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Inter-Annual Seasonal Variations in the Seawater Thermohaline Structure in the Northern Gulf of Aqaba, Red Sea

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ABSTRACT

Temporal and spatial variations of seawater temperature and salinity were investigated at three stations in northern Gulf of Aqaba for six years "May 1997-April 2003". The results showed that, thermal stratification characterized the upper water column during summer (May-December). The strongest stratification appeared in August exceeding 250 m. Mixing conditions characterized the winter-spring seasons (January-April), which exceeded the deepest measurement point (450 m). Composite variations with time in the stratification depth during summer and the mixed layer depth during the winter-spring season fitted an exponential association. Both the stratification build up and erosion (mixing deepening) rates were relatively high (~3.5 $m.day^{-1}$) at the beginning of their respective seasons. The processes slowed down significantly late in the season reaching 0.24 and 0.52 $m.day^{-1}$ for building and erosion, respectively. An interesting phenomenon of higher salinity water overlaying lower salinity water occurred clearly during summer. Local evaporation and lower salinity water carried by the thermohaline currents in intermediate waters from the Red Sea are the most likely reasons of this phenomenon. The inter-annual salinity variation in the upper 450 m was not significant and ranged only between 40.12 and 40.75 PSU, while the temperature variation was relatively high and ranged between 21.02-27.99 ^oC. This indicates that the thermodynamic processes in the seawater of the Gulf were mainly controlled by temperature, whereas salinity played a minor role. No significant inter-annual differences in the upper 300 m potential temperature, salinity, and potential density were detected among the three study stations at the northern Gulf of Aqaba.

Keywords: Seawater Temperature, Salinity, Stratification, Mixing, Gulf of Aqaba, Red Sea.

1. INTRODUCTION

The Gulf of Aqaba is a fingerlike extension projecting north-northeastward between large deserts to the east and west, and is separated from the Red Sea by a sill of 265 m depth at the straits of Tiran (Fig. 1a). It is located in the sub-tropical arid area between 28°-29°30$^/$ N and 34°30$^/$-35° E. The length of the Gulf is about 180 km, with maximum width of 25 km, which decreases to about 5 km at the northern tip (Fig.1b). The mean depth of the Gulf is about 800 m, with a maximum of about 1800 m close to that of the Red Sea. Thus, the Gulf of Aqaba has a distinguished aspect ratio in term of its dimensions (Morcos 1970; Hulings 1989) that plays a significant role in shaping its physical, geochemical and biological characteristics.

Local investigations of temperature and salinity in the northern Gulf of Aqaba have been carried out in the Jordanian waters by e.g. Badran and Foster (1998), Al-Najjar (2000), Badran (2001) Manasrah (2002), Manasrah *et al.* (2004). Water mass characteristics in the upper 200 m in summer differ from winter. During summer, the temperature and salinity in the upper 200 m range between 21 to 26 °C and 40.35 to 40.55 PSU, respectively. Mixing dominates during winter in the northern Gulf (T ~20-21 °C and S ~40.55-40.65 PSU). Below 200 m the water is homogenous during summer and winter having the same values of temperature and salinity in the upper 200 m during winter (Table 1). Salinity inversion was detected by Paldor and Anati (1979) in October; waters in the upper 150 m with salinity 40.77 PSU overlay waters with lower salinity (40.67 PSU) in the 150-300 m depth interval. The same phenomenon was also reported by Wolf-Vecht *et al.*

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(1992) and Manasrah (2002). Salinity minimum in the northern Gulf of Aqaba existed at 100 m all through summer penetrated down to 200 m in November.

In the present study, we are presenting for the first time, long-term records of temperature and salinity that have been generated continuously down to 450 m depth for six years (1997-2003) in the northern Gulf of Aqaba.

The aim of the study is to investigate the seasonal and inter-annual variation of the seawater temperature and salinity in the northern Gulf of Aqaba. These data are generated at a time the northern Gulf of Aqaba is witnessing a boom in investment that may result in considerable changes in its basic characteristics and thus provide more important to the scientific database that can be used for management purposes and may constitute the baseline for the thermohaline quality of these waters.

2. MATERIALS AND METHODS

Temperature and salinity in the upper 450 m water column at the reference station S2 (Fig. 1b) in front of the Marine Science Station (MSS) were measured on biweekly intervals for six years (May 1997- April 2003). In addition, profiles of temperature and salinity in the upper 300 m were taken monthly at stations S1 and S3 (Fig. 1b). All three stations were about 3 km offshore.

