EGYPTIAN JOURNAL OF AQUATIC RESEARCH 1110-0354
VOL. 31, NO.1 2005.

HEAT AND SALT STORAGES IN THE OFFSHORE WATER OF THE RED SEA

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Key words: Heat storage, salt storage, Red Sea.

ABSTRACT

The seasonal changes of heat and salt storages in the offshore water of the Red Sea were studied using a historical data collected from different cruises during the period from 1924 to 1998. The heat storage within water column of different depths exhibits a seasonal variability. The heat storage is low during winter and high during summer. Also, the heat storage increases from north to south. The maximum values of heat storage are found in the southern central part of the Red Sea. It reached about $29.9x10^9$ J/m^2 within the water column of 300m depth. The seasonal change of heat storage from the annual mean is negative during winter and spring, while it is positive during summer and autumn. It has higher values during winter and summer, while its value decreased during spring and autumn.

The salt storage within the water column decreases from north to south. The maximum values are observed at extremely northern Red Sea, while the minimum ones are found at extremely southern Red Sea, near Bab-El-Mandab Strait. The maximum value of salt storage within the water column of 300m depth reaches about 12.59 ton/m^2 during summer. The salt storage differs slightly from one season to another. The maximum values of salt storage are observed during summer in the northern regions of the Red Sea, while they are found in the southern regions during winter. The seasonal changes of salt storage from the annual mean vary between -110 kg/m^2 and 100 kg/m^2.

INTRODUCTION

The heat and salt storages in the upper layers of the ocean control the formation and the mixing of the water and consequently are responsible for the dynamic and the thermodynamic forces of the ocean. The heat and salt storages in the upper layers may be subjected to considerable changes in space and time of the temperature and salinity of sea water either zonally or meridionally as well as from one season to another.

Several works describe the annual cycle of the heat storage in the world oceans or major portions of the world oceans, such as Bathen (1971), Colborn (1975), Merle (1983), Levitus (1984), Maiyza (1993) and El-Gindy *et al* (1995). Also many works describe the annual cycle of salt storage in the world oceans and seas such as Levitus (1986) and Hazek (1997).

In the Red Sea no detailed work was addressed to this subject. So, this study is an attempt to recognize the spatial and temporal changes of the heat and salt storages in the upper 300m layer in the Red Sea as well as the spatial variability of their amplitudes.

MATERIAL AND METHODS OF ANALYSIS

All the available hydrographic data, concerning temperature and salinity, taken in the Red Sea through the period from 1924 to 1998 were used to calculate the heat and salt storages in the sea. Data were obtained from World Ocean Atlas 1998 (WOA98), CD-Rom Documentation, version 1.0, Ocean Climate Laboratory, National Oceanographic Data Center, April 1999.

It is known that, the seasons in the Red Sea considered as two main seasons, winter (from December to March) and summer (from June to September), and two transitional periods, spring (April – May) and autumn (October – November). In this study we choose one month to represent each season, February represents winter season, May represents spring, August represents summer and November represents autumn.

The data were measured at standard depths. To obtain better quality hydrographic data, the unstable stations were corrected for temperature and/or salinity. It is worthy to mention that only a few observations were rejected because of their poor quality, perhaps due to personal, instrumental and/or location error. Using the above randomly distributed temperature and salinity data, the values at nodal grid points were calculated for each season. The Red Sea was covered by 20 grid stations. Figures (1a & 1b) show the stations taken at each season and the grid stations which used in this analysis. The latter grid data are used in the calculation of heat and salt storages.

The heat storage (HS) and Salt storage (SS) at any grid station are given by Levitus (1984 & 1987):

$$HS = \int_0^z \rho CpTdz$$

$$SS = \int_0^z \rho CSdz$$

where:
HS is the heat storage (J/m^2),
SS is salt storage (kg/m^2),
ρ is the density of sea water (kg/m^3),
Cp is the specific heat capacity (J/kg.°C),
C is the conversion factor (= 1kg/1000gm),
T is the temperature of sea water (°C),
S is the salinity of sea water (gm/kg),
z is the depth (m) of sea water column above which major changes in heat content occurs. Here four levels were chosen for z: 50m, 100m, 150m and 300m depths.

