Changes in Atlantic Water characteristics in the south-eastern Mediterranean Sea as a result of natural and anthropogenic activities

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Abstract

The paper investigates the changes in the characteristics of Atlantic Water (AW) flowing eastwards along the Egyptian coast in the south-eastern Mediterranean during the period 1959–2008.

Vertically, only one water mass could be observed in winter in the upper 200 m layer, whereas in summer, there were three distinct water masses. The subsurface water mass, of Atlantic origin, occupying the 50–150 m layer and characterized by low salinities from < 38.60 to 38.80 PSU, moves throughout the study area from west to east and spreads over a range of density between 27.5 and 28.5 σ_t.

Temperature and salinity have indicated increasing trends for both temperature and salinity during the last 25 years (1983–2008), reaching 0.85°C decade^{-1} and 0.073 PSU dec^{-1}, respectively, for the Mediterranean surface waters. For the Atlantic water, the trends were 0.28°C dec^{-1} for temperature and 0.014 PSU dec^{-1} for salinity.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

Surface salinity trends of the waters coming from the south-eastern Atlantic during the 1980s and 1990s reached 0.04 decade^{-1}, with relatively low values ($\sim$ 0.01 dec^{-1}) just west of the Strait of Gibraltar (Reverdin et al. 2007). This Atlantic water (AW), occupying the upper 200 m layer, is likely to flow into the Mediterranean Sea, through the Strait of Gibraltar, with its general characteristics of $S \approx 36.0$–36.5, $\theta \approx 13.5$–$20°$C and potential density $\sigma_t \approx 26.5$–27 kg m^{-3} (Millot 2007).

Surface AW flowing into the Mediterranean is subject to evaporation and mixing with the underlying waters, causing a progressive increase in salinity from 36.25 in the Gibraltar area to 37.25 in the Strait of Sicily and to values higher than 38.50 in the Levantine Sea. Its west to east path across the Mediterranean can be tracked by the subsurface salinity minimum (Lacombe & Tchernia 1960), representing the signature of their Atlantic origin.

Millot (2007), using an autonomous CTD set at 80 m depth on the Moroccan shelf to monitor the inflowing AW during the period 2003–2007, found that the AW was subject to considerable salinification at a rate of about 0.05 yr^{-1}, i.e. $\sim$ 0.2 in the 4-year period of observation, together with consequent densification ($\sim$ 0.03 kg m^{-3} yr^{-1} in the same period, i.e. 0.12 kg m^{-3}). A much larger warming ($\sim$ 0.3°C dec^{-1}) of the AW was found off the coast of Spain (Pascual et al. 1995).

The temperature and salinity trends of some typical Mediterranean waters were $\sim$ 0.03°C dec^{-1} and 0.01 dec^{-1} respectively. Hypothetically these changes are attributed either to anthropogenic modifications (Rohling & Bryden 1992) or to local climatic changes (Bethoux et al. 1990).

The present work aims to achieve a better understanding of the long-term changes in AW flowing along the Egyptian Mediterranean coast, and to show the seasonal variability in the salinity of the inflowing AW resulting from mixing processes and interannual variability.

1.1. Area of investigation

The study area along the Egyptian Mediterranean coast lies between longitudes 25°30′E and 34°E and extends northwards to latitude 33°N (Figure 1).

Its surface area is about 154 840 km^2, with an estimated water volume of about 225 km^3. The most important feature of this area is the presence of different water masses which converge and mix. These are: a surface water mass of high salinity; a subsurface water mass of minimum salinity and maximum oxygen, which is of Atlantic origin and extends between 50–150 m; an intermediate water mass of maximum of salinity that extends below

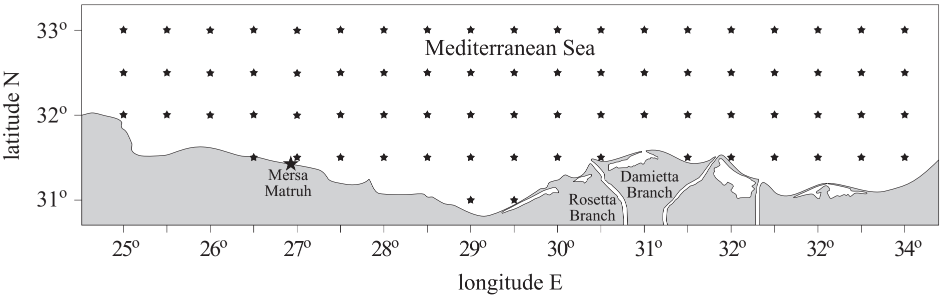

Figure 1. The Egyptian Mediterranean coast

150 m to about 300–400 m depth; and the deep Eastern Mediterranean waters (Said & Eid 1994a).