Temperature, salinity and depth (pressure) profiles at all stations (S1, S2 and S3) have been measured using self contained Conductivity, Temperature and Depth meters (CTD) Model Ocean Sensors OS200 and OS453. The oceanographic equipment necessary for the present investigation were fitted on a Boston Whaler (6 m × 2 m) equipped with a winch, an electric generator Model GP 5203 SB, a Global Positioning System (GPS) Model GP-80 and a depth finder of the Echo scan series. The data were analyzed using Microsoft Excel and Matlab.

3. RESULTS

3.1 Thermohaline Structure in the Northern Gulf of Aqaba

Potential temperature profiles recorded from May 1997 till April 2003 are shown in Fig. 2a, salinity in Fig. 2b and density in Fig. 2c. Seasonal variations in temperature were the most dominating signals. Thermal stratification existed during summer (May-December), and was strongest during August where it reached a maximum depth of 250 m. The thermocline vanished during winter-spring seasons (January-April). However, the maximum mixing depth reaching down to 450 m was recorded during spring (February-April).

The difference in salinity in the upper 450 m over the study period was less than 0.63 PSU. This indicates that the changes in salinity were small and mainly attributed to high evaporation. Higher salinity water overlay lower salinity one during the period July-December of the years 1997, 1998, 1999 and 2002. The same phenomenon appeared, but to a weaker extent during September-November 2000 and July-November 2001. The salinity difference usually started to build up at 60 m in August, plunged to 200 m in December, but it dwindled later until it vanished completely during spring.

The behavior of potential density σ_θ followed basically the potential temperature with respect to the stratification and mixing time and scale (Fig. 2c), i.e., salinity played a minor role in defining density changes in the water column.

The maximum differences within the upper 250 m of the water column in potential temperature (21.02-27.99 °C), salinity (40.15-40.67 PSU) and density σ_θ (26.55-28.72 kgm^{-3}) were recorded during August giving strong stratification. During the months of February and March the mean difference in the potential temperature, salinity, and density σ_θ in the upper 450 m of the water column were 21.63-21.22 °C, 40.36-40.55 PSU, and 28.44-28.64 kgm^{-3}, respectively, resulting in well mixed water column conditions. Thus the mean annual ranges of the three variables in the upper 450 m were about 7.08 °C, 0.63 PSU, and 2.33 kgm^{-3}, respectively. The maximum annual change in temperature occurred at the surface; therefore, a simple model of sea surface temperature (SST) variation with respect to time was found (Fig. 3). The relation is $SST = 23.72+2.54\sin(0.018\ Days-4.44)$, where *Days* is Julian day and cosine argument is in radian. The SST measured by the model ranged between 21.18 to 26.26 °C comparing with the real mean range of about 5.4 °C. It was found using the model that the maximum SST was in September 4th, and the minimum was in March 14th.

3.2 Mechanisms of Development of the Stratification and Mixing Conditions

Repeatedly every year over the six years of the study, summer thermal stratification started to build up in the upper 100 m during May with a temperature gradient between the surface and 100 m of about 21.2-23 °C. The maximum change in air temperature during May ranged between 20 and 40 °C with mean value of about 29 °C (Fig. 4). Therefore, the minimum value of air temperature was approximately similar to that of the water temperature, while the mean air temperature exceeded the maximum water temperature by about 6 °C. Increase in the air temperature continued gradually until it reached maximum in August (27 to 41 °C). During this period (May-August) stratification continued to strengthen and penetrate deeper, reaching a temperature of ~21 at about 250 m depth and ~27 °C at the surface during August. In most years not much change was observed in September. The degradation of stratification usually began in October, also similar to the case of build up in the upper 60 m. At this time of the year daily air temperature dropped considerably during night (~18 °C) well below the water temperature (~25.5 °C) (Figs. 2 and 4). From October onwards the air temperature decreased progressively, leading to a continuous loss of buoyancy and resulting in the density of the surface water crossing a critical threshold after which vertical convection occurred. This was followed by continuous convective deepening throughout winter and spring.

