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Annual cycle curves of heat storage for the Red Sea

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Received 10th March 2010, Accepted 11th April 2010

Abstract

The annual cycle curves of heat storage for the Red Sea within different layers as well as the horizontal distribution of the amplitude of the annual signal are presented and described. The results obtained are based on monthly objective analyses of data downloaded from the National Oceanographic Data Center NODC, Washington, D.C. of 2005. The main ambient features obtained are the large annual cycle at 15º.0 – 20º.0 N latitude as well as the strong fluctuations appears in the curves during summer and the lags in the occurrence of maximum heat storage at the different subsurface layers. The horizontal distribution of the amplitudes of the annual signal are presented for the upper layers 50-, 100- , 200- and 300- m layers, and their relationship with the water characteristics in the region and its physical characteristics.

1. Introduction

The visible light penetrating the volume of the sea contains only a minor fraction of the total energy of sunlight, but this can produce direct heating in the illuminated layer. Long wave radiation is strongly absorbed. The very shallowness of long wave heating permits the ocean to distill large amounts of water (about one meter per year) into the lower atmosphere. This evaporative process tends to change the atmosphere with latent heat, which is eventually released in a precipitation process at some other places on the earth (von Arx, 1974).

The oceans and atmosphere are so closely interconnected in so many ways and both are ultimately dependent on solar heating for the energies of their motion, as well as their characteristic properties. The transport of freshwater by the atmosphere influences the salinity of the surface layers of the oceans and through the distribution of heat alters the winds which tend to govern at least the surface circulation. These in turn, produce further modification of the distribution of heat and of the atmospheric circulation.

The stress of the wind on the sea surface produces currents in a pattern which tends to resemble the pattern of the surface winds. Through agency of mechanical coupling with the atmosphere, and perhaps also by regional excess of evaporation over precipitation, the advective modes of ocean circulation are made responsive to the distribution of solar heat.

As sea water is not easily penetrated by the sun's light and heat, it has an enormous capacity for heat storage (von Arx, 1974). Accordingly, it is characterized by its high specific heat which makes it of grand importance in storing a large amount of heat from the atmosphere during summer and releasing back in winter. The amount of heat storage in the sea is subjected to continuous change spatially and temporally according to the type of forces acting on it.

Heat storage computations and its annual cycle for global and large basins have been carried out by several authors such as Bathen (1971), Colborn (1975), Oort and Vonder Haar (1976), Lamb and Bunker (1982), Levitus (1987) Maiyza (1993), El-Gindy *et al*. (1995), and Kamel and Eid (2005).

Merle (1983) and Levitus (1984) drew maps of heat storage for the World Oceans but do not provide a good description of the features of a narrow, deep and semi enclosed water basins like the Red Sea.

Therefore, the spatial and temporal changes of heat storage in the Red Sea have been estimated and discussed in the present study, which could help in studying the water circulation in the Red Sea.

1.1. Acquisition of Data and Analyses

The hydrographic data used throughout the present study obtained with all respects and thanks from the Ocean Climate laboratory (OCL), National Oceanographic Data Center (NODC), WDC and downloaded from their web site (www.nodc.noaa.gov). The data represent the monthly water temperature and salinity values of 0.25º quadrangle climate means at the standard depths (0,10,20,30,50,75,……….1500 m) in the Red Sea.

The available data (about 7.9 million temperature profiles and 2.7 million salinity profiles) were processed by the advanced system of Quality Control developed by OCL, NODC, WDC (WOA5) and using all available data, up to 2004, regardless of the year of observations (Boyer, *et al*., 2006).