2. Material and methods

The hydrographic data used in the present study were taken from the results of several expeditions carried out by Egypt and different countries from within and outside the Mediterranean region over the last 50 years (1959–2008). The temperature and salinity were averaged and mapped on a 0.5°x0.5° grid for winter and summer seasons (Figure 1). The number of stations used in this study was 188 in winter and 204 in summer. The grid points with missing data were filled by interpolation of the surrounding values. Winter was represented by data collected during the period from January to March, while summer was represented by data collected from July to September. To seek better quality of hydrographic data, a few observations were rejected because of their poor quality, perhaps due to personal, instrumental, and/or location errors.

The water discharge from the Rosetta Branch of the River Nile for the period 1956–2007 was obtained from the Irrigation Department of the Egyptian Ministry of Public Works and Water Resources (Cairo).

3. Results and discussion

3.1. Coastal water off the Egyptian Nile Delta

Using long-term (1912–1971) time series of data on the Nile River discharge into the Mediterranean before and after the construction of the Aswan High Dam in 1964, Gerges (1976) showed that the average yearly discharge before damming was about 62 km^3. The summer of 1964 witnessed the last normal Nile flood, which was exceptionally high and reached 63.73 km^3. From 1965 onwards, the Nile discharge decreased remarkably to a yearly average of 12.75 km^3 for the 7-year period following the damming (1965–1971), with a total discharge of only 4.10 km^3 in 1971.

The present study shows that the average yearly discharge of the River Nile from 1966 to 2007, i.e. for the last 42 consecutive years, amounted to only 3.92 km^3, representing about 8% of the average value for the period prior to 1965. Figure 2 illustrates the total amount of Nile water discharged yearly to the Mediterranean through the Rosetta Branch during that period.

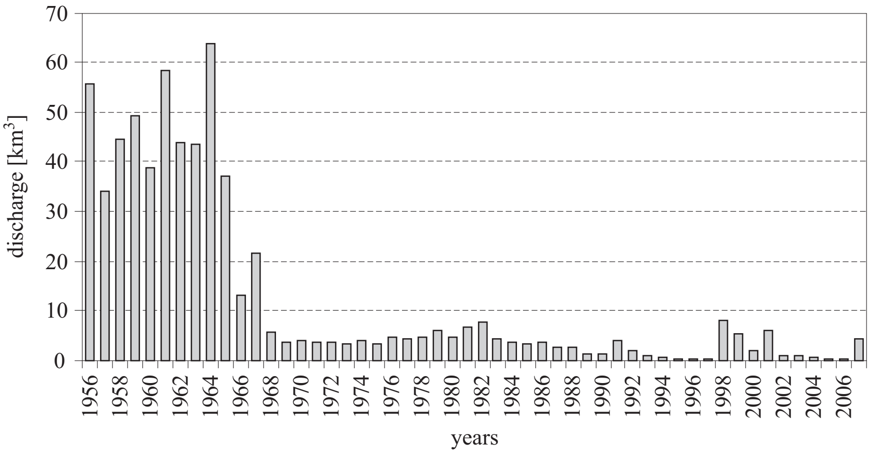

Figure 2. Yearly discharge [km^3] of the River Nile through the Rosetta Branch

The deviation of the Nile water discharge from the average through the Rosetta Branch (Figure 3) indicates that the yearly values during the last three decades are less than the average yearly discharge. Moreover, the annual cycle of the discharge has also changed. The discharge usually occurred from July or August until December or January, with the maximum discharge, representing about 25 to 30% of the total discharge, observed during September/October (Gerges 1976). At present, the discharge is only through Rosetta, and the maximum is recorded in the winter months. About 65% of the total annual discharge flows into the sea during the three months of December, January and February (Figure 4). Such a change in both the total amount and pattern of freshwater discharge to the Mediterranean would certainly affect the physical, chemical as well as the biological conditions of the south-eastern part of the Mediterranean Sea.

The most pronounced and direct effect of the damming of the River Nile is evidently reflected in the salinity distribution in the coastal water off Egypt.