The heat and salt storages were calculated at each grid station and then be averaged at four regions to facilitate the comparison between the values of these parameters over the Red Sea. The regions were chosen according to latitudes and represented as:

Region I lie between 22-28°N; Region II lies between 20-22°N; Region III lies between 17-20°N and Region VI lies between 13-17° N (Figure 1c).

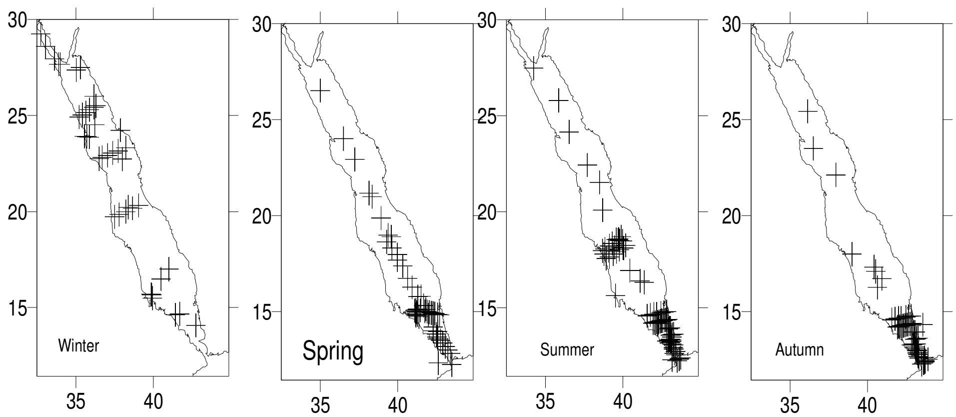

Fig.(1a). Location of hydrographic stations used in the present study.

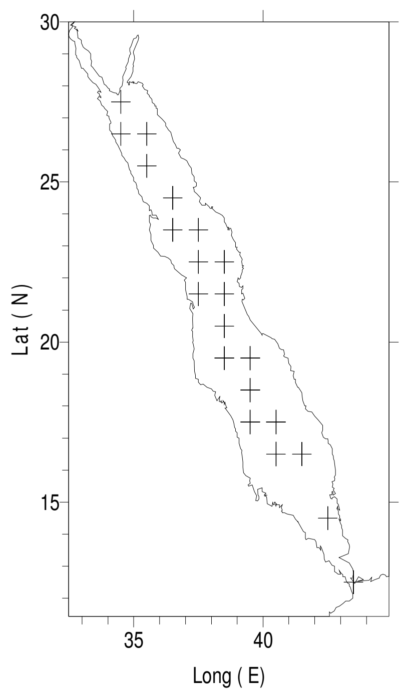

Fig.(1b). Location of grid stations.

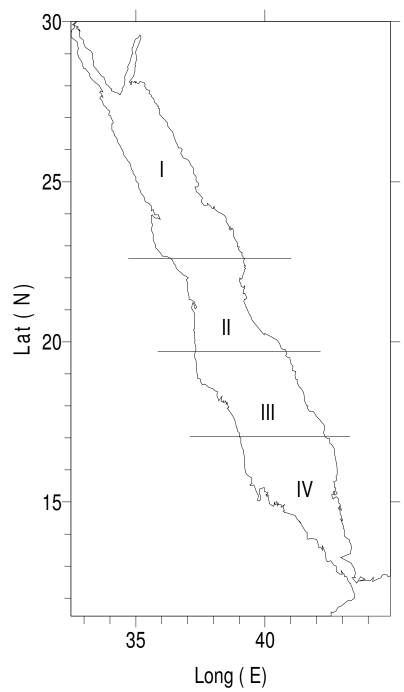

Fig.(1c). Selected regions of Red Sea.

RESULTS

1. Heat storage in Red Sea:

a- Heat storage within the water column:

The heat storage was calculated within the upper water column of 50m, 100m, 150m and 300m depths during different seasons in the Red Sea. The general patterns of the heat storage values within these water columns in the Red Sea are almost the same. Thus, the distribution of heat storage within 300m layer is only drawn as shown in Figure (2). Generally, the heat storage in the Red Sea showed a seasonal trend; where it is low during winter and high during summer. The minimum values are observed at extremely northern part of the Red Sea (due to the minimum water temperature), while the maximum ones are occurred in the southern part between latitudes 17-19°N (Region III) of the Red Sea (due to the maximum water temperature).

