1 1/2 years after this event.

1.1. Regional setting

The Amvrakikos Gulf, a semi-enclosed embayment in North-western Greece, is approximately 35 km long and 6–15 km wide (Fig. 1a). Its maximum depth is 65 m, and it is separated from the open Ionian Sea by a beach–barrier complex. The Gulf and the Ionian Sea are connected through a narrow, elongated channel, the Preveza Straits, that is approximately 6 km long and ranges in width from 0.8 to 2 km (Fig. 1b). The channel at its entrance is approximately 2 km wide and gradually narrows, reaching a width of approximately 0.8 km at the mid-channel (Fig. 1b). The sill depth over this distance is between 2 and 10 m, including a man-made navigational channel. Past the middle, the channel gradually widens reaching a width of approximately 2.5 km, and the sill deepens to approximately 20 m (Fig. 1b). The Gulf is bounded by rock to the south and east, and to the north by the delta plain of the Arachthos and Louros rivers and associated lagoons (Fig. 1a).

The Gulf was formed in the Middle Quaternary period (Anastasakis et al., 2007). During the isotope stage, MIS3 and MIS2 (ca 50–11 ka BP), when the sea level was lower than 55 m in relation to its present position, the western part of the Gulf emerged, whereas the eastern part was occupied by a lake (Kapsimalis et al., 2005). The marine transgression took place at approximately 11 ka BP and the Gulf attained its present shape at approximately 4 ka BP (Kapsimalis et al., 2005). Therefore, it can be said that the evolution of the Gulf was similar to that of the Baltic Sea and the Black Sea.

The oceanographic regime at the entrance to the Gulf is characterised by a semi-diurnal tide with an average tidal range of only 5 cm and a maximum recorded range of 25 cm (Variagin, 1972). Inside the Gulf, a low energy wave regime prevails, due to the limited fetch of approximately 35 km (Poulos et al., 1998). Two large rivers, the Louros and Arachthos discharge approximately 609×10^5 m^3 and 2002×10^6 m^3, respectively, per year (Therianos, 1974). Since 1980, two dams control the run-off of the Arachthos River. The Gulf has a positive water balance, the water input from rivers run-off is 2063×10^6 m^3 and the precipitation is approximately 1200 mm/year (Hellenic Meteorological Service), whereas the output due to evaporation is approximately 1180 mm/year (Public Power Corporation S.A.)

The water column is highly stratified during the year with a high salinity gradient between 5 and 10 m deep (Friligos and Koussouris, 1977; Friligos et al., 1997). The surficial water layer in the summer (July) has a salinity ranging from 31 to 33 ppt and a temperature ranging from 23.5 to 27 °C. The bottom water layer has salinities of between 37 and 38 ppt (Piper et al., 1982) and temperatures of between 17.3 and 19.0 °C. The Gulf is characterised by high primary productivity with phytoplankton densities between 7.5×10^5 and 2.0×10^7 cells/l (Gotsis Skreta et al., 2000) and high levels of eutrophication with average yearly concentrations of PO_4-P, NH_4- N and NO_3-N of approximately 0.4, 0.45 and 2.2 μg at/l, respectively (Friligos et al., 1997). Furthermore, the Amvrakikos Gulf contains 3.8, 1.4 and 3.9 times more PO_4-P, NH_4-N and NO_3 N, respectively, than the Ionian and the Aegean Seas (Friligos et al., 1997).

2. Data collection and methodology

The present paper is based on data collected from two research cruises that were carried out in June and August 2009. The June cruise focused on the study of the water circulation along the Preveza Straits which connects the Gulf to the open sea. Temperature and salinity measurements were carried out throughout the water column at a total of 25 stations (Fig. 1b) using an Aaandera RCM9-MKII. During the same period, current measurements were carried out at one station during a tidal cycle using the Aaandera RCM9-MKII (Fig. 1b). The August cruise focused on the study of the water column structure in the Gulf. A total of 17 stations were visited, where the temperature, salinity, dissolved oxygen (DO), redox potential (Eh) and pH were simultaneously measured using the following three probes for inter-comparisons: an Aaandera RCM9-MKII, a YSI 600 XL and an IN-SITU TROLL 9500. On both cruises, the salinity was measured using a Practical Salinity Scale (psu). In addition to the measurements of the physical properties of the water column, twelve short core samples were collected from the seafloor for the study of the prevailing conditions on the seafloor (Fig. 1a). Sediment samples taken from the short cores were examined for the following properties: (1) colour, using a Muncell colour chart; (2) grain-size content, using a Mastersizer 2000; (3) total organic carbon (TOC) content, using Carlo Erba Elemental Analyzer EA1108; and (4) foraminifera species, using a microscope. A Minirover MK II ROV was also used at three stations to visually inspect the seafloor (Fig. 1a). The position of the sampling stations and the ROV dives were fixed using a differential GPS. The achieved accuracy was 2–3 m.

