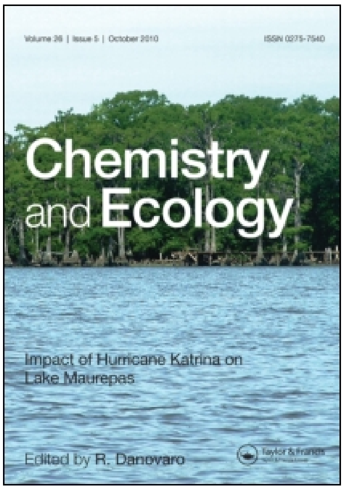

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Spatial and seasonal variability of dissolved oxygen and nutrients in the Southern Adriatic coastal waters

Paola Rivaro[a]; Carmela Ianni[a]; Serena Massolo[a]; Nicoletta Ruggieri[b]; Roberto Frache[a]
[a] Sezione di Chimica Analitica ed Ambientale, Dipartimento di Chimica e Chimica Industriale, Università di Genova, Genoa, Italy [b] Dipartimento per lo Studio del Territorio e sue Risorse, Università di Genova, Genoa, Italy

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SPATIAL AND SEASONAL VARIABILITY OF DISSOLVED OXYGEN AND NUTRIENTS IN THE SOUTHERN ADRIATIC COASTAL WATERS

PAOLA RIVARO[a,*], CARMELA IANNI[a], SERENA MASSOLO[a], NICOLETTA RUGGIERI[b] and ROBERTO FRACHE[a]

[a]*Sezione di Chimica Analitica ed Ambientale, Dipartimento di Chimica e Chimica Industriale, Università di Genova, via Dodecaneso, 31-16146 Genoa, Italy;* [b]*Dipartimento per lo Studio del Territorio e sue Risorse, Università di Genova, corso Europa 26-16132 Genoa, Italy*

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The main objective of this paper is to present vertical and horizontal patterns of dissolved oxygen and nutrients found during four seasonal surveys (March, June, September and December 2000) in the Southern Adriatic Sea coastal waters. The multivariate technique Principal Component Analysis has been applied to our dataset considering the following parameters: seawater temperature, salinity, dissolved oxygen and nutrients (nitrate, nitrite, phosphate, silicate). The resulting plot shows in a self-explanatory way that a seasonal trend was not observable in the investigated period and that no significant differences occur between the stations sampled in the Taranto Gulf and those along the Adriatic coast. Water column stratification persists in all seasons, except in spring, in the shallowest stations. The surface layer is characterized by a low nutrient content. The influence of the Northern Adriatic Surface Water in the Southern Adriatic sub-basin seems to be very low and can be traced by nitrate and silicate only in spring and winter. Regarding deep waters, nitrate distribution shows an increasing gradient moving from the coast to the open sea, having the lowest concentration in the shelf area and the highest in the most offshore stations of the Otranto Strait. In the Otranto Strait area the vertical distributions of physical and chemical parameters show, at middle depths, the inflow of Levantine Intermediate Water, traced by both the maximum of salinity, nitrate and phosphate and the minimum of oxygen. The LIW signal is lost moving northward. The outflow of Adriatic Dense Water is less evident, being traced only in spring by an oxygen increase at the bottom layer in the shelf area. The N:P ratio is highly variable but in the range already observed in the Southern Adriatic, suggesting a P-limitation, which can both contribute to the low primary productivity of the area and support the N:P ratio anomaly of the Eastern Mediterranean.

Keywords: Dissolved oxygen; Nutrients; Adriatic Sea; Northern Adriatic Dense Water; Levantine Intermediate Water

1 INTRODUCTION

The Adriatic Sea is an elongated, semi-enclosed basin with a NW–SE orientation, which connects to the Ionian Sea through the Otranto Strait. It may be considered as having three parts, defined on the basis of their oceanographic and bathymetric features, increasing in depth to the Otranto Strait, as shown in Fig. 1 (Gacic *et al.*, 1999).

*Corresponding author. Fax: +39-010-3536190; E-mail: rivaro@chimica.unige.it

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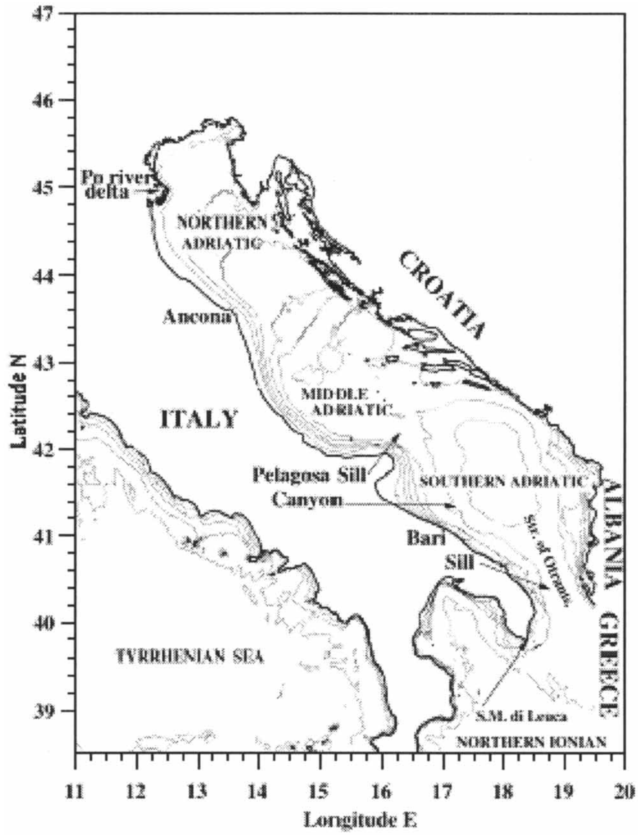


FIGURE 1 Bathymetric map of the Adriatic Sea (from Manca *et al.*, 2002, modified).

The Adriatic Sea is well known as the main source of deep water in the Eastern Mediterranean. The densest water of the Mediterranean is in fact, the Northern Adriatic Dense Water (NAdDW) ($\sigma_\theta \cong 29.52$), which forms in winter over the northern shelf (Malanotte-Rizzoli *et al.*, 1997; Manca *et al.*, 2002). In addition, dense water formation (South Adriatic Deep Water, SAdDW, $\sigma_\theta \cong 29.16$) was observed over the South Adriatic Pit during winter (Gacic *et al.*, 1999; Manca *et al.*, 2002). These water masses flow along the Italian coast towards the Otranto Strait, forming the Eastern Mediterranean Deep Water (EMDW).

Levantine Intermediate Water (LIW) can be found at intermediate depths, with the core between 200 and 400 m; this inflowing water mass is characterized by a salinity of ≥ 38.75 and is relatively rich in nutrients (Civitarese *et al.*, 1998). Zavatarelli proposes that it could represent another source of nutrients (Zavatarelli *et al.*, 1998).

The South Adriatic Basin is also an important exchange area for surface waters: here, the Adriatic Surface Water (ASW) flowing southward along the Italian shelf encounters the Ionian Surface Water (ISW), coming from the Ionian Sea along the Greek and the Albanian coasts. ASW differs from ISW in having lower salinity, higher nutrients and dissolved oxygen content, because it comes from an area influenced by river inputs (Zore-Armanda, 1969; Socal *et al.*, 1999). The tongue of LIW runs along the eastern Adriatic coast, almost reaching the western continental slope (Gacic *et al.*, 1999).

With regard to the primary productivity, the southern region of the Adriatic Sea is characterized by lower values than the northern area, where river inputs provide high nutrient concentrations and re-mineralization of organic matter in sediments represents another important source of nutrients in the water column (Giordani *et al.*, 1991; Zavatarelli *et al.*, 2000). Low nutrient concentrations in the upper 50 m layer, near oxygen saturation, high transparency and both low phytoplankton cell density and biomass reflect the oligotrophic characteristics of the area, as reported by Viličić *et al.* (1989, 1995).

Phytoplankton abundances observed in the Southern Adriatic are mostly similar to those measured in the Otranto Strait, in the Ionian Sea and in the Levantine Basin (Viličić *et al.* 1995). Exceptions to this can be observed in some western coastal areas, where relatively high nutrient concentrations are received from the southward coastal current from the northern basin (Artegiani *et al.*, 1997).

Hydrological characteristics of the Southern region of the Adriatic Sea have already been reported in several papers (Orlić *et al.*, 1992; Artegiani *et al.*, 1997; Malanotte-Rizzoli *et al.*, 1997; Zavatarelli *et al.*, 1998; Manca *et al.*, 2002; Vilibić and Orlić, 2002) and are summarized in Table I.

The general surface circulation of the Adriatic Sea may be described as a large-scale cyclonic meander, with a northerly flow along the eastern coast and a southerly return flow along the Italian peninsula (Orlić *et al.*, 1992). The surface coastal boundary current, which is strongly influenced by the riverine freshwater input, is also called the Western Adriatic Current (WAC). Recent measurements demonstrated that the WAC has a strong time-dependent component which varies in time scales on the order of days due to a mesoscale variability and external forces (Ursella and Gačić, 2001). In the Southern Adriatic, a separate cyclonic gyre exists in the Adriatic circulation, topographically controlled by the South Adriatic Pit and Palagruza Sill (Zore-Armanda, 1969; Manca *et al.*, 1998, 2001).

TABLE I Water-mass definitions.

Sea-water type	*Temperature (°C)*	*Salinity*	*Density (kg m^{-3})*	*Dissolved oxygen (μM)*	*Nitrate (μM)*	*Phosphate (μM)*	*Silicate (μM)*
Adriatic Surface Water (ASW)	<14*	≤38.30*	27.70*	223.2–254.5†	0–2.2.0†	0.01–0.12†	0.4–6.0†
Ionian Surface Water (ISW)	14.2–14.5*	>38.50*	27.50*	196.2–267.9‡	0.1–5.2‡	0.01–0.20‡	1.1–6.2‡
Levantine Intermediate Water (LIW)	14.0*	38.78*	29.12*	223.2–232.1§	1.0–6.0†	0.05–0.22†	2.0–6.5†
Adriatic Deep Water (ADW)	<13.4*	<38.70*	29.19*	223.1–241.1§	(–)	(–)	(–)
Northern Adriatic Deep Water (NAdDW)	9.8–11.4§	38.00–38.58§	>29.2†	236.6–272.3§	0.1–1.6†	0–0.16†	0.4–2.7†
Southern Adriatic Deep Water (SAdDW)	12.7–13.5†	38.52–38.70†	>29.1†	209.8–241§	1.3–5.3†	0.05–0.18†	3.3–8.0†

Note: (–): data not found.
*From Malanotte-Rizzoli *et al.* (1997).
†From Zavatarelli *et al.* (1998).
‡From Socal *et al.* (1999).
§From Vilibić and Orlić (2002).

The South Adriatic cyclonic gyre is also evident in the intermediate layer, where the outgoing vein flows along the western shelf break. In the bottom layer, the outflowing currents are predominant (Orlić *et al.*, 1992).

In 2000 the Interreg Italia–Grecia Project was carried out to assess the quality of the water along the Apulian peninsula between Torre Guaceto (BR) and Porto Cesareo (LE). This project provided an opportunity to improve the knowledge about physical and chemical properties in the Southern Adriatic basin. In fact, most of the studies on these topics in the Adriatic Sea were carried out on the Northern basin. The main objective of this paper is to present the vertical and horizontal patterns of dissolved oxygen and nutrients found during four seasonal surveys, in relation to the hydrographic properties of the water column.

2 MATERIAL AND METHODS

2.1 Study Area and Sampling

In the framework of the activities of the Interreg Italia–Grecia Project, four multidisciplinary surveys were carried out in March, June, September and December 2000 aboard the RV *Coopernaut Franca.* The location of seven transects as sampling stations was selected to monitor the general hydrological characteristics of the Apulia peninsula between Torre Guaceto (BR) and Porto Cesareo (LE) (Fig. 2). The seven transects were coast-open sea oriented and were composed of six stations each: three or four on the shelf, one at the shelf break and one or two along the slope. As a result of bad weather conditions, the March survey was limited to transects T1–T4 and station 48 was not sampled.

The hydrological casts were carried out using a Sea Bird Electronics SBE 9/11 plus probe, with double temperature and conductivity sensors coupled with a Carousel water sampler SBE 32. High-resolution temperature and salinity profiles were collected at each hydrological station. Water samples for chemical analyses were collected from 12 l Niskin bottles.

