Climatological analysis of the Adriatic Sea thermohaline characteristics

A. Giorgetti

Osservatorio Geofisico Sperimentale, Trieste, Italy

(Received June 23, 1998; accepted December 3, 1998)

Abstract. A comprehensive hydrographic data set of the Adriatic Sea, obtained merging the historical ATOS1 data set (Adriatic Temperature Oxygen and Salinity) with data from the MODB (Mediterranean Oceanic Data Base) and CTD data obtained from recent European research projects, is presented. Rigorous quality checks have been applied to eliminate duplicate profiles and obtain a coherent and scientifically validated data set. By including CTD data, a better seasonal coverage of the Southern Adriatic Depression, with continuous measurements down to the bottom has been acquired. This made it possible to supplement existing work with a climatological analysis, supported by a good data resolution, of the thermohaline fields along characteristic cross-sections and in the deepest layer of the basin. An interannual variability of the Adriatic Deep Water (ADW) that resides in the Southern Adriatic Depression was detected.

1. The Adriatic Sea data set: scientific validation of data

Within the framework of the MODB (Mediterranean Oceanic Data Base) project, a MAST-MTP Supporting Initiative for Ocean Data and Information Management, historical bottle data of temperature and salinity collected in the Mediterranean Sea since the beginning of the century (MED2, Brasseur et al., 1996) were merged with CTD data from different institutions producing the MED5 climatology of the Mediterranean Sea on the monthly and seasonal scales (MODB Group, 1996). In the case of the Adriatic Sea, the latest complete set of historical temperature and salinity bottle data, the ATOS1 data set (Adriatic Temperature Oxygen and Salinity, Artegiani et al., 1997), was completed with data from the MODB data set eliminating duplicate profiles. Subsequently, more recent CTD data collected in the framework of POEM (1985-1993), of the European MAST/MTP OTRANTO (1994-1995) and PRISMA (1995-1996) projects were inclu-

Corresponding author: A. Giorgetti; Dipartimento di Oceanologia e Geofisica Ambientale, Osservatorio Geofisico Sperimentale, P.O. Box 2011, 34016 Trieste, Italy, tel. +39 040 2140 206, fax +39 040 2140 319, e-mail: agiorgetti@ogs.trieste.it

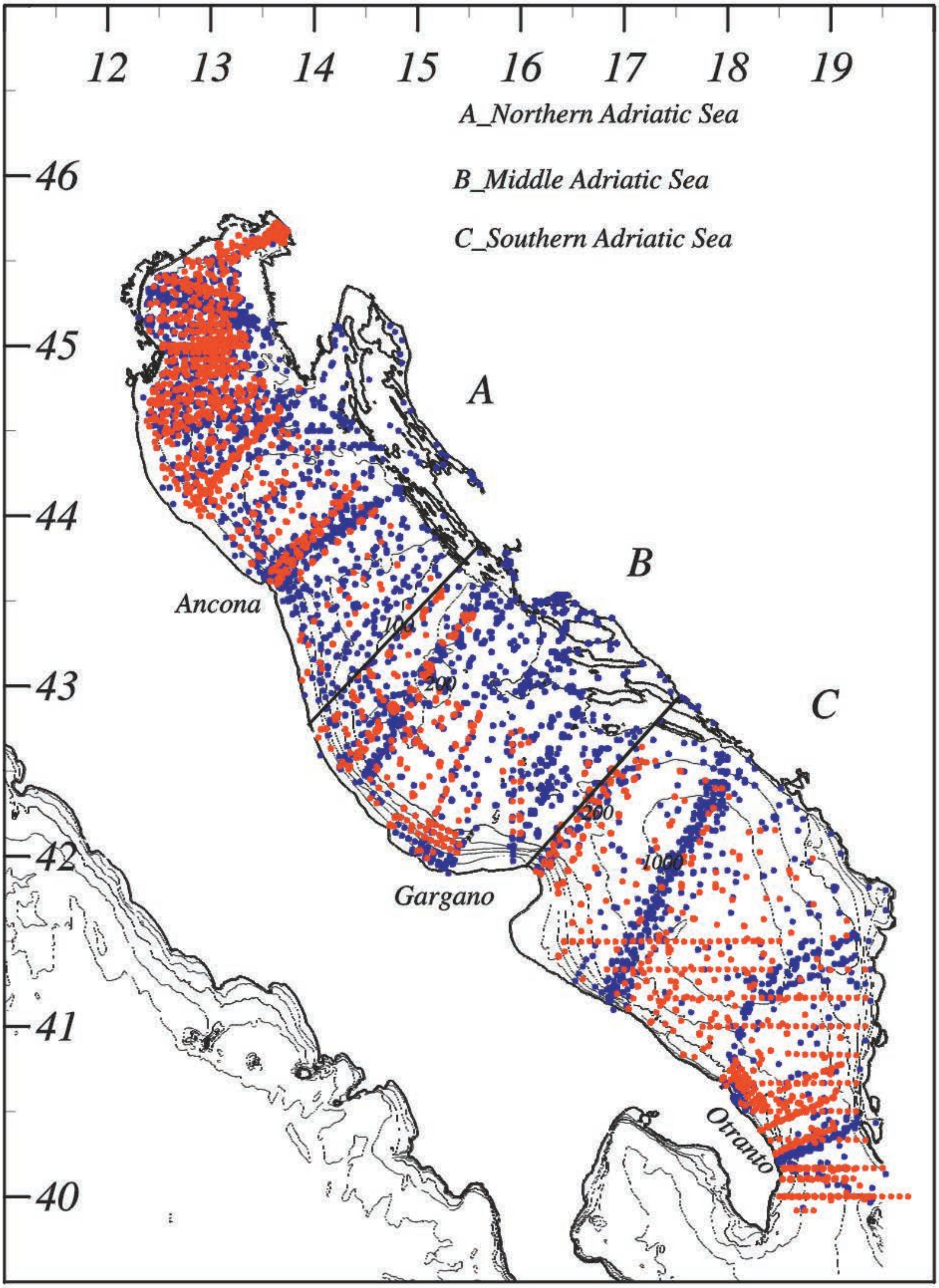


Fig. 1 - Map showing the bathymetry of the Adriatic Sea and the distribution of CTD (in red) and bottle hydrological profiles (in blue). Depth contours are given in metres.

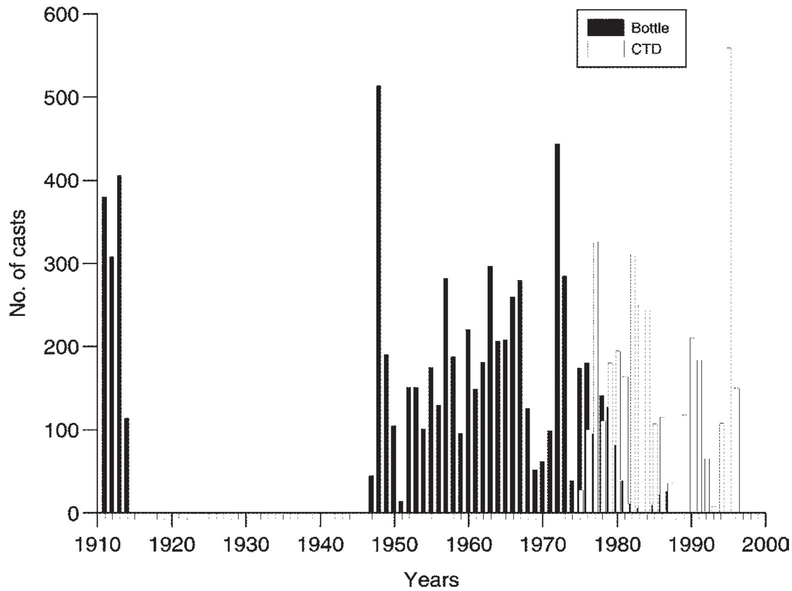


Fig. 2 - Temporal distribution of the Adriatic Sea data set: CTD (in white) and bottle data (in black).

ded. Thus, the Adriatic Sea data set has been considerably enriched both in terms of the number of hydrographic profiles and of the quality of the data. The new data set contains 10 742 stations (after quality control), distributed from North to South with a more homogeneous coverage of the Northern part (Fig. 1), covering the years 1911-1914 and 1947-1996 (Fig. 2). The data referring to the recent years, which increased the data collected in the Southern Adriatic by providing continuous measurements down to the bottom, allowed a more refined seasonal description of the thermohaline characteristics of the basin.

In order to start the merging procedure between the different data sets correctly, a rigorous check of the duplicate profiles was made. The historical ATOS1 data set was in fact partially included in the MODB, and more completely in the MED2 database. The search for twin profiles was not easy because, sometimes, the time of measurement for the same profile was missing only in one data set, and the position was not exactly the same. The criterion chosen was to eliminate the profiles which presented coordinates closer than 1 km, with the same date of measurement (year, month and day) and the same hour or, with the hour coded as missing.

Subsequently, the MODB Local Quality Control protocol (Brankart, 1994), valid for the Mediterranean data set, was applied to the Adriatic Sea. It was partially modified to ensure a globally coherent analysis, taking into account the peculiarities of the basin (Manca and Giorgetti, 1995). In fact, the thermohaline properties of the Adriatic Sea are affected by a large variability due to the discontinuity of bathymetry, river run-off and meteorological factors. It was noted that rejection of extreme but correct data could lead to the loss of important phenomena. On the other hand, local and particular phenomena, e.g. coastal processes, could affect the open-ocean climatological analysis. Table 1 contains the test intervals relevant for the range check of temperature and salinity data.