3. Data presentation

The study of the vertical profiles collected in the Straits, the Gulf and the open sea shows that there is a significant variability in the physical parameters characterising the water masses. The data collected at each station are presented and were analysed in relation to their location in the Gulf, in the Straits and in the open sea.

3.1. Water column structure in the Gulf

The vertical profiles at stations 9Au and 13Au shown in Fig. 2a present the general temperature, salinity and density conditions that prevail throughout the water column in the Gulf. The vertical profiles show that the water column is divided into two major layers, a brackish surface layer and a saline bottom layer, which are separated by a salinity-controlled strong pycnocline (Fig. 2a). The surface layer is homogenous, with a temperature between 29 and 30 °C and salinity between 32.5 and 33. The bottom layer is also homogenous, with a temperature of between 15 and 16 °C and salinity between 37 and 39. The thermocline develops between 8 and 16 m, whereas the halocline is sharp and develops between 8 and 12 m. In the eastern and northern parts of the Gulf at the uppermost part of the surface layer between depths of 0 and 3 m, a low salinity layer develops that appears to be associated with the plume of the Arachthos River. The southern and western parts of the Gulf are not affected directly by the rivers discharge.

A similar oceanographic regime prevails in winter in the Gulf. Measurements of temperature and salinity in the water column carried out by Poulos et al. (1998) near the mouths of the Arachthos and Louros rivers showed the presence of three layers: (1) a surficial layer that was approximately 3–4 m thick with salinity of between 16 and 20 ppt that is related to fresh water river inputs; (2) an intermediate layer between depths of 3 and 14 m, where temperature and salinity increase sharply; and (3) a bottom water layer from depths of 14–40 m with a rather constant temperature and salinity of approximately 37 ppt. According to Poulos et al. (1998), the intermediate layer results from the mixing of the upper layer fresh water with the more saline bottom layer.

The two layer water structure appears to control the vertical distribution of the DO in the water column in the Gulf. An examination of the profiles shows that the surface layer is well oxygenated with a concentration ranging from 7.5 to 9 mg/l (Fig. 2b). The narrow peak of the DO content in the sea water observed in the middle part of the pycnocline indicates that the DO cannot be advected downward through the interface of the surface and bottom layers and/or the excess oxygen production due to photosynthesis. Below the interface, the DO content continuously decreases reaching a concentration of 2 mg/l and 0 mg/l at water depths of approximately 25 m and 34 m below the surface, respectively (Fig. 2b). This sharp decline in O_2 concentrations indicates that the DO in the bottom layer is consumed by the sinking organic matter and cannot be replenished due to the strong pycnocline. The above distribution of the DO content in the water column all over the Gulf shows that at a water depth of approximately 25 m below surface, there is a zone between 7 and 9 m thick where dysoxic conditions prevail. Anoxic conditions prevail below this zone.

An ROV inspection of the water column showed that there is a high density jelly-fish population in the dysoxic layer and just above it. Recent studies indicate that jelly-fish are tolerant to low oxygen content (Arai, 1997; Lucas, 2001) and prefer areas of low oxygen content for food. In these areas, jelly-fish prey on food items such as fish larvae which have a low mobility due to the low oxygen content in the water and therefore cannot escape predation (Breitburg et al., 1994; Arai, 1997; Lucas, 2001).

Similarly, the pH distribution in the water column is controlled by the two layer structure. The pH of the surface layer is just above 8 (Fig. 2b), reflecting the entrainment and consequently the mixing of the inflowing sea water in the Gulf with the surface layer. The slightly lower pH value in the upper 2 m is probably related to the influence of river inputs, as it coincides with the low salinity values in the water surface (Fig. 2a,b). Below the halocline, the pH is approximately 7.6, indicating that the water is more acidic. It is here that most of the DO is used up in the formation of CO_2 during the decomposition of the organic matter, according to the reaction of $CH_2O + O_2 \rightarrow CO_2 + H_2O$, which combines with water molecules to form carbonic acid and its dissociation products. A similar pH decrease in the oxic/anoxic interface was also observed in other anoxic basins (Lewis and Landing, 1991; Balistrieri et al., 1994).

The Eh distribution in the water column is controlled by the DO content in the water. Where the DO content is above 2 mg/l,

