Athens Journal of Sciences- Volume 8, Issue 1, March 2021 – Pages 9-22

Behaviour of Temperature Variations in Subsurface Layers in the South-Eastern Mediterranean Sea

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The present work is a qualitative research, which aims at drawing the general behaviour of variations in the subsurface seawater temperatures within three distinctive subsurface layers in the south-eastern Mediterranean region. The work is based on hydrographic data collected over 65 years (1948–2012). The investigated layers are the subsurface, the intermediate and the deep water layers. The general trend of the mean annual temperature anomaly (MATA) was examined using the linear and quadratic regressions. Results revealed that the MATA over the water column in the south-eastern Mediterranean has the same trend, regardless of the place (layer) of investigation. Linearly, all MATA have increasing trends with different rates, with the exception of the 75 m level, which has a decreasing trend following that previously concluded for the surface water in the region. Also, the quadratic approach reflects the same trend of MATA over the water column, with different years of minimum occurrence. These same trends from the surface to deep can be attributed to the vertical convection processes in this region, and to the expanded impact of solar radiation which may reach more than 30 m depth.

Keywords: *South-eastern Mediterranean Sea, seawater temperature, linear regression, quadratic regression, cyclic trend*

Introduction

The Mediterranean Sea is known to be one of the few basins in the world where physical and dynamical processes interact; due to the deep convection processes and formation of intermediate and deep water masses (Wu and Haines 1996). The Mediterranean is known to play an indirect role in the water formation processes and thermohaline circulation in the North Atlantic with its very saline outflow to the Atlantic through the Strait of Gibraltar (Reid 1979, Lozier et al. 1995, Bethoux et al. 1998). In recent decades, the Mediterranean Sea has examined rapid change of increase in its temperature and salinity (Rohling and Bryden 1992, Schroeder et al. 2017, Iona et al. 2018), reflecting the global general warming trend (Levitus et al. 2012). During the period between late 1980s and mid-1990s, the circulation pattern the eastern Mediterranean basin practiced a remarkable change from the surface to the deep layers (Iona et al. 2018).

In the Eastern Mediterranean Basin, three water masses can be identified:

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https://doi.org/10.30958/ajs.8-1-1 doi=10.30958/ajs.8-1-1

1. The surface water, of Atlantic origin, which invades the eastern Mediterranean basin through the Strait of Sicily and extends from the surface to a depth of more than 100 m. During the cold period of the year, this surface water mass is a mixture of the surface old Mediterranean waters and the subsurface waters of Atlantic origin. In the warm period of the year, the former is overlying the later.
2. The Levantine Intermediate Water (LIW), which is formed by winter cooling and continuous evaporation processes in the region south-southeast of Rhodes. This layer extends from 150 to 600 m depth, and flows westward and out through the Strait of Gibraltar into the Atlantic Ocean (Maiyza 1984, Millot and Taupier-Letage 2005).
3. The Deep Eastern Mediterranean Water, which is partially formed by strong winter cooling, continuous evaporation and wind mixing processes, in the cold years, in the area between Rhodes and Crete islands (Maiyza 1984). According to Nielsen (1912), the Adriatic is also considered as a main source of this water mass.

All these water masses are strictly related in a form that any significant modification involving a single water mass may propagate its effects to the others. The observational evidence shows that significant surface anomalies in the Eastern Mediterranean may affect its deeper layers (Astraldi et al. 2002).

The Mediterranean Sea is characterized by seawater temperatures varying between 15.0°C and 17.0˚C along its upper 400 m in winter, while in summer, due to the warming effect, the sea surface temperature (30 - 50 m) increases to 28.0˚C and, consequently, a strong thermocline is developed (Millot and Taupier-Letage 2005). Between 50 and 100 m depth, the seawater temperature ranges between 17.0°C and 22.0°C; identified as the Atlantic water mass (Sharaf El-Din and El-Gindy 1987). Below this Atlantic layer, an intermediate water mass takes place with a temperature ranging between 15.0°C and 17.0˚C. Below the 1,000 m depth, the seawater temperature fluctuates between 13.3°C and 13.5˚C (Said 1990). Using Extended Bathy-Thermograph (XBT) data, the temporal and spatial variabilities of seawater temperatures were found to be significantly different in the Western and Eastern Mediterranean Basins (Fusco et al. 2003). While, in the former the winter cooling results in a loss of thermal stratification, the latter examines permanent stratification varying with the seasons and strongly affected by the system of gyres.

