Research in Marine Sciences
Volume 5, Issue 4, 2020
Pages 795 - 805

Heat storage characteristics in eastern Mediterranean Sea

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Received: 2020-08-14 *Accepted: 2020-11-01*

Abstract

Heat Storage in the ocean water (column and space) plays a main role in its dynamics. The historical hydrographic data is used to calculate the heat storage of eastern Mediterranean (10°E to 36°E and 30°N to 40°N) in the upper 100m and 300m layers. The results of monthly mean spatial distribution of heat storage, annual trend, and annual signal amplitude are presented in this study. For both layers, the maximum heat storage is located in the southern and southeastern part of eastern Mediterranean, while the minimum values are located in northern part. The maximum values of heat storage in the upper 100m and 300m layers are in the period of August-October (end of heating), while the minimum values are in the period of February-March (end of cooling), respectively. The signal amplitude value of heat storage for both layers is high at the southeast of Crete and moderate high at the south-southeast Rhodes Islands representing the convection zone in which the Levantine Intermediate water are formed and sink in winter season.

Keywords: Eastern Mediterranean; Heat storage; Hydrographic.

1. Introduction

On the Earth, the largest semi enclosed sea is called the Mediterranean Sea, a basin where an interaction of global interest occurs (Marullo *et al*., 2016). The evaporation of the Mediterranean Sea exceeds the river input and the precipitation, so it is a concentration basin, and become saltier water, mostly of Levantine origin, but with a significant additional contribution from the western basin, exits at intermediate water depths (Marullo *et al*., 2016).

The study area is the eastern Mediterranean basin which composed of three sub-basins; Levantine Sea, Ionian Sea, and Aegean Sea.

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Eastern Mediterranean (EM) is connected with western Mediterranean via Sicily Strait (Figure 1). It is separated from the western Mediterranean by a sill of 330m depth between Sicily and North Africa. It has a unique character compared with other semi-closed seas in arid zones. It is subdivided into two major depressions, the Ionian, and the Levantine sub-basin, by a ridge extending from Greece to Africa (Eid *et al*., 1999).

It is known that the most obvious processes that determine sea surface temperature variations are net surface heat flux, vertical advection, vertical mixing, and horizontal advection. The net surface heat flux is considered to be one of the extremely important factors because it is one of the primary ways by which the ocean may be cooled or heated (Eid *et al*., 1999).

The ocean heat transport and heat storage clarify the importance role of the ocean in climate change. The convergence of heat transport is the difference between the surface heat flux and the heat storage rate. Therefore, how much heat the ocean can release to the atmosphere, depends on the amount of heat advected and stored in the ocean (Dong and Kelly, 2004). The thermal balance (heat storage) of the upper ocean depends on the temporal variation of the depth of the mixed layer (Dong *et al*., 2009)

Through the Sicily Strait, about two thirds of the Atlantic surface water enters the eastern Mediterranean basin (El-Geziry and Bryden, 2010). Then, three processes occur to start the eastern gyre: one branch is spreading to the north-eastward, the second drift to central part of Ionian Sea and, the third, flowing eastward along Tunisian coast. In general, the proposed circulation in Ionian and Levantine seas is a cyclonic (El-Gindy and El-Dine, 1986).

The Mediterranean Sea general circulation pattern is composed of two sub-basin gyres: an anticyclonic in its southern part of the basin and cyclonic dominates the northern part (Roussenov *et al*., 1995). Furthermore, the geostrophic circulation of the eastern Mediterranean waters is mainly a large cyclonic gyre in the Levantine Sea. It is enclosing the southern part of the Aegean Sea and an anti-cyclonic gyre near the Egyptian coast (Said, 1999).

The water masses of the eastern Mediterranean can be distinguished into: surface, intermediate and deep water masses (El-Geziry and Bryden, 2010). The Levantine Intermediate Water (warmest and saltiest Mediterranean water formed with largest amount) at 150–600m depth is believed to be formed mainly in south-southeast of Rhodes Island. Due to Coriolis force, the Levantine intermediate water flows along the coasts of Rhodes and Crete in the northern part of the Levantine. The Levantine intermediate water masses circulation remains close to that of the surface layers (El-Geziry and Bryden, 2010).