The extreme values of the heat storage within the given water columns during different seasons are shown in Table (1). The minimum values of heat storage are almost found during winter for all water columns, while the maximum ones are observed during summer for the different water columns, except for 300m depth, they are found during autumn.

Table (2) shows the average amount of the heat storage within the water column extending from the surface to depths of 50m, 100m, 150m and 300m in the different regions of the Red Sea during the different seasons. It is clear that, the heat storage increases southwards towards region (III). The average minimum values of heat storage are 4.72×10^9 J/m^2, 9.40×10^9 J/m^2, 13.98×10^9 J/m^2 and 27.37x109 J/m^2 within the water columns of 50m, 100m, 150m and 300m depth respectively. While, the maximum ones are 6.29×10^9 J/m^2, 11.65×10^9 J/m^2, 16.36×10^9 J/m^2 and 29.74×10^9 J/m^2 within the same water columns respectively. The minimum values of heat storage are found during winter in region I, while the maximum values are observed during summer in region III.

b-Temporal variations of heat storage:

The deviation of heat storage at each station from the annual mean at that station (temporal variations) was determined for the upper water columns of 50m, 100m, 150m and 300m depth. Table (3) shows the average amount of these deviations in the different regions of the Red Sea during the different seasons. It is clear that, the seasonal deviations of heat storage are negative during winter and spring, while they are positive during summer and autumn. The deviation of heat storage from the annual mean has higher values during winter and summer, while its value decreased during spring and autumn. It means that, the heat storage (or average water temperature) within the different water columns is lowest during winter and increased slightly with time to reach its maximum amount during summer. Also, it is seen that, during winter and summer the maximum deviation of heat storage from the annual mean is observed at region I for all water columns except for 50m depth, where it is found at region IV. During spring, the maximum deviation is occurred at region II for all water columns. During autumn, the maximum deviation is found at region III for all water columns, except for 300m depth where it is found at region II.