Throughout this work, pressure is used as the vertical coordinate; following the IAPSO

Table 1 - Values used for the quality control (range check) of temperature and salinity data in the Adriatic Sea.

Temperature and salinity ranges:	
5 < T < 35°C & 25 < S < 40	for 0 < depth < 50 m
8 < T < 25°C & 36 < S < 40	for 51 < depth < 200 m
8 < T < 18°C & 37 < S < 40	for 201 < depth < 800 m
12 < T < 15°C & 38 < S < 40	for depth > 800 m

recommendations (UNESCO, 1985) on the other hand, temperature is given as potential temperature (θ), salinity (S) according to the practical salinity scale and density is presented as potential density excess (γ_θ). To perform the statistical check of the data, the Adriatic Sea was divided into three areas (the Northern, Middle and Southern Adriatic Sea) and the seasonally averaged vertical profiles of temperature and salinity were calculated. The seasonal mean and standard deviation of temperature and salinity data were computed for the three sub-basins at every decibar. All the values that varied from the mean by 3 to 5 standard deviations, depending on the depth of the profiles, were flagged and eliminated from the resulting analyses. Furthermore, the casts with a bottom depth lower than 15 m or with a unique value in temperature or salinity were eliminated, as well as the stations in the waters of the Croatian islands with a salinity of less than 25.

Finally, a consistency analysis of the data collected during the most recent cruises was performed to investigate the coherence of the various data sets before including them in the database. Table 2 contains the details of the number of bottle and/or CTD hydrographic profiles included, after quality control, in the comprehensive Adriatic Sea data set.

2. Water mass properties and vertical distributions

The Adriatic Sea is a quasi-rectangular basin 783 km long and with an average width of 243 km (Buljan and Zore-Armanda, 1976). It has been divided into three sub-basins on the basis of

Table 2 - The Adriatic Sea data set: detailed synthesis of the number of bottle and/or CTD hydrographic profiles.

	Bottle	CTD	Total
MODB Data	4086	2137	6223
ATOS1 Data	3088	-	3088
ASCOP Data	-	332	332
IRPEM-CNR Data	-	147	147
ITT-CNR Data	-	62	62
POEM Data	-	82	82
MTP/OTRANTO Data	-	251	251
PRISMA Data	-	557	557
Total	7174	3568	10 742

its topography (Artegiani et al., 1997a): the shallow Northern Adriatic basin, with a bottom depth reaching a maximum of 100 m (Fig. 1, area A), the Middle Adriatic basin, with two depressions, reaching approximately 270 m, and extending up to the Pelagosa sill (Fig. 1, area B), and the Southern Adriatic basin, bordering the Pelagosa sill in the North and the Otranto sill in the South, which includes a large depression reaching a depth of 1200 m (Fig. 1, area C). In Zore-Armanda (1963), a different division is presented: the Northern Adriatic region extends to a depth of 70 m.

The contribution of CTD data in the climatological analysis of the Adriatic Sea data set has been highlighted by means of θ-S diagrams, obtained comparing respectively, the monthly averaged temperature and salinity values of bottle data and the complete data set in the Northern and Southern Adriatic (Fig. 3). In these two areas, the number of hydrographic profiles were almost doubled with respect to the historical data set, passing from 2181 bottle casts to 4085 bottle and CTD casts in the northern part and from 1094 to 2193 in the southern part, respectively. The introduction of recent data, acquired with modern techniques of profiling, yielded a more refined seasonal thermocline in both areas, showing summer temperature values higher than 24 °C, and greather evidence of high density values ($\gamma_\theta > 29.5$ kg/m^3) in the Northern Adriatic in winter, with temperatures lower than 10 °C.

To describe the water masses involved in the basin scale circulation and analyze their seasonal variability, three main vertical cross-sections have been considered. The Ancona transect, as a sample for the Northern Adriatic basin, the Gargano transect, which separates the Middle from the Southern Adriatic basins, and the Otranto transect, between the Adriatic and the Ionian Sea (Fig. 1). Two seasons, namely winter and summer, defined as January, February, March and July, August, September respectively, were discussed and compared. All the stations within a bin of 20 km for the Ancona and Gargano sections, and 10 km for the Otranto section, respectively, have been considered. The data selected along a transect have been averaged on a regular grid because the measurement distribution, obtained with both CTD and bottle casts, was not uniform. The length of the vertical cross-section, as well as its bottom shape, might change from winter to summer, because only the portion of the section marked by the first vertical profile on the western side for the former and by the last one on the eastern side for the latter has been drawn. The vertical fields were finally plotted applying a bilinear interpolation with quadratic smoothing.

The vertical distributions of temperature, salinity and density along the Ancona section (Figs. 4-5) show a clear seasonal cycle of the thermal field, affecting the whole water column; strongly stratified in summer and vertically homogeneous in winter. They also show that the large amount of fresh water from river discharges along the Western coast influences the salinity. As a consequence of the winter horizontal front, appearing both in temperature and salinity (Fig. 4), the southward coastal current along the Italian coast is reinforced (Hendershott and Rizzoli, 1976; Malanotte-Rizzoli and Bergamasco, 1983). Even if the salinity field is characterized by fresh water input, the density field presents relatively high values, clearly related to the thermal field ($T \approx 10$-11 °C). In summer (Fig. 5), the salinity field still shows less saline waters extending from the West, while the temperature field evidences a well-developed thermocline, and the water column is strongly stratified.

The vertical distributions along the Gargano section in winter (Fig. 6) show a vertical homo-

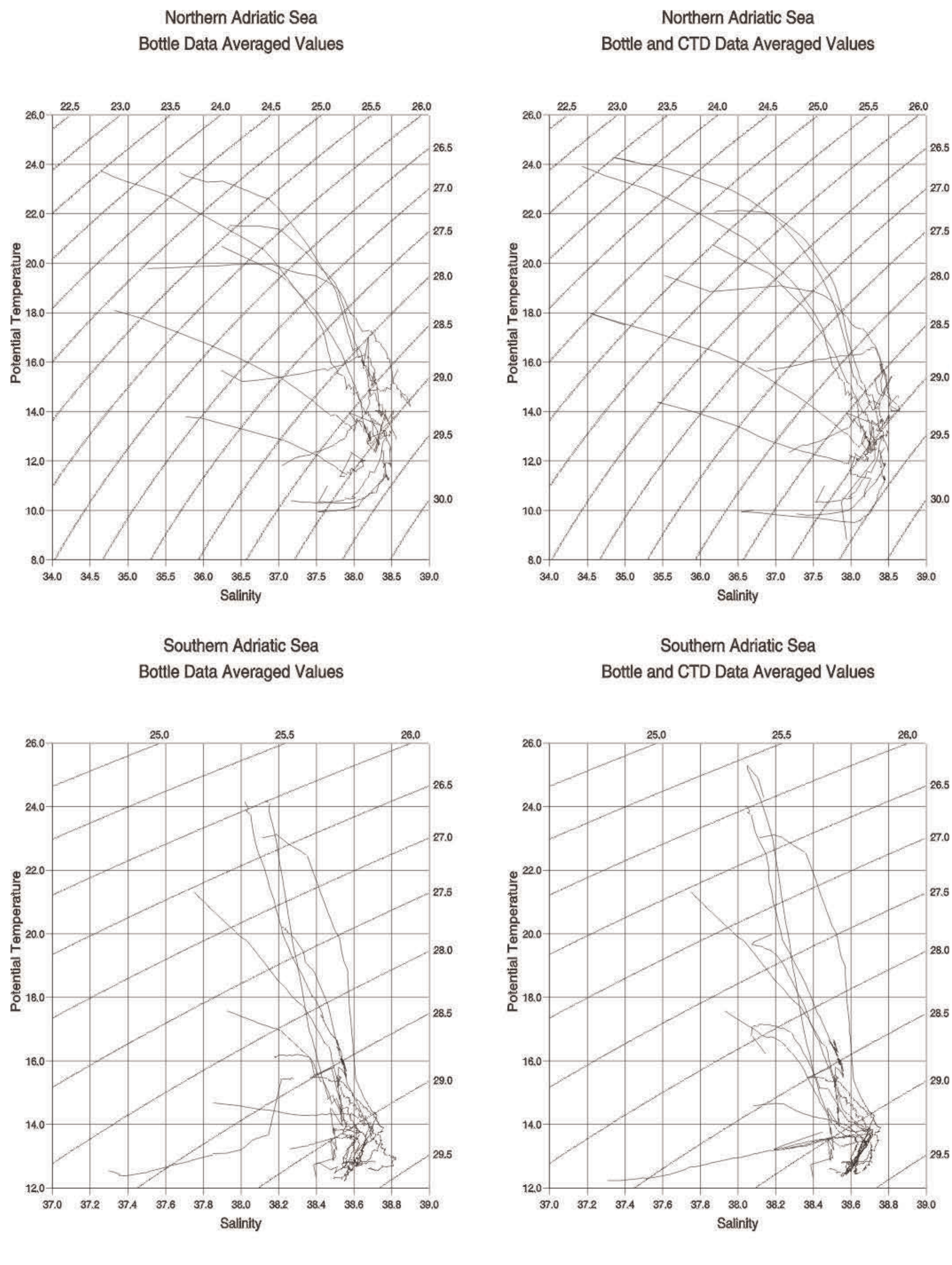


Fig. 3 - Potential temperature and salinity diagrams for monthly average temperature and salinity values calculated from bottle data (left panels) and from the complete data set (right panels) in the Northern Adriatic (upper panels) and the Southern Adriatic (lower panels) respectively.