The long-term trends of temperature in the Mediterranean Sea have been the subject of many researches since the 1990s. Table 1 in Vargas-Yanez et al. (2009) summarises the main findings of the previous work on the long-term trends of temperature in the Mediterranean basin over the period 1990-2006. The long term variations in the sea surface and air temperatures anomalies in the south-eastern Mediterranean region were previously investigated by Maiyza and Kamel (2009), Maiyza et al. (2010), Maiyza et al. (2011). Their results revealed a cyclic behaviour in the changes of these thermal anomalies over decades instead of the common idea of continuous increase. The linear trends of variations in the two parameters were also examined by many authors, of them: Nykjaer (2009), Samuel-Rhoads et al. (2013), Shaltout and Omstedt (2014), Adloff et al. (2015), Tonbol and El-Geziry (2015), Pastor et al. (2018), Tonbol et al. (2018).

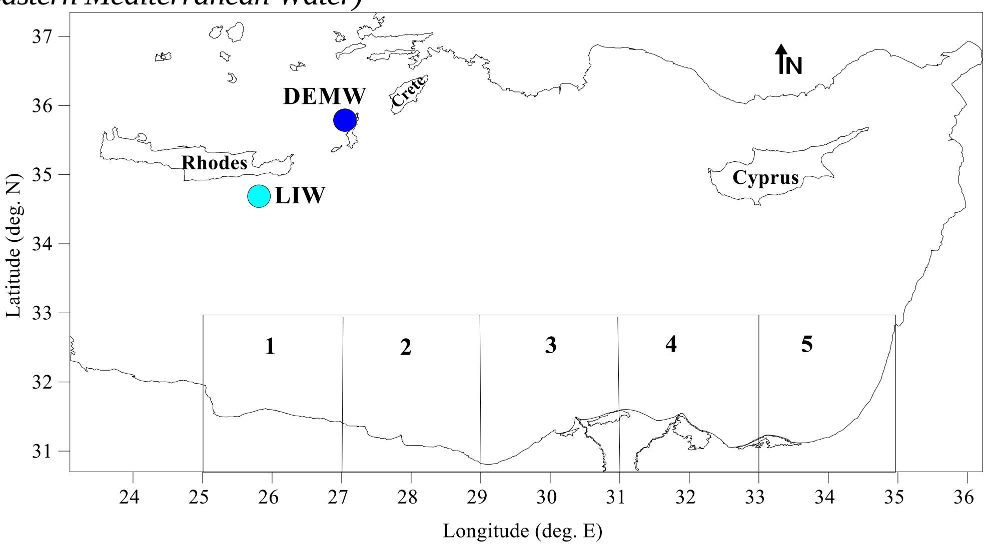
The present work is a qualitative research aiming to draw the general behaviour of variations in the seawater temperature anomalies in the south-eastern Mediterranean region at three distinctive layers, namely: subsurface, intermediate and deep. The work is based on hydrographic data collected between 1948 and 2012. This can be considered as a continuation of the previous work, by the authors, on the variations of sea surface temperature; in order to build a robust conclusion on the behaviour of variation of seawater temperature in the south-eastern Mediterranean region.

Data and Methods of Analysis

The present area of investigation occupies the region of the south-eastern Mediterranean Sea off the Egyptian Mediterranean coast, divided into 5 grids of 2° x 3° size each. This area extends latitudinally from the Egyptian Mediterranean coast to 33° N and longitudinally from 25° E to the Asian coast (Figure 1).

The available seawater temperature data covers 65 years (1948–2012). The data files arise from the World Data Centre (WDC) A (Washington) & WDC B (Moscow), from the Russian cruises through the Physical Oceanography of Eastern Mediterranean (POEM) project and from the Egyptian National Oceanographic Data Centre (ENODC). However, the present work can be considered as a qualitative research; due to the well-known bad spatial and temporal data distributions.

Figure 1. *The Five Grids of Interest, and Locations of Water Mass Formation in the Eastern Mediterranean (LIW: Levantine Intermediate Water, DEMW: Deep Eastern Mediterranean Water)*



The whole data set is categorised in three main subsurface temperature groups: a subsurface layer (represented by 75 and 100 m levels), an intermediate layer (300 and 500 m levels) and a deep layer (1,000, 1,500 and 2,000 m levels). Variations in the seawater temperature anomalies in each layer are discussed.

The deviation from the monthly mean, obtained from the Climatological Atlas of the Mediterranean Sea (Maiyza et al. 1993), is computed on monthly basis to express the monthly temperature anomaly (MTA), using the following equation:

$$\Delta T = T - T_m \quad (1)$$

where,

ΔT is the MTA,
T is the mean monthly temperature, mean for specific month every year and
T_m is the monthly mean temperature, mean for specific month of all years

The mean monthly temperature anomaly (MMTA) of all occupied grids is considered as the MMTA of the area under study. Also, the mean annual temperature anomaly (MATA) of all occupied months is considered as the area MATA.