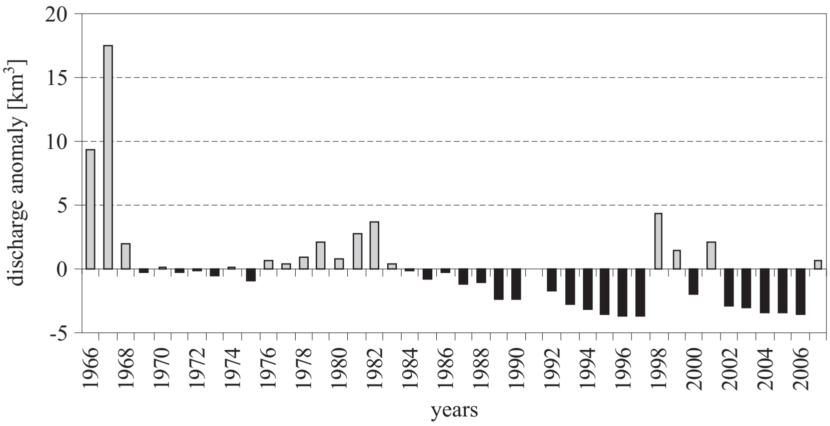

Figure 3. Anomaly of yearly discharge [km^3] of the River Nile

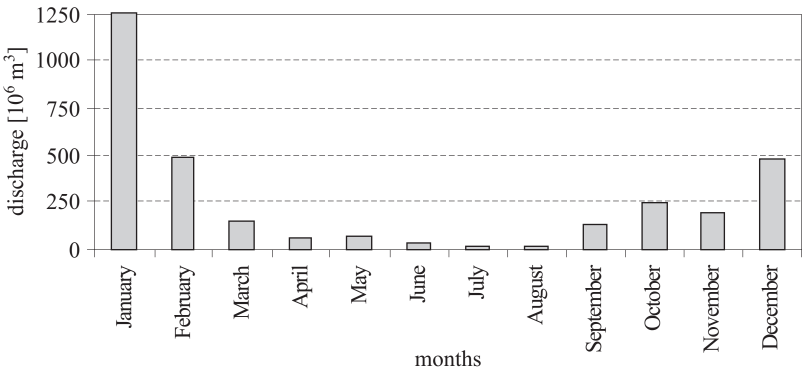

Figure 4. Monthly discharge [km^3] of the River Nile during 1966–2008

The salinity distribution in this region is highly complex owing to the interaction between different factors: the intensive evaporation, the flow of low salinity AW, the existence of intermediate water of high salinity (Levantine water) and the river discharge. The last of these factors is now of minor importance, and hence any distribution of salinity is controlled by the other factors.

Figure 5 illustrates the long-term variation of surface salinity in the coastal water of the study area during 1964–2008. As mentioned earlier, in 1964, the river discharge was the greatest since 1956, and the surface salinity was very low (26.675 PSU). From 1966 onwards, a considerable decrease in freshwater discharge was recorded and a remarkable increase in salinity was observed. The salinity increased from 28.309 PSU in 1966 to around 38 PSU in the 1970s and reached more than 39 PSU in 2008.

Figure 5. Long-term variation in the surface salinity of the coastal water of the study area during 1964–2008

3.2. Characteristics of Atlantic waters off the Egyptian coast

The following are the main characteristics of Atlantic Water, observed along the Egyptian Mediterranean coast, deduced from an analysis of the horizontal and vertical distributions of these characteristics in winter and summer.

In winter, the surface water temperature varied between 16.6 and 18.5°C, with slightly colder or warmer spots (Figure 6a). There is a general tendency for temperature to increase eastwards, with the lowest values (16.6–16.8°C) observed at longitudes between 26° and 30°E and latitudes 32–33°N, while the highest values are confined to the eastern part of the study area. A region of water temperature >18.0°C is observed at the offshore stations between longitudes 31°30′ and 32°30′E and latitudes 32–33°N (Figure 6a).

The surface salinity changes between 38.60 and 39.30 PSU, with a generally increasing eastward trend (Figure 6b). The most prominent feature of the salinity distribution at the surface is the presence of a nucleus of salinity >39.00 PSU that lies between longitudes 27 and 29°E. This nucleus is characterized by low temperature (16.6°C) and high density 28.7 σ_t (Figure 6c). The above feature coincides with the location of the well-recognized gyre known as the Mersa Matruh gyre. This gyre is one of several such sub-basin scale gyres interconnected by intense jets and meandering currents that were established long ago in the south-eastern Levantine basin by the POEM Group (1992).