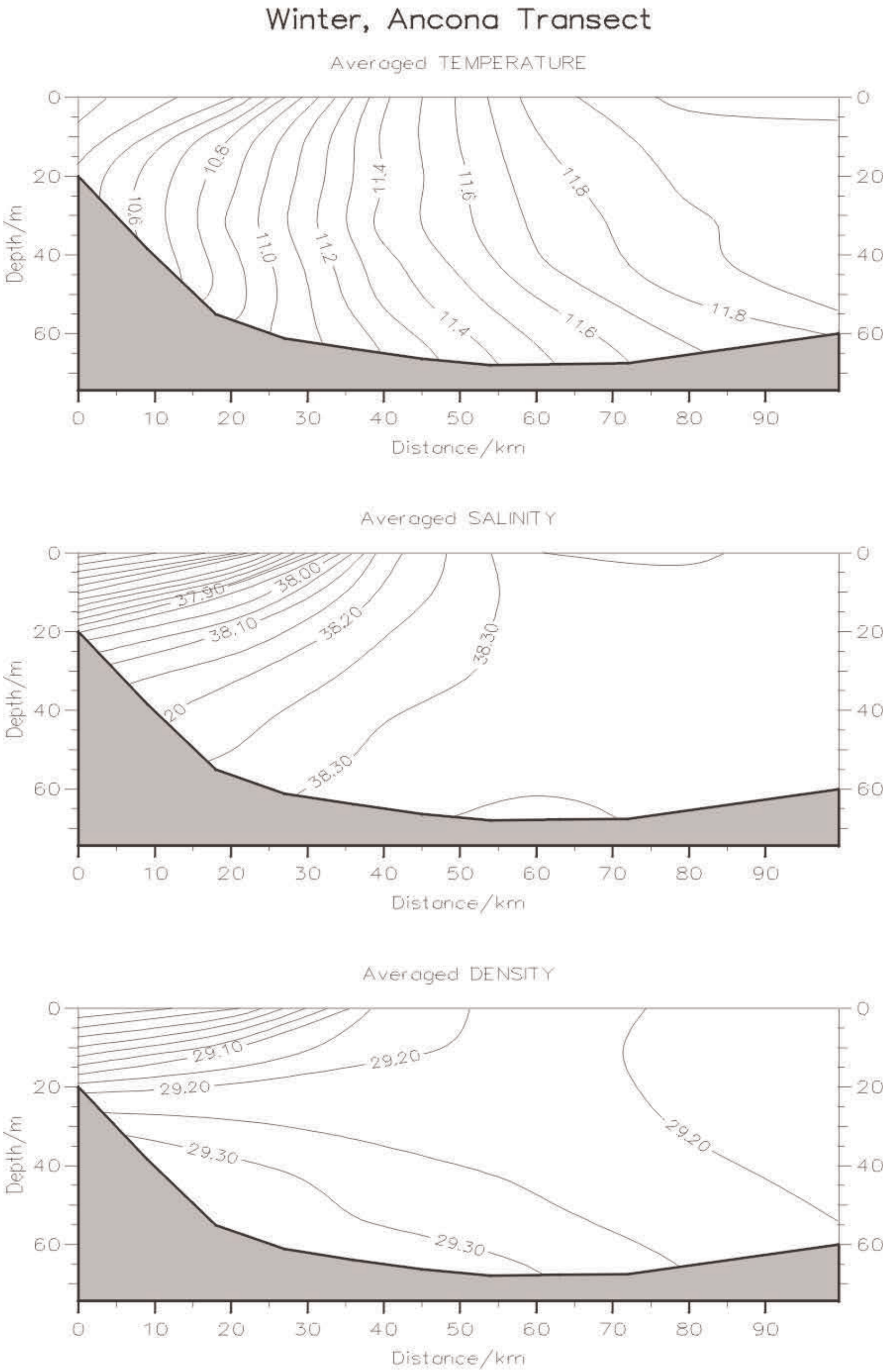


Fig. 4 - Potential temperature (upper panel), salinity (middle panel) and density (lower panel) vertical distribution along the W-E hydrographic section at Ancona during winter. Contour intervals are respectively 0.1 for temperature and 0.05 for salinity and density.

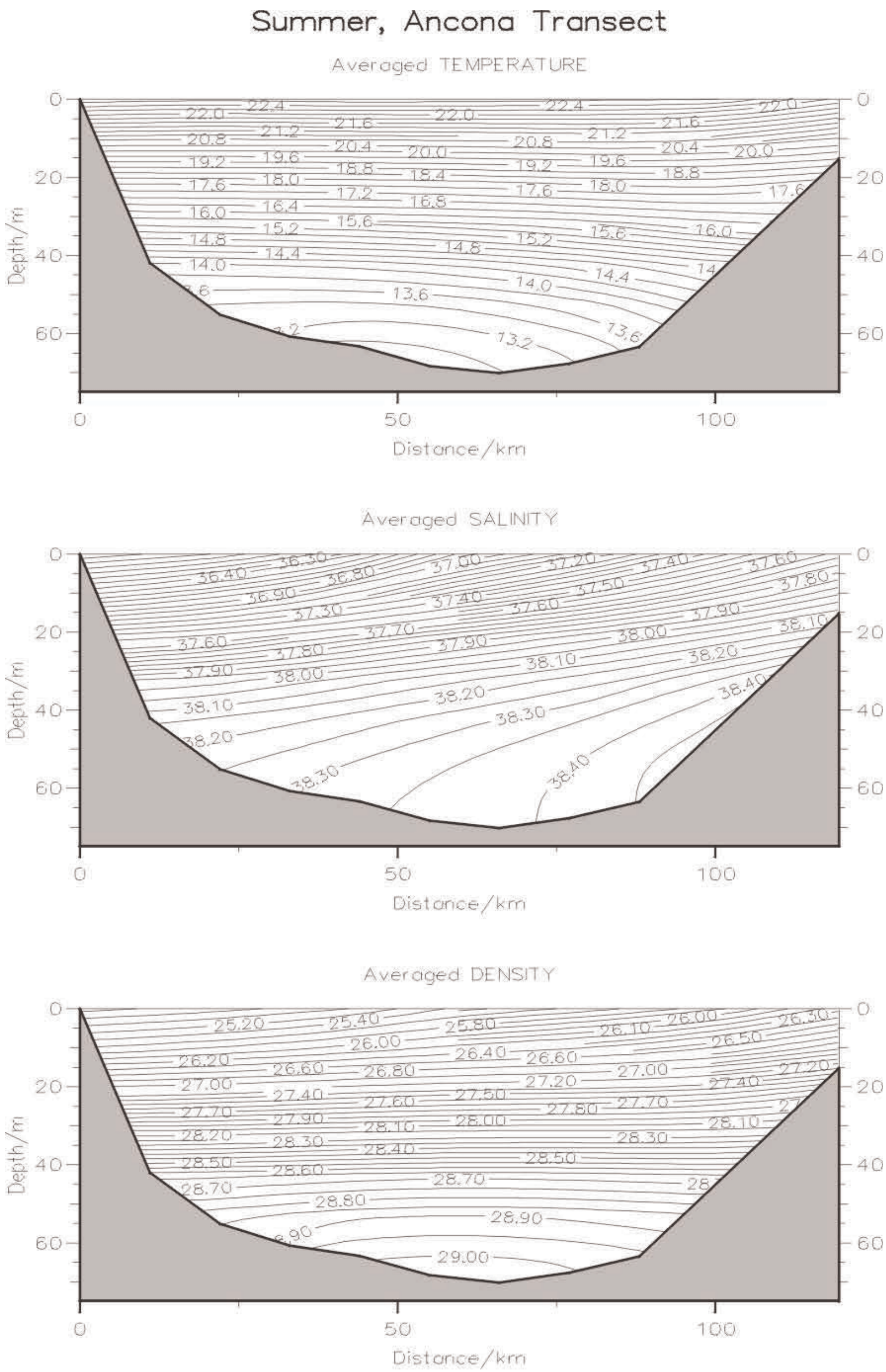


Fig. 5 - Same as Fig. 3 but for summer. Contour intervals are respectively 0.2 for temperature and 0.05 for salinity and density.