Standard deviation and variance were calculated for the entire population of raw data from which the means (monthly, annual, and anomalies) at each level were calculated; to show whether the derived annual values are reliable or not.

The general trends of the MATA variations are examined using both the linear and the quadratic regression approaches. The representative equations for each level in every specified layer are generated.

Results

Statistical Summary of the Present Data Population

Table 1 shows the minimum, maximum, arithmetic mean, standard deviation and variance of the calculated anomaly at each examined level. The year of occurrence is also mentioned. It can be shown that the maximum MATA is reached in the same year over the different levels of concern at every layer. This has one exception: the 2,000 m, which differed that the two levels in the same deep layer: 1,000 and 1,500 m. The low values of standard deviations and variances reflect a sort of homogeneity in the applied data.

Table 1. *Statistical Analysis of MATA at Every Level*

	75 m	100 m	300 m	500 m	1000 m	1500 m	2000 m
Min.(°C)	-1.75 (1967)	-2.47 (1958)	-0.99 (1993)	-0.19 (1962)	-0.03 (1965)	-0.11 (1965)	-0.12 (1948)
Max.(°C)	+4.64 (2007)	+6.09 (2007)	+0.39 (2012)	+0.19 (2012)	+0.05 (1990)	+0.03 (1990)	+0.20 (2012)
Mean(°C)	-0.04	+0.15	-0.06	-0.02	+0.005	-0.07	+0.02
St. Dev.	1.20	1.30	0.29	0.10	0.03	0.04	0.08
Var.	1.46	1.80	0.08	0.01	0.00	0.002	0.006

Subsurface Layer (75 and 100 m levels)

Over the period of investigation (1948–2012), the linear trend of the MATA distribution at the 75 m level (Figure 2) has the same decreasing trend concluded by Maiyza and Kamel (2009) for the surface layer. The same slight decrease in the MATA trend is proven with a rate of -0.003°C/year. On the other hand, at the 100 m level the liner trend (Figure 3) is reversed to be an increasing one with a rate of +0.02°C/year. From a quadratic point of view, the trends of two anomalies tend to follow that of the surface temperature anomaly concluded by Maiyza and Kamel (2009). The obtained parabolic curves seem to be of cyclic behaviour. However, this cycle is more obvious for the 75 m level (Figure 2) than for the 100 m one (Figure 3). While for the 75 m level there is a general decrease from 1948 to 1985 followed by a general increase onwards, there is an all over decrease from 1948 to 1955 followed by an onward increase for the 100 m level.

At the 75 m level, the trend models of the MATA are respectively represented by the Equations:

$$y = -0.0035\ x - 0.0942;\ r = 0.08 \quad (2)$$
$$y = 0.0003\ x^2 – 0.0223\ x + 0.1441;\ r = 0.13 \quad (3)$$

At the 100 m level, the variations of the subsurface MATA are respectively given by:

$$y = 0.0234\ x – 0.6726;\ r = 0.31 \quad (4)$$
$$y = 0.0004\ x^2 – 0.0056\ x – 0.2748;\ r = 0.32 \quad (5)$$

The predicted half cycle at the 75 m level, based on the roots pf the resultant quadratic equation (3) extended from 1954 to 2014, i.e., 60 years, while that at the 100 m level (Equation 5) extended from 1929 to 1981, i.e., 53 years.