The 0.25º Latitude / longitude grid climatological fields resolve many features in the small, isolated regions like the area of the present study compared to the previous 1º and 0.5º grid analyzed fields

The heat storage (HS) at any grid point is estimated according to the following equation (Levitus, 1984 and 1987):

The heat storage (HS) at any grid point in the basin is defined as:

$$HS= \int_0^z \rho C_p T dZ \quad (J/m^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Monthly heat storage is estimated using the finite difference approximation:

$$HS = \rho\, Cp\, \Sigma_i \tfrac{1}{2}\, [T_i+T_{i+1}]\, [Z_{i+1}-Z_i] \ldots\ldots\ldots(2)$$

where:

C_p : is the specific heat capacity (J Kg^{-1} ºC),

ρ : is the sea water density (Kg m^{-3}),

Z_i : =i - level depth,

T_i : =i - level temperature.

i : is the seria number of the applied layers

The specific heat capacity Cp and the sea water density ρ are calculated by using Excel User-defined function based on the FORTRAN programs in the UNESCO REPORT NO. 38, 1981, pp. 99-188.

2. Results and Conclusions

Annual cycle curves of Heat Storage for the Red Sea:

The annual cycle curves of heat storage are given at eight zonal lines (from 13°.125 to 27°.125 N) with 2° Lat. apart, including three grid points on each line (one to the west-W, the other at the center-C and the third to the east-E) for six successive layers of 50m thick (Figures 1-2).

The annual cycle curves in the southern part show some peculiarities:

- The curves are generally characterized by summer crests and winter trough, which means the layer gains heat in summer and loses it in winter.
- The summer crests are wider and flatter with longer storing duration.
- The winter trough is flatter and shorter in duration.

Within the upper layer, the heat storage decreases in winter and increases in summer. Its distribution appears as normal distribution but the crest may become more peaked or more flatter and broader. It has a large storage period. In the crest, a dip may appear in the crest, while a steep depression may be formed.

As a result of one of the following reasons: (1) a change in the wind stress, (2) a decrease in air temperature and (3) the intrusion of the Gulf of Aden water.

These depressions vary in shape and type from one location to another.

In Addition, the heat storage increases from the north toward the region of maximum heat storage, which showing values greater than 6.5 x 10^9 J/m^2. A rotational motion of the cyclonic character appears near the southwestern part. At the subsurface layer, a sudden decrease appears in the summer peak, which is dramatically influenced during summer.

The observed heat depression heat storage curve may be related to the upwelling in flow from the Gulf of Aden intermediate water.

The distribution of maximum heat storage values in the subsurface layer indicates the presence of a large anticyclonic motion occupies mostly, the central and the northern parts of the basin. On the two sides at Lat. 21.0-23.0 ºN appear two rotational motions of cyclonic characters on the western and eastern sides. At the entrance, an anticyclonic motion occupies nearly the entrance. The shape drop in the heat storage to the north of the sill with values lesser than 3.7 x 10^9 J/m^2. It is evident that the inflowing water intruded into the basin at the intermediate depth. It strongly spreads by advection and convection processes. It traps the Red Sea water on its progression into the Sea. It undergoes a series of interaction and mixing with the Red Sea warm saline water. The water becomes cooler and denser and then ascending the sill, where it spreads as a deep warm saline water near the bottom.

The distribution of heat storage within the third layer certifies and supports our suggestion of the entrainment of the Gulf of Aden water deeply to far distances into the Sea. The basin becomes nearly homogenous of 4.7- 4.8 x 10^9 J/m^2. The cyclonic rotational motion nearly occupies the whole basin.

At Lat. 13.125 º N to the west, the region is shallow and accordingly, there is only a layer of thickness 10m (Figure 1). The annual cycle curve shows a normal distribution.

For the other two locations at the center and to the east, the curves for the surface layer show a dip at July of 5.71 x 10^9 J/m^2 with two peaks of 5.83 x 10^9 J/m^2 at May and June as well as at September of 5.93 x 10^9 J/m^2 at the center, while to the east the dip occurs also at July of 5.65 x 10^9 J/m^2 and the two peaks at May and September of 5.84 x 10^9 J/m^2 and 5.89 x 10^9 J/m^2 respectively. For the lower layers, the heat storage during summer is dramatically reduced to very low values below 3.70 x 10^9 J/m^2 in August at the center and below 3.40 x 10^9 J/m^2 to the east for the layer 100-150m.