2.2 Analytical Procedures

Dissolved oxygen was measured aboard the ship using an automated micro-titration procedure (Grasshoff, 1983), following a modified Winkler method. Sub-samples for the determination of nutrients (silicate, phosphate, nitrate plus nitrite) were collected directly from the Niskin bottle, filtered through a 0.7-μm GFF filter and stored at $-30^{\circ}C$ in 50 ml low-density polyethylene containers, prior to analysis. The samples were analysed at the Dipartimento di Chimica e Chimica Industriale of the Università di Genova, using a five-channel continuous flow Technicon® Autoanalyzer II, according to the methods described by Hansen and Grasshoff (1983). The measurement precision was ± 0.05 μM for nitrate + nitrite, ± 0.01 μM for phosphate and ± 0.03 μM for silicic acid. The detection limits were 0.025 μM for nitrate + nitrite, 0.04 μM for phosphate and 0.10 μM for silicic acid.

2.3 Statistical Analysis

The Principal Component Analysis (PCA) is an exploratory data analysis, which, through the calculation of linear combinations of the original variables (principal components), results in a great reduction in the dimensionality of the data. In many cases, a simple plot of the first two principal components shows a high percentage of the total variance of the data set.

Applications of the PCA to marine environmental data have been reported to extract the main patterns of temporal change or geographical variation of the investigated phenomena

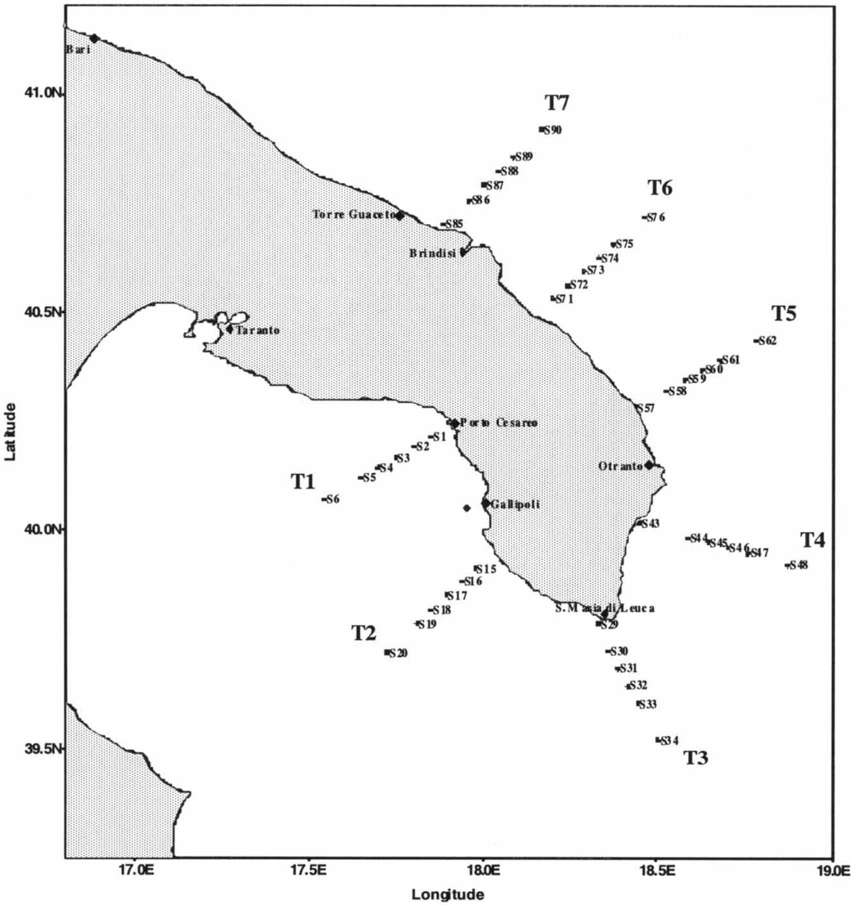


FIGURE 2 Sampling locations of the four seasonal cruises Interreg II Italia–Grecia.

(Meloun *et al.*, 1992; Rivaro *et al.*, 1998; Grotti *et al.*, 1999). In our study, a PCA has been performed on the data matrix composed of 817 objects and seven variables (temperature, salinity, dissolved oxygen, nitrate, nitrite, phosphate and silicate).

3 RESULTS AND DISCUSSION

Figure 3 shows the biplot of PCA that concerns the matrix of our data. Two significant components were identified indicating 36.37 and 20.09% of the total variance. By studying the loadings of the variables on the components, it can be seen that nitrate, silicate and phosphate are highly correlated ($R^2 = 0.71$) and show an inverse correlation with temperature and dissolved oxygen. Surface and sub-surface samples (identifiable in the plot by "a" and "b") are characterized by high values of both temperature and dissolved oxygen and low values of nutrients. Salinity resulted in an inverse correlation to oxygen. A group of objects, formed by samples collected in the most offshore stations at intermediate and near bottom depths (identifiable in the plot by "f" and "k"), are associated with the highest nutrient and salinity values and the lowest oxygen concentrations. The PCA results do not indicate a seasonal trend in our dataset. In addition, the PCA plot does not separate the stations sampled in

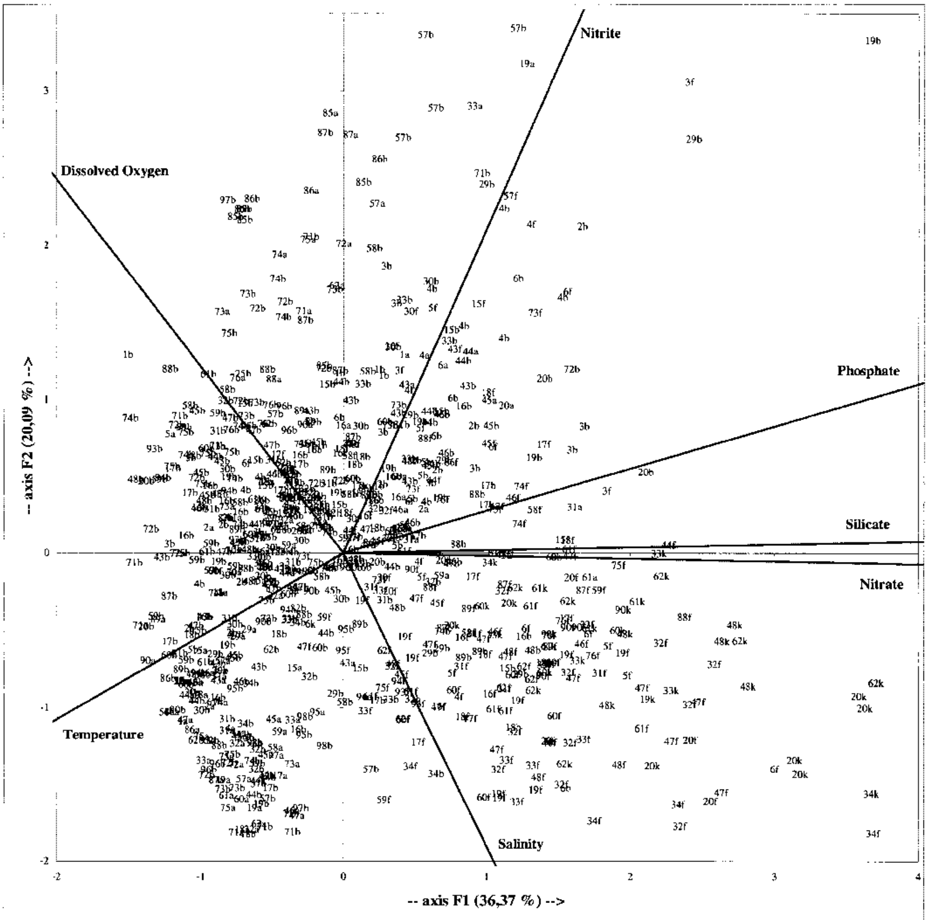


FIGURE 3 Principal-component analysis plot. The following suffixes were used for depths: a: 0–5 m; b: 5–90 m; f: 91–450 m; k: 451 m-bottom.

the Taranto Gulf from those along the Adriatic coast, highlighting that no significant differences occur between the samples in regards to the variables considered.

To describe the general features of the chemical parameters in the studied area, we show selected vertical sections. In particular, results refer to T4 as an example for the general pattern found in the Otranto Strait area, and to T7 as a representative of the Southern Adriatic basin. The patterns of chemical and physical variables are reported for all seasons in the case of T4 and only for June and December for T7.

Vertical sections of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate are reported in Figs. 4–9. The data were interpolated by the kriging method. Figure 4 shows the spring situation found in section T4. The surface temperature shows higher values in the eastern part of the section (14.5°C), where a weak vertical stratification occurred, compared to the shelf area (13.4°C).

The coastal subsurface layer is characterized by the presence of a cold, less saline (38.65) water, identified as SAdDW. Dissolved oxygen concentration (around 240 μM) falls in the range reported in Table I for this water mass, confirming its presence. Moreover this high oxygen content suggests that it was recently ventilated.

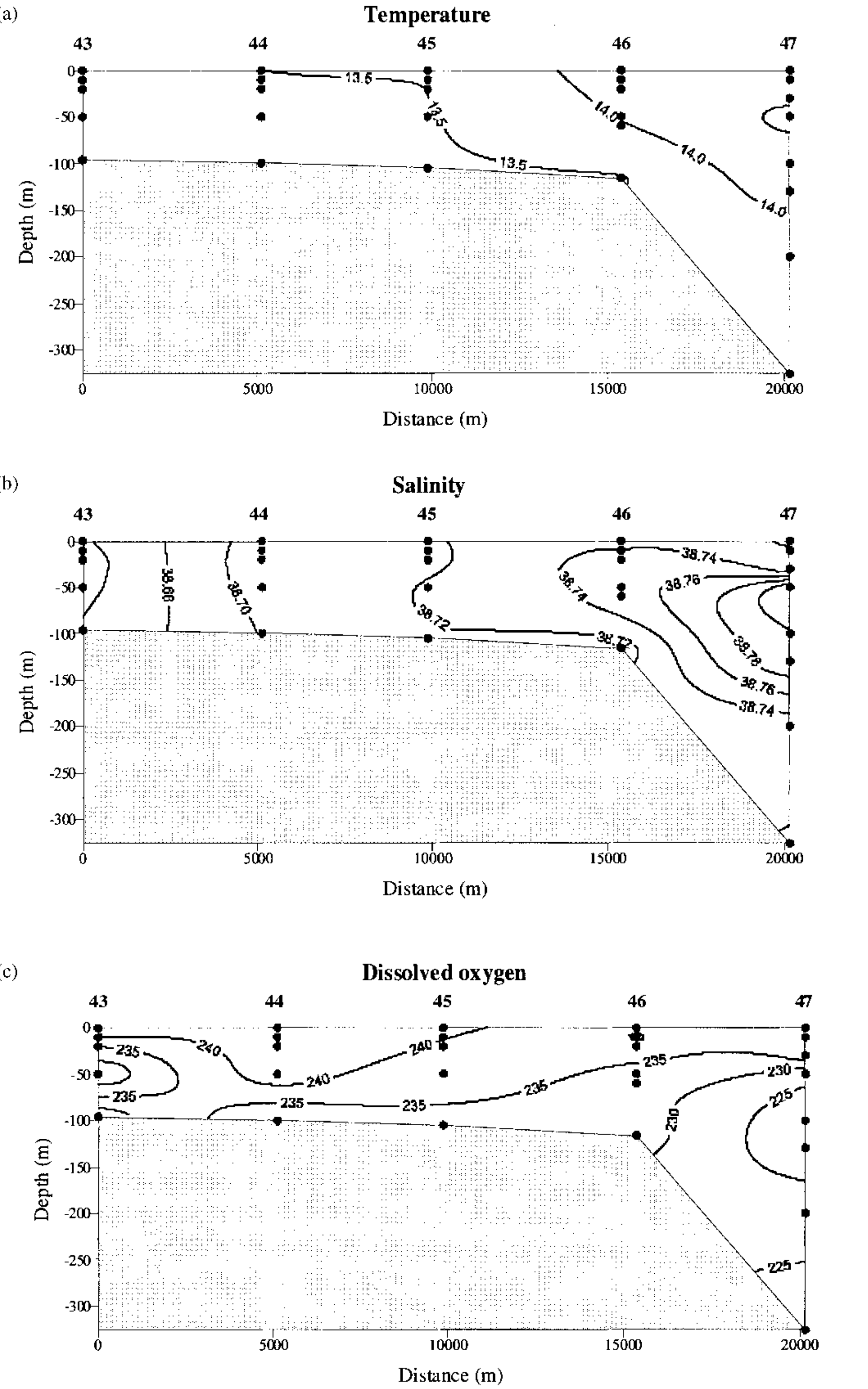


FIGURE 4 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T4-March Survey.