Figure 2. *General Regressions of Subsurface Temperature at the 75 m Level*

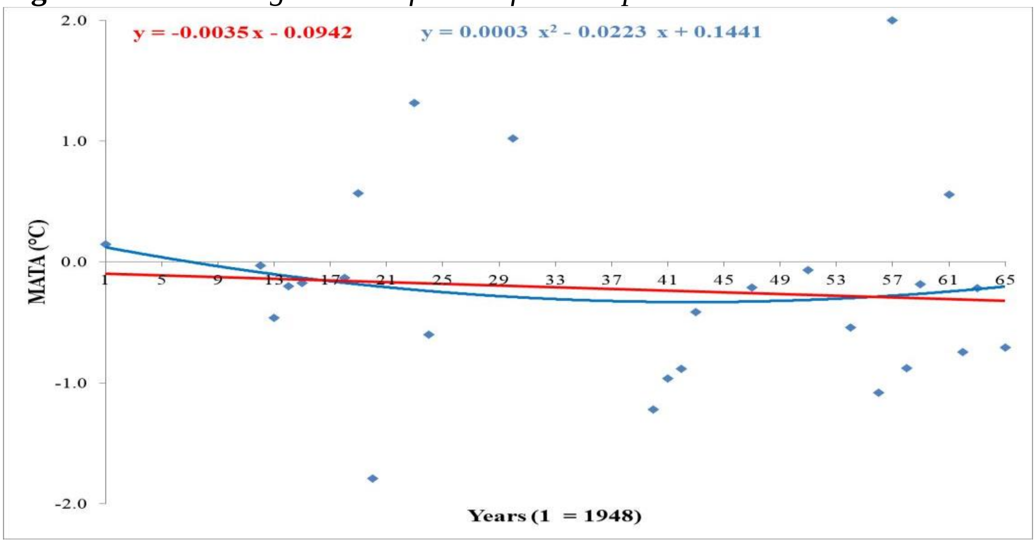
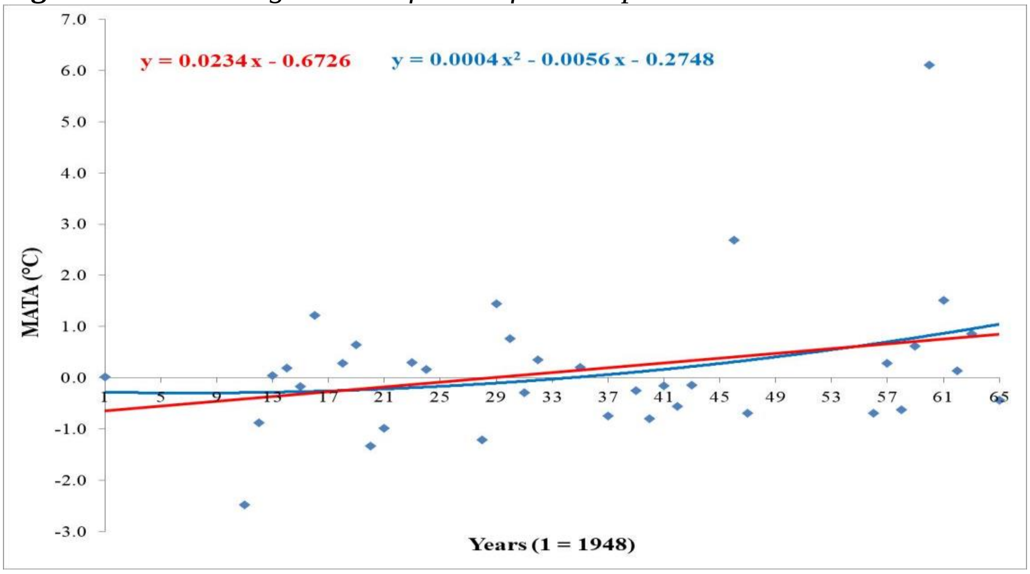


Figure 3. *General Regressions of Subsurface Temperature at the 100 m Level*



Intermediate Layer (300 and 500 m Levels)

The Eastern Levantine Intermediate Water (ELIW) mass is the warmest and saltiest mass created in the entire Mediterranean basin and can simply be followed up to Gibraltar just beneath the incoming surface Atlantic waters (El-Geziry 2010, El-Geziry and Bryden 2010). It is a fact that this LIW mass, during its spreading phase, reaches the basin's deep water formation areas and, being extremely saline (39 salinity), helps in the preconditioning of the water column (Drakopoulos and Lascaratos 1999).

The distributions and regressions of the MATA at the two levels presenting the LIW are shown in Figures 4 and 5. Linearly, the MATA at the two levels examines increasing trends with rates of +0.002 °C/yr and +0.005 °C/yr for the 300 m and 500 m levels, respectively. Quadratically, the two figures may reflect a general cyclic trend in the intermediate MATA, as in the subsurface layer. This is more obvious in the 300 m level with a general decrease from 1948 to 1974, followed by an onward increase.

The MATA regression models at the 300 m level are respectively presented by the Equations:

$$y = 0.0016\,x - 0.0543;\ r = 0.13 \quad (6)$$
$$y = 0.0003\,x^2 - 0.0156\,x + 0.1541;\ r = 0.42 \quad (7)$$

The MATA regression models at the 500 m level are given by:

$$y = 0.0054\,x - 0.1763;\ r = 0.91 \quad (8)$$
$$y = 4E\text{-}05\,x^2 + 0.003\,x - 0.1504;\ r = 0.91 \quad (9)$$

The roots of Equations (7) and (9) revealed half cycles of 28 years (1960–1987) and of 144 years (1839–1982) for the MATA at the 300 m and 500 m levels of intermediate layer, respectively.