The ocean surface upper layer heat storage may be subjected to great variability in space and time. In spite of the reality that heat storage plays a fundamental role in the dynamics of the ocean, only a few authors have addressed this topic in the Mediterranean Sea (Picco, 1990; Maiyza, 1993; Kamel *et al*., 2013).

Hecht *et al*. (1985) studied the regional distributions and temporal variations of heat storage in the southeastern Levantine Basin. Tzvetkov (1985) studied the heat storage in the Mediterranean Sea. Moreover, Tzvetkov and Assaf (1982) clarified that the winter storms of Mediterranean are intensified by the thermal gradient between the intrusions of cold continental air masses and warm sea. The main

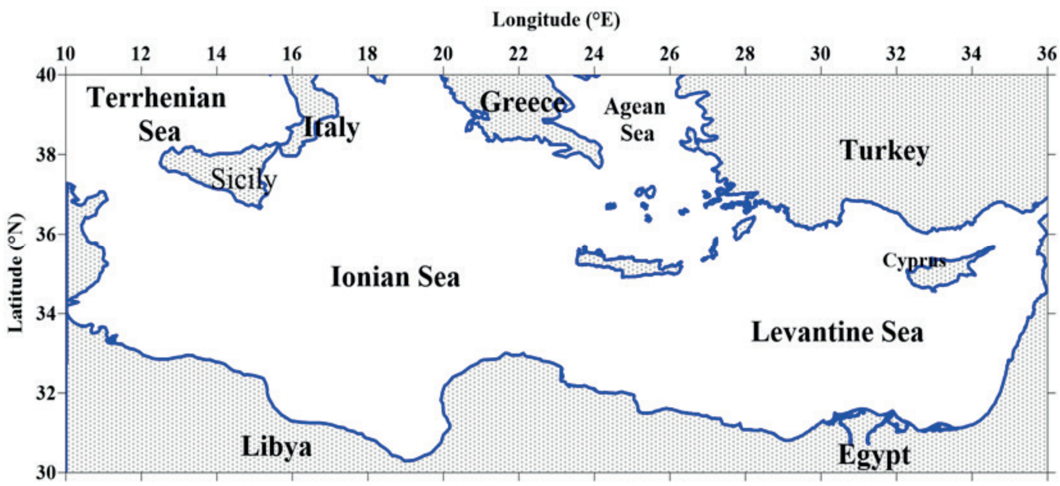

Figure 1. Eastern Mediterranean Sea

results obtained by them were: A nearly weak correlation (R = 0.55) was found between winter precipitation and the southeast Mediterranean heat storage, and high correlation (R = 0.9) was found between precipitation and the depletion of heat storage. They concluded that the upper heat storage represented an index for weather prediction.

Maiyza (1993) presented of the monthly climatological fields of heat storage for the Eastern Mediterranean. The zonal annual trends of monthly mean heat storage in the Levantine, Aegean and Ionian seas as well as the horizontal distribution of the amplitude of the annual signal were shown. The geographical distribution of the amplitude of the annual signal was in a good agreement with some general circulation schemes of the Eastern Mediterranean Sea.

The objectives of this study is to illustrate the following important subjects for the eastern Mediterranean: the monthly geographical distribution of the heat storage, the monthly mean heat storage as annual trend and the spatial distribution of heat storage annual signal amplitude in the upper 100 and 300m.

2. Materials and methods

The hydrographic data used here were retrieved from World Ocean Atlas 2013 (WAO2013) (Locarnini, *et al*. 2013 and Zweng, *et al*. 2013) and U.S. National Oceanographic Data Center (NODC) (Boyer, et. al. 2018), which contains collected in-situ data from over 3200 stations in the Eastern Mediterranean Sea. The data collected from 1950 to 2010 was used in this research. The WOA series is a continuation of the Climatological Atlas of the World Ocean a set of global quarter-degree gridded climatological mean fields of oceanographic variables in the ocean to be used. The measurements have been carried out by various instruments (CTD, MBT, XBT, and sampling bottles). After removal of duplications and application of quality control procedures (elimination of profiles: with data less than 300m or with excessive temperature gradients and the vertical thermal gradients are not logical.)