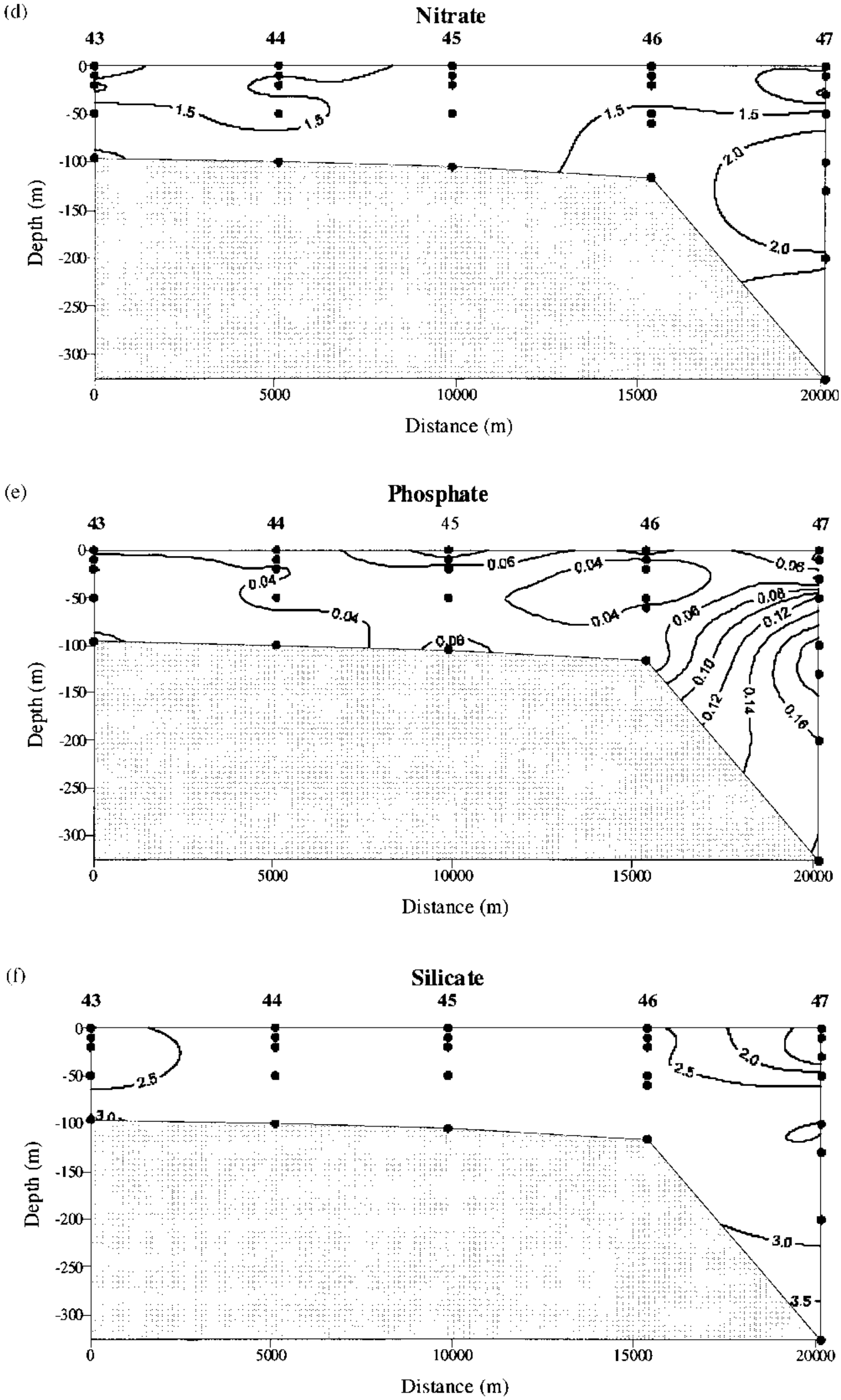


FIGURE 4 Continued.

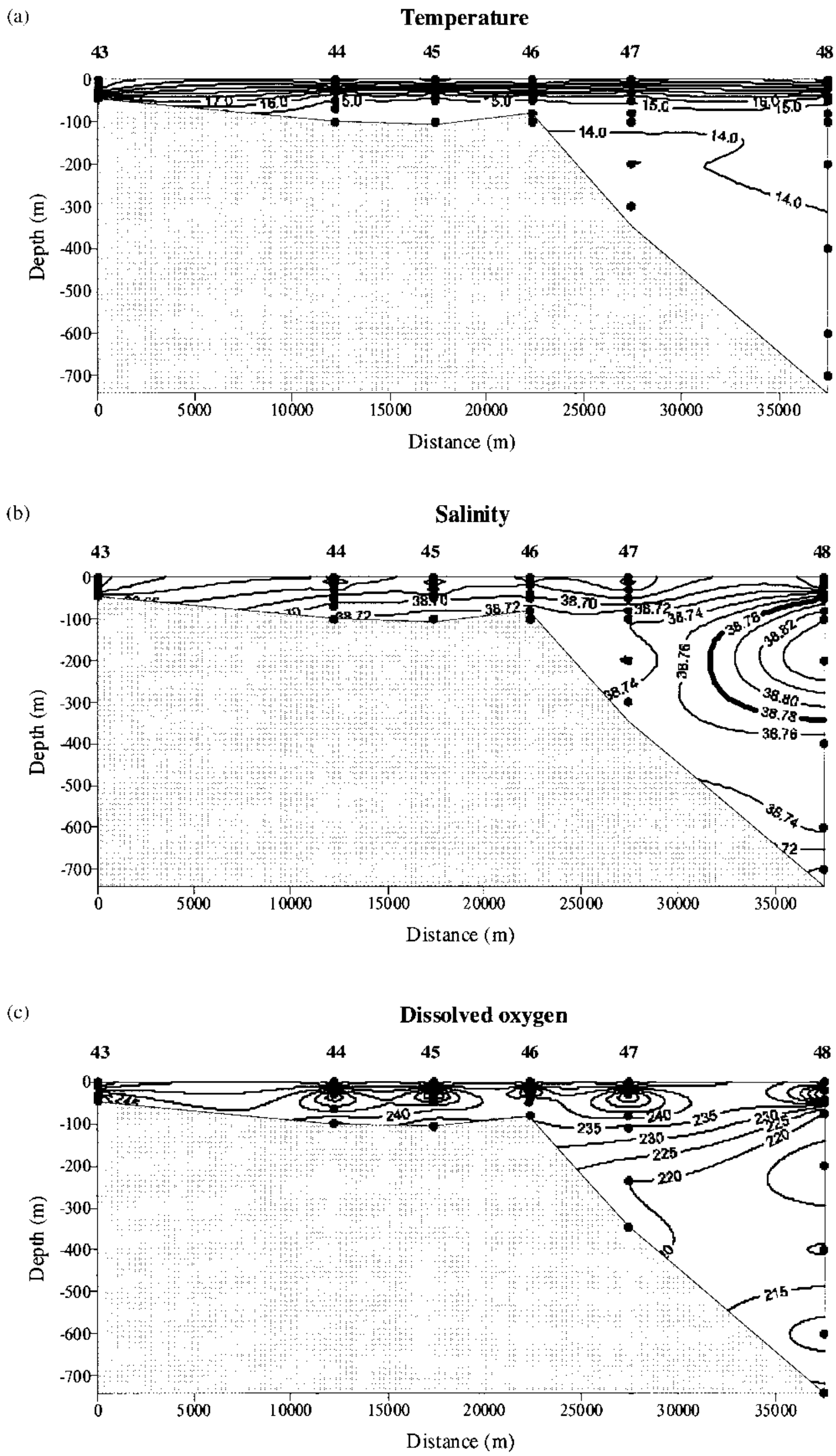


FIGURE 5 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T4-June Survey.

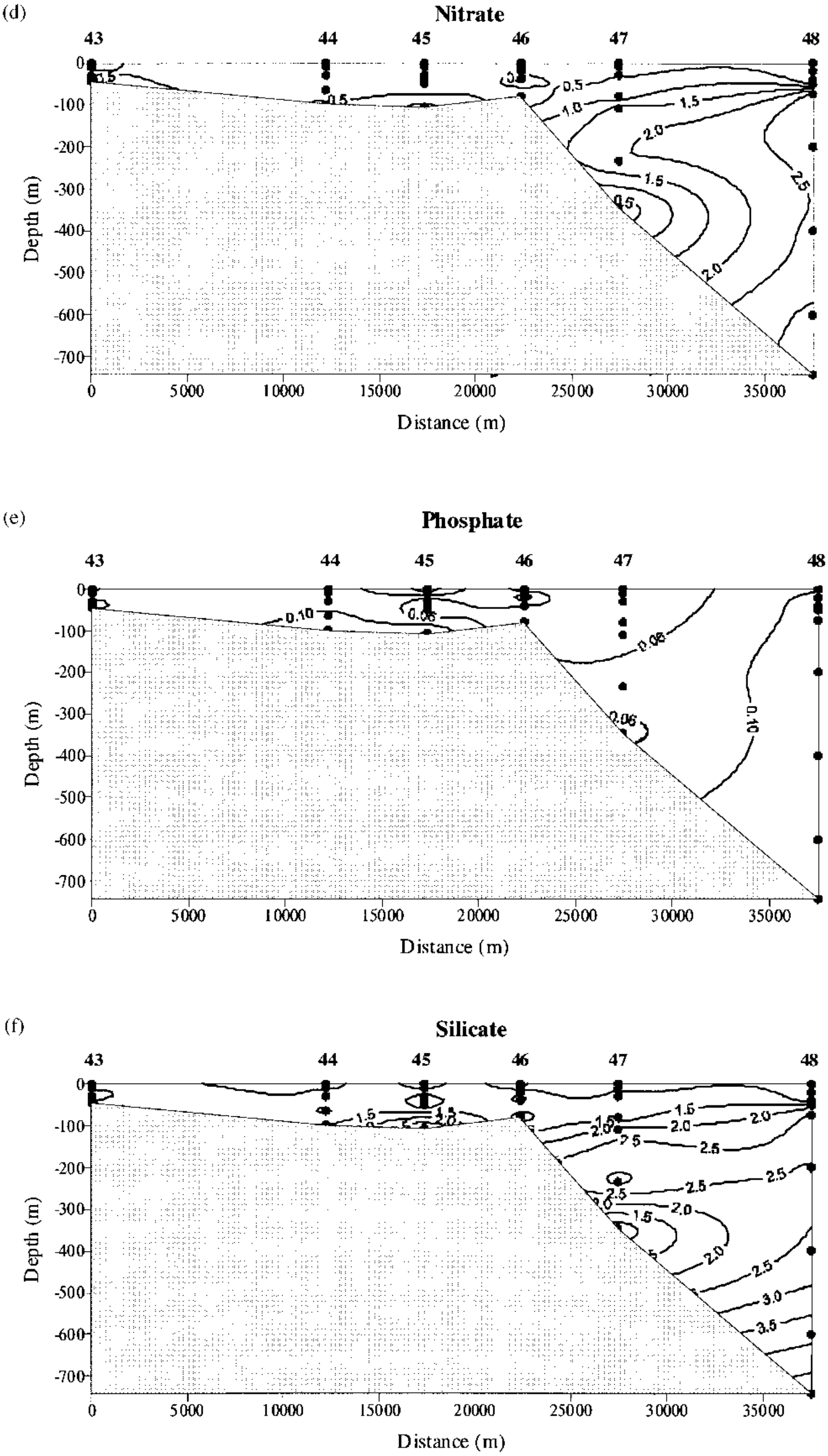


FIGURE 5 Continued.