Figure 4. *General Regressions of Intermediate Temperature at the 300 m Level*

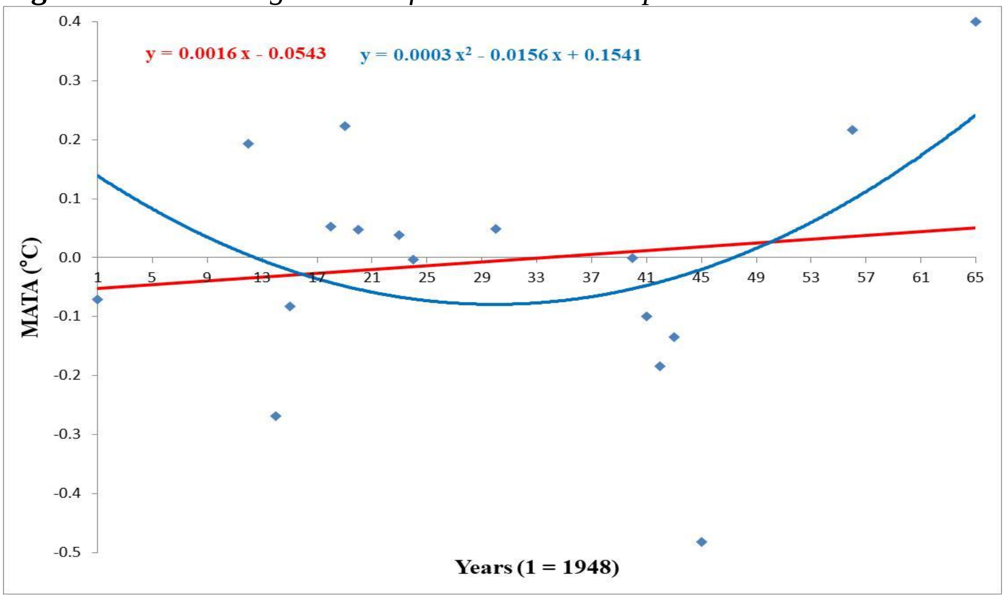
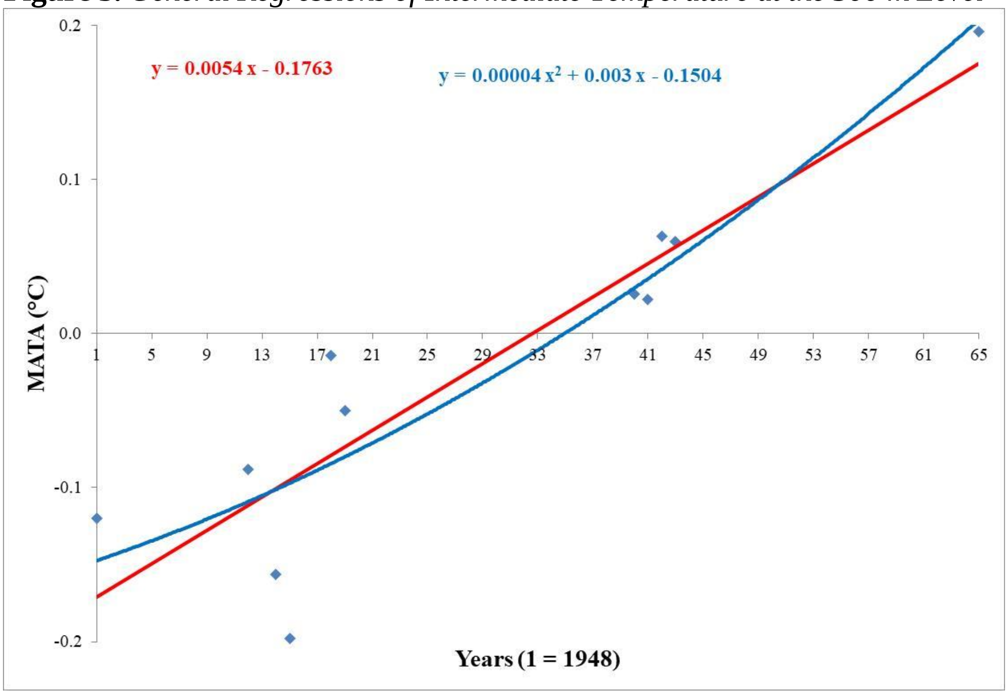


Figure 5. *General Regressions of Intermediate Temperature at the 500 m Level*



Deep Layer (1,000, 1,500 and 2,000 m Levels)

The source of formation of the deep and near-bottom waters in the Eastern Mediterranean Sea was suggested by Nielsen (1912) to be in the southern regions of the Adriatic and Aegean Seas. Pollak (1951) suggested only the Adriatic and that the deep outflow through the Strait of Otranto was far from continuous. Wüst (1961) noted the maximum value of dissolved oxygen content (> 4.4 ml/1) and minimum water temperature at the deep (2,000 m) levels (<13.2 °C) to the south of the islands separating the Aegean from Levantine Seas. Maiyza (1984) concluded that formation of the deep water mass takes place to the east of Crete Island in the northern Levantine Sea. His conclusion agrees and resolves the contrast between the three mentioned results of Nielsen (1912), Pollak (1951) and Wüst (1961).