Heat storage for Eastern Mediterranean was computed as the following:

(1) The available profiles data was separated into months (from January to December) to ensure that the data for each month well cover the entire study area.
(2) Heat storage was calculated for each profile for both layers 100m and 300m in each cell, each month for the Eastern Mediterranean.
(3) To calculate the heat storage for each cell separately, we calculate the average of the heat storage from the output results from the previous step.
(4) In order to obtain a complete picture of the heat storage for a study area, the previous steps were repeated for all months.

Microsoft Excel 2016 and Golden software (Surfer15) has been used to calculate and map the heat storage of Eastern Mediterranean Sea, respectively.

According to (Levitus, 1984; Levitus, 1987), at any point in the ocean the heat storage (J/m^2) is defined as:

$$H = \int_0^z \rho \, C_\rho \, T \, dz$$

where, H is the heat storage (J/m^2), ρ is sea water density (kg/m^3), T is water temperature (°C), Z is layer depth (m) and C_p is specific heat capacity (J/kg °C).

3. Results

3.1. Heat storage in horizontal distribution

The heat storage monthly distribution in the upper 100m layer of eastern Mediterranean is represented in (Figure 2). During January it decrease gradually from less or more than to 7.5×10^9 J/m^2 along southern part of Ionian and Levantine basins to 7.0×10^9 J/m^2 along eastern part of Levantine basin and then reaches to less than 6.5×10^9 J/m^2 along northern part of Ionian and Aegean basins. The spatial distribution of heat storage in the rest of the year (Figure 2) is nearly the same as in January with little bit differences in magnitude.

In general, the lowest heat storage magnitude (6.0×10^9 J/m^2) is represented in March, while August month has the highest heat storage magnitude (9.0 ×10^9 J/m^2) (Figure 2). The extreme of minimum and maximum monthly mean values of heat storage in the upper 100m layer of eastern Mediterranean are shown in (Table 1). The monthly distribution of heat storage in the upper 300m layer of eastern Mediterranean is represented in (Figure 3). The distribution of heat storage during January decreases gradually from 19.0×10^9 J/m^2 along southern part of Ionian and 20.0×10^9 J/m^2 along southern part of Levantine basins to equal to or less than 19.0×10^9 J/m^2 nearly in the middle of them, and to equal to or less than 18.0×10^9 J/m^2 along northern part of Ionian and Aegean basins and off the eastern Tunisian coast.

Table 2 shows the extreme values of minimum and maximum monthly mean of heat storage in the upper 300m layer. The heat storage is almost low in Northern Levantine Sea, between Cyprus and Crete islands, all year round. The intermediate water mass formation occurs during winter in south south-east of Rhodes Island, characterized by Rhodes gyre. Due to vertical convection (reach more than 300m depth) the intermediate water distributed in the north Levantine with lower heat storage.

3.2. Annual trend of monthly mean heat storage

To represent the differentiation of the mean monthly annual trend of heat storage in the upper 100m and 300m layers, the Levantine