3.3 Mixed/ Stratified Layer Penetration Rate

For the purpose of presenting an objective definition of stratification; it is defined herein as the condition when the temperature gradient is equal to or greater than 0.025 °Cm^{-1} ($\frac{\Delta T}{\Delta Z} \geq 0.025\ ^{\circ}Cm^{-1}$), while mixing is defined as the condition when the temperature gradient is equal to or less than 0.005 °Cm^{-1} ($\frac{\Delta T}{\Delta Z} \leq 0.005\ ^{\circ}Cm^{-1}$). The conditions in between ($0.025 > \frac{\Delta T}{\Delta Z} > 0.005$) are considered transition conditions. The variations of both stratification depth S_h (m) during summers and mixing depth M_h (m) during winter-spring seasons together with the low pass filtered air temperature (°C) during the period May 1997 to April 2003 are shown in Fig. (4). The best fitted function of S_h and M_h with time was an exponential association (Fig. 5). The stratification and mixing penetration rates ($\frac{dS_h}{dt}$ and $\frac{dM_h}{dt}$ mday^{-1}) after April 1st and after October 1st, respectively were fast (~3.5 mday^{-1}) in both early summer and winter-spring seasons, and then slowed down in both late seasons to reach about 0.24 and 0.52 mday^{-1}, respectively. It took about 200 days until the upper 250 m became completely stratified. In general, the mixing penetration rate was faster than the stratification deepening rate. The upper 250 m took only about 100 days to become completely mixed, matching the conditions of the permanently mixed deep layer. The statistical analysis of the results revealed that the inter-annual variations in S_h and M_h during the six summers and winter-spring seasons from 1997 to 2003 were not significant (Table 3).

4. DISCUSSION

4.1 Annual and Inter-Annual Variation of Temperature and Salinity

The temporal distribution of the temperature in the upper 450 m in the northern Gulf of Aqaba showed a clear annual cycle and some inter-annual variation. In summer the seawater density was controlled mainly by temperature, with the salinity playing only a small role counteracting the temperature effect and weakening the stratification by the salinity inversion that developed in the upper waters due to direct evaporation. In winter both temperature and salinity influenced the seawater density in the same direction, as the salinity increased as the temperature was going down. Paldor and Anati (1979), who expressed winter and summer conditions similar to our findings, showed that some very weak stratification remains during winter which is mainly due to salinity, while the major summer stratification is mainly due to temperature.

The peaks of seawater surface temperature, which occurred in August, had different values in the different years. The lowest maximum annual water temperature (25.19 °C) was recorded in August 2000 and the highest maximum annual water temperature (28.04 °C) was recorded in August 1999. The differences in the surface temperature could be related to inter-annual variations of the surface heat flow, annual variations of the weather conditions, and to the seasonal differences in the temperature of the Red Sea water that flows into the Gulf of Aqaba.

High evaporation during summer that increases the surface salinity, high surface water temperature that decreases the density and the inflow of low salinity water carried by the thermohaline in the intermediate waters from the Red Sea, may explain the phenomenon of higher saline water existing above lower saline water during summer. This is a well established phenomenon that has been reported in several previous studies, such as those of Paldor and Anati (1979) and Wolf-Vecht *et al.* (1992), who reported waters in the upper 150 m of salinity 40.77 PSU overlay waters of lower salinity (40.67 PSU) in the 150-300 m of the water column. According to Manasrah (2002) a salinity minimum layer existed at 100 m all through summer then penetrated down to 200 m during November.

In order to clarify the mechanism of the annual and inter-annual variation of temperature and salinity, the heat storage (Jm^{-2}) in different segments (0-100, 100-200, 200-300 and 300-400 m) in the 450 m of the water columns was calculated based on the formula:

$$HS = \frac{1}{8}\sum_{i=1}^{N}(Cp_i + Cp_{i+1})(\rho_i + \rho_{i+1})(T_i + T_{i+1})(Z_i - Z_{i+1})$$

where HS is the heat storage, N is the number of the depth levels which were set in the water column, Cp_i is the specific heat capacity (J kg $°C^{-1}$) at the ith level, ρ_i is the water density (kgm^{-3}) at the ith level, T_i is the water temperature at the ith level and Zi (m) is the ith level depth. The results of HS calculations (Fig. 6) showed that the maximum heat loss in the 0-100, 100-200, 200-300 and 300-400 m water columns were 1.483×10^9 Jm^{-2} between August and March, 0.656×10^9 Jm^{-2} between November and April, 0.284×10^9 Jm^{-2} between January and June, and 0.157×10^9 Jm^{-2} between February and August, respectively. Average HS of upper 100 m reflects a significant heat loss during August-March and a significant heat gain during April-August. This is due to the direct solar radiation and heat exchange at the air-sea interface. In general, the intermediate layers (100-200 and 200-300 m) lost heat to lower layers (300-400 m) during the whole year, while they lost heat to the upper layers (0-100 m) during January-April. Moreover, the intermediate layers gained heat from upper layer during May-December. This implies that intermediate layer plays a major role in heat transferring from upper layers to lower layers. Maiyza (1995) reported a high HS in the north-eastern Red Sea than in the Gulf of Aqaba. The HS in the 0-100 m water column in the Gulf ranged from 8.55×10^9 to 10.21×10^9 Jm^{-2}, whereas in the Red Sea the range was 9.29×10^9 to 10.45×10^9 Jm^{-2}. Both values are higher than our calculated values. Noteworthy mentioning that the measurements of Maiyza (1995) were carried out in the southern parts of the Gulf of Aqaba.