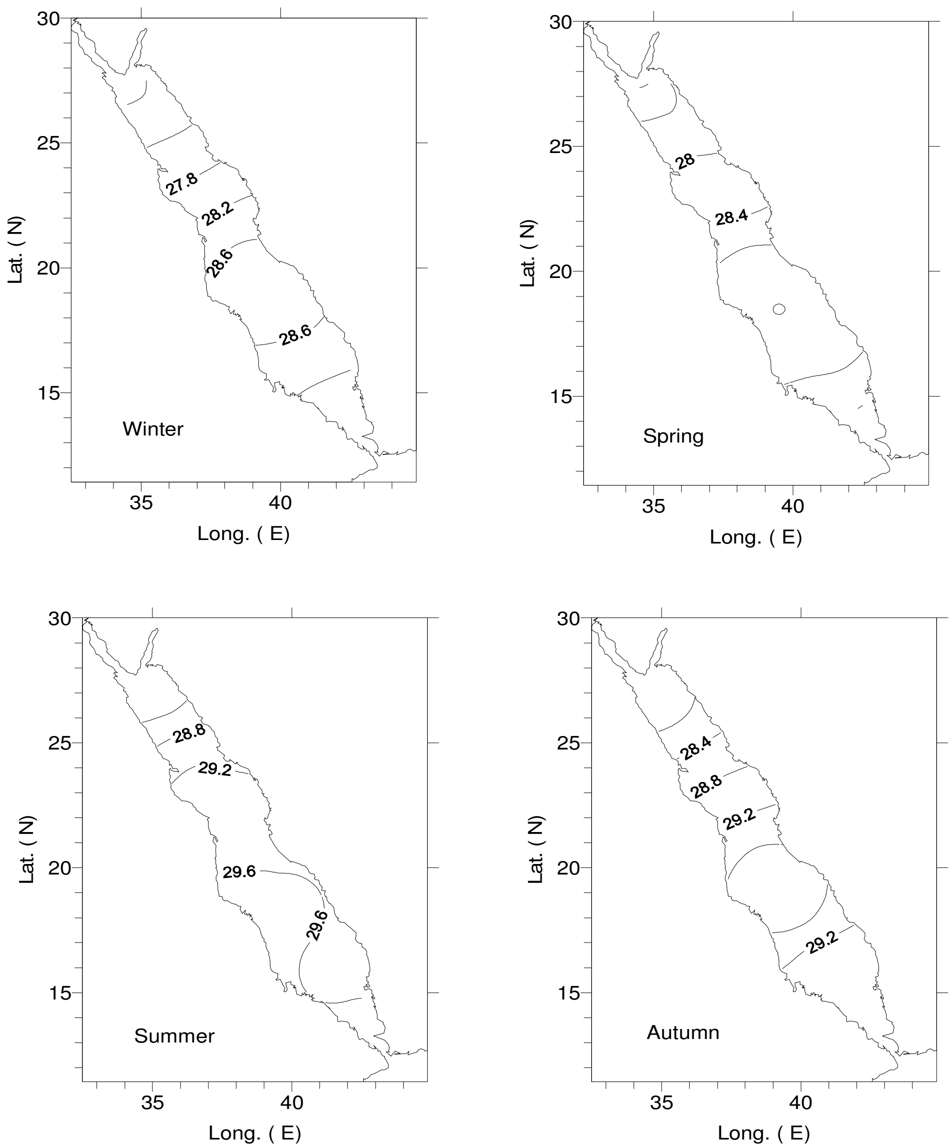

Fig.(2). Heat storage (1.0E9 J/m^2) within water column of 300m during different seasons.

Table 1. The minimum and maximum values of heat storage (10^9 J/m^2) within different water columns during different seasons.

Season	50m		100m		150m		300m	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Winter	4.56	5.42	9.13	10.67	13.64	15.48	26.98	28.95
Spring	4.92	5.84	9.57	11.04	14.10	15.80	27.51	29.23
Summer	5.52	6.39	10.29	11.79	14.83	16.50	28.13	29.89
Autumn	5.22	6.18	9.94	11.70	14.43	16.48	27.72	29.92

Table 2. The average values of heat storage (10^9 J/m^2) in different regions of the Red Sea during different seasons.

Depth of Water column	Region	Winter	Spring	Summer	Autumn	Year
50m	I	4.72	5.05	5.77	5.38	5.23
	II	5.12	5.45	6.15	5.87	5.65
	III	5.37	5.77	6.29	6.15	5.90
	IV	5.16	5.64	6.27	5.80	5.72
	Red Sea	5.05	5.42	6.07	5.76	5.58
100m	I	9.40	9.80	10.73	10.28	10.05
	II	10.13	10.46	11.33	11.12	10.76
	III	10.55	10.95	11.65	11.56	11.18
	IV	10.14	10.64	11.38	10.91	10.77
	Red Sea	9.98	10.38	11.21	10.91	10.62
150m	I	13.98	14.39	15.34	14.88	14.65
	II	14.90	15.14	16.03	15.85	15.48
	III	15.34	15.68	16.36	16.31	15.92
	IV	14.79	15.29	16.08	15.53	15.42
	Red Sea	14.67	15.04	15.88	15.58	15.29
300m	I	27.37	27.82	28.70	28.25	28.04
	II	28.37	28.56	29.45	29.32	28.92
	III	28.80	29.10	29.74	29.73	29.34
	IV	28.25	28.73	29.52	28.92	28.86
	Red Sea	28.11	28.46	29.27	28.99	28.71

Table 3. Average of seasonal deviation of heat storage (10^9 J/m^2) from the annual mean (temporal variations) in different regions of the Red Sea.

Depth of water column	Region	Winter	Spring	Summer	Autumn
50m	I	-0.51	-0.18	0.54	0.15
	II	-0.53	-0.2	0.5	0.22
	III	-0.53	-0.13	0.39	0.25
	IV	-0.56	-0.08	0.55	0.08
	Red Sea	-0.53	-0.16	0.49	0.18
100m	I	-0.65	-0.25	0.68	0.23
	II	-0.63	-0.3	0.57	0.36
	III	-0.63	-0.23	0.47	0.38
	IV	-0.63	-0.13	0.61	0.14
	Red Sea	-0.64	-0.24	0.59	0.29
150m	I	-0.67	-0.26	0.69	0.23
	II	-0.58	-0.34	0.55	0.37
	III	-2.58	-0.24	0.44	0.39
	IV	-0.63	-0.13	0.66	0.11
	Red Sea	-0.62	-0.25	0.59	0.29
300m	I	-0.67	-0.22	0.66	0.21
	II	-0.55	-0.36	0.53	0.40
	III	-0.54	-0.24	0.40	0.39
	IV	-0.61	-0.13	0.66	0.06
	Red Sea	-0.6	-0.25	0.56	0.28

c- Temporal and spatial variations of heat storage:

The temporal and spatial variations of heat storage are studied by calculating the deviation of heat storage at each station from the annual mean value of heat storage of the whole Red Sea. Table (4) shows the average amount of these deviations in different regions of the Red Sea during the different seasons. It is seen that, the deviation of heat storage from the annual mean value of whole Red Sea is negative during winter with high values at northern region (I) for all water columns except within 150m and 300m depth, the deviation is positive at region III. In general, these deviations indicated that the heat storage increases southward and reach a maximum amounts at region III.

During spring, the temporal and spatial variations showed negative values at northern regions (I & II) and positive ones at southern regions (III & IV). The maximum negative values are found at region I, while the maximum positive one is observed at region III. It means that the minimum values of heat storage are found at region I, while the maximum ones is occurred at region III.

During summer, the deviation of heat storage from the average value of whole Red Sea is positive with maximum deviations at region III for all water columns.

During autumn, the temporal and spatial variations are negative at region I, while they are positive at the rest with maximum value at region III for all water columns.

The result of table (4) reflects the distribution of heat storage (i.e. the distribution of water temperature) within the Red Sea. The negative values indicate to the low heat storage (low temperature), while the positive one indicates to high heat storage (high temperature). Thus, table (4) showed increases of heat storage southward toward region III where the maximum heat storage are occurred.

Table 4. Average of seasonal deviation of heat storage (10^9 J/m^2) from the average value of the whole Red Sea. (temporal and spatial variations) in different regions of the Red Sea.

Depth of water column	Region	Winter	Spring	Summer	Autumn
50m	I	-0.86	-0.53	0.19	-0.2
	II	-0.46	-0.13	0.57	0.29
	III	-0.21	0.19	0.71	0.57
	IV	-0.42	0.06	0.69	0.22
	Red Sea	-0.53	-0.16	0.49	0.18
100m	I	-1.22	-0.82	0.11	-0.34
	II	-0.49	-0.16	0.71	0.5
	III	-0.07	0.33	1.03	0.94
	IV	-0.48	0.02	0.76	0.29
	Red Sea	-0.64	-0.24	0.59	0.29
150m	I	-1.31	-0.9	0.05	-0.41
	II	-0.39	-0.15	0.74	0.56
	III	-1.95	0.39	1.07	1.02
	IV	-0.5	0	0.79	0.24
	Red Sea	-0.62	-0.25	0.59	0.29
300m	I	-1.34	-0.89	-0.01	-0.46
	II	-0.34	-0.15	0.74	0.61
	III	0.09	0.39	1.03	1.02
	IV	-0.46	0.02	0.81	0.21
	Red Sea	-0.6	-0.25	0.56	0.28

2. Salt storage in Red Sea:

a- Salt storage within the water column:

The salt storage is calculated within the upper water column of 50m, 100m, 150m and 300m depths during different seasons in the Red Sea. In general, the salt storage decreases from north to south, where the maximum values are obtained at extremely northern Red Sea, while the minimum ones are found at extremely southern Red Sea, near Bab-El-Mandab Strait. The extreme values of salt storage within the different water columns are shown in Table 5. The horizontal distribution of salt storage within the water column of 300m depth is shown in Figure (3). The minimum and maximum values of salt storage are 12.06 ton/m^2 and 12.59 ton/m^2. They are observed during summer at extremely southern and northern parts of the Red sea respectively. Also, it is seen that, there are nucleuses of high salt storage occupying the northern part of the Red Sea for all seasons, while there are only two nucleuses of low salt storage occupying the southern part during spring and autumn.