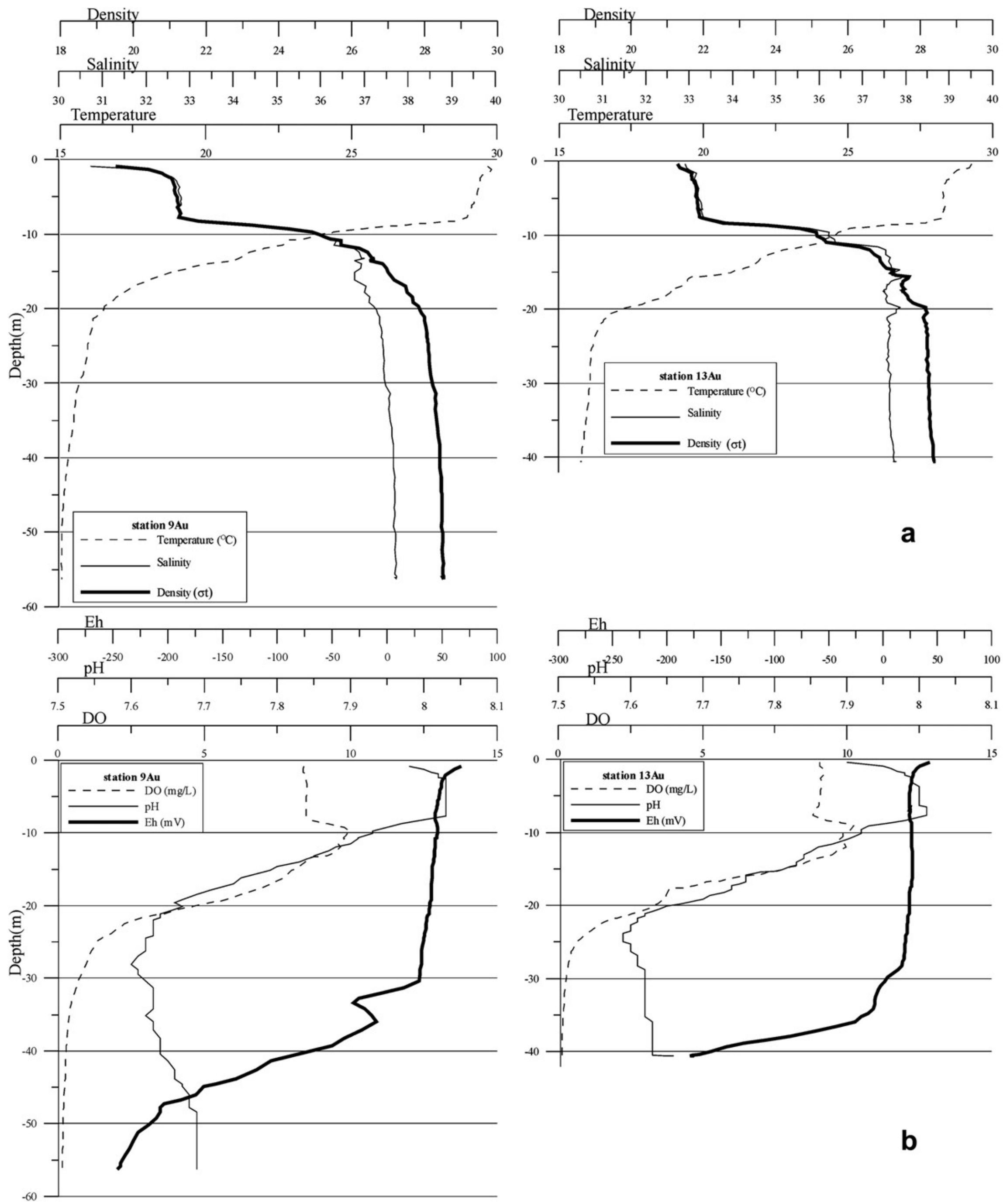

Fig. 2. Temperature, salinity and density profiles (a), along with DO, pH and Eh profiles (b) at stations 9Au and 13Au (August 2009; see Fig. 1a for the locations of the stations).

the Eh has values between 20 and 100 mV. Where the DO content decreases below 2 mg/l, the Eh drops sharply to between −100 and −250 mV, forming a redox cline (Fig. 2b). The presence of the redox cline leads to the chemical stratification of the water column in which oxidising conditions prevail above the redox cline while reducing conditions prevail below it. Furthermore, the presence of the sharp redox cline indicates that at this level of the water column, stable physical conditions with a high organic influx prevail and that the addition or removal of redox-sensitive components is faster than homogenisation by vertical mixing.

3.2. *Water column structure in the Preveza straits*

The temperature and salinity variation vs. depth along the central axis of the Straits (Figs. 3 and 4) delineates the oceanographic regime prevailing in June and August. The distribution of the physical parameters with depth shows a well layered and stratified water column in the inner part of the Straits, consisting of a surface and a bottom layer separated by a sharp thermocline/halocline (Fig. 3a). The surface layer extends from 0 to 10 m below surface and is homogenous, with temperatures between 26 and 28 °C and salinity values between 33 and 33.5. The thermocline and