4.2 Inter Station Statistical Comparison

Findings from the time series records generated at the three stations in the northern Gulf of Aqaba were subjected to statistical comparison. The hydrographic conditions at each station exhibited pronounced seasonality, and the annual variations of the hydrographic variables were much higher than the difference between the three stations for the same time and depth. As a result, a straightforward comparison between the variables would be of very little value if any. Therefore, a technique in which conditions were compared to a reference station was followed. Here, the difference between a specific value and its reference value was calculated and these differences were then used in the analysis of the variance. The reference was selected as a composite station that includes all the data recorded at the different stations (Badran 1996, Badran and Foster 1998).

The above technique was applied for comparison between the means of potential temperature, salinity and density σ_θ for six profiles in the upper 300 m of the water column taken at the stations S1, S2, and S3 in the northern tip of the Gulf of Aqaba during the period February 2000 to August 2001. The statistical analysis of potential temperature, salinity and potential density showed no significant difference between the stations in the upper 300 m depth during the entire study period (Table 4).

4.3 Mixing Variability

In some circumstances, the mixing rate in the northern Gulf of Aqaba may not follow the fitted exponential association function (Fig. 5). For example, clear fluctuations in the mixed layer deepness occurred during the spring of 1999, when an intensive convection event in the northern Gulf of Aqaba was observed (during R/V Meteor cruise 44/2 on February 26th 1999; Manasrah 2002). The potential temperature profile showed a mixed surface layer down to 520 m depth, whereas four days before, on February 22nd, the mixed layer reached 250 m depth only (Fig. 7a). During these four days, the air temperature did not cool the surface water remarkably and the wind blew quite steady from the northern direction. On the other hand, it might be that the constant loss of buoyancy of the surface water due to winter cooling cause the density of the surface water to pass a critical threshold after which vertical convection occurred. Besides, large variability in the vertical extension of the thermocline was observed on shorter time scales, probably associated with internal waves (Manasrah 2002) when the potential temperature profile taken at the afternoon of March 1^{st}, the thermocline descended from 370 m to 470 m during the following night (Fig. 7b).

The annual cycle of the mixed layer deepness was influenced by changes in the surface-water temperature. As in the oceanic region, the deep vertical mixing is convectively driven by sea-surface cooling (Genin *et al.* 1995). Interannual variations in the maximum depth of mixing (Fig. 4) were therefore directly linked to a variation in the net heat flux during winter, which was always negative (net upward heat flux) during winter. The very deep convection may occur within a significant cold winter, such as that in winter 1992 (Genin *et al.* 1995). The vertical mixing in the Gulf of Aqaba in that winter was unusually deeply mixed to >850 m, resulting in increased supply of nutrients to the surface waters. This fuelled extraordinarily large algal and phytoplankton blooms demonstrating the substantial effect that the hydrographic conditions may have on the biological productivity of the ecosystem. By spring of 1992, a thick mat of filamentous algae covered broad sections of the underlying reef causing extensive disturbance to coral health (Genin *et al.* 1995).