The Mersa Matruh gyre has been given different names such as the ‘Egyptian anticyclonic gyre’ by Said (1984, 1990), ‘The Egypt high’ by

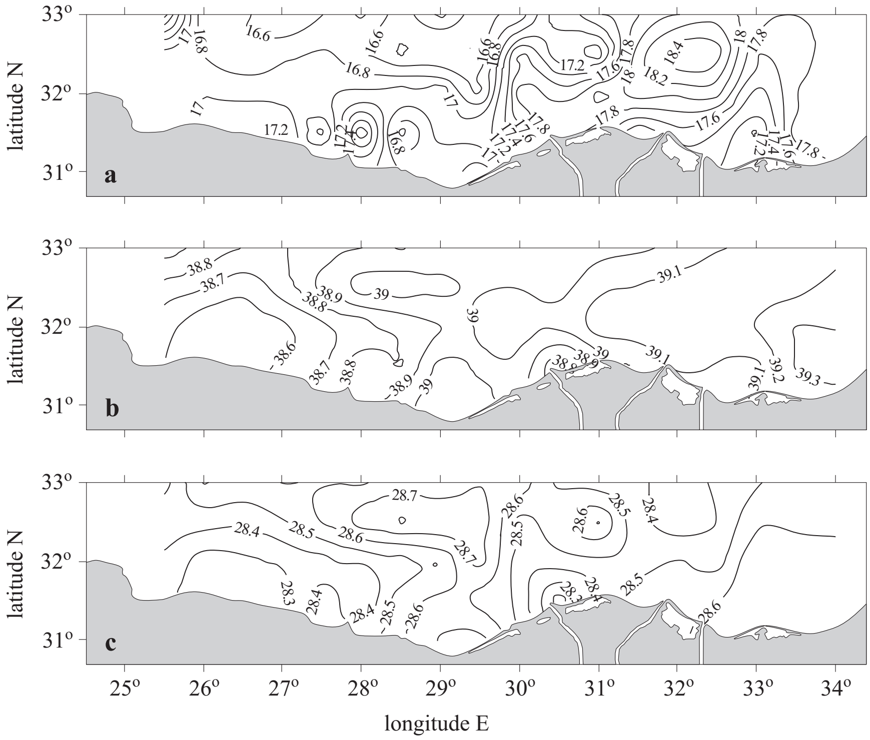

Figure 6. Surface distribution of water a) temperature, b) salinity and c) density during the winter season

Brenner (1989) and the 'Mersa Matruh gyre' by Özsoy et al. (1989). The Mersa Matruh gyre is characterized by an anticyclonic circulation from the surface to 500 m depth during the winter and summer seasons (Said & Eid 1994b). The gyre splits into two centres at 50 and 100 m. Below these levels, the gyre intensifies and splits into multiple centres. The eddy centres are shifted horizontally with depth. At 500 m depth, the gyre could be observed during both seasons. These features were also observed by Eid & Said (1995) in their work on the circulation off the Egyptian coast as deduced from steric height distributions. Later, Said & Rajkovic (1996) further observed that the Mersa Matruh gyre exhibits a strong winter to summer variability, reversing its general direction from anticyclonic to cyclonic.

The geostrophic current velocity at the edge of the Mersa Matruh gyre varied between 12.5 and 29.1 cm sec^{-1} in winter and between 6.5 and 13.1 cm sec^{-1} in summer (Said & Eid 1994b).

In order to study the vertical distribution of the hydrographic parameters, the average winter values of each of the water temperature, salinity and density σ_t were presented on a vertical section taken parallel to the