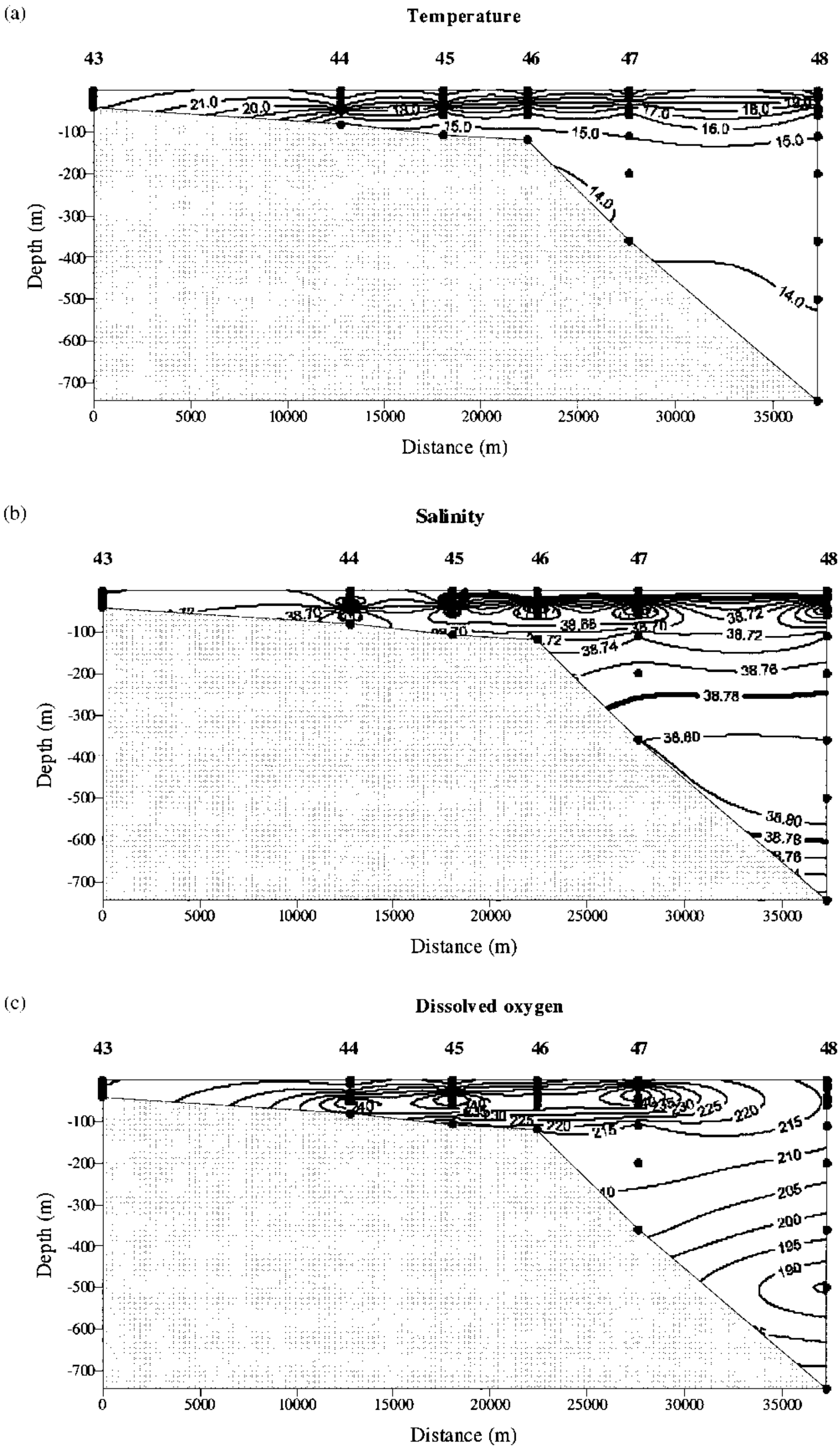
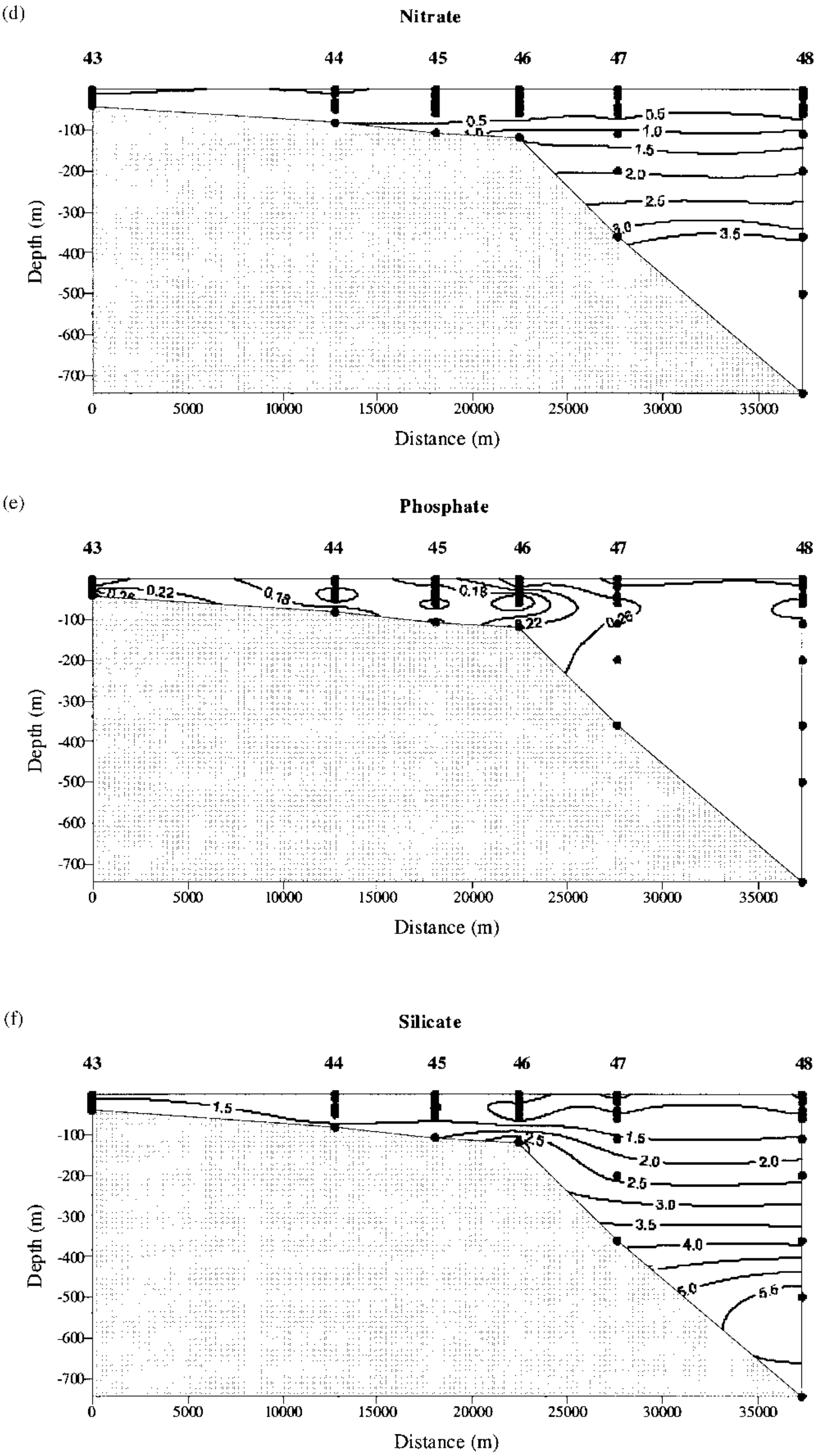


FIGURE 6 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T4-September Survey.



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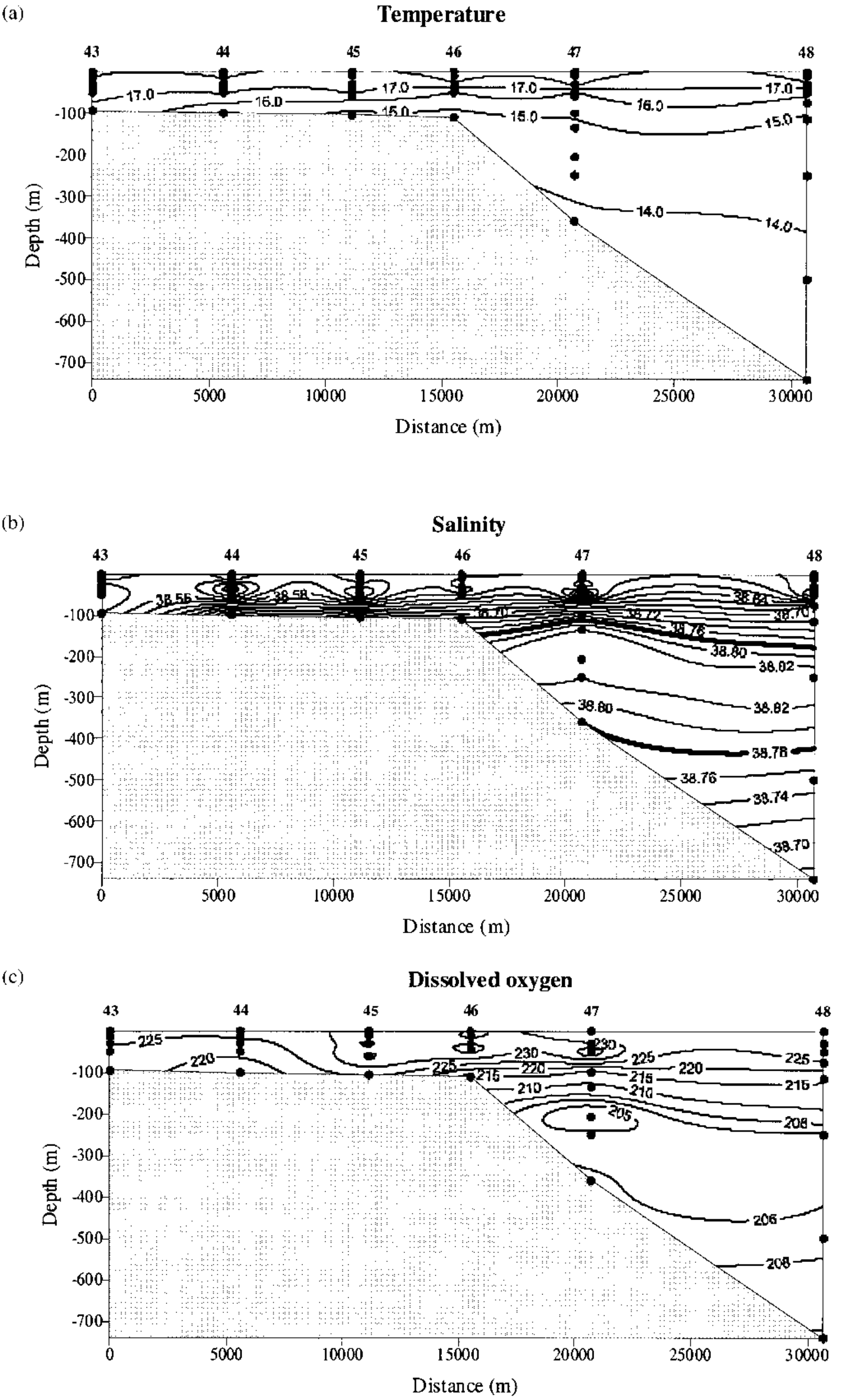


FIGURE 7 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T4-December Survey.

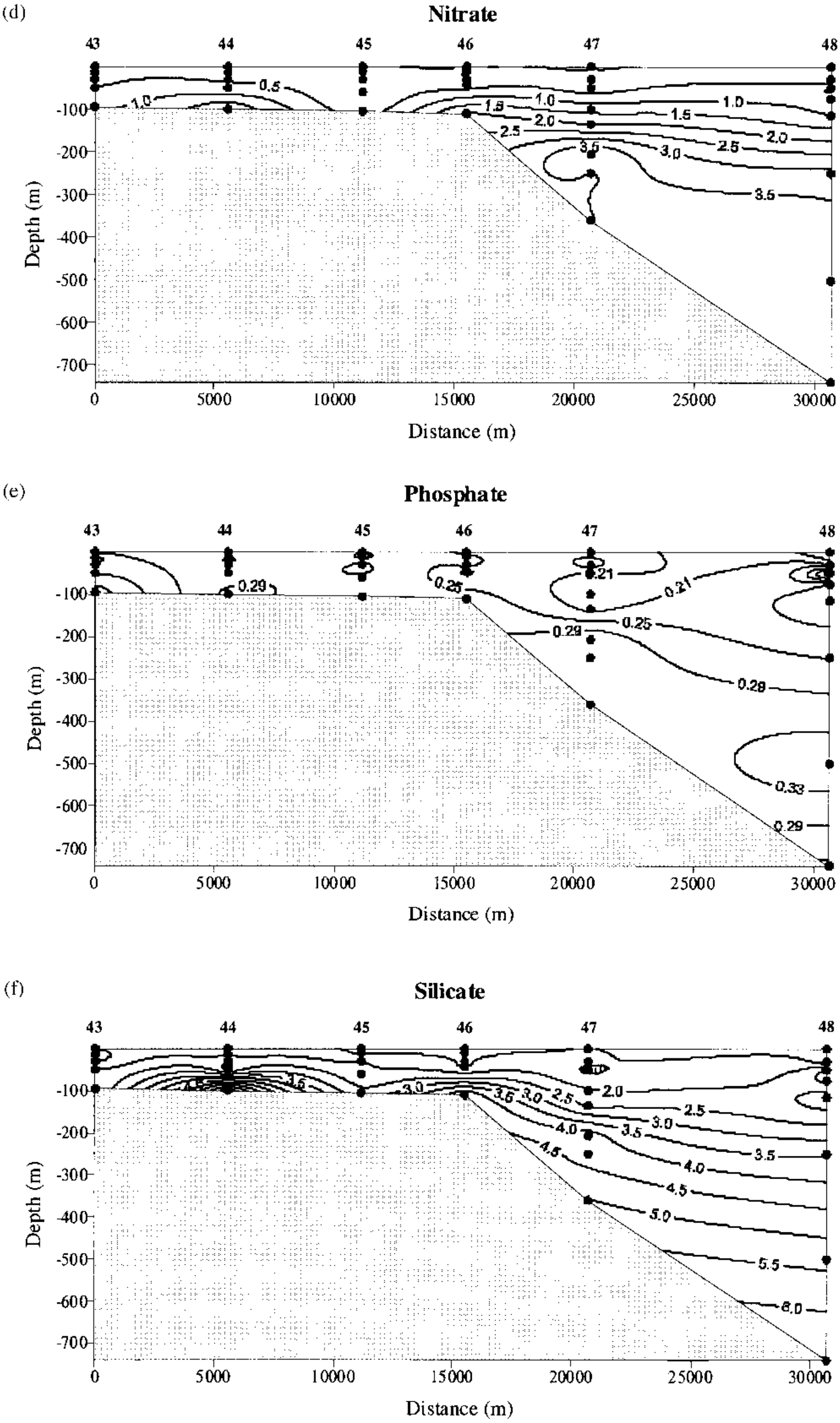


FIGURE 7 Continued.