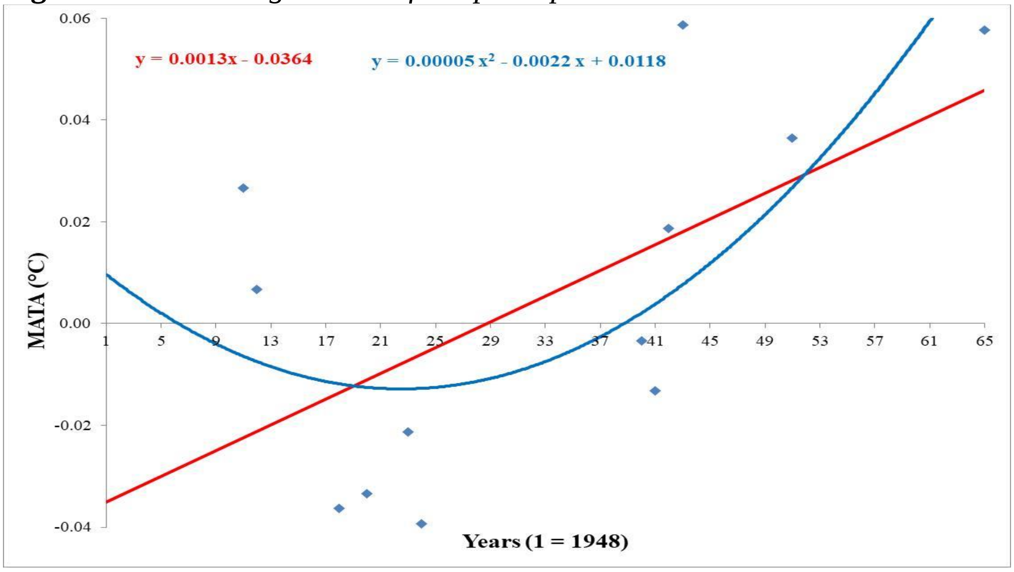
Field experiments conducted in the early 1980s in the international co-operative research programme: Physical Oceanography of the Eastern Mediterranean (POEM) demonstrated that a single homogeneous deep water body filled the entire Eastern Mediterranean below a depth of about 1,200 m (Manca et al. 2002). In the present work, the 1,000 m level is considered as the upper limit of this deep layer. It is well-observed that the MATA variations and trends at this level (Figure 6) are still following the general behaviour of a general linear increase but with a rate of +0.001°C/yr, and with a parabolic quadratic distribution with a minimum value in 1970. The regression models of the MATA at the 1,000 m level are respectively presented by the following Equations:

$$y = 0.0013\,x - 0.0364;\ r = 0.61 \tag{10}$$
$$y = 5E\text{-}05\,x^2 - 0.0022\,x + 0.0118;\ r = 0.72 \tag{11}$$

The predicted half cycle at the 1000 m level, according to Equation (11) extended from 1953 to 1985, i.e., 33 years.

At the 1500 m level (Figure 7), the linear trend of the MATA variations examined the highest rate of increase in the calculated rates, being +0.003°C/yr. The quadratic variations, on the other hand, are still reflecting a cyclic trend with a minimum occurrence in 1969.

Figure 6. *General Regressions of Deep Temperature at the 1000 m Level*

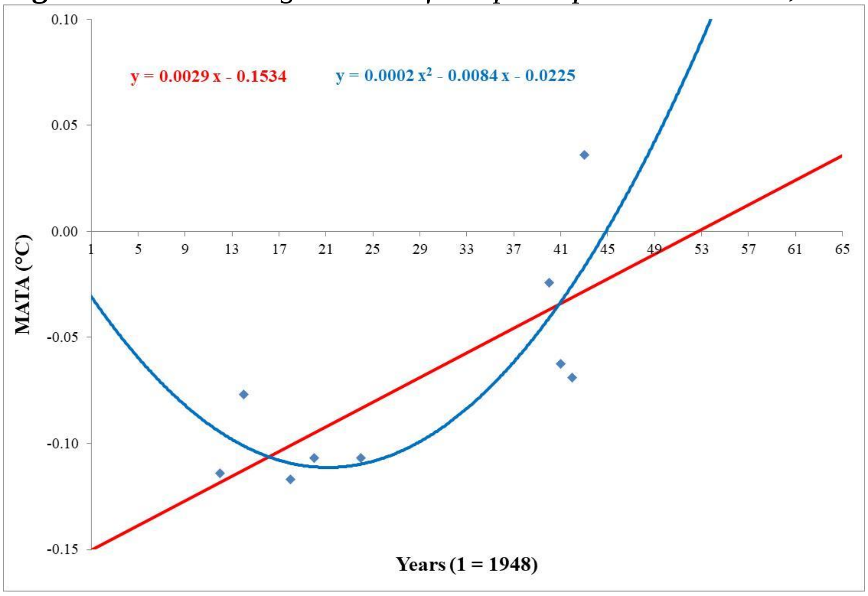


The two regression models at the 1,500 m level can be respectively presented by the following Equations:

$$y = 0.0029\, x - 0.1534;\ r = 0.75 \quad (12)$$
$$y = 0.0002\, x^2 - 0.0084\, x - 0.0225;\ r = 0.81 \quad (13)$$