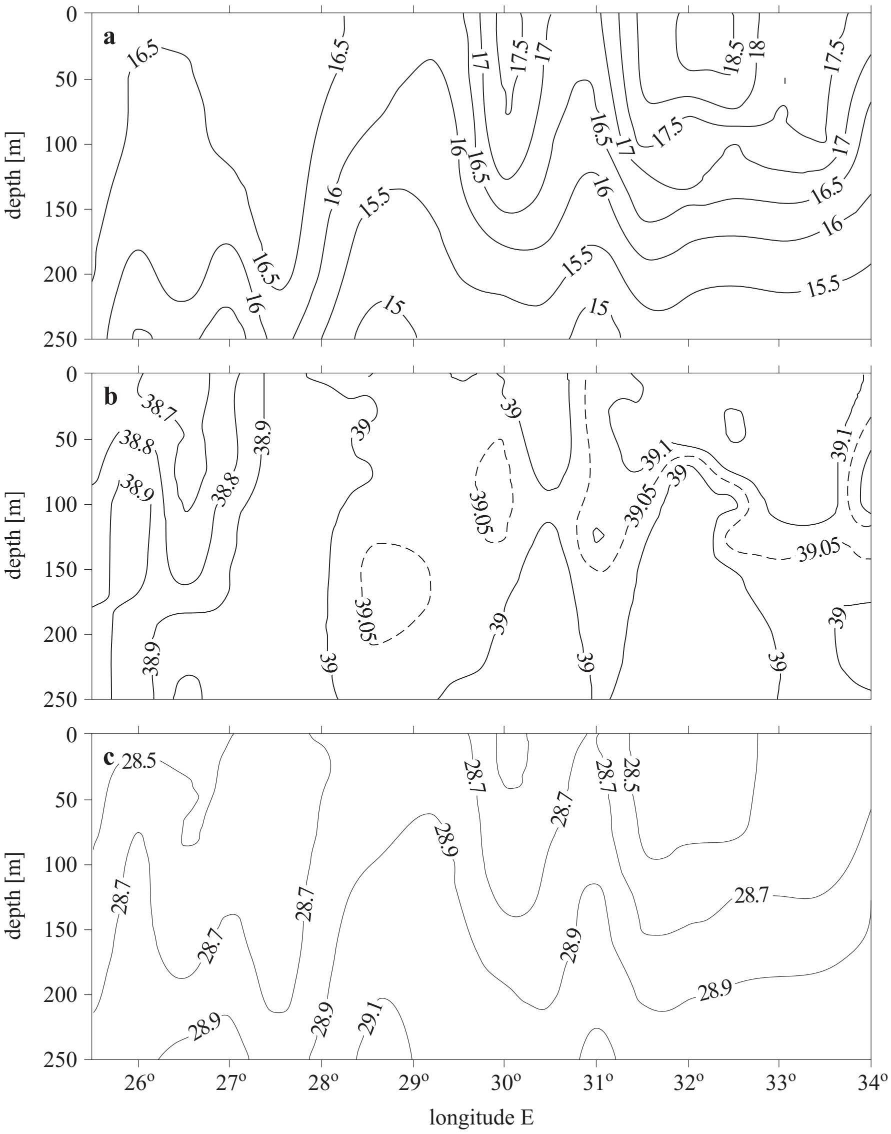

Figure 7. Vertical distribution of average a) water temperature, b) salinity and c) σ_t on a transect along latitude 32°30′N during winter

Egyptian Coast along latitude 32°30′N and between longitudes 25°30′ and 34°E (Figure 7).

The vertical distribution of the water temperature in the upper 200 m layer of this section shows great uniformity in temperature in the western part of the study area, which could be attributed to severe cooling at the sea surface in winter. In the eastern part of the area, the water temperature decreases from 18.5°C at the surface to 15.5°C at 250 m depth, indicating a gradient of 0.012°C m^{-1}. Salinity values increase eastwards and also show great homogeneity, obviously due to vertical mixing (Figure 7b).

Only one surface water mass could be observed during winter in the upper 200 m layer. It is characterized by temperatures from 15° to 17°C, a salinity maximum in the range of 38.90–> 39.10 PSU and corresponding density values of 28.5–28.9 σ_t (Figure 7). This water mass was previously observed and discussed in detail by Said et al. (2007).

In summer, the surface water temperature varied between 22 and 28°C, except in an area with slightly colder water (Figure 8). This is the area of

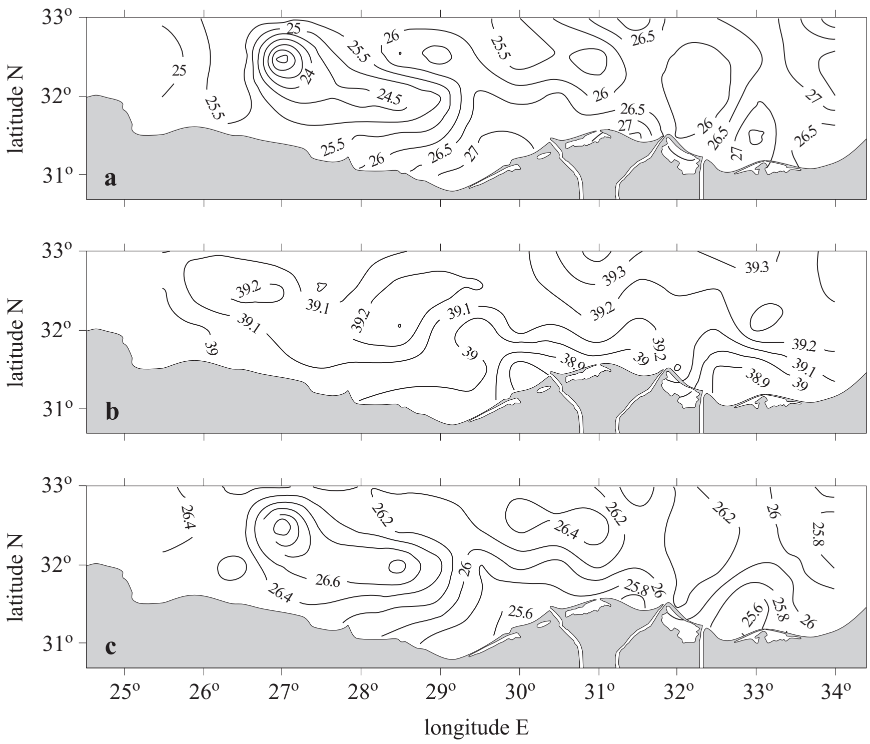

Figure 8. Surface distribution of water a) temperature, b) salinity and c) density during the summer season