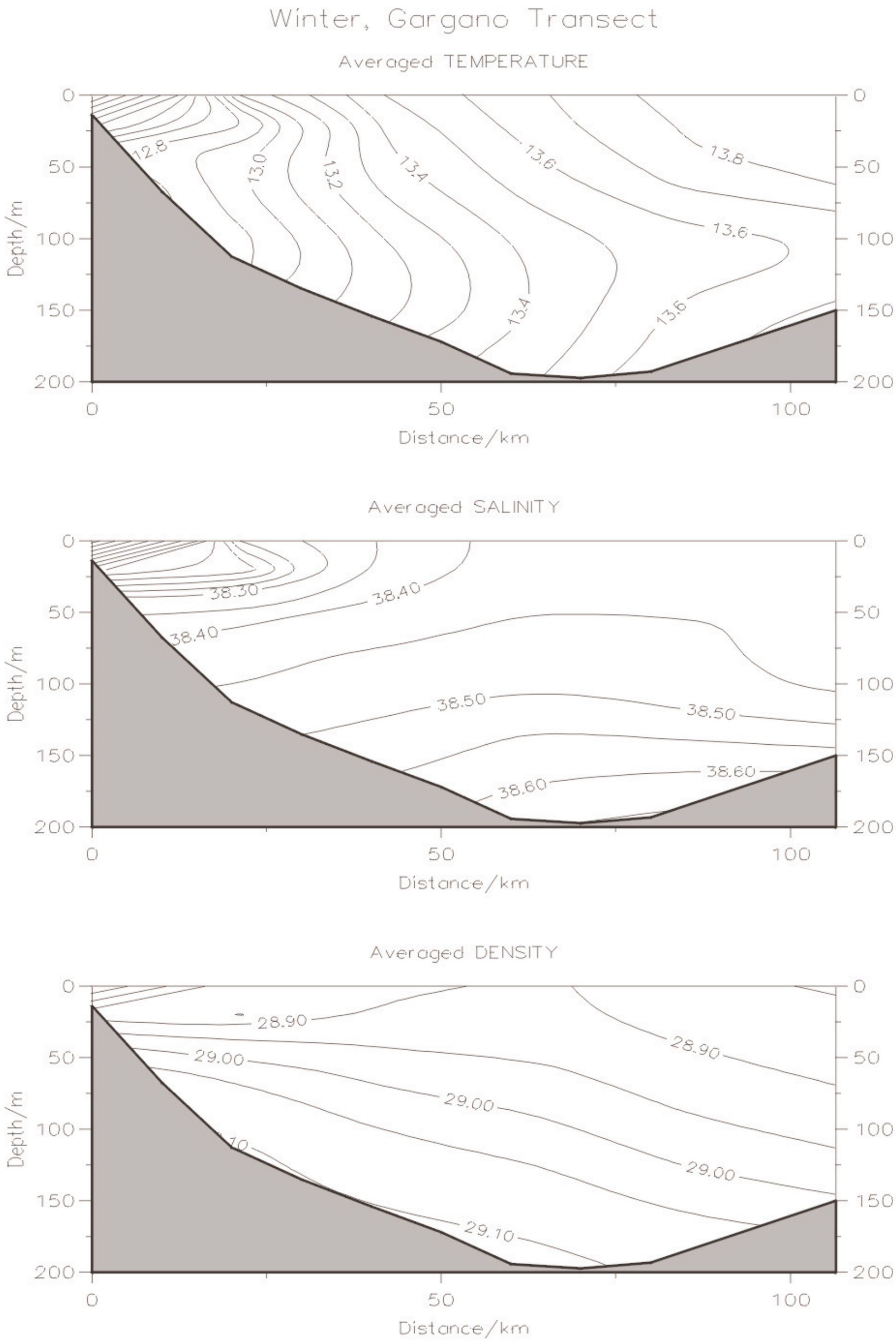


Fig. 6 - Potential temperature (upper panel), salinity (middle panel) and density (lower panel) vertical distribution along the W-E hydrographic section at Gargano during winter. Contour intervals are respectively 0.1 for temperature and 0.05 for salinity and density.

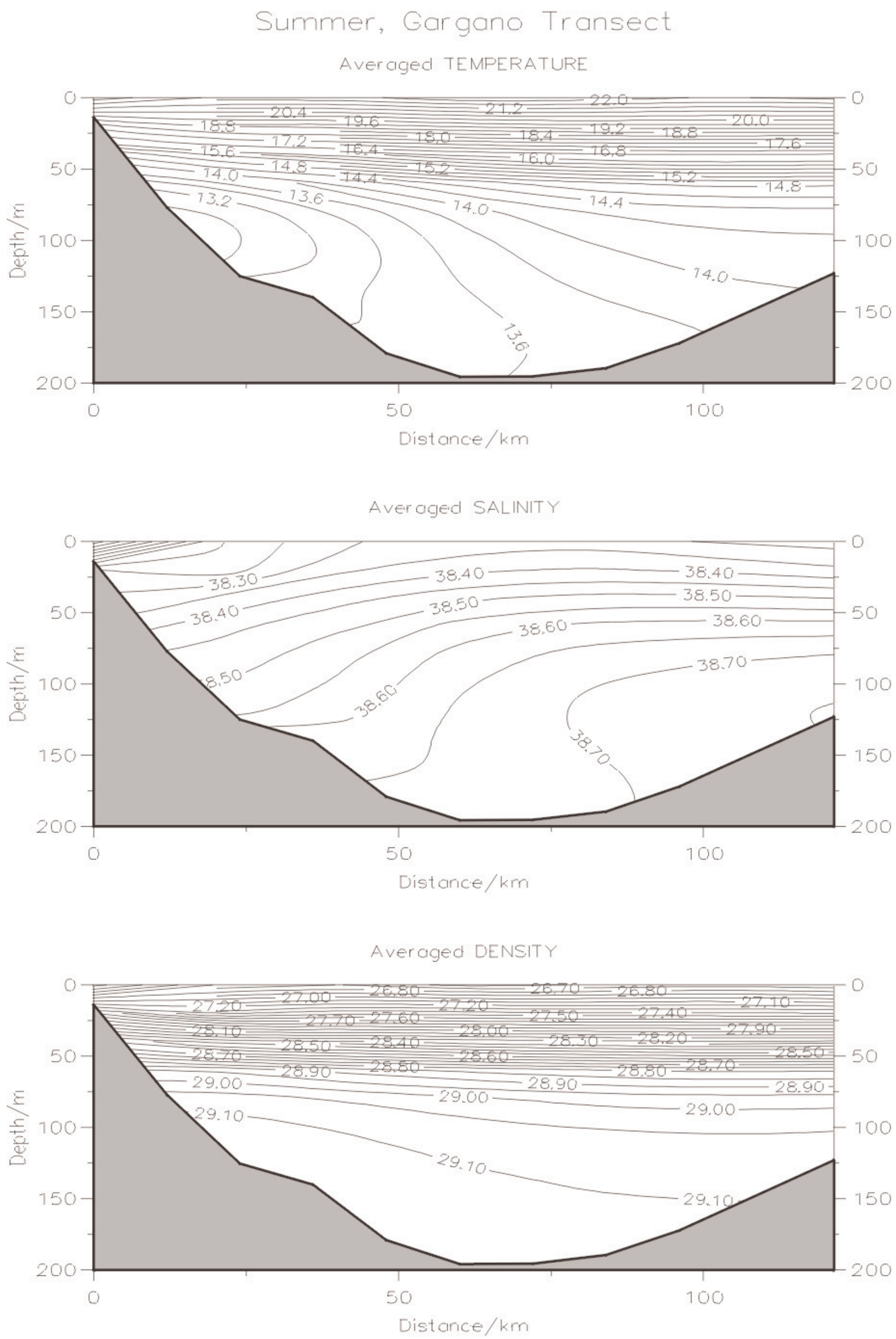


Fig. 7 - Same as Fig. 5 but for summer. Contour intervals are respectively 0.2 for temperature and 0.05 for salinity and density.