Table (6) gives the average amount of salt storage within the water column extending from the surface to depths of 50m, 100m, 150m and 300m in the different regions of the Red Sea during the different seasons. It is clear that, the salt storage changes slightly from one season to another. It attains a maximum value during summer at northern regions (I and II) and during winter at southern regions (III and IV). This pattern may be due to the current system and its thickness over Bab-El-Mandab Strait during winter and summer seasons.

b- Temporal variations of salt storage:

The deviation of salt storage from the annual mean (i.e. the temporal variations) was calculated for the upper water columns of 50m, 100m, 150m and 300m depth. Table (7) shows the average amount of these deviations at different regions of the Red Sea during the different seasons. It is seen that, at region I the deviation of salt storage from the annual mean is positive only during summer. It means that, the average salinity within the water column is low during winter and increases slightly during spring the reach a maximum amount during summer and then decreases again during autumn, which has the minimum value (except within 300m depth where the minimum salinity is observed during winter).

At region II, the temporal variations of salt storage are negative during winter and spring, while they are positive during the rest of the year. At this region the minimum salinity within the water column is found during winter (except within 50m depth, the minimum one is observed during spring) and increases to reach its maximum value during summer.

Table 5. The minimum and maximum values of salt storage (ton/m^2) within different water columns during different seasons.

Season	50m		100m		150m		300m	
	Min.	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Winter	1.91	2.06	3.89	4.15	5.96	6.23	12.21	12.52
Spring	1.88	2.07	3.87	4.14	5.92	6.23	12.08	12.48
Summer	1.92	2.08	3.81	4.17	5.80	6.27	12.06	12.59
Autumn	1.93	2.06	3.88	4.15	5.94	6.23	12.18	12.50

Table 6. The average values of salt storage (ton/m^2) in different regions of Red Sea during different seasons.

Depth of Water column	Region	Winter	Spring	Summer	Autumn	Year
50m	I	2.050	2.053	2.066	2.048	2.054
	II	2.016	2.014	2.025	2.020	2.019
	III	1.997	1.957	1.990	1.971	1.979
	IV	1.938	1.907	1.959	1.938	1.935
	Red Sea	2.012	1.997	2.021	2.005	2.009
100m	I	4.114	4.117	4.139	4.113	4.120
	II	4.051	4.051	4.073	4.072	4.062
	III	4.024	3.974	4.007	3.954	3.990
	IV	3.929	3.903	3.889	3.899	3.908
	Red Sea	4.048	4.033	4.053	4.031	4.041
150m	I	6.186	6.189	6.217	6.182	6.193
	II	6.107	6.109	6.143	6.139	6.124
	III	6.091	6.034	6.064	6.021	6.053
	IV	5.999	5.947	5.938	5.968	5.963
	Red Sea	6.114	6.094	6.118	6.099	6.106
300m	I	12.427	12.431	12.474	12.432	12.441
	II	12.332	12.336	12.391	12.368	12.357
	III	12.344	12.279	12.308	12.262	12.298
	IV	12.261	12.144	12.198	12.211	12.203
	Red Sea	12.358	12.326	12.370	12.340	12.349

Table 7. Average of seasonal deviation of salt storage (ton/m^2) from the annual mean (temporal variations) in different regions of the Red Sea.

Depth of water column	Region	Winter	Spring	Summer	Autumn
50m	I	-0.004	-0.001	0.012	-0.006
	II	-0.003	-0.005	0.006	0.001
	III	0.018	-0.022	0.011	-0.008
	IV	0.003	-0.028	0.024	0.003
	Red Sea	0.003	-0.012	0.012	-0.004
100m	I	-0.006	-0.003	0.019	-0.007
	II	-0.011	-0.011	0.011	0.01
	III	0.034	-0.016	0.017	-0.036
	IV	0.021	-0.005	-0.019	-0.009
	Red Sea	0.007	-0.008	0.012	-0.01
150m	I	-0.007	-0.004	0.024	-0.011
	II	-0.017	-0.015	0.019	0.015
	III	0.038	-0.019	0.011	-0.032
	IV	0.036	-0.016	-0.025	0.005
	Red Sea	0.008	-0.012	0.012	-0.007
300m	I	-0.014	-0.01	0.033	-0.009
	II	-0.025	-0.021	0.034	0.011
	III	0.046	-0.019	0.01	-0.036
	IV	0.058	-0.059	-0.005	0.008
	Red Sea	0.009	-0.023	0.021	-0.009

At region III, the deviation of salt storage from the annual mean are positive during winter and summer with maximum deviation during winter, while they are negative during spring and autumn with maximum deviation during autumn. It means that, the salt storage (or average salinity) at this region is maximum during winter. It decreases during spring and increases again during summer, finally it decreases to its minimum value during autumn.