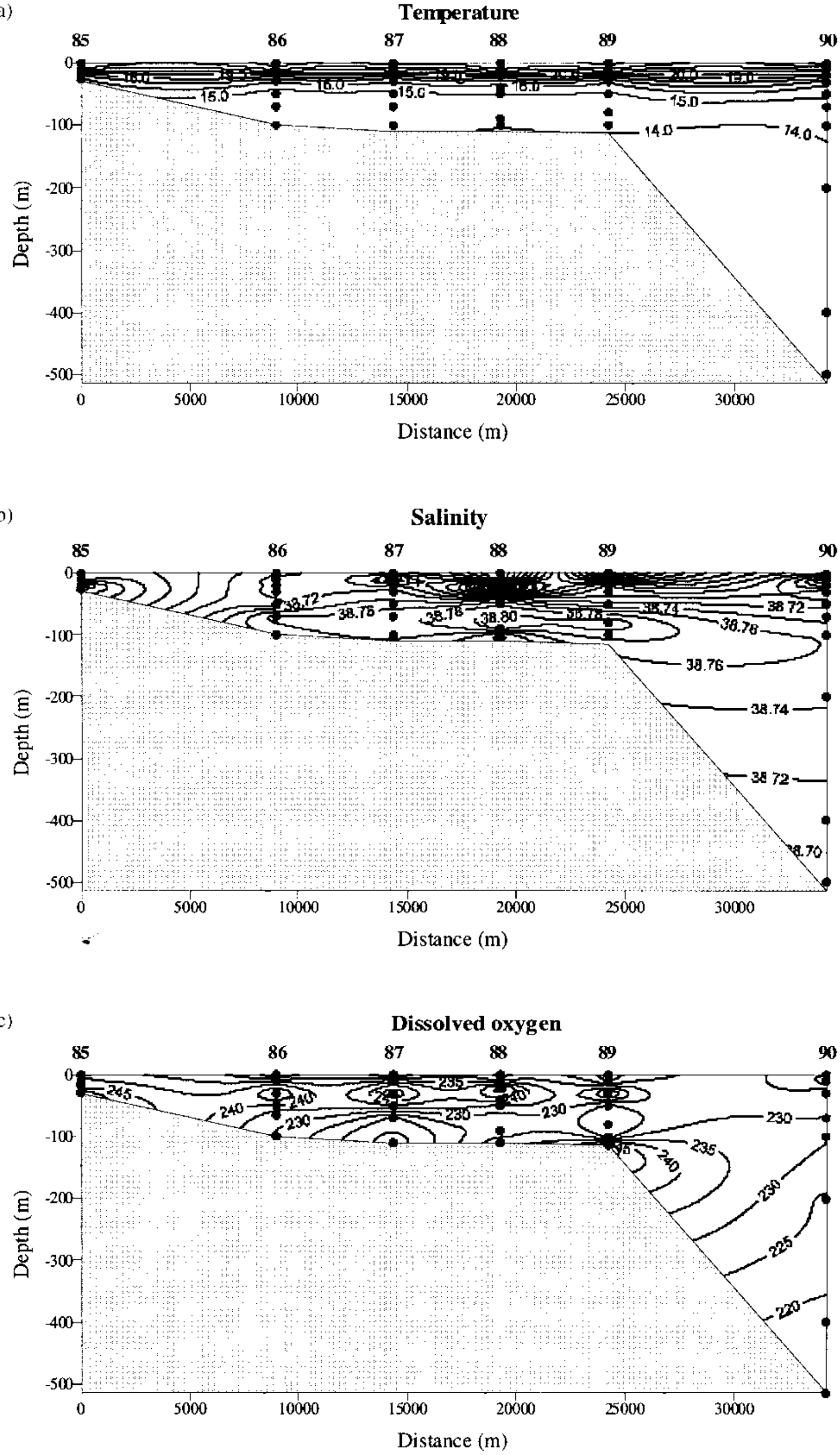


FIGURE 8 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T7-June Survey.

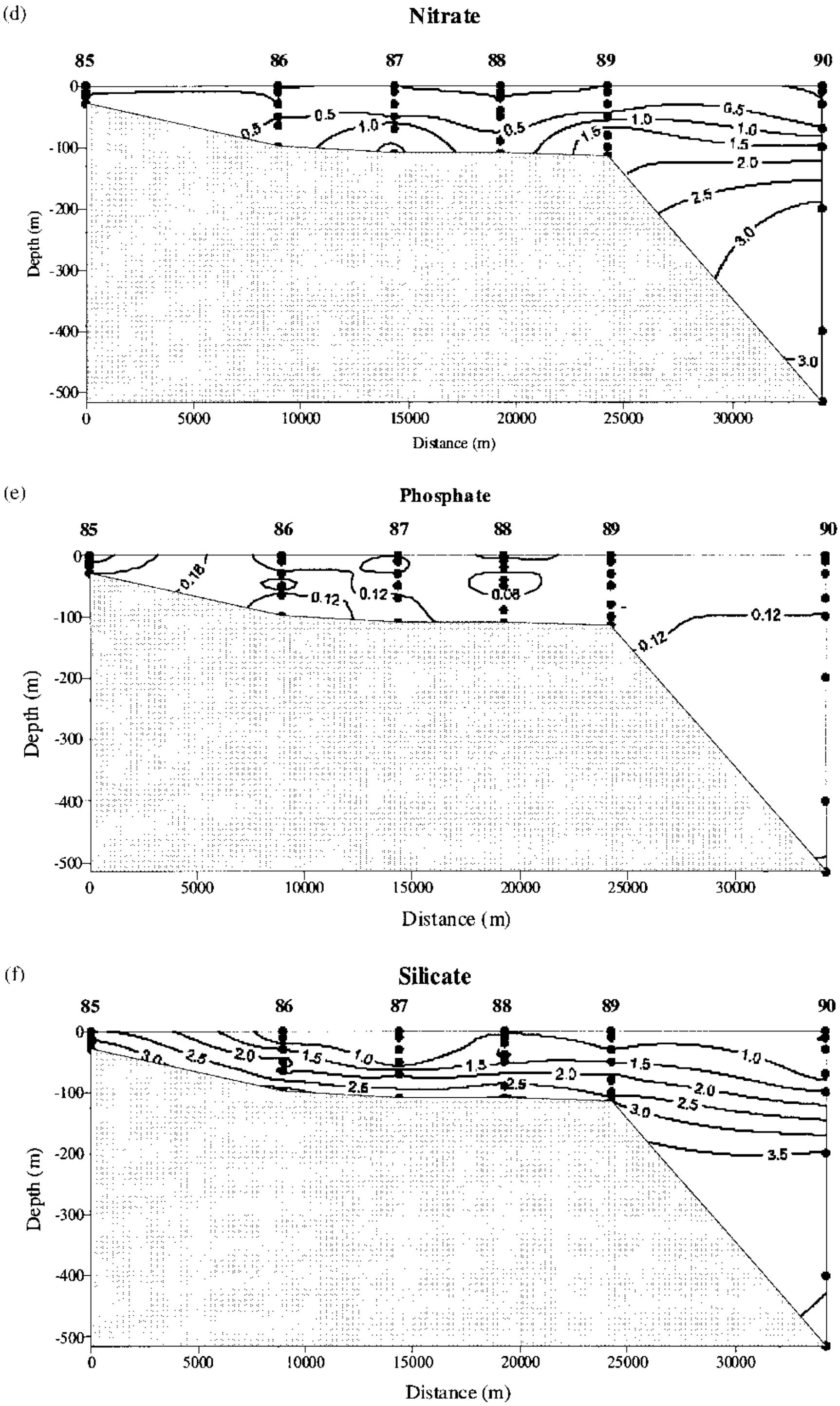


FIGURE 8 Continued.

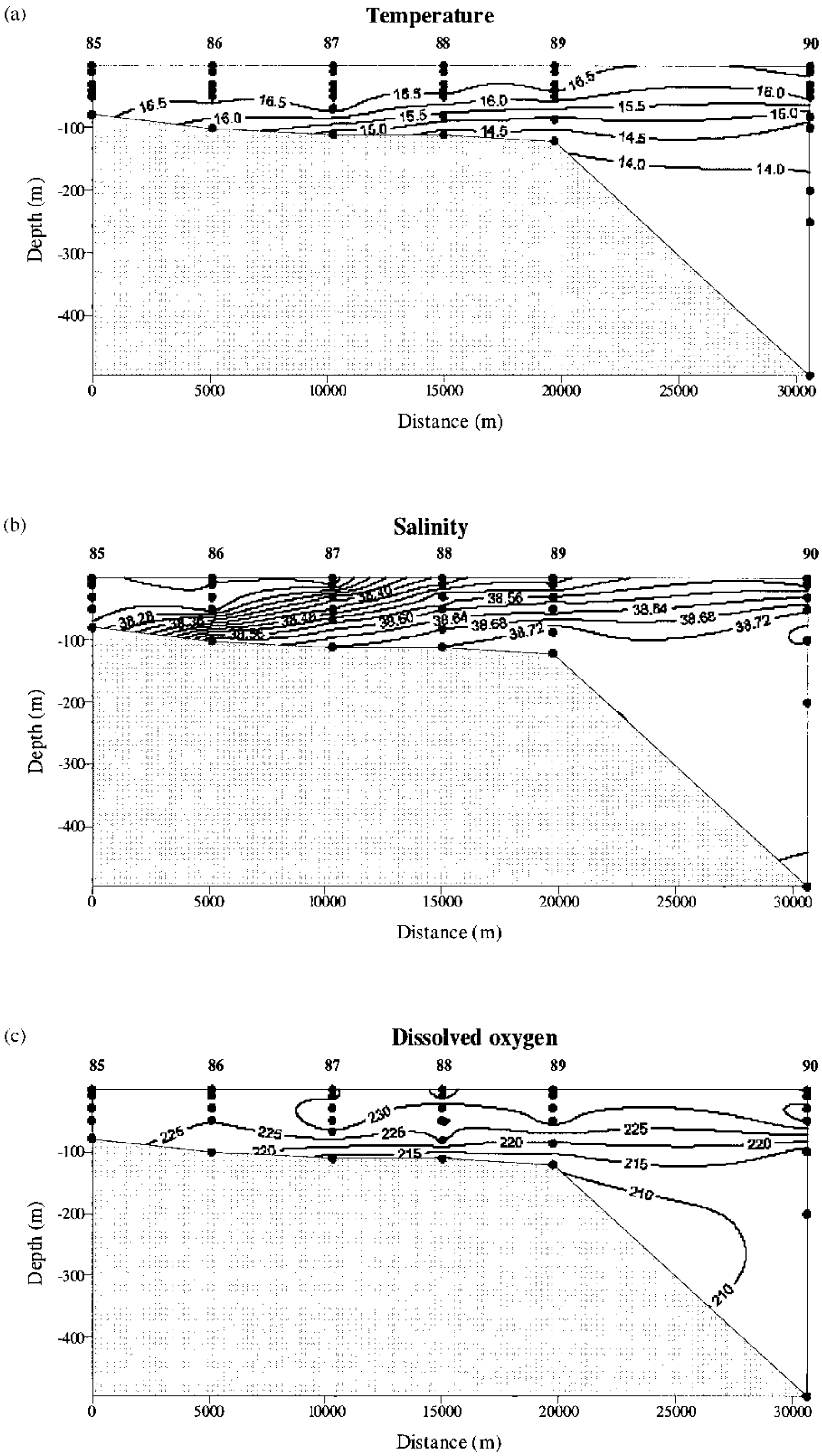


FIGURE 9 Vertical distribution of: (a) temperature (°C); (b) salinity; (c) dissolved oxygen (μM); (d) nitrate (μM); (e) phosphate (μM); (f) silicate (μM) along the section T7-December Survey.