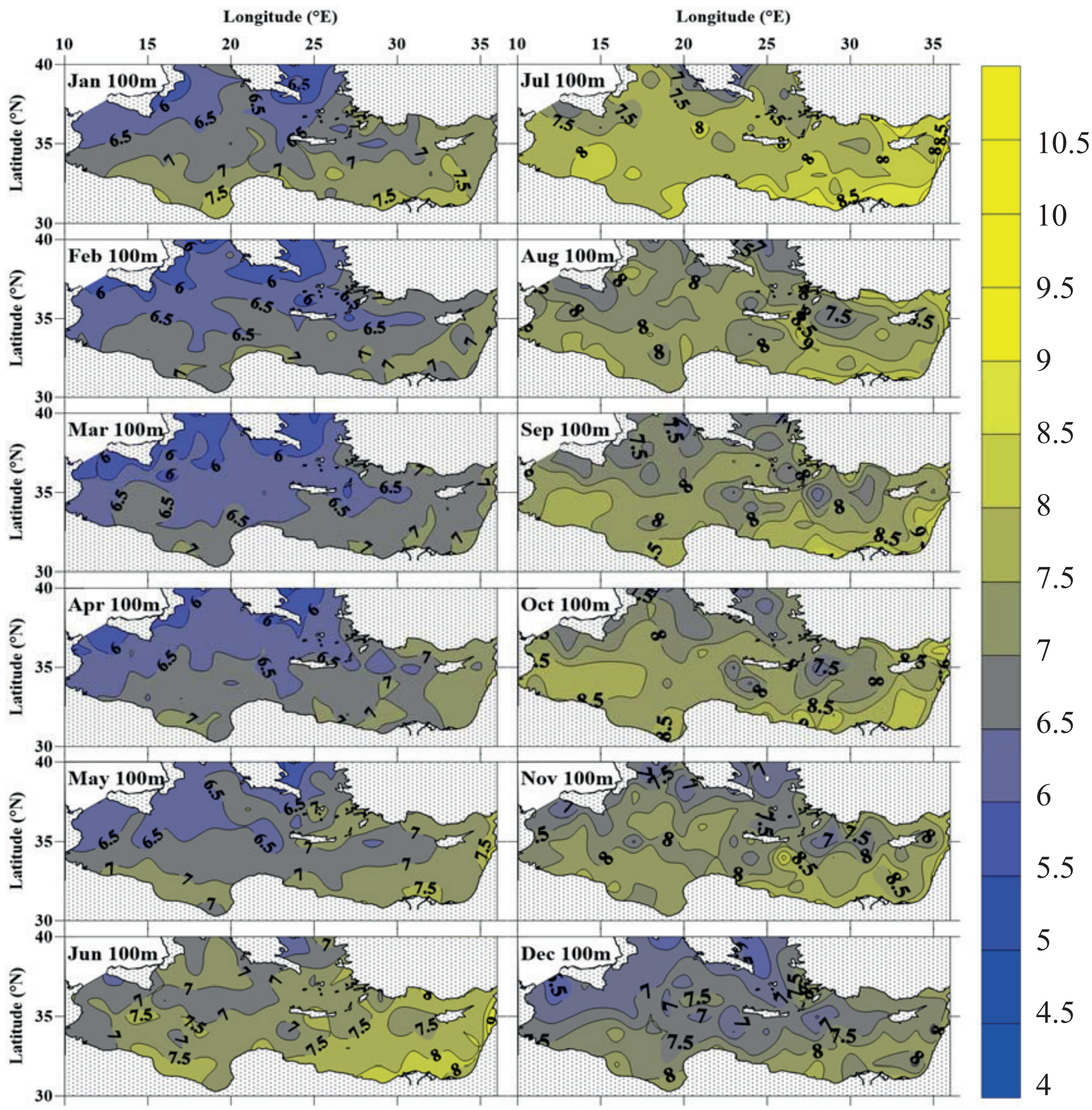

Figure 2. Monthly distribution of heat storage ($\times 10^9$ J/m^2) in the upper 100m, (EM, 1950-2010)

and Ionian basins are divided into two parts for each (north and south). The minimum heat storage in both layers is obviously in February or March, while the maximum heat storage in both layers is found in August, September or October (Figures 4 and 5). This illustrates the end period of the cooling and heating (Brenner, 1989), respectively.