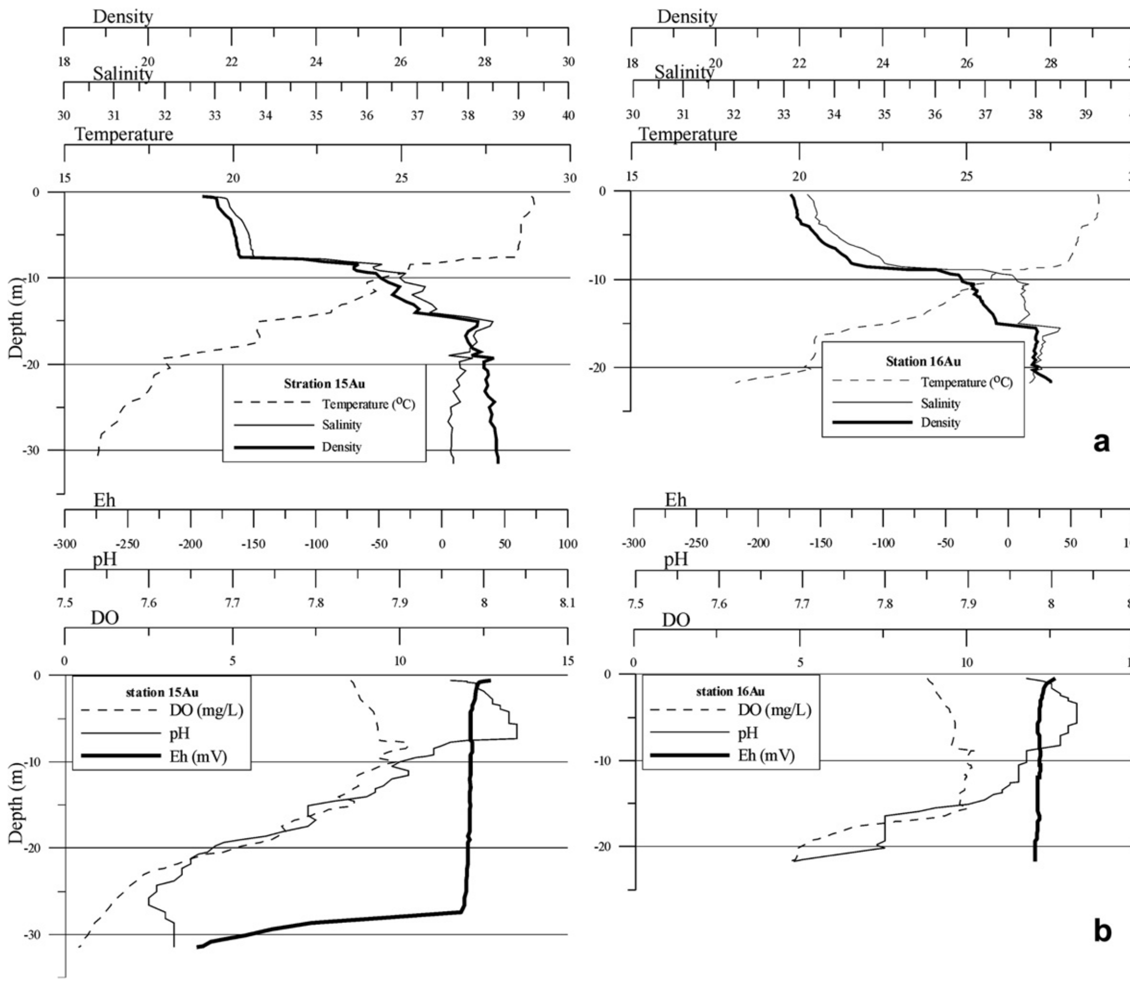

Fig. 3. Temperature, salinity and density profiles: (a) at station 15Au (Aug. 2009) and station 16Au (Aug. 2009), shown with DO, pH and Eh profiles (b) at station 15Au and station 16Au (see Fig. 1 for the locations of the stations).

halocline extend from 10 to 20 m and from 8 to 15 m, respectively. They are characterised by a temperature decrease from 26 to 18 °C and a salinity increase from 33 to 37.5. The bottom layer extends from 15 m to the seabed and is characterised by temperature and salinity values of approximately 17 °C and 37.5.

At the outer part of the Straits over the sill, the presence of a horizontal salinity and density gradient, which extends from the surface to the bottom, indicates the presence of a well-developed front due to the outflowing brackish water of the Gulf and the inflowing saline open sea water (Fig. 4a,b). Here, along the man-made navigational channel whose depth is approximately 10 m, the more saline and denser open sea water submerges under the brackish out-flowing Gulf water (Fig. 4a,b). The saline intrusion due to the density it acquires is not sufficiently dense to sink and displace the bottom water. Instead, the intrusion detaches itself from the seafloor as it deepens and moves at a water depth of between 15 and 25 m, isolating the bottom layer, which thus stagnates.

This along-Straits flow, as suggested by the distribution of salinity, was verified by current measurements. There is a brackish water outflow in the surface layer and a saline water inflow in the bottom layer, attaining speeds of up to 60 and 80 cm/s.

The distribution of DO, pH and Eh in the water column in the inner part of the straits is controlled by the two-layer structure in the Gulf (Fig. 3b).