The heat storage ranges for the curves to the east from the surface downward are: 0.68, 1.74, 1.71, and 1.16 x 10^9 J/m^2 respectively. Thus, the second and third layers have either storing capacity greater than that at the surface and at the lowest curve or be influenced by external forces. Such reduction may result from one of the following reasons:

i. A change from the NE to the SW monsoon, and the advection of the cold water from the northern part toward the south,
ii. A sudden decrease in the air temperature,
iii. The intrusion of the cold low saline Gulf of Aden water to the sea.

It is evident that the dramatic reduction observed during summer within the subsurface is the result of the upwelling processes from the Gulf of Aden.

Therefore, one may conclude the following:

- The surface layer gains or loses heat easily than the subsurface layers.
- The surface layer is slightly affected by the upwelled water, thus it shows only a dip in its peak. While the second and third layers are in direct contact with the intermediate water in the Gulf of Aden. Accordingly they show sharp decrease in their heat storage. For deeper layers, there are insignificant variations, and they appear as they have constant heat storage.

At Lat. 15.125 º, 17.125º N:

The behavior of the curves at these latitudes are nearly similar to that at Lat. 13º.125 N with less reduction in summer (Figure 1).

The ranges of heat storage at Lat. 15º.125 N in the upper three layers from the surface are: 1.12, 0.83, and 0.18 x 10^9 J/m^2 respectively.

Meanwhile, at Lat 17º.125 N, the heat storage ranges are:

To the west for layer surface: 1.05, 0.42, and 0.09 x 10^9 J/m^2.

To the east for surface layer: 1.03, 0.68 x 10^9 J/m^2.

At the center for layer surface: 1.07, 0.30 x 10^9 J/m^2.

At Lat. 19.125º N:

To the west: The curve for the surface layer has a flatten crest instead of a sharp crest, which reveals a long warm duration (From July to October) with heat storage of 6.06-6.16 x 10^9 J/m^2 (Figure 1).

At the center: A quite clear dip appears in the curve.

To the east : Long flatter troughs and crests appear in the second and third layers. Such peculiarities may be related to the cyclonic and anticyclonic rotational motions exist in this region.

The ranges vary between 0.96 and 0.12 x 10^9 J/m^2. It is evident that the heat storage increases from north to south.

At Lat. 21.125 º-27.125º N:

In the northern part and at the three locations: to the west, at the center and to the east, some peculiarities are also observed in the annual heat storage curves particularly within the subsurface layers (Figure 2). Within the surface layer, the three representative curves at the first three latitudes (21º.125-25º.125N) are normally distributed with troughs in February with heat storage (10^9 J/m^2):

Location	W		C		E	
	HS	Month	HS	Month	HS	Month
21º.125N	5.02	Feb.	5.14	Feb.	5.13	Feb.
23º.125N	4.75	Feb.	4.90	Feb.	5.07	Feb. & Mar.
25º.125N	4.58	Feb.	4.71	Feb.	4.76	Mar.

and crests in August and September with heat storage (10^9 J/m^2):

21º.125N	6.13	Aug.	6.16	Aug.	6.16	Aug.
23º.125N	6.00	Sep.	6.02	Sep.	6.09	Aug.
25º.125N	5.74	Aug.	5.83	Aug.	5.88	Sep.

It is clear from the above distribution that the heat storage is higher on the eastern side (Arabian) than on the western side (African), and increases from north to south.

Within the other layers, clear fluctuation occur which varies from one latitude to another particularly at Lat. 21º.125 N and 23º.125 N.

At Lat. 27º.125N, the annual heat storage curves (Figure 2) within the different layers (0-50 m to 250-300 m) show some variability differ from that observed in the annual heat storage curves in the northern part. Within the surface layer, the curves at the three locations (W-C-E) have one trough of 4.57 x 10^9 J/m^2 in February, 4.58 x 10^9 J/m^2 in February, and 4.63 x 10^9 J/m^2 in March respectively, as well as one flatten crest of about 5.42 x 10^9 J/m^2.

Within the next five layers, the fluctuations are clearly observed. All the curves have two crests and two troughs. The second dip which occur in August or September may be related with the flatten crest observed in the upper layer. But the changes in the upper layer during summer are not so strong as that acquired within the lower layers. Thus, the only explanation for such depressions during summer in the lower layers is the upwelling processes that occur in the northern part as a result of the influence of the strong NNW winds, which drive the surface layer in the north towards the south to the Gulf of Aden.