3.3. Annual signals horizontal distribution

The difference between the maximum and minimum values of monthly heat storage for each 0.5°×0.5° is defined as an annual signal (Maiyza, 1993; Kamel *et al*., 2013). Figure 6 illustrates the annual signal geographic distribution for the upper 100 and 300m layers in the eastern Mediterranean. The amplitude of the annual signal ranges from less than 1.5×10^9 J/m^2 to more than 3×10^9 J/m^2 in the upper 100m

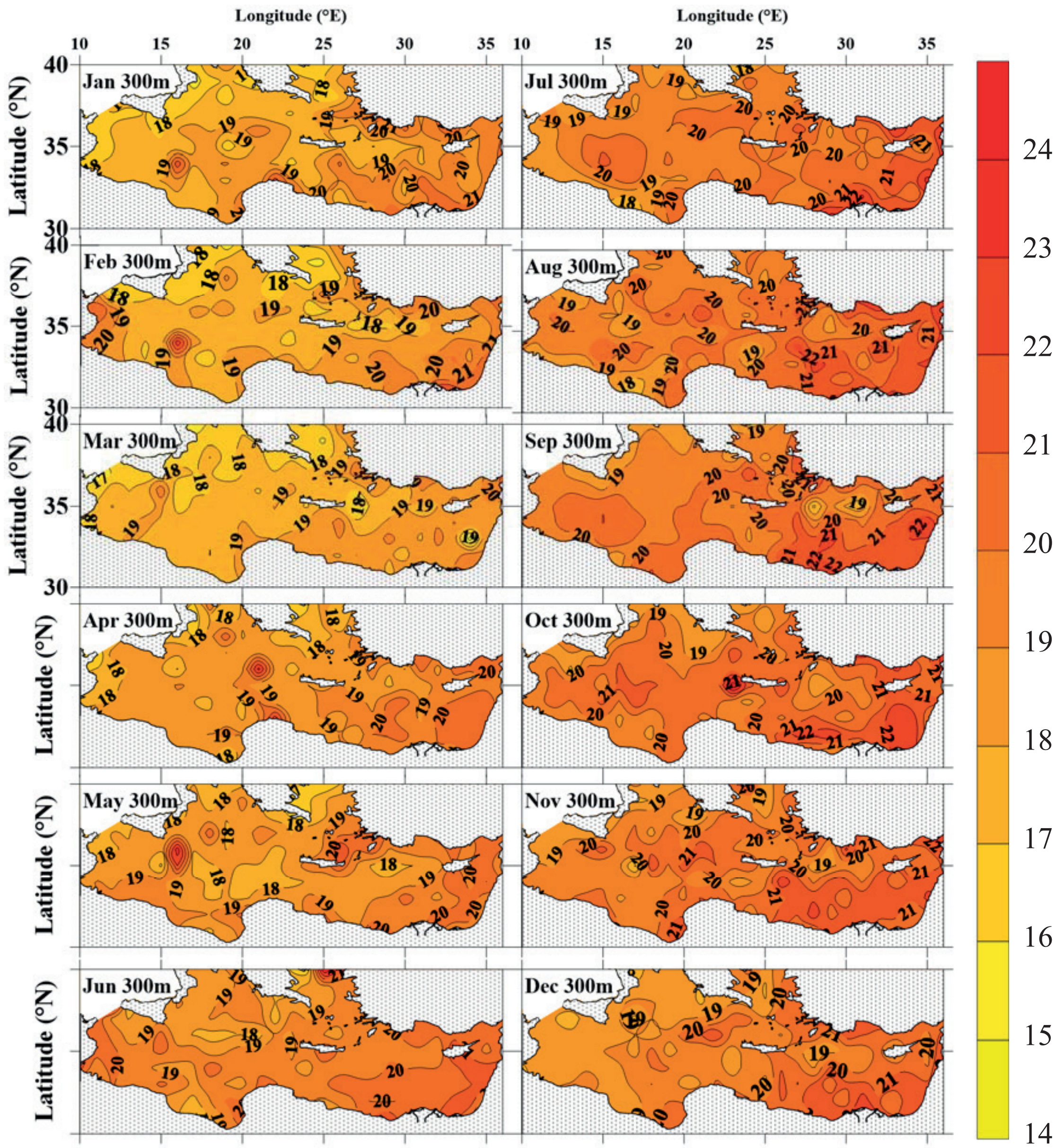

Figure 3. Monthly distribution of heat storage ($\times 10^9$ J/m^2) in the upper 300m, (EM 1950-2010)

and from less than 2.0×10^9 J/m^2 to more than 4.5×10^9 J/m^2 in the upper 300m.