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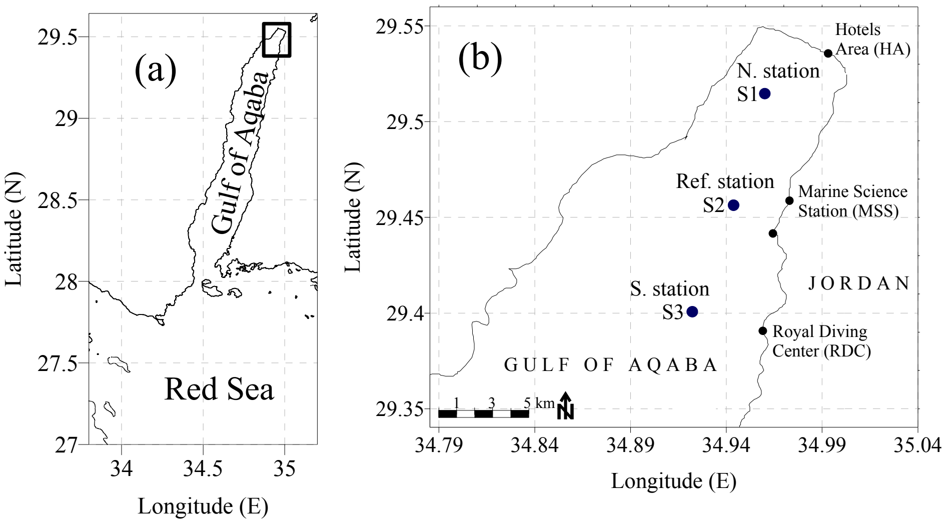
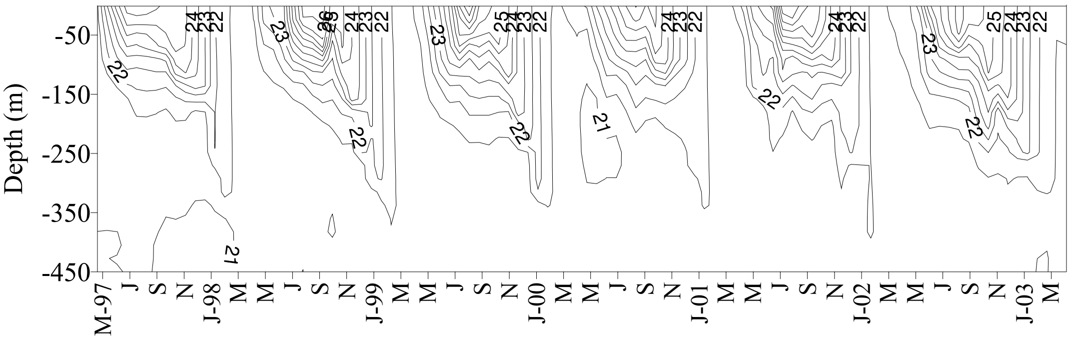
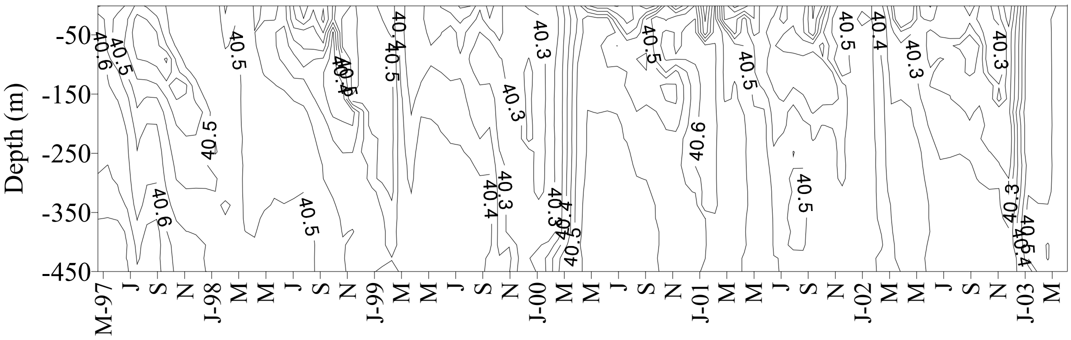


Fig. 1: (a) Map of the northern Red Sea and the Gulf of Aqaba showing the location of the study area. (b) Study area and measurement stations along the Jordanian sector of the Gulf of Aqaba.

(a) Potential temperature (°C)