If so, then there is a probability to find the cold fresh water that streamed in summer from the Gulf of Aden over the sill into the Red Sea at the intermediate depths. Again, this feature has been experienced during the French " MARION DUFRESNE EXPEDITION" to the Red Sea during summer 1982 (Maillard and Soliman, 1986).

Generally, the maximum and minimum heat storage values (10^9 J/m^2) throughout the year over the whole Red Sea proper are:

Layer Maximum (10^9 J/m^2) Minimum(10^9 J/m^2)
Within the surface layer: 6.58 Aug. in the south 4.57 Feb. in the north
Within the second layer: 5.53 July & Dec. in the south 3.59 Aug. in the south
Within the third layer : 5.05 Apr. in the south 3.34 Aug. in the south
Within the fourth layer : 4.88 Apr. in the south 3.72 Aug. in the south
Within the other two layers (200-250m & 250-300m): Insignificant.

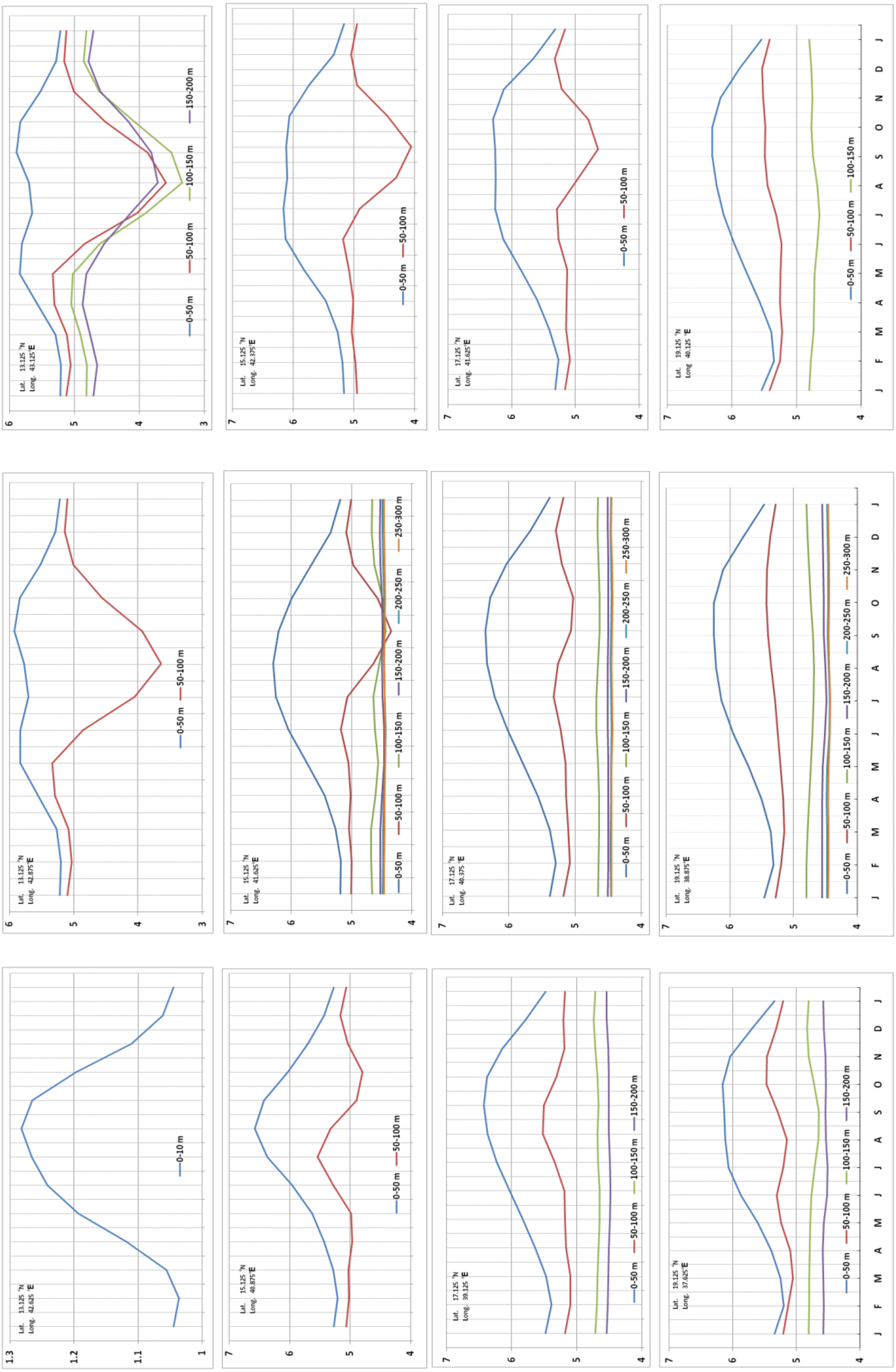

Figure 1. The annual cycle of the Heat Storage ($10^9 J/m^2$) of different layers at certain latitude, W: to the west, C: in the centre and E: to the east.