the above-mentioned Mersa Matruh gyre, which lies between longitudes 27° and 29°E. The gyre area is characterized by low water temperatures (22–25°C), salinities of 39.10–39.20 PSU and a high density (26.4–27 σ_t).

Figure 9 illustrates the vertical distributions of the temperature, salinity and potential density σ_t for a transect along latitude 32°30′N between

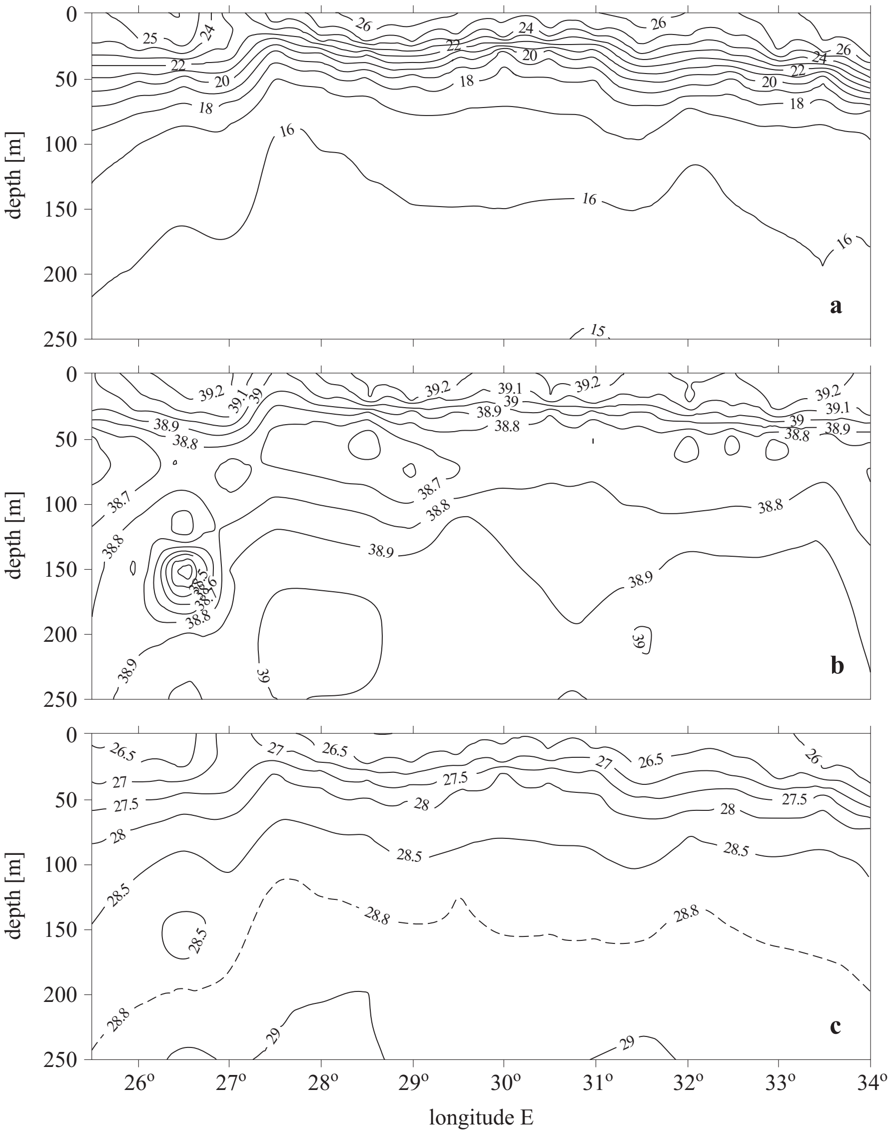

Figure 9. Vertical distribution of average a) water temperature, b) salinity and c) σ_t on a transect along latitude 32°30′N during summer

longitudes 25°30′ and 34°E. The temperature distribution clearly shows that due to the warming effect of the sun in summer, the surface water temperature increases to 28.0°C, and a strong thermocline is clearly developed. Within the 20–100 m layer, the temperature decreases, on average, by about 6°C from 24 to 18°C, giving rise to a large vertical temperature gradient. High salinity values of 38.90–39.20 PSU are found in the upper 50 m layer. The salinity generally decreases with increasing depth to reach 38.80 PSU at 150 m depth but then increases downwards. A layer of salinity values from < 38.60 to 38.80 PSU is observed at 50–150 m depth throughout the area from west to east. It spreads over the range of density between 27.5 and 28.5 σ_t.