3.3. Structure of the open sea water column

The vertical profiles at station 17Au in the open sea at a distance of 2 km from the entrance to the Straits, shows that the water column structure is different from that along the Straits and in the Gulf (Fig. 5). There is a two layer structure that is primarily controlled by the temperature. The salinity difference between the upper and the bottom layer is only 3.0 indicating strong mixing. The DO distribution is reversed compared to the DO distribution in the Gulf, with a well oxygenated upper layer with a DO concentration of between 9 and 11 mg/l, whereas the bottom layer is oversaturated with DO values ranging from 11 to 15 mg/l. The oxygen oversaturation in the bottom layer is probably caused by the oxygen production due to photosynthesis, due to the higher concentration and photosynthetic activity of phytoplankton in the deeper parts of the water column. The pH distribution in the water column follows the DO distribution, with the pH being lower at the surface and higher in the bottom layer. The Eh values are positive, ranging between 10 and 35 mV.

3.4. Sediment seafloor conditions

The study of the short cores collected in the Gulf in depths of more than 30 m (Fig. 1) shows that the floor of the Gulf is covered by a uniform black (N 2.5) silt layer with a thickness of between 3

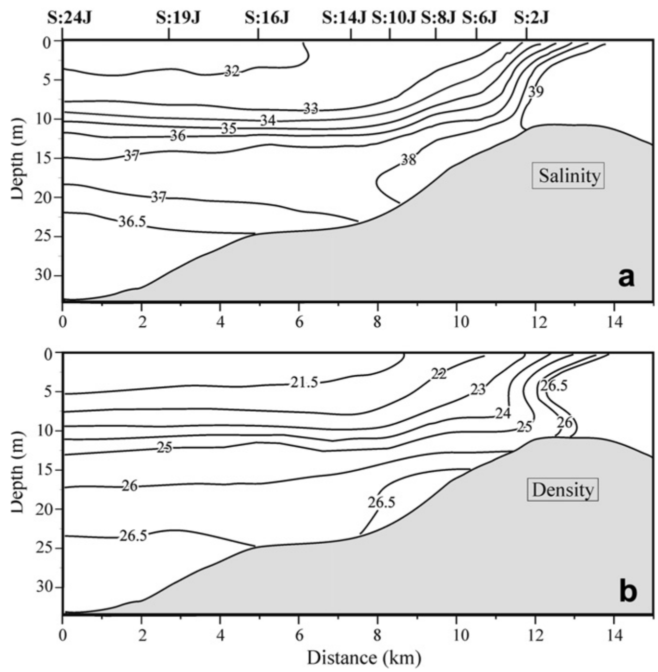

Fig. 4. Vertical distribution of salinity (a) and density (b) along the Straits (section ABCD; see Fig. 1b for the location of the sections).

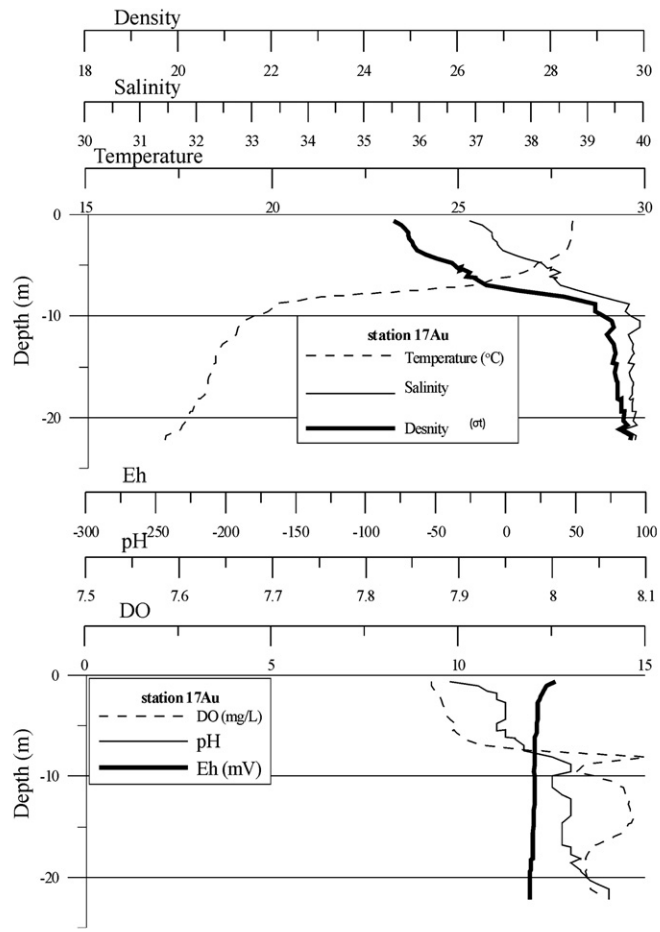

Fig. 5. Temperature, salinity and density profiles (a), and DO, pH and Eh profiles (b) at station 17Au (August 2009; see Fig. 1a for locations of stations).

and 10 cm (Fig. 6). The clay and silt content ranges between 26 and 33% and from 66 to 68%, respectively. The sand-sized fraction forms less than 3% of the sediments. Underneath the black layer, there is a greenish–grey (5GY 4/1) mud layer that is more than 50 cm in thickness with a clay content of between 38 and 46% and a silt content of between 60 and 68% (Fig. 6). The TOC content in the surface black layer ranges from 5 to 8.6%. In contrast, the TOC in the underlain greenish–grey layer is less than 5.0% (Fig. 6).