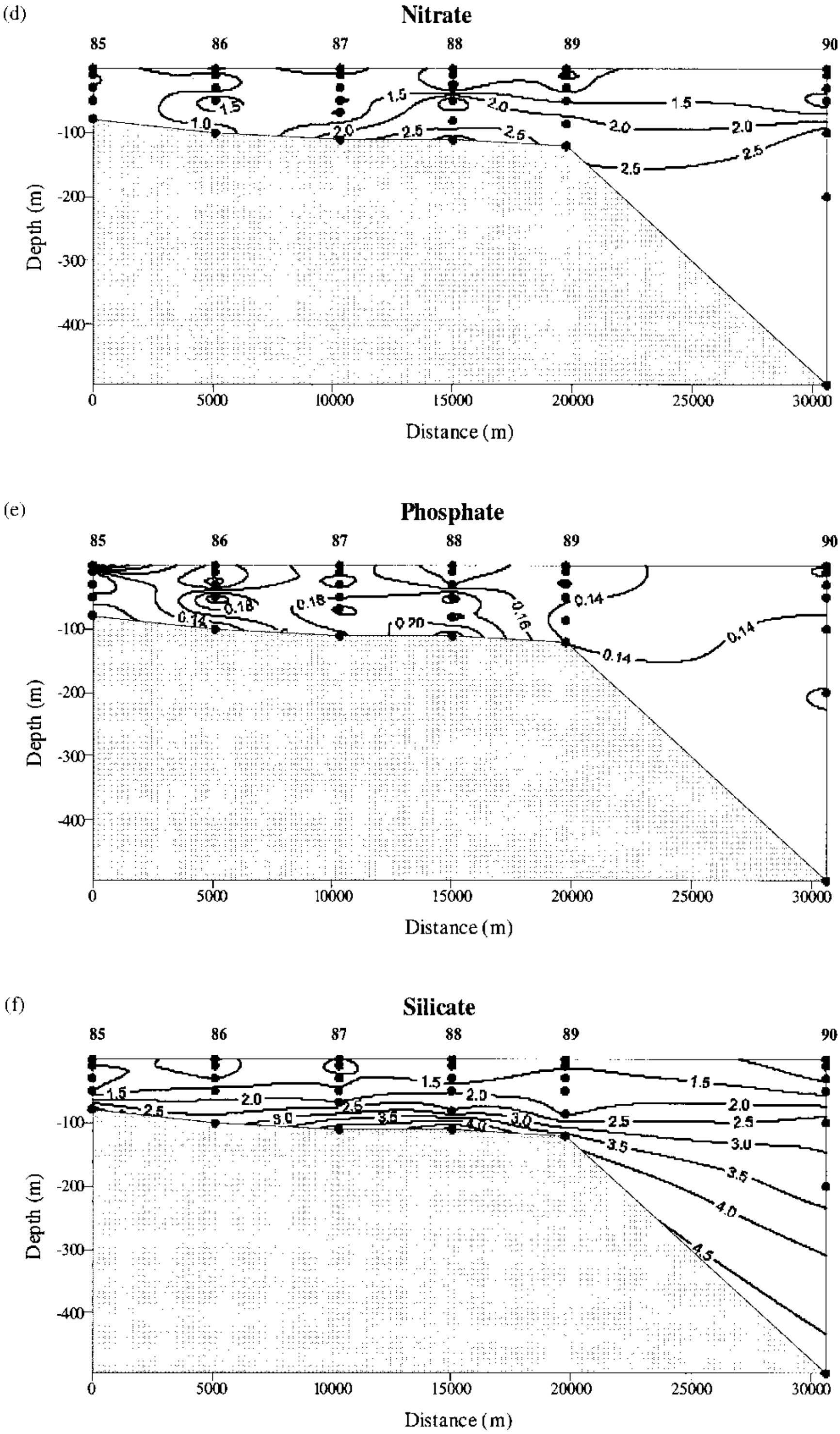


FIGURE 9 Continued.

At station 47, where the water temperature was higher, the surface concentration of dissolved oxygen fell to 230 μM. The minimum (206 μM), with a saturation of 81%, was observed where a core of high-salinity water (38.80) was found at intermediate depths (100 m). With regard to nutrients, it can be seen that they present a homogeneous distribution in the shelf area, whilst concentrations increase with depth on the slope. In particular, nitrate and phosphate reach 2.5 and 0.19 μM, respectively, in the high-salinity core (Fig. 5 shows vertical distributions of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate at section T4 in June).

Thermal stratification is well established, with surface values around 23.0°C; the thermocline is settled around 20 m, and below it the temperature profile is homogeneous, around 14.0°C. Salinity measurements indicate a core ≥38.80 well established off the continental slope between stations 47 and 48 at intermediate depths.

Surface waters were slightly oversaturated with dissolved oxygen (102–109%). The vertical oxygen distribution displays a distinct subsurface maximum (around 260 μM with a saturation of 117%) at 30–40 m depth, and a minimum at the intermediate and bottom depths of station 48 (210 μM as the mean value, with a saturation of 83%).

Low levels of silicate and nitrate, which in some cases fall below the detection limit, are observable in the shelf area along the whole water column. An increase occurs below 100 m at stations 47 and 48, where their concentrations rise to 3.0 μM in correspondence with the salinity maximum and the oxygen minimum. Phosphate increases at station 48 and a second relative maximum can be observed at stations 44 and 45 near the bottom. In any case, phosphate concentrations are always below 0.13 μM.

Figure 6 represents the distribution of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate of section T4 found during the September survey. Thermal stratification is still present, with surface values around 22.0°C. Below the thermocline, settled around 50 m, the water temperature is homogeneous, around 14.0°C. The salinity profile shows the highest values at depths between 200 and 600 m in slope stations.

Dissolved oxygen content reaches its maximum (around 250 μM) at subsurface depths, while surface and bottom values range between 185 and 220 μM. The nitrate concentration is close to the detection limit above 100 m in the whole section, while below this depth values increase, reaching the maximum (3.6 μM) in the bottom waters. This pattern is particularly evident for eastern stations; while in the shelf area the water column is characterized by very low concentrations at every depth. Phosphates are always below 0.32 μM with the highest values found at intermediate depths. The silicate profile shows a surface-to-bottom positive gradient along the whole transect. The concentrations reach values ≥5.6 μM close to the bottom in station 48.

Figure 7 shows the distribution of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate in winter. The water column stratification persists in this survey too, with surface temperatures around 18°C. Salinity also shows a stratified structure with a high-salinity core (≥38.8) between 200 and 300 m in the eastern stations (47 and 48).

Dissolved oxygen concentrations reach maximum values (around 235 μM) between the surface and 50 m, while minimum values (around 203 μM) can be observed where the high-salinity core is present. Nutrient profiles show a surface-to-bottom positive gradient. With regard to nitrate, this pattern is much more evident for eastern stations, where concentrations rise from 0.5 μM at the surface to 3.6 μM at the bottom. Silicate concentrations range between 1.0 and 6.6 μM in surface waters.

Phosphate concentrations are homogeneous in the water column in shelf stations. However, in the eastern stations maximum values (around 0.3 μM) can be observed at intermediate depths (200–500 m).

The vertical distributions of thermohaline and chemical properties in the sub-picnocline layers therefore show evidence of the inflow of Levantine Intermediate Water in the eastern part of this section. As previously observed by Manca *et al.* (2001), the lateral extension of LIW presents a seasonal variability, being more extensive in summer and autumn. During these seasons, a maximum salinity was observed in its core. The LIW core appears with a maximum salinity ($\geq$38.75) at depths between 200 and 300 m, reaching the western continental slope. In addition, the presence of canyons in this part of the investigated area can force the LIW to depths around 150 m. LIW is characterized by low dissolved oxygen and high nutrient concentrations, which reflect biological degradation processes.

Previous studies reported this feature also in relation to the bacterial oxidation of the organic matter sinking out of the euphotic zone that could modulate the nutrient concentration (Zavatarelli *et al.*, 1998). For this reason, it was suggested also that LIW could represent a nutrient source for the Southern Adriatic basin. Nevertheless, in the area investigated in this study, LIW does not seem to be a source of nutrients for the phytoplanktonic population, because it is held only at intermediate depths off the continental slope, persisting the stratification of the water column.

The same consideration can apply to silicate, the maximum layer occurring below the LIW depth, as already observed by Gacic *et al.* (1999) (the distribution of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate along the section T7 in the June survey is shown in Fig. 8). Thermal stratification is well established, with surface values around 23.0°C; the thermocline settled around 20 m, below which the temperature is homogeneous, around 14.0°C. The salinity ranges between 38.72 and 38.76, with the only exception in station 85, where values around 38.63 were measured. This could be related to the freshening of waters caused by the Torre Guaceto coastal springs. Surface waters were slightly oversaturated with dissolved oxygen (102–113%).

The vertical oxygen distribution displays a distinct subsurface maximum (around 250 μM) at depths between 30 and 40 m that were apparent in the shelf area, with a maximum saturation value of 136%. With the exception of station 85, the stations located within the shelf area show low levels of nitrate at every depth. These fall below the detection limit at those depths where the oxygen maximum was measured. In the offshore stations, the concentrations of nitrate and silicate increase to 3.0 and 3.5 μM, respectively, below 100 m. Phosphate concentrations are always below 0.16 μM, except in station 85.

Temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate profiles in the same section found during the winter survey are shown in Fig. 9. Thermal stratification persists in the water column, particularly in eastern stations with surface values around 16.5°C, but below 100 m the temperature falls to 14.0°C. In station 85, this pattern cannot be observed because the water column temperature is homogeneous.

Salinity displays a stratified water column, with values ranging from 38.60 to 38.74 in station 89 and 90, whilst a frontal zone separates the fresher water found near the coast. All chemical parameters, except phosphate, present a stratified profile; dissolved oxygen reaches 230 μM in surface waters, while at bottom depths values fall to 215 μM.

Nitrate and silicate profiles show a surface-to-bottom positive gradient. With regard to nitrate, this pattern is much more evident for eastern stations, where surface concentrations are about 0.5 μM, and bottom values are close to 3.0 μM. Silicate concentrations fluctuate between 1.0 μM in surface waters and 4.5 μM close to the bottom.

Considering the reported sections, in particular, concerning the intermediate layer, the LIW core is evident only in the Otranto Strait transect, while the signature of this water mass in terms of both salinity maximum and oxygen minimum is lost in T7. The LIW intrusion also influenced the nitrate and silicate concentrations in the bottom layers, which resulted in higher concentrations in the southernmost transect. In the surface layer, on the contrary, the highest nitrate concentrations can be observed in T7, in which the influence of waters coming from the Northern Adriatic basin is stronger.

In the studied area, the thermal stratification persists in all seasons, except in spring, when vertical homogenization was found in the shallowest station. The halocline is present throughout the year. Surface temperature and salinity showed a west–east gradient in winter and spring. The western side of the sections was composed of fresher and colder waters than the eastern side, thus allowing the differentiation between the Adriatic Surface Water and the warmer and more saline Ionian Surface Water. In summer and autumn, these horizontal gradients were not evident, with the values being more homogeneous.

The oxygen concentrations did not show any marked seasonal variations in the studied area, in contrast to what was observed by other authors (Zavatarelli *et al.*, 1998). The surface layer is characterized by high dissolved oxygen concentrations and low nutrient contents. As a result of the warming of the surface layer, lower concentrations of dissolved oxygen were observed in summer than in winter.

With regard to the spatial distribution of dissolved oxygen, the highest surface levels were recorded in March in the more coastal stations, where temperature and salinity were lower than in the offshore stations. In September and December, the opposite occurred in the northern part of the investigated area, where the offshore waters were richer in oxygen. The surface distribution of dissolved oxygen was affected by the presence of a cyclonic gyre (Fig. 10a).

Figure 10b shows the spatial oxygen distribution observed in September at the 40 m layer. It can be seen that the range of this parameter in the Southern Adriatic basin and the Otranto Strait was wider and higher than in the Taranto Gulf.

In summer and autumn, the subsurface layer conserves high winter concentrations of oxygen, showing a maximum at about 40 m with a saturation of 110% as a mean value. Its presence can be attributed principally to both the warming of surface waters and a deep Chlorophyll Maximum Layer, situated at the same depth (Fiocca *et al.*, 2002). This feature has previously been reported by Civitarese *et al.* (1998) and Zavatarelli *et al.* (1998), but it was observed in spring and summer, with a saturation reaching 121%.

At bottom depths, the concentrations ranged between 210 and 225 μM (Fig. 10c), with a tongue of water richer in oxygen observed in the northern part of the investigated area. On the contrary, the most offshore stations sampled in the Otranto Strait area had the lowest oxygen concentrations because of the intruding LIW, as previously indicated.

The PCA plot highlights that no strong seasonal variations were observed in terms of oxygen content representing December distributions, as shown in Fig. 11. The only significant difference relates to the subsurface layer, where no increase was recorded due to phytoplanktonic activity and a decreasing coast–offshore gradient being well defined in the whole area (Fig. 11b). Bottom layers in the shelf area are well oxygenated in both the Ionian and Adriatic areas (Fig. 11c). This feature is important considering the role of Adriatic Deep Water in ventilating the Eastern Mediterranean.