At the 1,500 m level, the half cycle of the MATA, roots of Equation (13), extended from 1945 to 1992, i.e., 48 years.

Figure 7. *General Regressions of Deep Temperature at the 1,500 m Level*

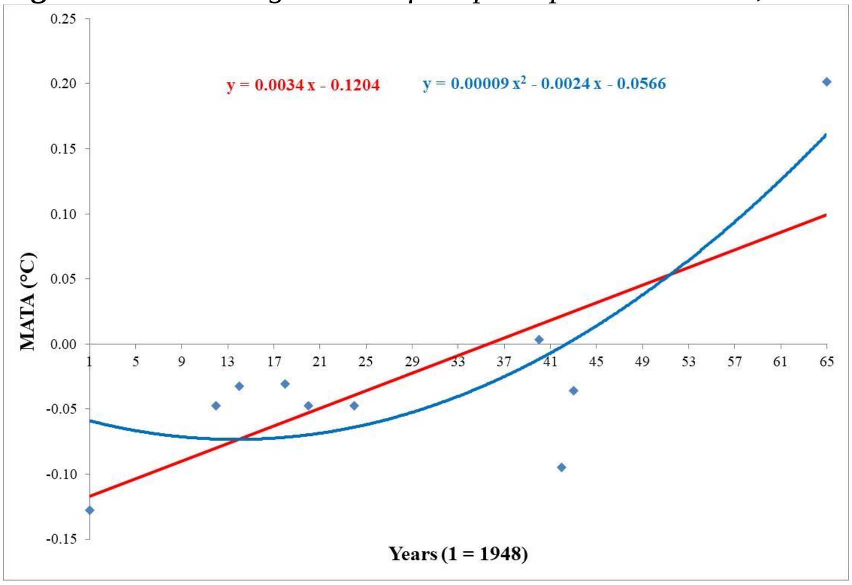


The general trends of the MATA variations in the 2,000 m level are shown in Figure 8. Linearly, the same rate of increase at the 1,500 m level, of +0.003°C/yr, still exists. From a quadratic point of view, there is a general decrease from 1948 to 1961, followed by a general increase onwards. The regression models of the MATA at the 2,000 m level are respectively presented by the following Equations:

$$y = 0.0034\, x - 0.1204;\ r = 0.74 \quad (14)$$
$$y = 9E\text{-}05\, x2 - 0.0024\, x - 0.0566;\ r = 0.83 \quad (15)$$

The roots of Equation (15) of the MATA occurrence at the 2,000 m level revealed a half cycle extending from 1934 to 1989, i.e., 56 years.

Figure 8. *General Regressions of Deep Temperature at the 2,000 m Level*



Discussion

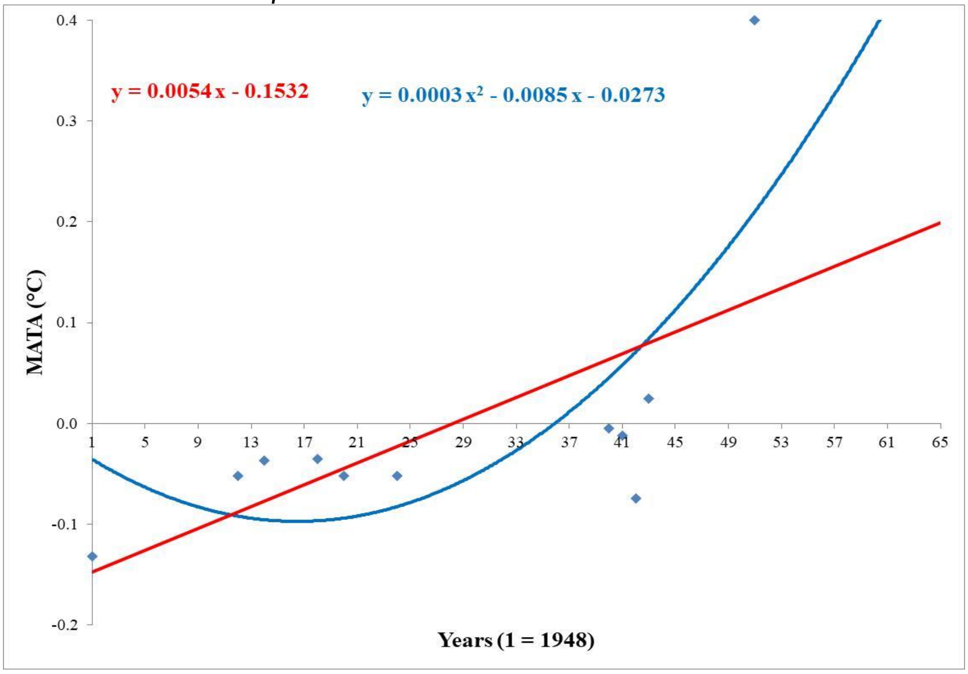
The long-term variations in the sea surface temperature anomaly in the south-eastern Mediterranean basin were previously studied by Maiyza and Kamel (2009) and Maiyza et al. (2010). Their results revealed a cyclic behaviour of variation with a minimum surface temperature anomaly in the year 1985.