A preliminary examination regarding the presence of foraminifera in the cores showed low species diversity associations dominated by *Ammonia* spp., *Bulimina* Spp., *Bolivin*a spp. and *Nonionella* spp. in the surficial black silt layer. These taxa, which characterise coastal and estuarine environments, are euryhaline and tolerant to low oxygen bottom waters (Amorosi et al., 2005; Alday et al., 2006). However, it cannot be affirmed whether the foraminifera tests found were living or dead specimens as the samples were not treated with rose Bengal. Furthermore, due to its watery texture, the black silt layer was disturbed during coring and it was therefore not possible to determine whether the foraminifera tests found were from the upper part of the core or not. In the greenish–grey mud layer, the benthic foraminifera assemblages present higher species diversity values and are dominated by the above-mentioned taxa, and by Miliolidae. This benthic assemblage indicates that during the deposition of the greenish–grey layer, the oxygen content in the near-bed sea water was higher than that at present, when the black silt layer is being deposited. The visual inspection of the oxic and anoxic environments on the seafloor with an ROV (Fig. 1) showed that the oxic seafloor is characterised by brown sands with bivalve shells (Fig. 7a), whereas the anoxic seafloor is covered by a white mat that is approximately 1–2 cm in thickness resembling Filamentous Beggiatoa-like cells (Fig. 7b). The study of the sedimentary column on the seabed with a 3.5 kHz seismic profiler shows the presence of gas, probably methane, in the sediments (Papatheodorou et al., 1993).

The study of the cores collected along the Preveza Straits and in the Gulf in water depths of less than 30 m show that the floor is covered by a brown, silty sand layer with a sand content of between 34 and 51%. The sandy fraction is almost entirely biogenic, and is comprised principally shells of molluscs, ostracods and benthic foraminifera. A comparison of the sediment colour, texture and foraminifera observed in the present survey and in two surveys carried out in 1979 (Piper et al., 1982) and 1986 (Tziavos and Vouloumanos, 1994) showed great dissimilarities. The black layer observed in the seafloor surface in the 2009 survey was not observed in the 1979 and 1986 surveys. At that time, the surface layer was greenish–grey in colour. The low species diversity association observed in the black layer in the 2009 survey was not observed in the 1979 survey, where a diverse foraminifera fauna, with as many as 40 species of shallow water and holosaline affinities, were observed in the greenish–grey surface layer (Piper et al., 1982). Similarly, Tziavos and Vouloumanos (1994) in the 1986 survey mentioned the presence of benthic foraminifera in water depths of more than 30 m in the surface sediments of the Gulf except for surface sediments in the north eastern part of the Gulf where the Arachthos River is discharged. They attributed the absence of foraminifera around the mouth of Arachthos River to oxygen deficiency. Poulos et al. (2008) re-examined the samples studied by Tziavos and Vouloumanos (1994) found that the benthic fauna content in the surface sediments offshore is low and can be explained by the low dissolved oxygen content measured in the water near the seabed. However, they came to this conclusion by correlating the benthic foraminifera found in the surface sediment samples collected in 1986 with dissolved oxygen measurements in the water, but neither the date of measurement (probably two

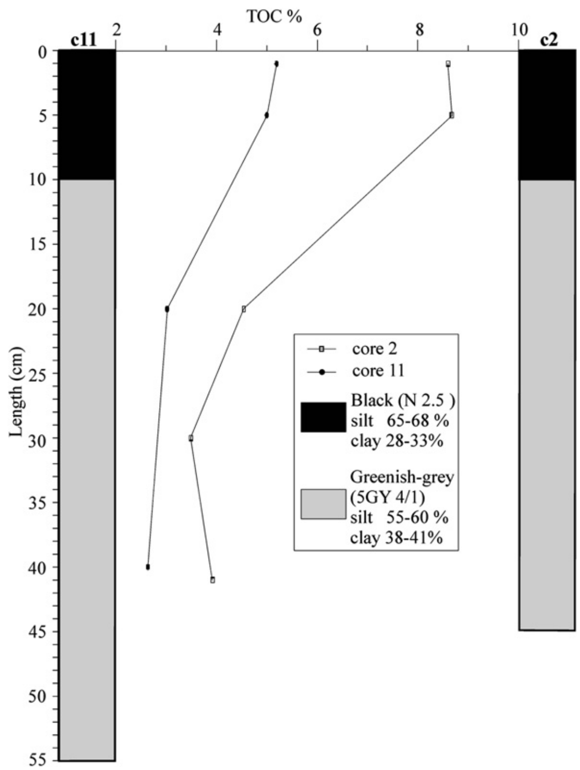

Fig. 6. Core description and TOC profiles for core 2 and core 11 (see Fig. 1 for the locations of cores).

decades later) nor the number and the location of the stations are shown in their paper.