In the upper 100m layer the annual signal distribution in the Levantine basin ranges from less than 1.5×10^9 J/m^2 to more than 3.0×10^9 J/m^2. In the Ionian basin this signal ranges from 1.5×10^9 J/m^2 to 2.0×10^9 J/m^2 whereas in Aegean Sea it is ranges from 2.0×10^9 J/m^2 to 2.0×10^9 J/m^2.

The Levantine basin upper 300m layer, the annual signal distribution ranges from less than 2.5×10^9 J/m^2 to 4.0×10^9 J/m^2, while in the Ionian basin this signal ranges from 2.0×10^9 J/m^2 to 4.0×10^9 J/m^2 whereas in Aegean Sea it is ranges from 2.5×10^9 J/m^2 to more than 4×10^9 J/m^2.

Table 1. Extreme values of heat storage J/m^{2}in the upper 100m layer (EM 1950-2010)

Month	Minimum	Maximum	Mean
January	5.27	8.01	6.79
February	5.20	7.37	6.33
March	5.34	7.50	6.37
April	5.33	7.89	6.57
May	5.41	8.70	6.88
June	6.00	9.80	7.31
July	5.95	10.67	7.69
August	6.82	10.11	8.05
September	6.15	10.74	8.05
October	6.67	9.99	7.91
November	6.42	9.73	7.67
December	6.06	9.72	7.45

Table 2. Extreme values of heat storage J/m^2 in the upper 300m layer (EM 1950-2010)

Month	Minimum	Maximum	Mean
January	16.24	22.66	19.22
February	16.47	23.73	18.91
March	15.54	21.39	18.65
April	16.00	23.30	18.82
May	16.05	23.57	19.13
June	16.60	23.91	19.47
July	16.81	24.13	19.74
August	17.29	24.58	20.06
September	16.71	23.43	20.03
October	17.69	24.69	20.27
November	16.87	22.82	20.02
December	17.16	22.98	20.23

4. Discussion

In the Strait of Sicily, the circulation is complex due to the topography with numerous islands and banks, and to the large width of the Strait which explain the distribution of heat storage near this area. At the exit of the Strait of Sicily (entrance of Ionian Sea), three kinds of processes occur, so that the eastern gyre at its beginning starts to split into several components (Millot and Taupier-Letage, 2005).

At the entrance of the Strait of Sicily, the Algerian current splits into two branches: a northern flow branch enters the Tyrrhenian Sea and a southern flow branch enters the Strait of Sicily itself. Observations show that two-thirds

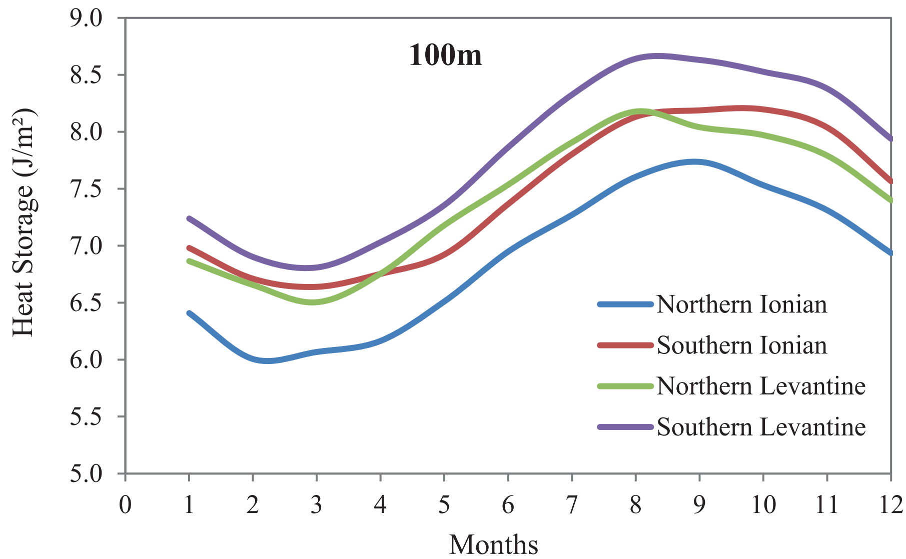

Figure 4. The annual trend of the monthly mean heat storage in the upper 100m layer (10^9 J/m^2), (EM 1950-2010)