The present work is a qualitative research, which aims at drawing the general behaviour of variations in the seawater temperature within three distinctive layers in the south-eastern Mediterranean region; based on hydrographic data collected between 1948 and 2012. These are the subsurface, the intermediate and the deep layers.

All examined linear trends of MATA are of increasing behaviour except that at the 75 m level, which examined a decreasing trend following that concluded by Maiyza and Kamel (2009) for the surface MATA. This may lead to a conclusion on the extended thermal effect of the surface layer in the region of interest. Also, results revealed that the highest rate of increase of the MATA linear trends was +0.02°C/yr (100 m level), while all other rates varied between +0.001 and +0.005°C/yr. This range is in agreement with that concluded by Iona et al. (2018) for the Levantine Basin.

The resultant parabolic curves for the entire levels tend to reflect a cyclic behaviour similar to that detected by Maiyza and Kamel (2009) for the sea surface temperature anomaly. However, the year of minimal MATA occurrence differs from one level to another. This observed similarity in the behaviour of MATA variations may be, partially, attributed to the thermal nature and physical property of the water column in the investigated region. The transparency of the water column within the investigated region may extend to about 30 m depth, which permits the sun rays to impact on the thermal expansion even to the subsurface layers.

Figure 9. *General Regression of Deep Temperature at the 2000 m Level for the New Extended Area of Interest*



Any water mass is formed at the surface, inside or outside the basin of interest, and then sinks to the appropriate level and spreads afterward (Dobravolsky 1947, Marchall and Schott 1999). The hydrographic and atmospheric conditions within the formation areas especially during winter season are critical in defining the general characteristics and behaviour of the water formed (Schroeder et al. 2017). Hence, in order to come closer to the area of formation of the Levantine Intermediate Water, the most important water mass in the Mediterranean basin with its extended effect to the Atlantic, it has been more convenient to expand the present area of interest northward to Latitude 35°N. The trend of the MATA has, therefore, been re-examined at the 2000 m level. Wüst (1961) studied the physical properties at this level and put two question marks (see Figures 5 and 7 in Wüst 1961), remarking the sinking zone of fresh surface waters characterized by maximum dissolved oxygen and minimum water temperature between Rhodes and Crete. The result of the present re-examination is shown in Figure 9, reflecting a linear trend of increase in the MATA variations with a rate of +0.005°C/yr. The new MATA varied between a minimum of -0.13°C in 1948 and a maximum of +0.4°C in 1998, with a general mean of -0.03. The standard deviation and the variance of the new MATA are 0.13 and 0.02, respectively. In the meantime, the resultant parabolic curve tends to follow that of the MATA variations at all overlaying layers in the present work and at the surface layer concluded by Maiyza and Kamel (2009). The predicted half cycle from the resultant quadratic equation at this extended region expanded from 1946 to 1982, i.e., 37 years. The minimum year of occurrence is 1962. This, indeed, supports the conclusion that the origin of the deep Levantine water is mainly from the modified sinking surface water. This is also consistent with the conclusions that formation of the warmer LIW is initiated by a transformation processes (evaporation and cooling) and sinking of the surface water either in the Levantine Basin or in the Cretan Sea (Georgopoulos et al. 1989, Rohling and Bryden 1992, Lascartos et al. 1999, Schroeder et al 2017).

Conclusions

To conclude, the general behaviour of the MATA for all levels within the south-eastern Mediterranean region: subsurface, intermediate and deep do have the same trend deduced for the surface layer, but with different magnitude and different time of occurrence. This can be attributed to the late winter vertical convection on the extreme cold and salter water column with transparency (~30 m) in this region. The observed trend of "cyclic" parabolic behaviour is observed at all levels and even close to region of formation of the deep water mass.

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