4. Discussion

The above oceanographic conditions prevailing in the Amvrakikos Gulf during the summer in conjunction with the overall morphology of the Gulf, suggest that the Gulf is characterised by a fjord-like water circulation. A well-stratified two layer structure in the water column develops in the Gulf, whereas along the Straits and over the sill, a two-layer model flow prevails, with brackish out-flowing water at the surface and saline inflowing water near the seabed. This morphology and water circulation pattern makes the Amvrakikos Gulf the only Mediterranean Sea fjord. The salinity and density distribution along the axis of the Straits suggests that the deep water is trapped by the sill. The brackish surface layer is well mixed and is separated from the bottom layer by a well developed thermocline/halocline zone. The strong thermocline/halocline inhibits the downward diffusion and advection of the DO, resulting in low DO concentrations of less than 2 mg/l in water deeper than 25 m and of approximately zero in water depths of more than 33 m. The sharp redox cline with values between 0 and 120 mV and between 0 and −250 mV that develops at dysoxic and anoxic boundaries suggest that oxidising and reducing biochemical processes, respectively, prevail. Thus, of the total area of 411.4 km^2 occupied by the Gulf, an area of 87.2 km^2 is characterised by dysoxic conditions and another 130.4 km^2 is characterised by anoxic conditions. Correspondingly, in a total volume of 10.4 10^9 m^3 of water in the Gulf, 7.4 10^9 m^3 (71.5%) is well oxygenated, 1.7 10^9 m^3 (17%) is dysoxic and 1.2 10^9 m^3 (11.5%) is anoxic.

The rotten egg odour in the sediment–water interface, along with the black coloured silt in the surficial sediments, the white mat cover on the seafloor and the methane in the sediments indicate that sulphuric organic substances via anaerobic bacteria are reduced to H_2S, which is oxidised to FeS_2 in the presence of Fe_2 ions, thus blackening the mud. Also, H_2S can be oxidised by *Beggiatoa* strains to elemental S and then by *Thiobaccilus* to sulphates (Judd and Hovland, 2007).

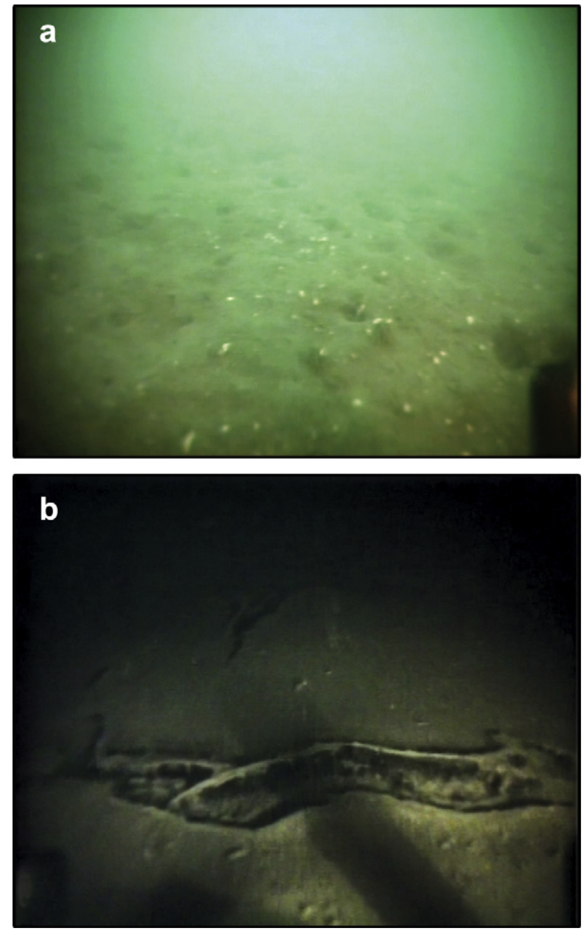

Fig. 7. ROV photographs of the oxic (a) and anoxic (b) zones of the seafloor showing brown sands with bivalve shells and a white mat of Beggiatoa-like cells covering the seabed, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The fjord-like oceanographic regime that prevails in the Gulf, the oxic/dysoxic and dysoxic/anoxic interfaces at depths of 25 and 35 m, respectively, an easily accessible depth, make the Gulf a potential analog of larger basins such as the Black Sea and the Baltic Sea where redox reactions in the water column and in the sediments can be examined in great detail and at little cost.

Two questions are raised in this paper by the observed presence of hypoxia and anoxia in the Gulf. When did the anoxia occur, and how? Did this anoxia result from natural processes or from human interference?