The surface layer resulted in generally poor levels of nutrients. In fact, it was only in March, when a homogeneous distribution of chemical parameters in the water column was observed, that nutrients surface concentrations showed fairly high concentrations. Surface nitrate concentrations, for example, which were always <0.5 μM, reached 1–1.5 μM in March; these results agree with data reported for this area by Zavatarelli (1998) and Fiocca (1998a, 1998b). Silicate surface concentrations showed the highest concentrations (2.5–2.8 μM) in winter, while the phosphate surface content was near the detection limit in every season. This pattern could be caused by thermal stratification of the water column, basically present all year long. This does not allow mixing processes between the intermediate and bottom layers, which are richer in nutrients because of re-mineralization processes.

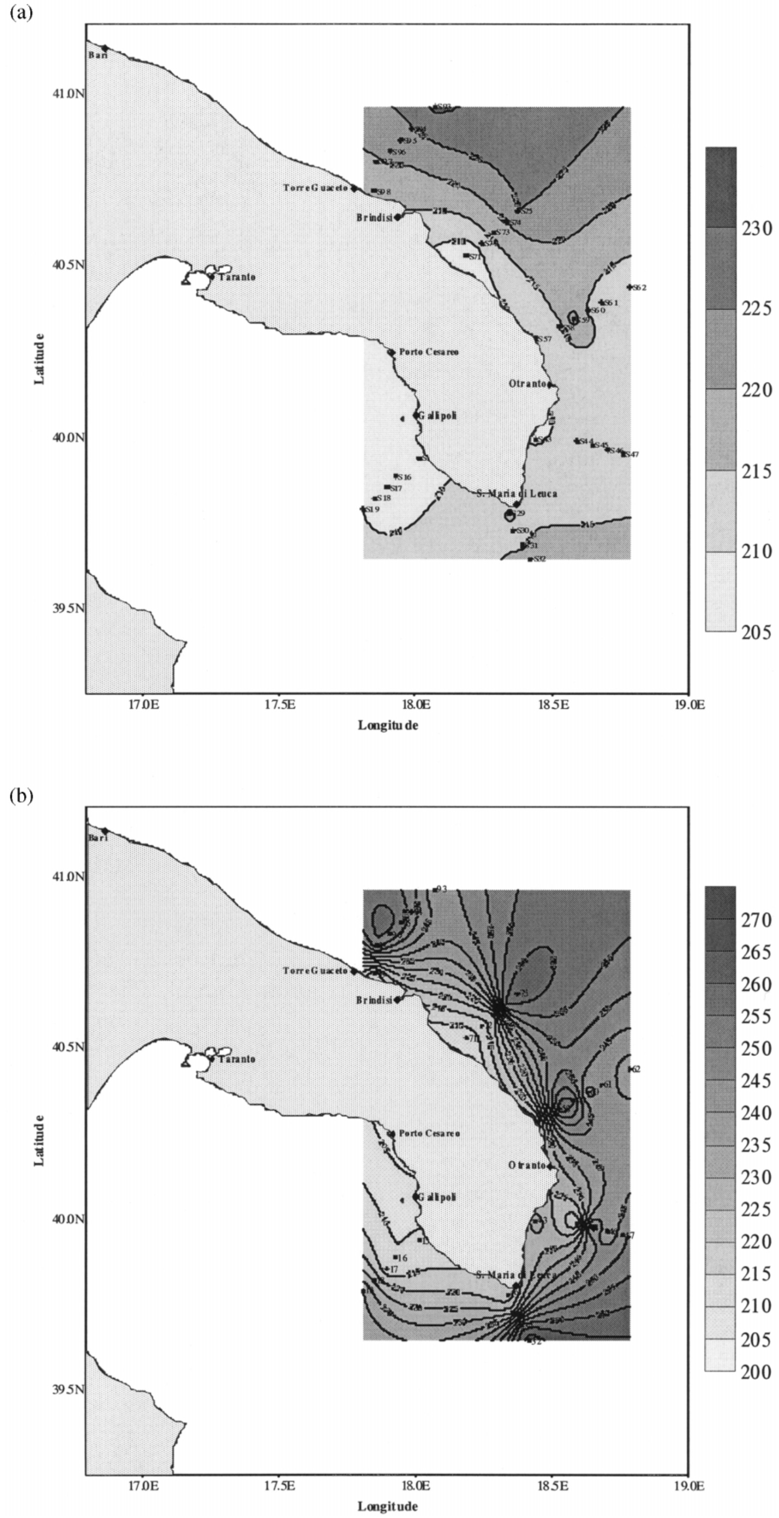


FIGURE 10 September distribution of: dissolved oxygen (μM) at: (a) surface layer (2 m); (b) sub-surface layer (40 m); (c) bottom layer.

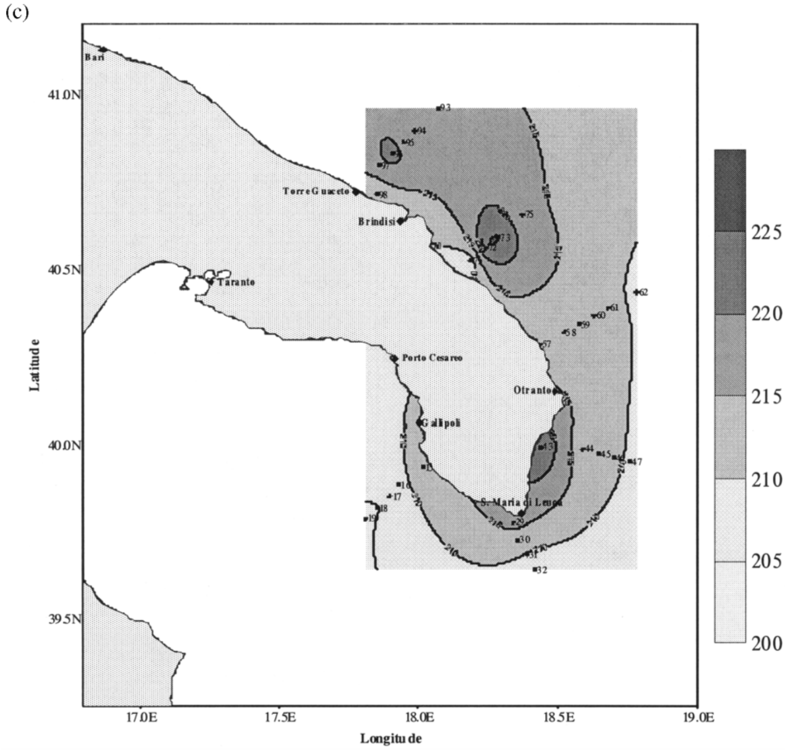


FIGURE 10 Continued.

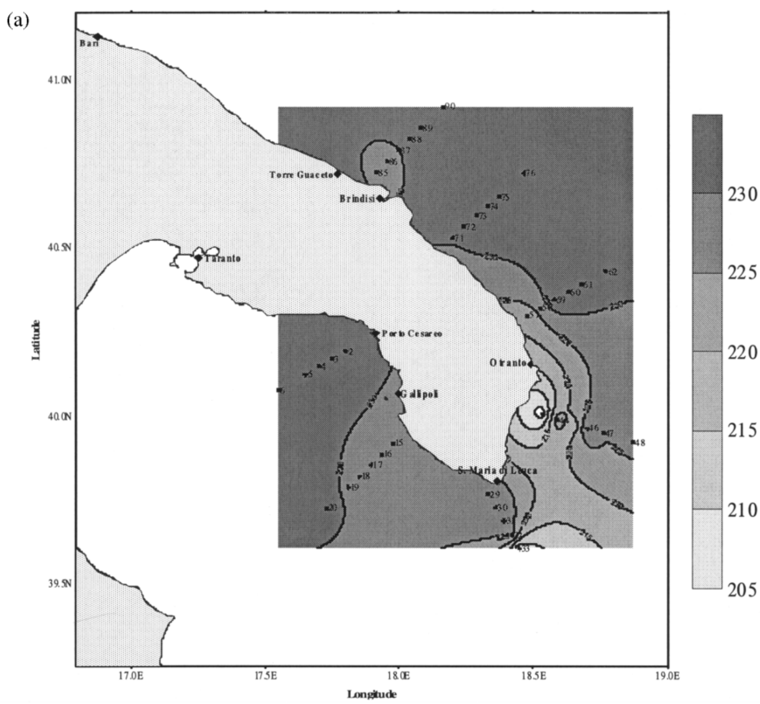
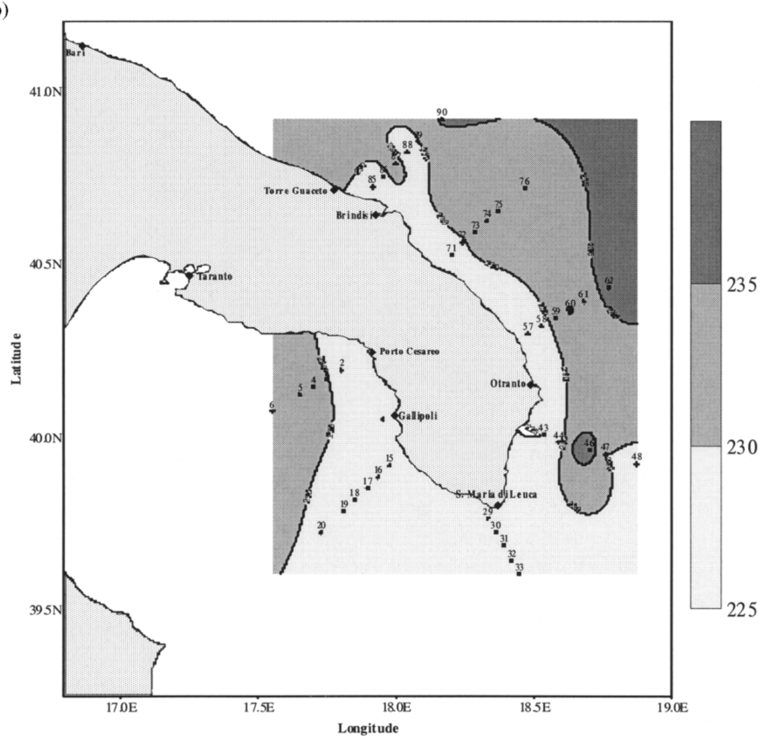


FIGURE 11 December distribution of: dissolved oxygen (μM) at: (a) surface layer (2 m); (b) sub-surface layer (40 m); (c) bottom layer.

(b)



(c)

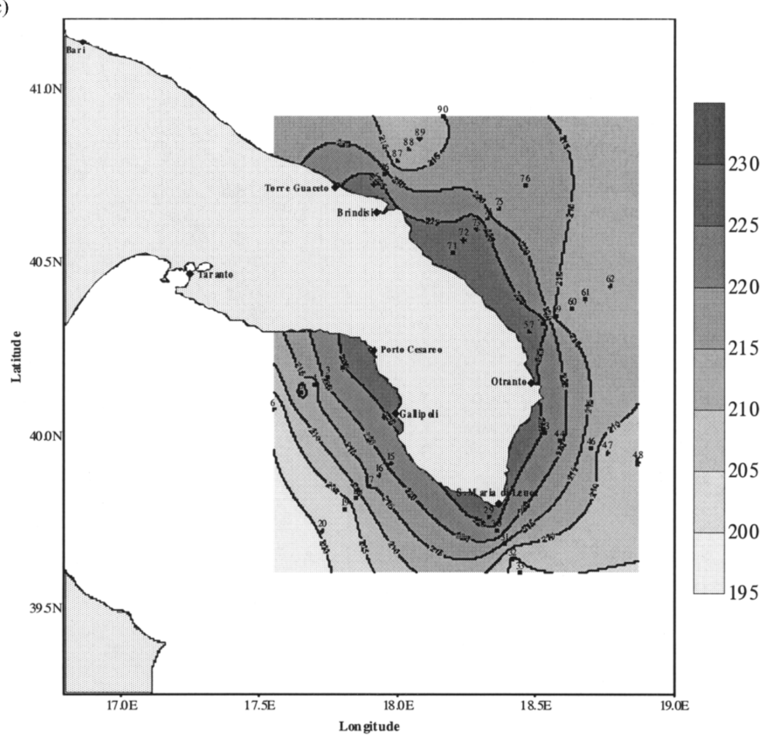


FIGURE 11 Continued.

The low concentrations of silicate may be related to a diatom population control of this nutrient. In fact, many authors report that diatoms, which are the most numerous component of microphytoplankton, are abundant in this area (Viličić *et al.*, 1995; Socal *et al.*, 1999).

In September, silicate surface data showed a gradient from about 2.0 μM to less than 1.0 μM moving from coast to open sea (Fig. 12). This pattern agrees with chlorophyll measurements carried out in the same period (Fiocca *et al.*, 2002), thus proving the influence of diatoms in controlling the concentrations of silicate.