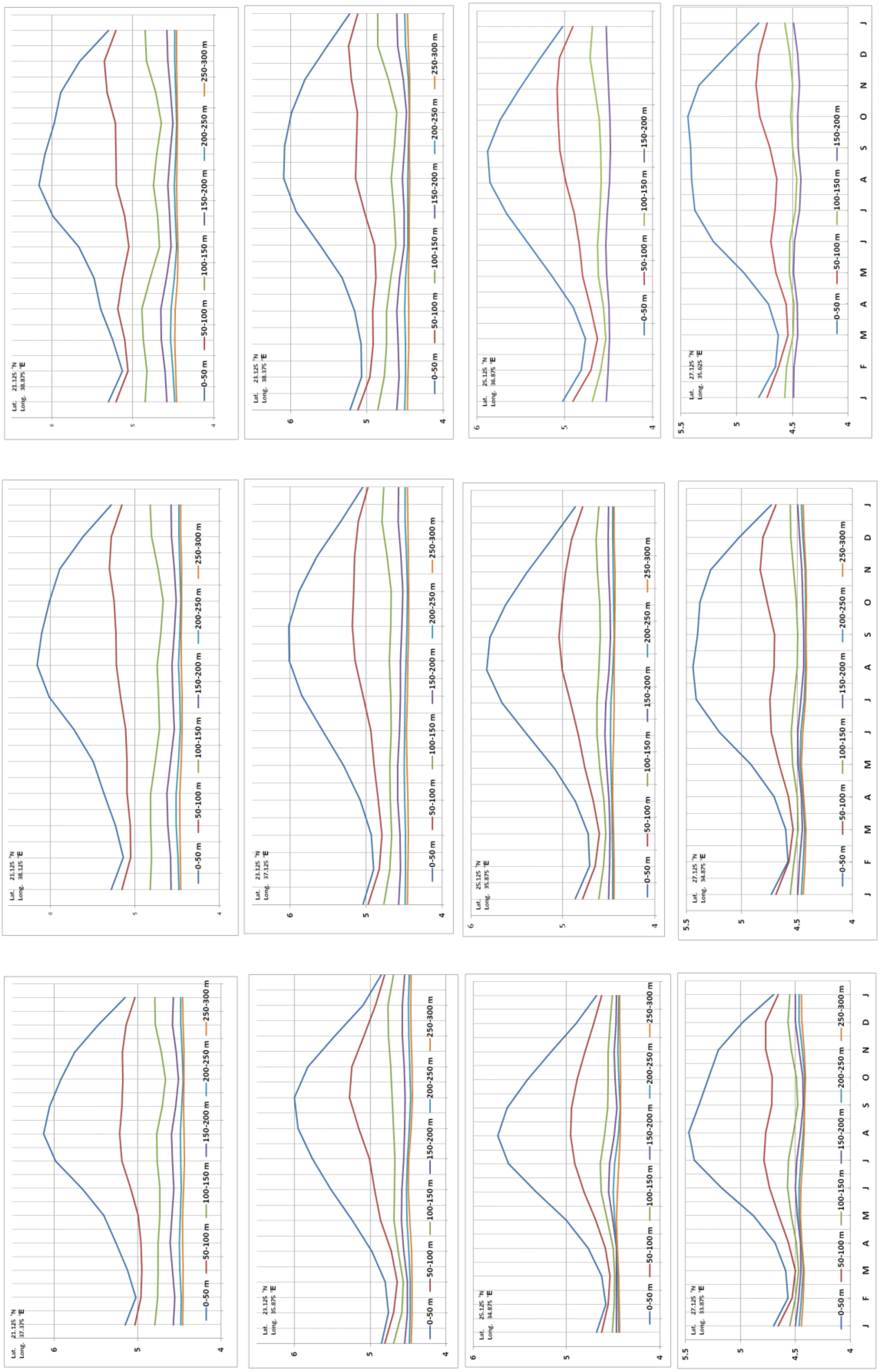

Figure 2. The annual cycle of the Heat Storage (10^9J/m^2) of different layers at certain latitude, W: to the west, C: in the centre and E: to the east.