Three water masses could be observed in the upper 250 m layer in summer. The surface water mass occupies the upper layer from 30 to 50 m depth, and has temperatures from 22° to 28°C and salinities from 38.8 to 39.20 PSU. Then there is a subsurface water mass with temperatures of 16 to 22°C and minimum salinity (< 38.60–38.80 PSU). This water mass is of Atlantic origin, is characterized by maximum oxygen contents of > 5.2 ml l^{-1} (Said & Eid 1994a) and occupies the 50–150 m layer. Below this layer, the Levantine intermediate water mass (LIW) of temperature < 16°C and maximum of salinity (38.90–39.10 PSU) is clearly identified. This water mass is formed in some regions of the eastern Mediterranean, from where

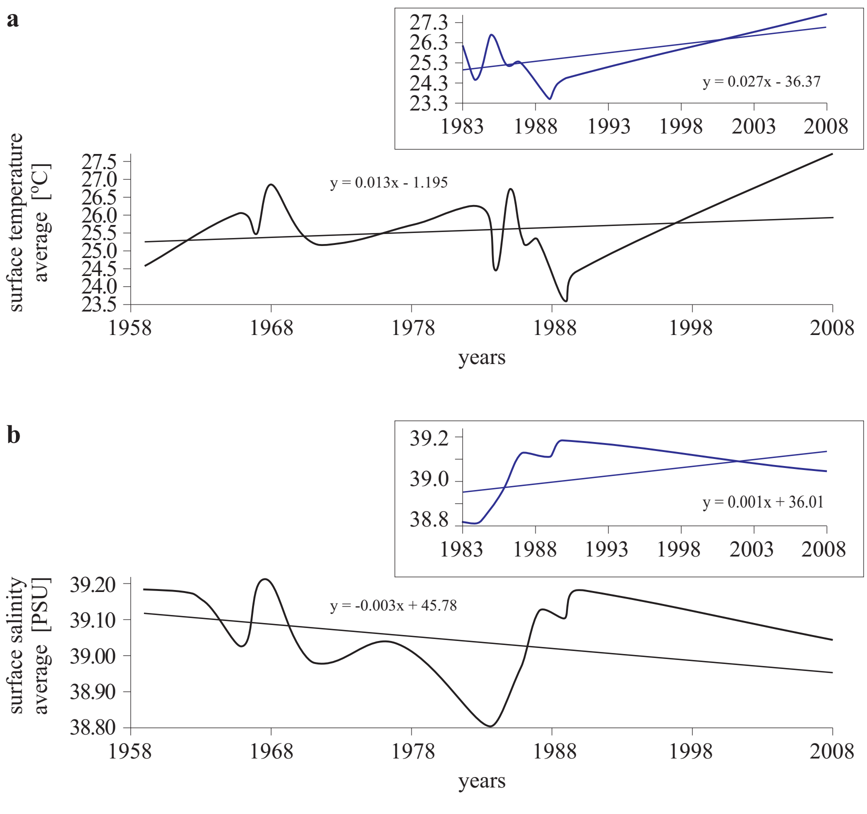

Figure 10. Annual average of a) temperature and b) salinity for Mediterranean surface water during 1958 to 2008