At region IV, the pattern of salt deviation from the annual means is slightly differing from that occurred at other regions. Within 50m depth, the deviation of salt storage from the annual mean is negative only during spring (minimum value). The maximum deviation is found during summer. Within 100m depth, the deviation of salt storage is positive only during winter (maximum value). The minimum deviation is occurred during autumn. Within 150m & 300m depth, the positive deviations are found during winter and autumn, while the negative one is observed during spring and summer. The maximum deviation (maximum salinity) is observed during winter, while the minimum deviation (minimum salinity) is found during summer within 150m depth and during spring with 300m depth.

This pattern of the temporal variations of salt storage reflects the circulation pattern as well as the water exchange through the strait of Bab El-Mandab.

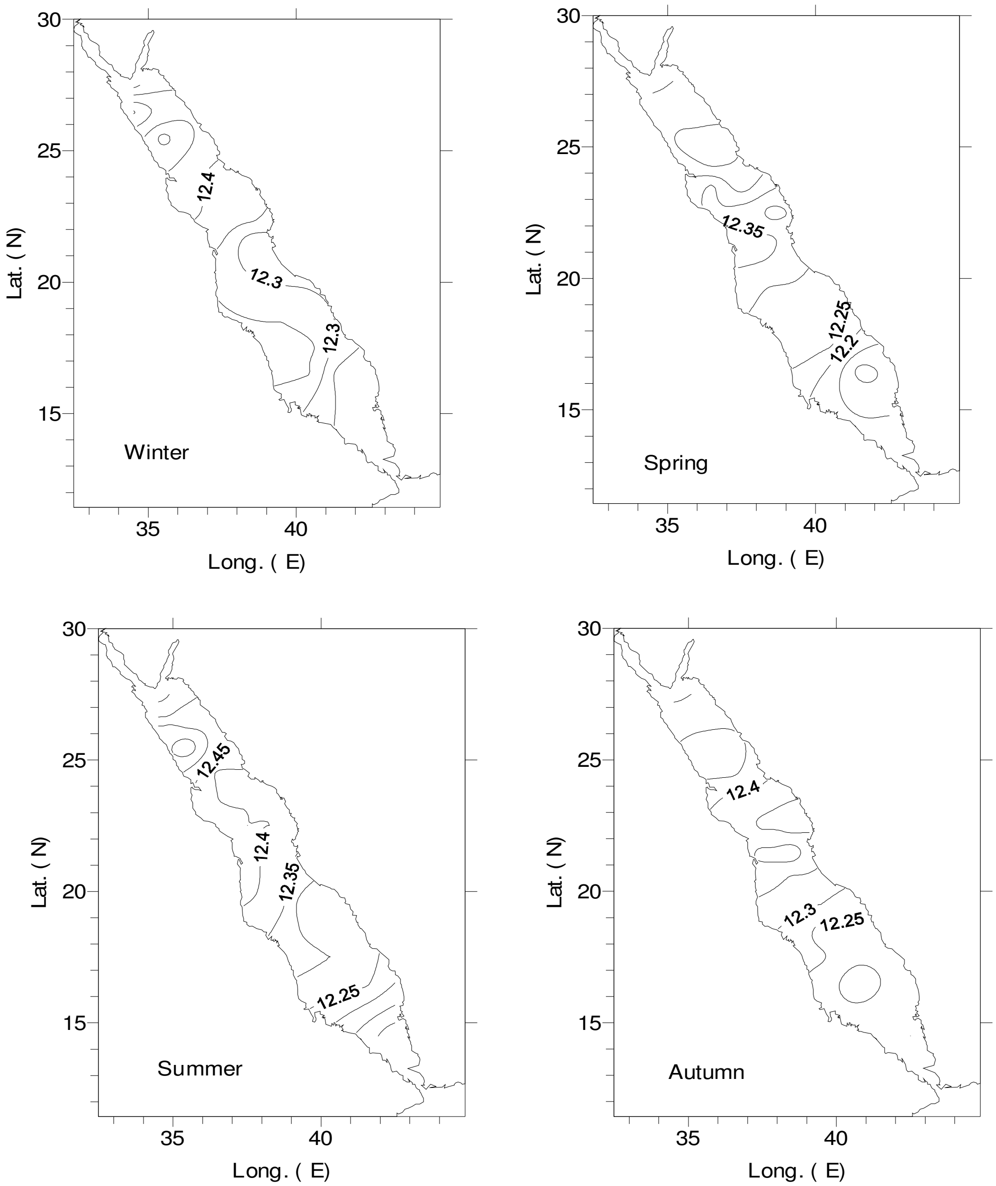

Fig.(3). Salt storage (ton/m^2) within water column of 300m depth

during different seasons.

c- Temporal and spatial variations of salt storage:

The deviation of salt storage at each station from the annual mean value of the whole Red Sea is calculated for the selected water columns. The average amount of these deviations in the different regions of the Red Sea is shown in table (8). From this table, it is clear that, the deviations of salt storage are generally positive in regions I & II with maximum deviations in region I, while they are negative in regions III & IV with maximum deviation in region IV, except within 300m depth during winter and spring, the positive deviation occurred in region I only.

In general, this pattern indicated that the averages of salt storage (average salinity values) have a higher value at the northern part of the Red Sea, decreasing slightly southward toward Bab EL-Mandab. This pattern reflects the distribution of salinity within the Red Sea and the contribution of circulation pattern as well as the water exchange through Bab El-Mandab strait.

Table 8. Average of seasonal deviation of salt storage (ton/m^2) from the average value of the whole Red Sea. (temporal and spatial variations) in different regions of the Red Sea.