In any case, seasonal variations in nutrient concentrations in the surface waters decreased in the Southern Adriatic sub-basin with respect to the northern and central sub-basins. This is due to the lack of major river inputs, apart from Otranto, discharging into the Adriatic Sea near Bari. Nevertheless, with regard to spatial distribution in the surface layer, nitrate exhibited a north–south declining concentration gradient, as shown in Fig. 13a.

In the deep waters, nitrate distribution shows an increasing gradient moving from the coast to the open sea. The lowest concentrations are evident in the shelf area and the highest in the most offshore stations of the Otranto Strait (Fig. 13b). Apart from mineralization processes, this pattern can be influenced by both the intrusion of LIW on the slope and the outflow of SAdDW in shelf area. In fact, the mean values of nitrate and silicate in our study were in agreement with those reported for these water masses in Table I, thus sustaining this hypothesis.

With regard to the N:P ratio, the calculated values fall between 15 and 70 in spring, which is in agreement with those reported by other authors for this area (Civitarese *et al.*, 1998; Socal *et al.*, 1999). In particular, the highest values were found in the shelf area corresponding to the intermediate and bottom depths in station 43, as shown in Fig. 14a. Hydrological characterization indicated the presence of SAdDW at the same depths.

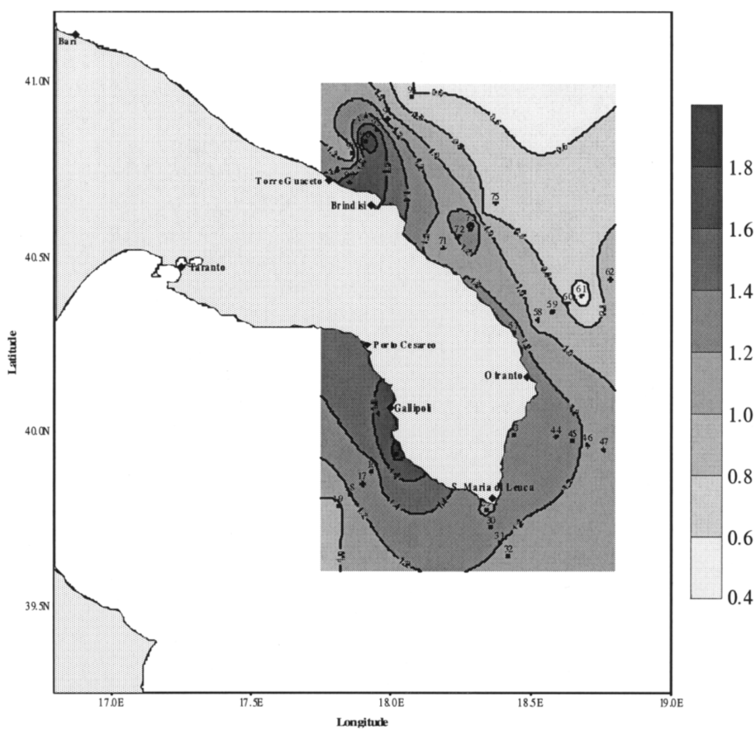


FIGURE 12 September silicate surface distribution (μM).

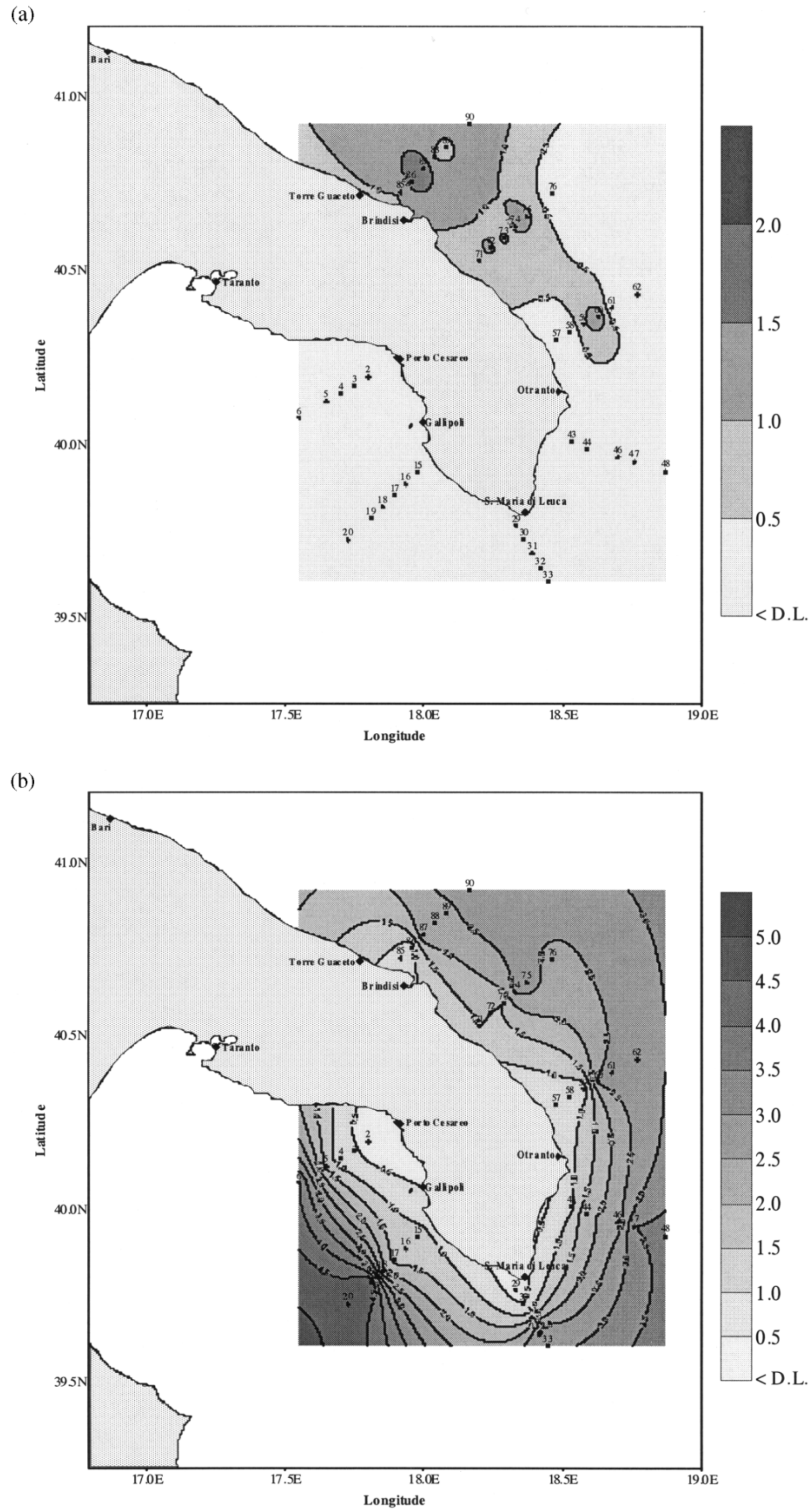


FIGURE 13 December nitrate distribution (μM) at: (a) surface layer (2 m); (b) bottom layer.

The same phenomenon was observed by Civitarese also, who reported an increase in the N:P ratio in the area occupied by the NAdDW outflows. The cause for this wide ratio is not clear and various theories have been put forward to explain it (Civitarese *et al.*, 1998; Kress and Herut, 2001). In any case, because of the wide N:P ratio, the productivity in the area can be thought to be P-limited, in contrast to the N limitation found in most of the world's oceans (Kress *et al.*, 2001). The pattern of N:P distribution along the transect shows a lenses distribution, probably influenced by the cyclonic circulation.

A different feature was found in winter, as shown in Fig. 14b, when the N:P ratios were lower than the standard value of 16:1 and a stratified distribution was observed. Zavatarelli *et al.* (1998) also reported a similar distribution with the highest values in the deep waters. This characteristic can be due to both surface nutrient (particularly nitrogen forms) depletion and deep-water mineralization processes starting at the end of the summer.

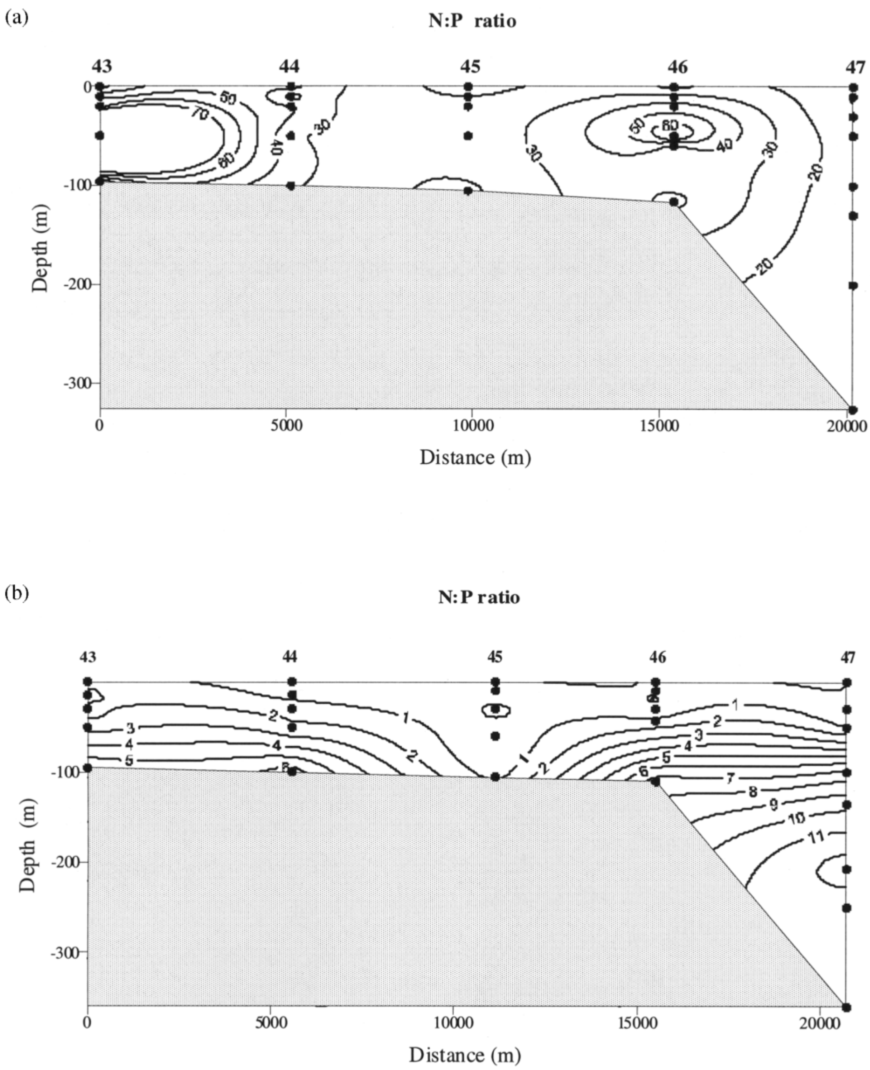


FIGURE 14 Vertical distribution of N:P ratio in section T4: (a) March Survey; (b) December Survey.

4 CONCLUSION

The multivariate analysis applied to our dataset allowed us to conclude that a seasonal trend was not observable in the investigated period. In addition, no significant differences with regard to the considerate variables (temperature, salinity, dissolved oxygen and nutrients) were found between the stations sampled in the Taranto Gulf and those along the Adriatic coast.

In particular, nutrients show little variability in terms of seasonal variations, always being at low levels, also in those stations sampled close to the coastline, which do not seem to be affected by anthropogenic input. This pattern can influence the distribution and the abundance of phytoplanktonic blooms, which in fact were not particularly relevant in the sampling period.

The N:P ratio was highly variable except for in the range already observed in the Southern Adriatic, suggesting a P-limitation, which can contribute to the low primary productivity in this area and support the N:P ratio anomaly of the Eastern Mediterranean. The influence of the Northern Adriatic Surface Water in the Southern Adriatic sub-basin seems to be very low and can be traced by nitrate and silicate only in spring and winter.

Bottom layers in the shelf area are well oxygenated both in the Ionian and in the Adriatic slopes. This feature is important, considering the role of Adriatic Deep Water in ventilating the Eastern Mediterranean. On the other hand, the intruding Levantine Intermediate Water was evidenced not only by physical characteristics but also by dissolved oxygen minimum and nutrient maximum in the Otranto Strait.

The signature of LIW in terms of both salinity and nutrient maximum and oxygen minimum is lost in the northernmost sections sampled. Nevertheless, the LIW does not seem to be a source of nutrients for phytoplanktonic population: in fact, because of the observed stratification of the water column, it is forced at intermediate depths and influences only the most eastern stations. Chemical parameter distributions along the Otranto Strait show stronger evidence of the influence of the inflow of LIW than that of the outflow of Adriatic waters.

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