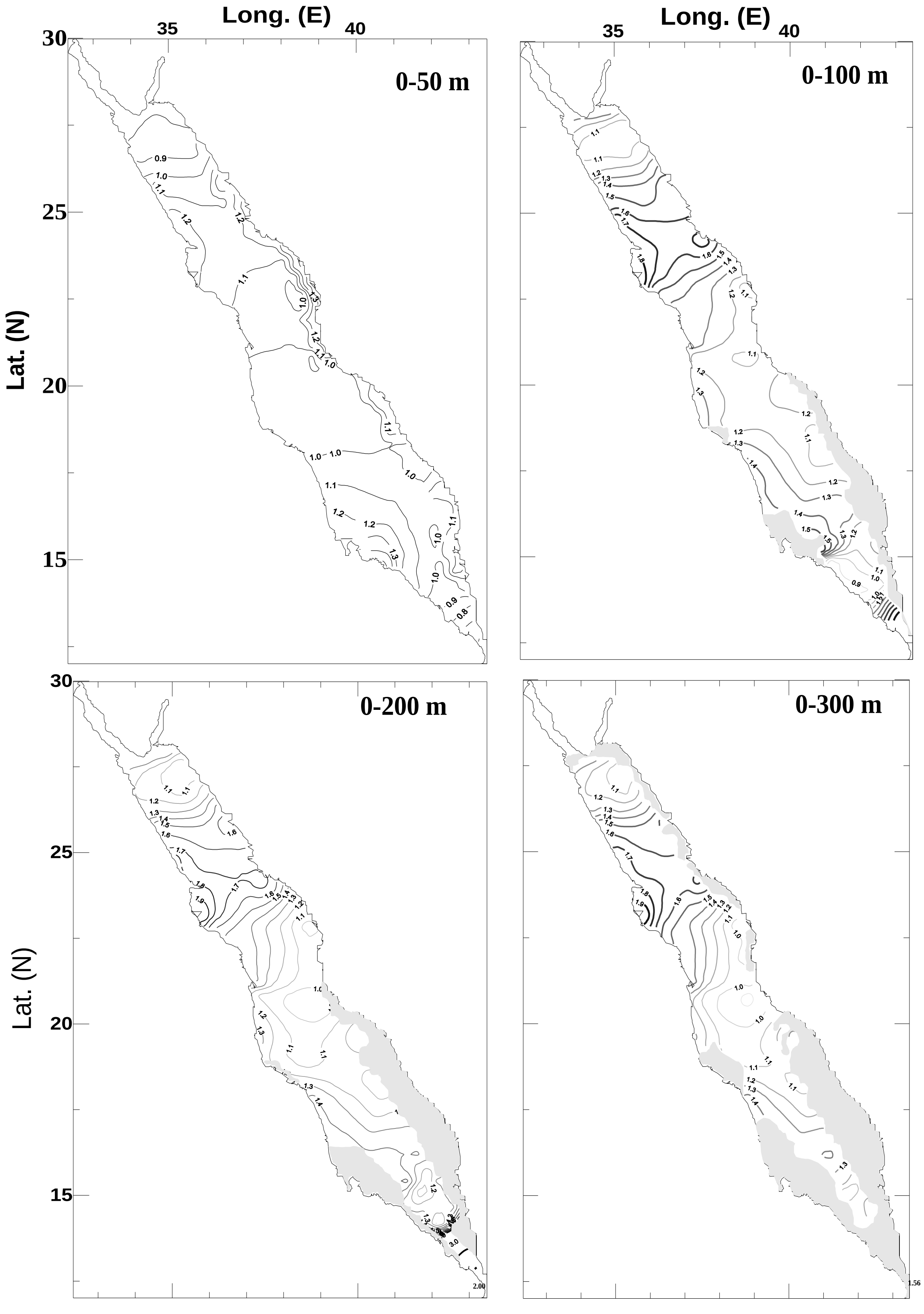

Figure 3. Horizontal distribution of annual signal of heat storage (10E9 J/ m^2) within different layers of the Red Sea.

From the previous discussion, one may conclude the followings:

1. The western part is the least affected area across the sea due to the upwelling phenomenon, while the central and eastern parts are highly affected. This conclusion approved an important fact: When the Gulf of Aden water flows into the Sea, it is directed northward mainly along the eastern side then along the axial line.

2. The heat gain or loss within the sequential layers decreases sharply with depth and ceases at 200m depth and below.

2.1. Horizontal distribution of the annual signals

Annual signal is defined as the difference between the monthly maximum and minimum heat storage in a 0.25 quadrangle (Maiyza, 1993). The horizontal distributions of the annual signals within the layers: 50-, 100-, 200- and 300- m are given in Figure (3).

Within the upper surface layer (0-50 m), the amplitudes of the annual signals are minimum lesser than 1.0, in the extreme northern part of the basin, at its central part and at the entrance. Relative high values of more than 1.2 are found in the northern part in the region between latitude. 22-25^{o} N and in the region of Archable Islands.

Within the layers 50-, 100-, 200- and 300- m the amplitudes of the annual signals are nearly similar to that shown in the upper surface layer 0-50m within the northern and southern parts. Meanwhile within the central part, the region of relative high values is extended between 18^{o} and 25^{o} N.