Depth of water column	Region	Winter	Spring	Summer	Autumn
50m	I	0.041	0.044	0.057	0.039
	II	0.007	0.005	0.016	0.011
	III	-0.012	-0.052	-0.019	-0.038
	IV	-0.071	-0.102	-0.05	-0.071
	Red Sea	0.003	-0.012	0.012	-0.004
100m	I	0.073	0.076	0.098	0.072
	II	0.01	0.01	0.032	0.031
	III	-0.017	-0.067	-0.034	-0.087
	IV	-0.112	-0.138	-0.152	-0.142
	Red Sea	0.007	-0.008	0.012	-0.01
150m	I	0.08	0.083	0.111	0.076
	II	0.001	0.003	0.037	0.033
	III	-0.015	-0.072	-0.042	-0.085
	IV	-0.107	-0.159	-0.168	-0.138
	Red Sea	0.008	-0.012	0.012	-0.007
300m	I	0.078	0.082	0.125	0.083
	II	-0.017	-0.013	0.042	0.019
	III	-0.005	-0.07	-0.041	-0.087
	IV	-0.088	-0.205	-0.151	-0.138
	Red Sea	0.009	-0.023	0.021	-0.009

CONCLUSION

The hydrographical data collected by different cruises in Red Sea throughout the period from 1924 to 1998 are used to calculate the seasonal changes of heat and salt storages within the water column extending from the surface to 50m, 100m, 150m and 300m depths.

The distributions of heat storages show seasonal variations. They have high values during summer and low ones during winter. In general, the average amount of heat storage in different regions of the Red Sea tends to increase southward. The maximum values occur in region III. This pattern just reflects the distribution of water temperature over the Red Sea. The average deviation of heat storage from the annual mean is negative during winter and spring, while it is positive during summer and autumn. For the Red Sea as a whole, the average heat deviations during winter and summer are higher than that during spring and autumn.

The distribution of salt storage differs slightly from one season to another. In general, the salt storage decreases from north to south. The maximum values of salt storage are found at extremely northern Red Sea, while the minimum ones are found at extremely southern Red Sea. The average deviation of salt storage from the annual mean for the Red Sea as a whole is positive during winter and summer and negative during spring and autumn. The positive deviation during summer is almost higher than that during winter.

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