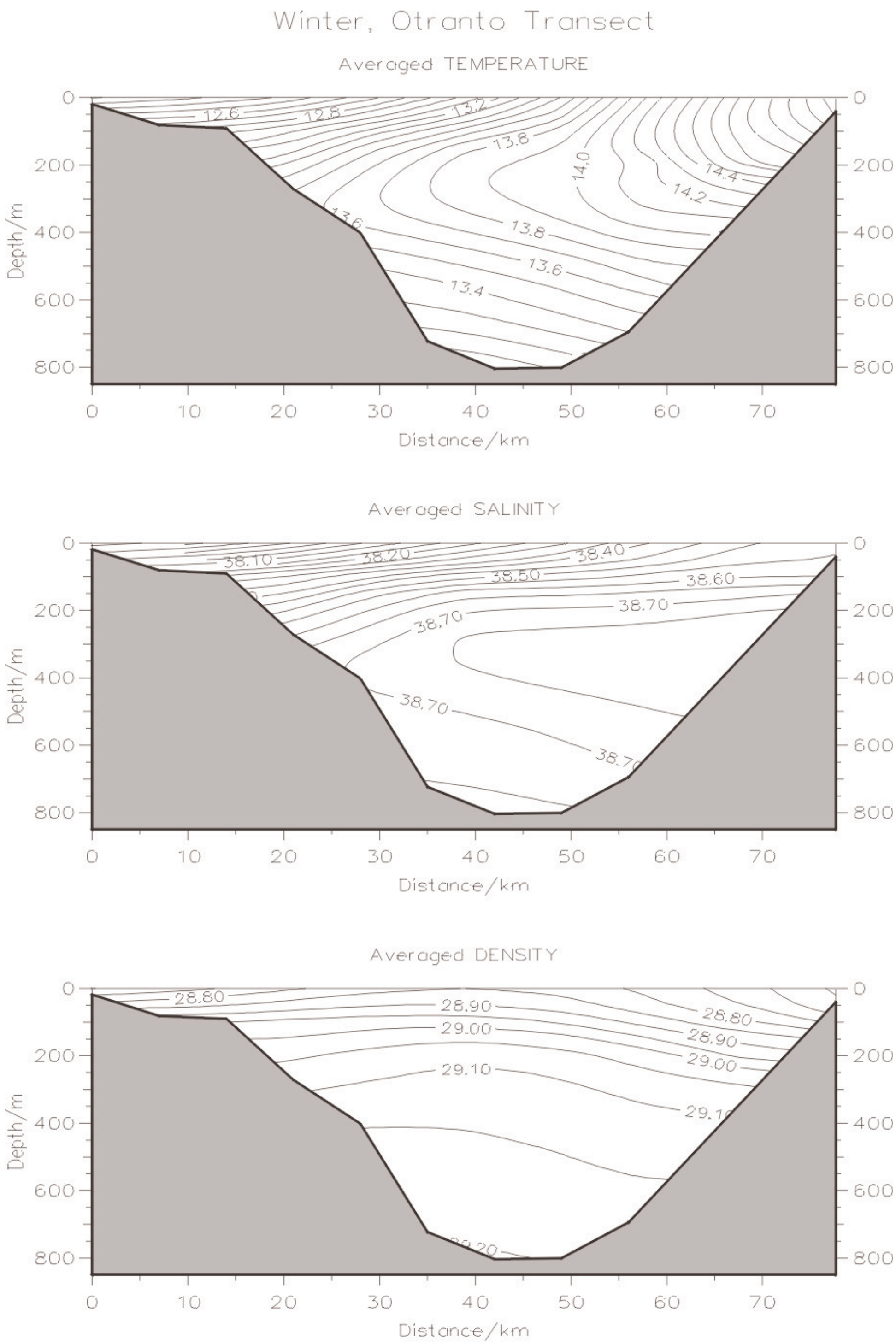


Fig. 8 - Potential temperature (upper panel), salinity (middle panel) and density (lower panel) vertical distribution along the W-E hydrographic section at Otranto during winter. Contour intervals are respectively 0.1 for temperature and 0.05 for salinity and density.

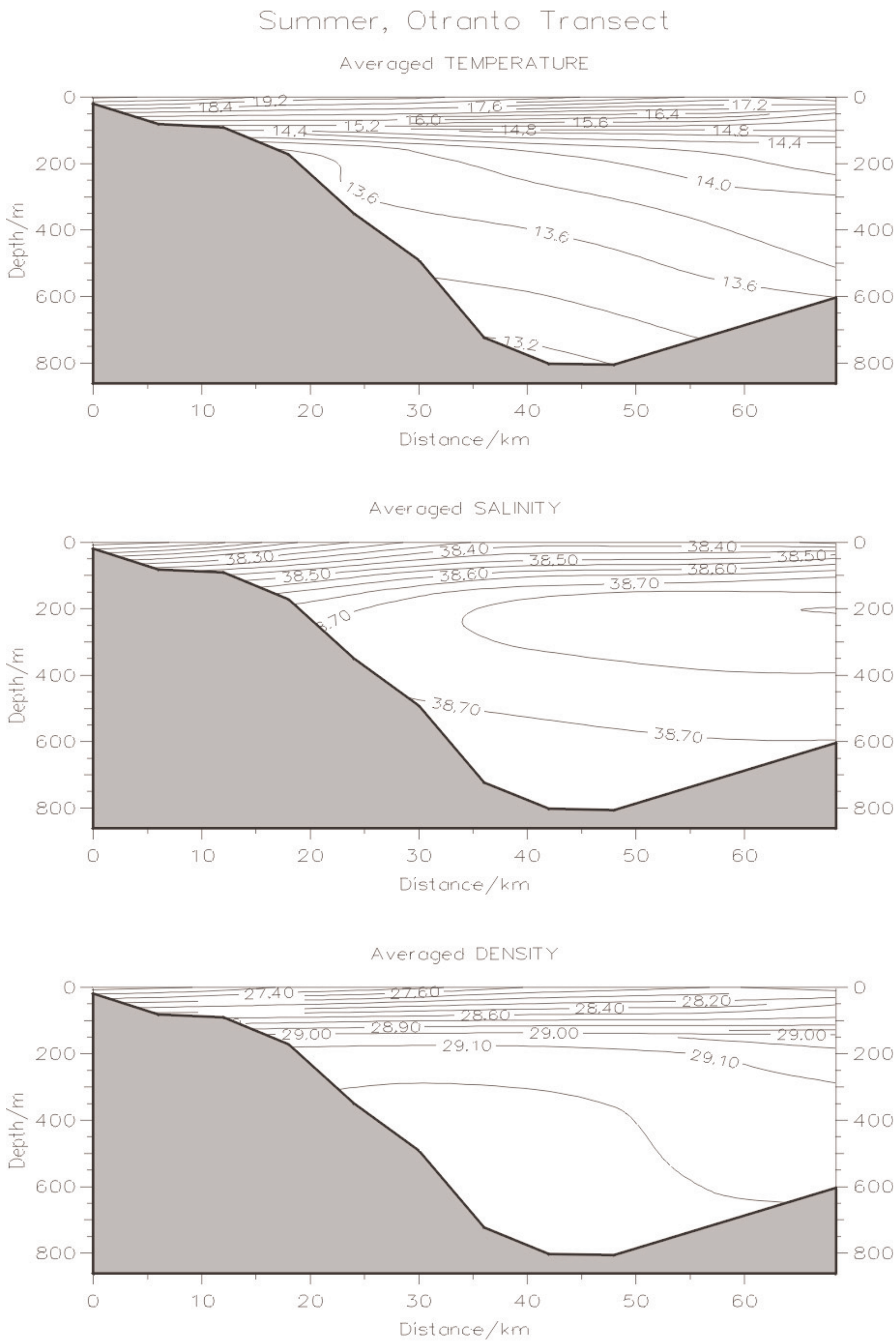


Fig. 9 - Same as Fig. 7 but for summer. Contour intervals are respectively 0.2 for temperature and 0.05 for salinity and density.

genization of the thermal field, as well as a front, with a temperature and salinity minimum along the Western coast evidencing the flow of the Northern Adriatic Surface Water along the Italian shelf (Artegiani et al., 1989; Franco and Bregant, 1980; Artegiani and Salusti, 1987). On the other hand, the signal associated with the Northern Adriatic Dense Water (NADW), which flows southward along the western continental slope, is evident mainly in spring but also in summer (Artegiani et al., 1993) in the bottom layer as a temperature and salinity minimum (Fig. 7). This water mass can be delimited by the 13.6 °C isotherm and the 38.65 isohaline, with a density range of 29.10 to 29.14 kg/m^3. The signal associated with the Levantine Intermediate Water (LIW), which propagates northward along the eastern side, is only evident as a maximum in the salinity field, with values higher than 38.65, extending from a depth of 50 m down to the bottom. The summer surface stratification extends down to about 50 m.

The temperature field along the Otranto section during winter (Fig. 8), shows a surface front which separates the Adriatic outflowing water (T < 13.6 °C) from the inflowing water of Ionian origin (T > 13.7 °C). The maximum in the salinity field highlights the signal associated with the Levantine Intermediate Water (LIW), which enters the Adriatic with a salinity higher than 38.70 along the eastern flank of the section in the layer between 100 and 600 m of depth. The density field evidences a dome-shaped structure which characterizes the water exchange regime, with an inflow along the eastern side, and an outflow along the western side. The deepest part of the section is occupied by the Adriatic Deep Water (ADW) which flows over the sill of Otranto and can be delimited by the 13.5 °C isotherm and the 38.65 isohaline, having a density of more than 29.20 kg/m^3. During summer (Fig. 9), the LIW (S > 38.70) with a greater horizontal extension occupies the cross section from the eastern to the western continental slopes, as a layer between 100 and 600 m of depth (Zore-Armanda, 1969).

3. Horizontal fields

The horizontal seasonal analyses of temperature, salinity and density fields were performed to highlight the dominant seasonal features of the Adriatic Sea general circulation. The horizontal maps were obtained utilizing both the objective analysis (Gandin, 1965; Bretherton et al., 1976; Carter and Robinson, 1987) and the variational inverse method (Wahba and Wendelberger, 1980; Brasseur et al., 1996) with a grid resolution of 1/10° and keeping, as much as possible, the same correlation length and decay scale parameters. The two methods are mathematically equivalent even if the variational one is numerically more efficient and better suits the geometry of the domain. In the case of the Adriatic Sea, the comparison between the two (Giorgetti, 1997) suggested that the density of observations is less important than the method used to interpolate the data, which is contrary to the conclusions obtained applying the two methods to the Mediterranean Sea (Roussenov and Brasseur, 1991); the fields put in evidence a good correspondence in the resulting thermohaline structures. The horizontal maps presented were obtained by averaging the points within a radius of 12 km and implementing the objective analysis with 0-crossing of 100 km, setting a decay scale of 60 km in the isotropic correlation function, fixing a maximum number of 10 influential points and assuming an error variance of 10%. The fields have been plotted with a grid step of 10 km on both coordinates and blanking the values with an error variance higher than 50%.