The thickness of the surficial black mud, which is between 3 and 10 cm in relation to the sedimentation rates of approximately 0.35 cm/yr (Tsabaris et al., 2009 and Tsabaris pers. comm.), suggest that the anoxic conditions appeared in the Gulf in the last 20–30 years. This time frame is also indicated by the results of two surveys carried out in 1979 and 1986 by Piper et al. (1982) and Tziavos and Vouloumanos (1994), respectively. Both of these studies mentioned that the surficial sediments were greenish to grey and that the biogenic part of the sediment consists mainly of benthic ostracods and foraminifera.

The excessive use of fertilisers, the increase in animal stock, the intensive fish farming and the increased sewage discharge occurred over the last 50 years due to increased rural development. The occurrence of dysoxia and anoxia during the last 20 to 30 years suggests that the above factors have altered the balance of nutrients in the Gulf and have resulted in the prevalence of anoxic and dysoxic conditions.

The detailed mapping of the oxic/dysoxic and dysoxic/anoxic interfaces in the water column suggests that over the last 20 to 30 years, habitat loss occurred on the Gulf seafloor over an area of 217.5 km^2 of the total 411.4 km^2 (i.e., just more than 50% of the total Gulf area). In the water column, habitat loss occurred over a water volume of 2.9×10^9 m^3 (28.5%) of the total 7.4×10^9 m^3 in which the elimination of benthic fauna disrupts the food web in the Gulf.

The revealed anoxic conditions that gradually developed in the Gulf over the last 20 to 30 years following this investigation allowed for speculation regarding the physical processes which could have caused the massive fish mortality in aquaculture rafts in the north eastern part of the Gulf (Fig. 1a). Temperature and salinity measurements carried out by the Fisheries Commission in the Gulf in the vicinity of the affected fish farms soon after the occurrence of the event showed that the sea water temperature in the surface layer was approximately 16.5 °C compared to the typical winter temperatures of 12–13 °C (Poulos et al., 1998). Similarly, the salinity measured on the surface layer was approximately 36, whereas the typical winter salinity value is approximately 20. The temperature and salinity values measured immediately after the event were similar to those which prevail in the bottom layer in winter (Poulos et al., 1998). It can therefore be suggested that the irregularly high temperature and salinity values measured were due to a rise in the oxic/dysoxic interface caused by the uplifting of the bottom water.

As there was no detailed oceanographic survey in the Gulf immediately after the occurrence of the fish mortality, we can only speculate on the potential mechanisms that could have caused the dysoxic/anoxic interface to rise. The potential mechanisms are: (1) a massive intrusion of dense open sea water through the straits, driven by either a fluctuation in the sea levels between the open sea and the Gulf, or by differences in density; and (2) gravity-driven river hyperpycnal flows. In both cases, the high density water fills the deeper parts of the basin, thus uplifting the anoxic layer. Two other mechanisms which can shift the dysoxic/anoxic interface are internal waves, either in the form of standing waves (seiching) or, frictionally-damped progressive waves. However, taking into consideration the distribution of the fish farms over the Gulf (Fig. 1a) and the fact that the three affected fish farms are located exactly opposite the mouth of the Arachthos River, the formation of a gravity-driven hyperpycnal flow at the river mouth was the most likely mechanism responsible for the fish mortality. The size and expansion of the dysoxic/anoxic water masses in the Gulf suggest that the "accident" can recur at any time, confirming the fact that low oxygen concentrations in coastal ecosystems have become a major ecological problem (Diaz and Rosenberg, 2008).

Based on the oceanographic and environmental conditions prevailing in the Gulf following this survey, measures must be taken to end the deterioration of the water masses in the Gulf to protect the marine environment and to save the fishing and mariculture industry in the Gulf. The recommended steps to be taken at this stage to achieve improvement in water quality in the Gulf include the reduction in the nutrient input from agricultural and farming activities and the introduction and/or improvement of the treatment of municipal and industrial effluents (Conley et al., 2009). Further, complementary remediation efforts cannot be implemented at present due to the uncertainties regarding the potential effects on the biota and the lack of knowledge regarding the physical and biogeochemical processes that operate in the Gulf. These efforts include: (1) engineering solutions to increase oxygen in the bottom water by increasing the inflow of open sea oxygenated water or by vertical mixing; (2) the chemical removal of phosphorus; and (3) biomanipulation (Conley et al., 2009) However, any remediation measures must consider climatic changes expected over the next 50–100 years. The expected climatic changes would change the physical processes operating in the Gulf due to the rising of the sea level and changes in the water budget. According to UNEP/MAP (2010), the temperature is expected to increase to between 2.2 and 5.1 °C, whereas the precipitation is expected to decrease by 27% between 2080 and 2090 in relation to the temperature and rain conditions that occurred between 1890 and 1999 in southern Europe. Similarly, sea level is expected to rise at the end of the century to between 0.3 and 0.5 m. The above-mentioned changes in air temperature and precipitation would gradually change the present day positive water balance (precipitation + runoff > evaporation) to a negative one, resulting in changes in the water circulation from estuarine to anti-estuarine. At the same time, due to the sea level rise, the depth increase over the sill at the entrance to the Gulf would increase the inflow of well-oxygenated open sea water.

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