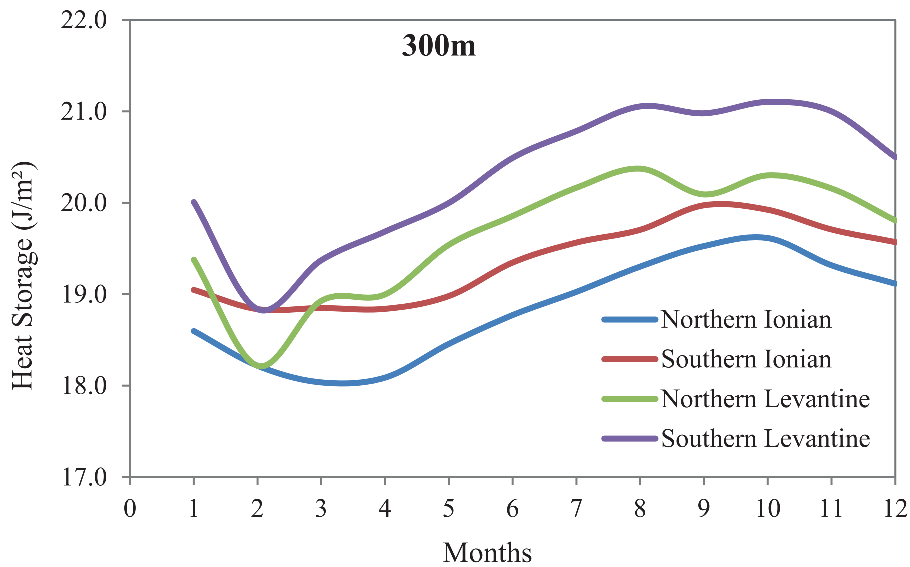

Figure 5. The annual trend of the monthly mean heat storage in the upper 300m layer (10^9 J/m^2) (EM 1950-2010)

of the Atlantic waters enter the Strait of Sicily while one third flows into the Tyrrhenian Sea (Bethoux 1980). Heat storage in the upper 100m layer increases from 6×10^9 J/m^2 to 6.5×10^9 J/m^2 during period of January-May and from 7×10^9 J/m^2 to 8×10^9 J/m^2 during the rest of the year. This is because of the spreading of first north-eastward component. The second component is the generation of mesoscale eddies that tend to drift in the central part of the Ionian Sea give rise to heat storage from also 6×10^9 J/m^2 to 6.5×10^9 J/m^2 during period of January-May and