The surface horizontal fields indicate mostly the upper thermohaline circulation features, influenced by the seasonal structure. In winter, the temperature field highlights, mainly in the northern part, the cooling of the surface layer due to the prevalence of the cold and dry northerly wind, which triggers a dense water formation process (Franco and Michelato, 1992; Zore-Armanda and Gačić, 1987). The density field (Fig. 10) presents high values at the surface reaching as much as 29.4 kg/m^3 in the Northern Adriatic, while the Middle and Southern Adriatic exceed 29.1 kg/m^3. In spring, the salinity field is affected by coastal river run-offs, which results in a frontal area of light water along the Northern Italian coast. The flow of light water reaches its maximum extension in summer, spreading into the Northern portion of the open sea and southward along the Western coast (results confirmed by satellite imagery, e.g. in Barale et al. (1984) and Gačić et al. (1997)). In autumn, the density field shows, in a more refined way, the presence of three sub-basin scale cyclonic circulation patterns, in the Northern Adriatic, the Middle Adriatic Pit, and the Southern Adriatic Pit mostly associated with the distribution of the salinity field. These features interact with the basin scale general circulation, characterized by a northward flow along the eastern coast, and a southward flow along the Western coast (Artegiani et al., 1997b; Orlić et al., 1992).

In every season, at the intermediate level (not shown), the salinity fields show values higher than 38.7 from the signal of the LIW inflowing through the Otranto Strait. The LIW occupies the eastern side of the southern basin, while the western side is dominated by less saline water.

The bottom fields were obtained averaging the last three values of each profile, under the condition that they were measured at one tenth of the total station depth. The bottom density (Fig. 11) shows a clear seasonal cycle in the Northern part, highlighting the fact that the winter surface heat loss influences the whole water column (reaching bottom densities $\gamma_\theta > 29.5$ kg/m^3 in the northernmost part), while the Middle and Southern Adriatic Depressions act as reservoirs of high density water throughout the year. The bottom density is strongly correlated to the seasonal structure of the bottom thermal field (not shown here) in the shallow part of the basin, and therefore mostly indicative of the formation sites and of the flow of the NADW. During winter, this water mass is formed by convection near an ocean boundary (Malanotte-Rizzoli, 1991) in the shallow Northern Adriatic continental shelf, slowly moving southwards along the western coast and filling, during spring, the Middle Adriatic Depression (Artegiani et al., 1989; Franco and Bregant, 1980; Artegiani and Salusti, 1987). One branch, with densities of less than 29.15 kg/m^3 (see Figs. 6 and 7), protrudes into the Southern Adriatic (Zoccolotti and Salusti, 1987). Here, the NADW mixes with the ADW, formed during winter in the Southern Adriatic, consequence of open-ocean deep convection processes ($\gamma_\theta > 29.18$ kg/m^3), and outflows across the Otranto Strait into the deep layer of the Ionian Sea (Pollak, 1951; Ovchinnikov et al., 1985).

4. Interannual variability

Most of the basin's deep layer is occupied by dense water produced during winter. In the North Adriatic, the thermohaline properties of dense water are mostly subject to the direct expo-

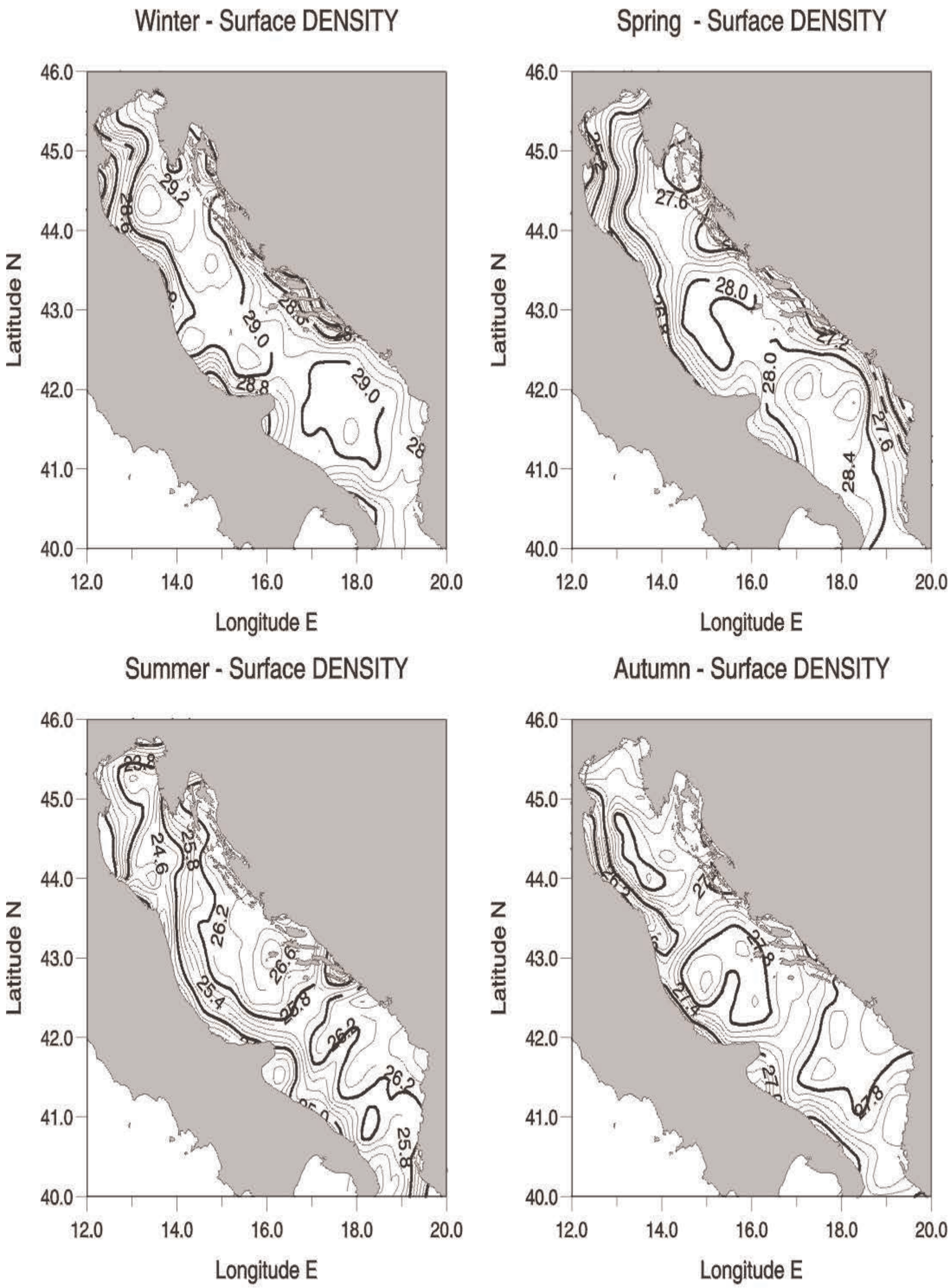


Fig. 10 - Seasonal horizontal distribution of density at the surface. Contour intervals are respectively 0.1 for winter and 0.2 for spring, summer and autumn.