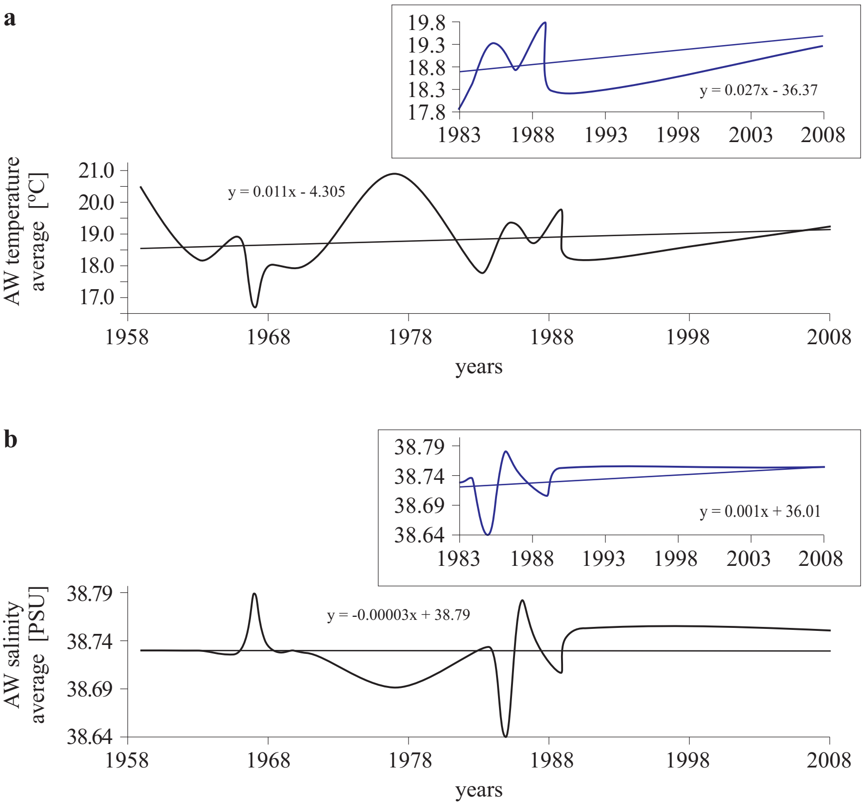

Figure 11. Annual average of a) temperature and b) salinity for Atlantic water during 1958 to 2008

it spreads. Regions of LIW formation in the eastern Mediterranean have been extensively discussed and are more or less identified by Wüst (1961), Morcos (1972), Ozturgut (1976), Özsoy et al. (1981), Ovchinnikov (1984), Sukhovey & Said (1985), Said (1985), Abdel-Moati & Said (1987) and Said & Karam (1990).

In the present study, long-term comparisons of water temperature and salinity for the Mediterranean surface waters and the Atlantic waters along the Egyptian Coast are shown in Figures 10 and 11. The seasonal cycle of the local temperature differs markedly from that of the salinity. For the Mediterranean surface waters, the annual average of temperature and salinity (Figure 10) fluctuated between 23.51 and 27.71°C and 38.81 and 39.21 PSU, respectively, with a general trend of increasing temperature and decreasing salinity throughout the study period. During the last 25 years (1983–2008), the decadal temperature and salinity trends reached 0.85°C dec^{-1} and 0.073 PSU dec^{-1} respectively.

For Atlantic waters, the annual average temperature was between 16.72 and 20°C, giving a temperature trend of 0.28°C dec^{-1} for the last 25 years. In the meantime, the annual average salinity of AW varied between 38.64 and 38.788 PSU, indicating a salinity trend of 0.014 PSU dec^{-1} for the last 25 years. This increase in temperature and salinity of AW with time is therefore confirmed as being attributable to anthropogenic modifications, especially the damming of the River Nile, in addition to local climatic changes, as suggested earlier by Rohling & Bryden (1992) and Bethoux et al. (1990).

4. Conclusions

1. As a result of the erection of the Aswan High Dam in 1965, the yearly fresh water discharge of the River Nile into the south-eastern Mediterranean has decreased to a remarkable extent. The annual cycle of the discharge has also changed. At present, the discharge is only through the Rosetta Branch of the Nile Delta, and the maximum discharge is recorded in winter months. Such a change in both the total amount and pattern of freshwater discharge has obviously affected the characteristics of the coastal waters off the Nile Delta.

2. Three water masses could be observed in summer, namely, a surface water mass in the upper 30–50 m with temperature 22–28°C and salinity 38.8–39.20 PSU; a subsurface water mass of Atlantic origin occupying the 50–150 m layer with temperature 16–22°C and minimum salinity ($<$ 38.60–38.80); and the Levantine intermediate water mass (LIW) with temperature $<$ 16°C and maximum salinity (38.90–39.10 PSU).

3. Temperature and salinity anomalies of the surface water indicate increasing trends in the last 25 years that have reached 0.85°C dec^{-1} and 0.073 PSU dec^{-1} respectively. For the Atlantic waters, the rate of increase was 0.28°C dec^{-1} for the temperature and 0.014 PSU dec^{-1} for the salinity.

4. The observed increase with time of temperature and salinity of the Atlantic Water in the eastern Mediterranean off the Egyptian coast is hereby confirmed to be attributed to two main factors: anthropogenic modifications, especially the damming of the River Nile, and to local climatic changes. The amount and type of information available to date on the latter factor calls for further work to be carried out on this question.

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