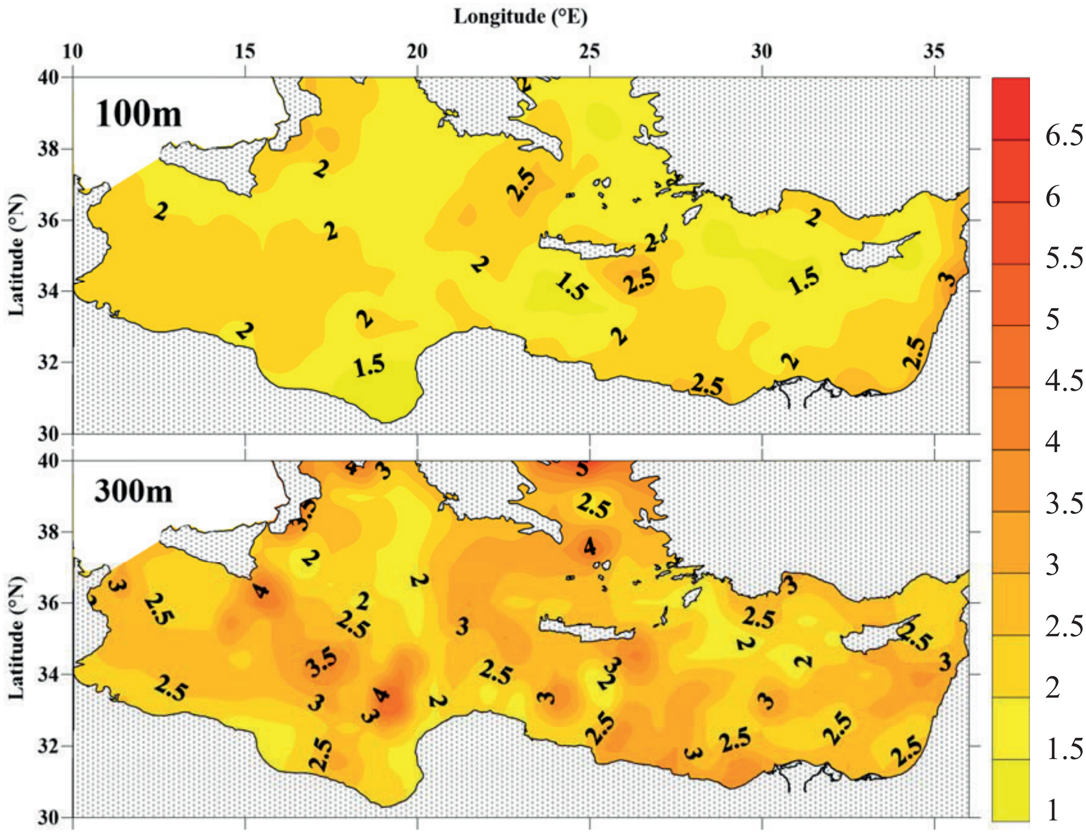

Figure 6. Annual signal amplitude of 100m and 300m layers (EM, 1950-2010)

from 7×10^{9} J/m^{2} to 8×10^{9} J/m^{2} during the rest of the year. The third component is the regular flow along the Tunisian coast flowing eastward give rise to heat storage as well as mentioned of the previous two components.

The heat storage in the northward of the Eastern Mediterranean (off African coast) is gradually decreasing due to the decreasing of sun insolation northward (i.e. latitudinal effect). Due to the current behavior in southern part of Levantine Basin (cyclonic character of North African current) (Maiyza, 1993) which advecting the surface layer of high or low heat storage along southern part of Levantine Basin (African coast) northward along eastern part of Levantine Basin (Asian boundaries).

The heat sources in the upper 100m layer are mainly due to solar radiation through surface layer and advection from western Mediterranean through Strait of Sicily.

The warmest and saltiest water formed in the whole Sea is the Levantine Intermediate Water (LIW), which flows, in the northern part of the Levantine, along the coasts of Crete and Rhodes (El-Geziry and Bryden, 2010). Thus, in the upper 300m layer the heat source is mainly from the vertical convection due to Rhodes cyclonic gyre, where the heat is advected horizontally within the intermediate water mass.

Conclusion

In the water column and space the heat storage plays a main role in ocean dynamics. The historical hydrographic data is used to calculate the heat storage of eastern Mediterranean in the upper 100m and 300m layer.

In the upper 100m and 300m layers, the maximum heat storage is located in the southern and southeastern part of the eastern Mediterranean during August-October (end of heating), while the minimum values of it is founded in the northern part of eastern Mediterranean during February-March (end of cooling).

During the winter season, the vertical convection and formation of Levantine Intermediate Water are located at the south-southeast of Rhodes and Crete islands. In this area, the minimum heat storage in the upper 100m and 300m layers is obviously during March and February, respectively.

The magnitude of the heat storage signal amplitude for both layers is high at the southeast of Crete and moderate high at the south-southeast Rhodes Islands representing the convection zone in which the Levantine Intermediate Water are formed and sink in winters season.

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