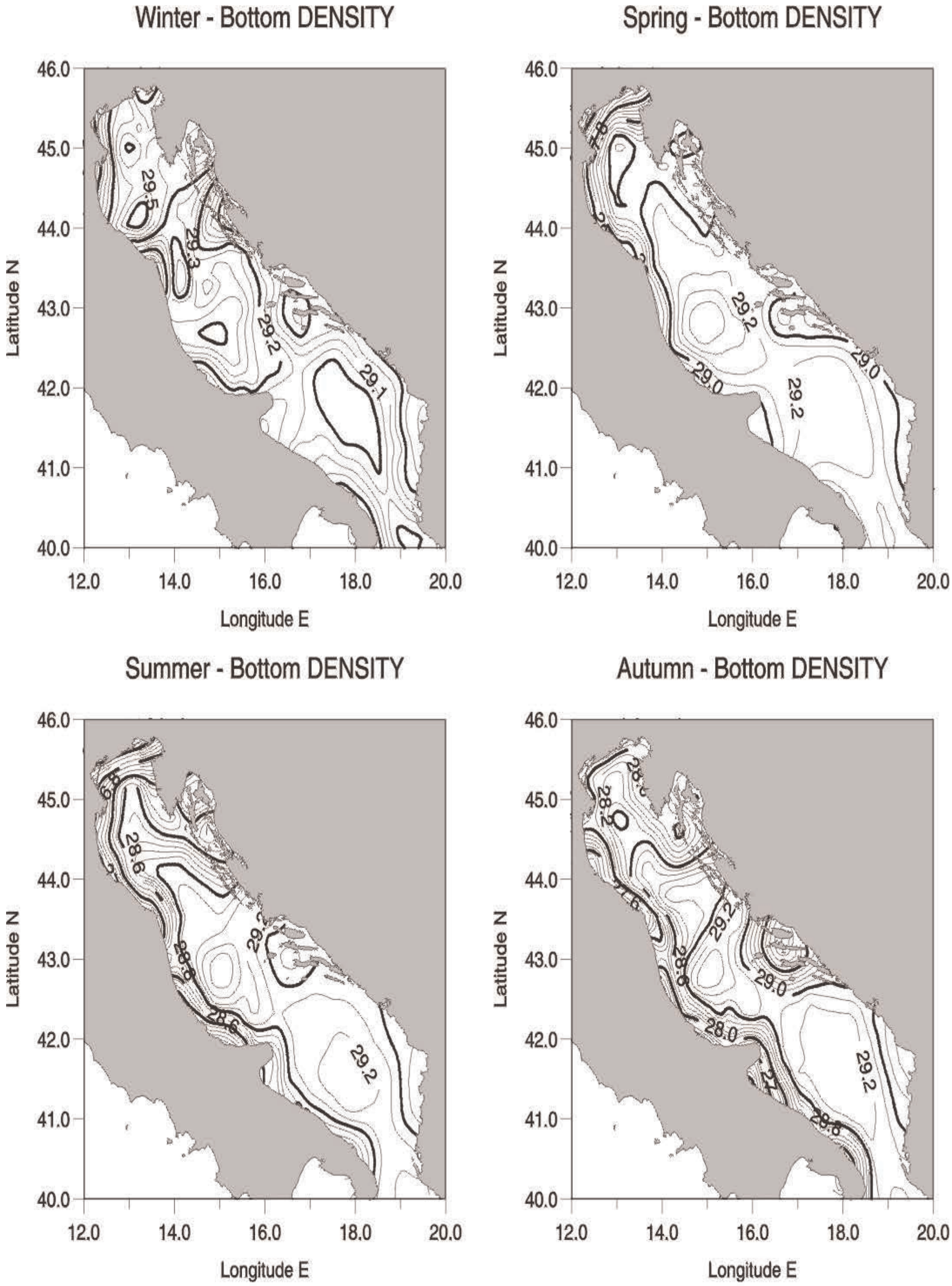
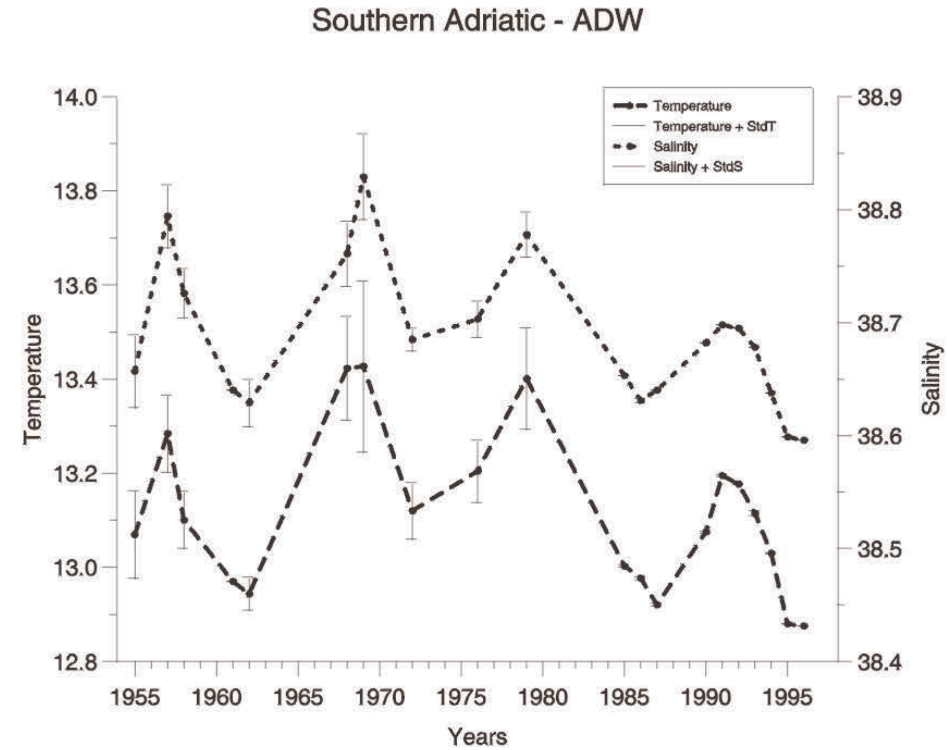


Fig. 11 - Seasonal horizontal distribution of density near the bottom layer. Contour intervals are respectively 0.05 for winter and 0.1 for spring, summer and autumn.

sure of the whole water column to the cooling effect of the strong north-easterly Bora wind. In the Middle and Southern Adriatic, the deep layers are less subject to seasonal variation. In order to follow the interannual variability of the ADW, found in the Southern Adriatic Depression below the isopycnal surface γ_θ = 29.2 kg/m^3, the time series of the annually averaged temperature, salinity and density values were constructed for the whole period of the data. To restrict the analysis to the deepest part of the Southern Adriatic Depression and eliminate the near-coastal signal, only hydrographic profiles with depths of more than 600 m were considered. To make the time series as continuous as possible, the analyses were further reduced to the period 1955-96, when only sporadic gaps in measurements were found (in the years 1956, 1963-64, 1970, 1981-84 and 1988-89). Moreover, to corroborate the statistical results, the standard deviation was calculated for each year, giving large values for bottle data and very small ones, lower than the instrumental accuracy, for the CTD data. An interannual variability over a ten-year time scale was detected, in both the temperature and salinity time series (Fig. 12). The same temperature variability, over a ten-year time scale, was observed deep down in the ocean (Levitus et al., 1994). Recent studies indicate that a 10-11 year cycle in the sea-surface temperature occurs over most of the North Atlantic Ocean and, that this periodicity tended to be in phase with the sunspot cycle (Muir, 1997). Peaks in 11-year periods, have also been reported in the air temperature and pressure power spectra (Hurrel, 1995 and Vilibić et al., 1996) and, the 11-year modulation of mean sea level has been assumed to be coherent with the 11-year variation in air temperature (Mazzarella and Palumbo, 1988). Moreover, there is a good correlation between the temperature, salinity and density maximum and minimum values. This could indicate that the dense water formation events are mostly connected to the presence of higher water salinity in the Southern Adriatic Sea, which is influenced by the inflow of the warm and salty LIW. This water mass, formed in the eastern Mediterranean and feeding the salinity maximum layer throughout the Mediterranean, moves to a small branch towards the Adriatic Sea (Wüst, 1961) and serves as preconditioned water to form denser waters in the Southern Adriatic (Ovchinnikov, 1985). Finally, in the last decade, when the majority of CTD casts were obtained, an overall decrease in temperature and salinity can be remarked. This is also reflected in the density.

5. Conclusions

Previous studies on the Adriatic Sea were based on the analysis of a limited number of data, collected mostly during quasi-synoptic surveys. Recently, Artegiani et al. (1997a, 1997b) performed a detailed climatological study of the Adriatic Sea general circulation on the basis of historical data (ATOS1), but they did not draw any definitive conclusions regarding the Southern Adriatic. In this study, we have tried to highlight the new signals emerging from the analysis of the historical data combined with the most recent CTD data. A preliminary overall consistency analysis and data quality control were necessary, before combining the CTD casts with the historical data set, for our purposes. The separate study of bottle and CTD data have showed the fundamental role of the latter for climatological analysis to improve the definition of the thermohaline properties and circulation of water masses in the Adriatic Sea. The addition of continuous



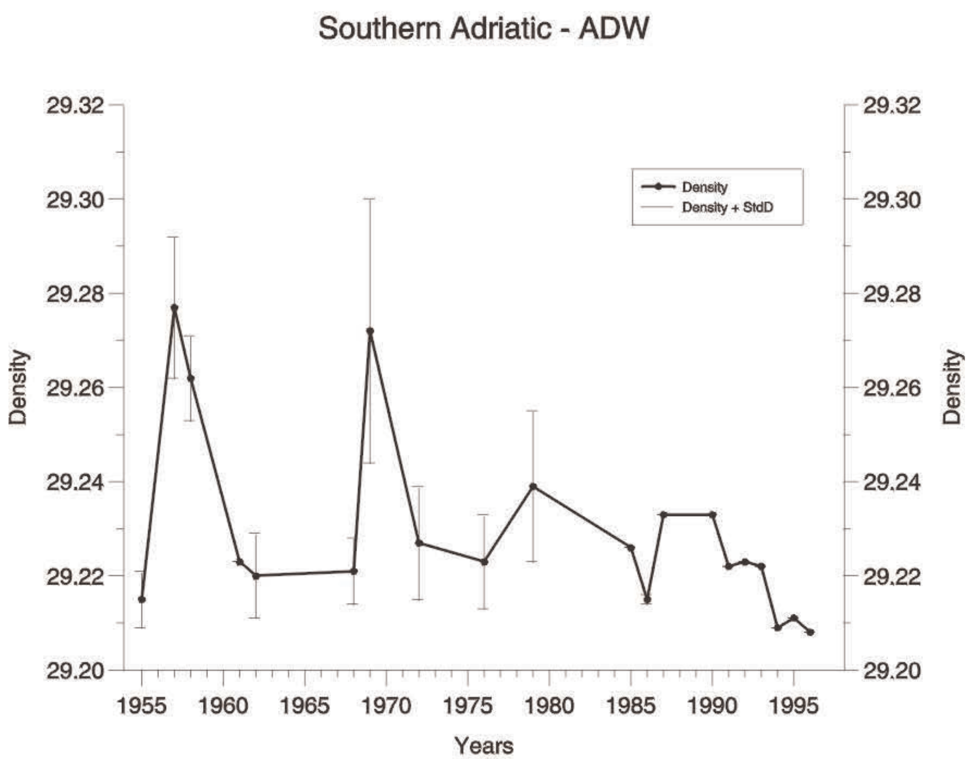


Fig. 12 - Time series of annually averaged temperature, salinity (upper panel) and density (lower panel) values and standard deviations in the Southern Adriatic Depression.