On considering the annual differences between maximum and minimum heat storage, Figure (3) is produced. High signals of more than 1.4 are observed in the south part of the basin and another one at the central part of northern 1.6 to the west, to small rotational motion appear one amplitude higher than 1.2 and the other is minimum of amplitudes lesser than 0.4. Another minimum is found at the extreme northern part of amplitude less than 0.8. The region of maximum amplitude is of anticyclic character, while that of minimum amplitude are of cyclic features. It is important to emphasis that the obtained annual heat storage signals are nearly similar to the water circulation in Red Sea, which implies the complexity of the water circulation in the Red Sea.

From the above illustrations, the regions of minimum annual signal amplitudes correspond to the regions of cyclonic rotational motions.

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منحنيات الدورة السنوية للمخزون الحرارى للبحر الأحمر

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يتعرض البحث للدورة السنوية للمخزون الحرارى لحوض البحر الأحمر ضمن طبقات مختلفة فضلا عن التوزيع الأفقي للفارق بين القيم السنوية العظمى والصغرى. تستند النتائج التي تم الحصول عليها على تحليلات البيانات الشهرية لدرجات الحرارة والملوحة لحوض البحر الأحمر بمستوياته القياسية المختلفة (WOA05). من بين الظواهر الأبرز للدورة السنوية للمخزون الحرارى ارتفاعها بين خطى عرض 15 و 20 ° شمالا ، فضلا عن التقلبات الشديدة فى المنحنيات خلال الصيف ، والتأخر فى تخزين الحرارة القصوى في الطبقات التالية. كذلك تم دراسة التوزيعات الأفقية للطبقات العليا 50 ، 100 ، 200 و 300 م ، وعلاقتها بالخصائص الفيزيائية لمياه كل منطقة من مناطق البحر الأحمر.