and accurate measurements yielded a more refined seasonal thermocline. Moreover, the increase of data for the Southern Adriatic Depression allowed us to corroborate previous studies with a detailed description of the deepest layer of the basin, through vertical sections and bottom horizontal maps. The large extension of dense water, produced during winter in the shallow Northern Adriatic, with density values higher than 29.5 kg/m^3, was depicted; also highlighted was the fundamental contribution of the Northern Adriatic Dense Water spreading into the Middle Adriatic Depression and throughout the basin. In addition, the important role of the ADW, formed during winter in the Southern Adriatic as a consequence of open-ocean convection, in the water exchange regime at the opening of the Adriatic Sea was described. It is worthwhile to note that the most important basin scale features, reported in the related literature, have also been shown on the climatological time scale. The results obtained here give an accurate estimate of the "mean state of the basin" for the different averaged periods and can be used as possible initial conditions in the framework of numerical simulations. Lastly, the complete Adriatic Sea data set presented here contains measurements which go up to the end of the century, with an almost continuous coverage for the last fifty years. This makes it possible to start the analysis of teleconnection patterns, which could be associated to significant climatic changes.

Acknowledgments. This research was supported by the O.G.S. under the European Commission's Marine Science and Technology Program (MAST II and III), Contracts MAS2-0093-0075.BE and MAS3-CT96-0051. I am grateful to O.G.S. staff for giving me the possibility of working with the ATOS1 data set and the CTD data collected over the last years. A deep acknowledgement goes to Dr. B. Manca for his scientific support in data analyses and the interpretation of results.

References

Artegiani A. and Salusti E.; 1987: *Field observation of the flow of dense water on the bottom of the Adriatic Sea during the winter of 1981.* Oceanol. Acta, **10**, 387-392.

Artegiani A., Azzolini R. and Salusti E.; 1989: *On the dense water in the Adriatic Sea*. Oceanol. Acta, **12**, 151-160.

Artegiani A., Gačić M., Michelato A., Kovačević V., Russo A., Paschini E., Scarazzato P. and Smirčić A.; 1993: *The Adriatic Sea hydrography and circulation in spring and autumn (1985-1987).* Deep-Sea Res., **40**, 1143-1180.

Artegiani A., Bregant D., Paschini E., Pinardi N., Raicich F. and Russo A.; 1997a: *The Adriatic Sea General Circulation.* Part I: Air-Sea Interactions and Water Mass Structure. J. Phys. Oceanogr., **27**, 1492-1514.

Artegiani A., Bregant D., Paschini E., Pinardi N., Raicich F. and Russo A.; 1997b: *The Adriatic Sea General Circulation.* Part II: Baroclinic Circulation Structure. J. Phys. Oceanogr., **27**, 1514-1532.

Barale V., Malanotte-Rizzoli P. and Hendershott M.C.; 1984: *Remotely sensing the surface dynamics of the Adriatic Sea.* Deep-Sea Res., **31**, 1433-1459.

Brankart J. M.; 1994: *The MODB Local Quality Control.* In: Tech. Rep., Univ. of Liege, Belgium, 5 pp.

Brasseur P., Beckers J. M., Brankart J. M. and Schoenauen R.; 1996: *Seasonal temperature and salinity fields in the Mediterranean Sea: Climatological analyses of an historical data set.* Deep-Sea Res., **43**, 159-192.

Bretherton F. P., Davis R. E. and Fandry C. B.; 1976: *A technique for objective analysis and design of oceanographic experiments applied to MODE-73.* Deep-Sea Res., **23**, 559-582.

Buljan M. and Zore-Armanda M.; 1976: *Oceanographic properties of the Adriatic Sea.* Ocean. Mar. Biol. Ann. Rev., **14**, 11-98.

Carter E. F. and Robinson A. R.; 1987: *Analysis models for the estimation of oceanic fields.* J. Atm. and Ocean. Tech., **4**, 49-74.

Franco P. and Bregant D.; 1980: *Ingressione invernale di acque dense nord-adriatiche nella fossa di Pomo.* In: Atti del IV Congr. AIOL, **26**, 1-10.

Franco P. and Michelato A.; 1992: *Northern Adriatic Sea: oceanography of the basin proper and of the western coastal zone.* In: Science of the Total Environment, Suppl. 1992, Elsevier Science Publishers B.V., Amsterdam, 35-62.

Gačić M., Marullo S., Santoleri R. and Bergamasco A., 1997: *Analysis of the seasonal and interannual variability of the sea surface temperature field in the Adriatic Sea from AVHRR data (1984-1992).* J. Geophys. Res., **102**, 22.937-22.946.

Gandin L. S.; 1965: *Objective analysis of meteorological fields.* In: Israel Program for Scientific Translations, **1373**, 242 pp.

Giorgetti A.; 1997: *Analisi climatologica delle strutture termoaline e di densità nel mare Adriatico.* OGS Rel. N. 2/97-OGA-1, Oss. Geof. Sperim., Trieste, 177 pp.

Hendershott M. C. and Rizzoli P.; 1976: *The winter circulation of the Adriatic Sea.* Deep-Sea Res., **23**, 353-370.

Hurrel J. W.; 1995: *Decadal trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation.* Science, **269**, 676-679.

Levitus S., Antonov J. I. and Boyer T. P.; 1994: *Interannual Variability of Temperature at a Depth of 125 Meters in the North Atlantic Ocean.* Science, **266**, 96-99.

Malanotte-Rizzoli P. and Bergamasco A.; 1983: *The Dynamics of the Coastal Region of the Northern Adriatic Sea.* J. Phys. Oceanogr., **13**, 1105-1130.

Malanotte-Rizzoli P.; 1991: *The Northern Adriatic Sea as a prototype of convection and water mass formation on the continental shelf.* In: Chu P.C. and Gascard J.C. (eds), Deep Convection and Deep Water Formation in the Oceans, Elsevier Ocean. Series, **57**, 229-239.

Manca B. and Giorgetti A.; 1995: *OGS/Italy Contribution to MODB - First Annual Report.* OGS Rel. n. 59/95-OGA-7, Oss. Geof. Sperim., Trieste, 41 pp.

Mazzarella A. and Palumbo A.; 1988: *Long-period variations on mean sea level in the Mediterranean areas. Boll. Ocean.* Teor. Appl., **6**, 253-259.

MODB Group; 1996: *Climatological Atlas of the Mediterranean Sea.* In: Scientific Report of the MAST-MODB initiative for ocean data and information management, Contr. no. MAS2.0093.0075.BE, Coordinating Institution University of Liège (P. Brasseur), 253 pp.

Muir M. S.; 1997: *Possible solar control of North Atlantic oceanic climate.* Nature, **266**, 475-476.

Orlić M., Gačić M. and La Violette P. E.; 1992: *The currents and circulation of the Adriatic Sea.* Ocean. Acta, **15**, 109-124.

Ovchinnikov I. M., Zats V. I., Krivosheya V. G. and Udodov A. I.; 1985: *Formation of Deep Eastern Mediterranean Waters in the Adriatic Sea.* Oceanology, **25**, 704-707.

Pollak M. I.; 1951: *The sources of the Deep Water of the Eastern Mediterranean Sea.* J. Mar. Res., **10**, 128-152.

Roussenov V. and Brasseur P.; 1991: *A Comparative Analysis of Climatological Fields in the Mediterranean Sea.* Univ. of Liège, 25 pp.

UNESCO 1985, *The international system of units (SI) in oceanography.* In: Tech. Papers in Mar. Science, **45**, 124 pp.

Vilibić I. and Leder N.; 1996: *Long-term variations in the Mediterranean Sea level calculated by spectral analyses.* Oceanol. Acta, **19**, 599-607.

Wahba G. and Wendelberger J.; 1980: *Some new mathematical methods for variational objective analysis using splines and cross validation.* Mon. Weath. Rev., **108**, 1122-1143.

Wüst G.; 1961: *On the vertical circulation of the Mediterranean Sea.* J. Geophys. Res., **66**, 3261-3271.

Zoccolotti L. and Salusti E.; 1987: *Observations of a vein of very dense marine water in the southern Adriatic Sea.*

Cont. Shelf Res., **7**, 535-551.

Zore-Armanda M.; 1963: *Les masses d'eau de la mer Adriatique.* Acta Adriatica, **10**, 1-96.

Zore-Armanda M.; 1969: *Water exchange between the Adriatic and the Eastern Mediterranean.* Deep-Sea Res., **16**, 171-178.

Zore-Armanda M. and Gačić M.; 1987: *Effects of bura on the circulation in the North Adriatic.* Ann. Geophysicae, **5**, 93-102.