(b) Salinity



(c) Potential density

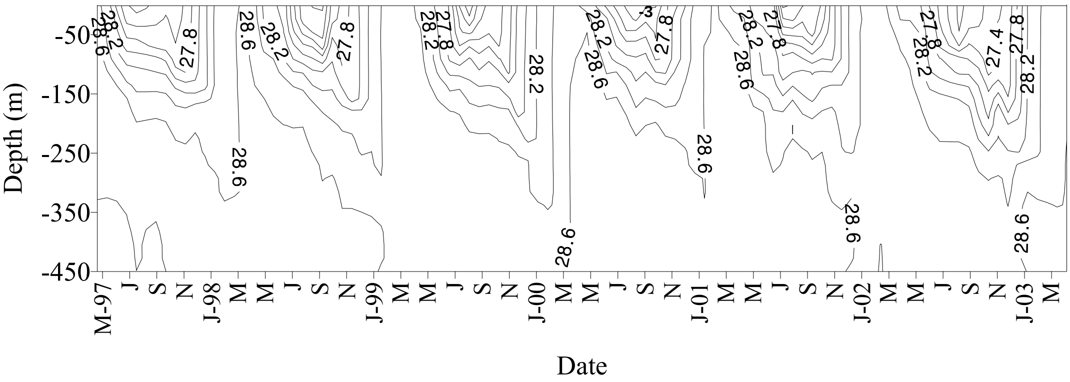


Fig. 2: Time series measurements of potential temperature (°C), Salinity, and density σ_θ in the upper 450 m water column during May 1997-April 2003 at the reference station (S2) in front of the MSS in the northern Gulf of Aqaba (after Manasrah *et al.*, 2006).

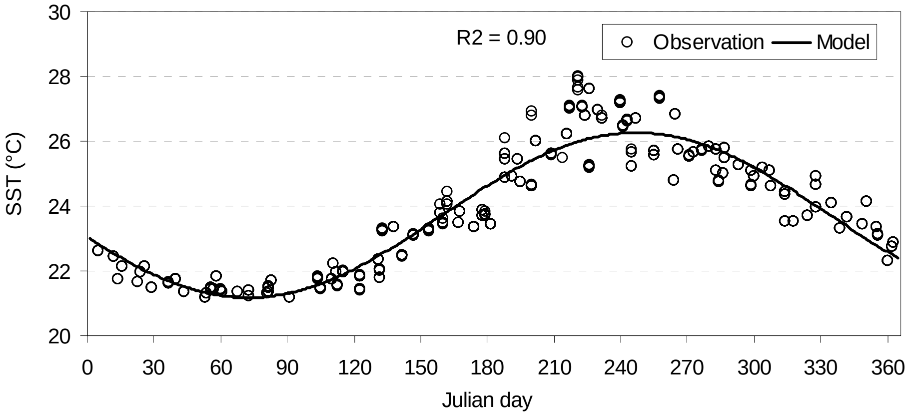


Fig. 3: Time series measurements and simple fit model of sea surface temperature (^{o}C) during May 1997-April 2003 in Julian day at the reference station (S2) in front of the MSS in the northern Gulf of Aqaba.

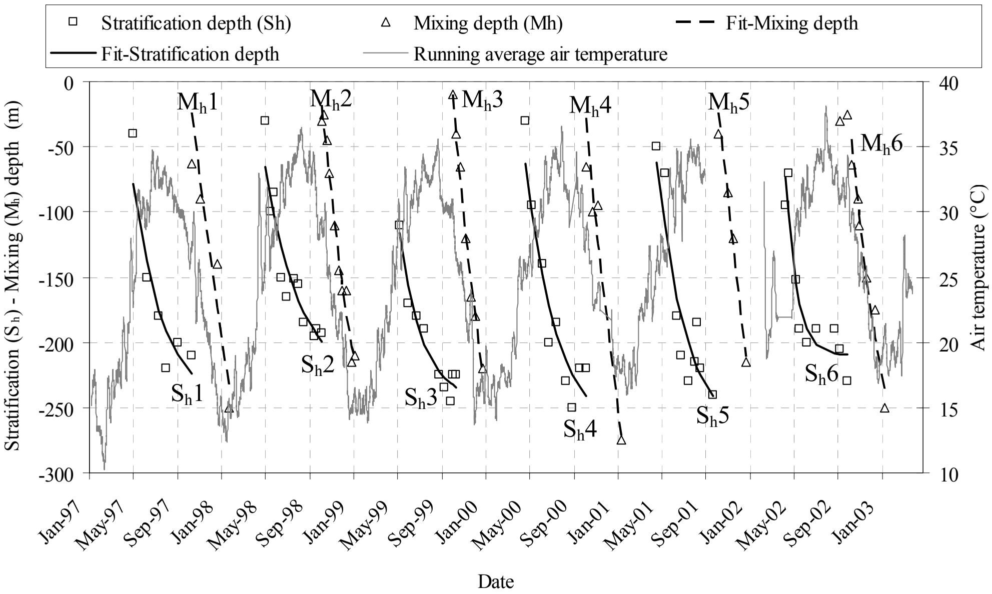


Fig. 4: Variation in the stratification deepness S_h (m) during summers and the mixed layer deepness M_h (m) during winter-spring seasons together with the low pass filtered air temperature (°C) during May 1997-April 2003 in the northern Gulf of Aqaba.

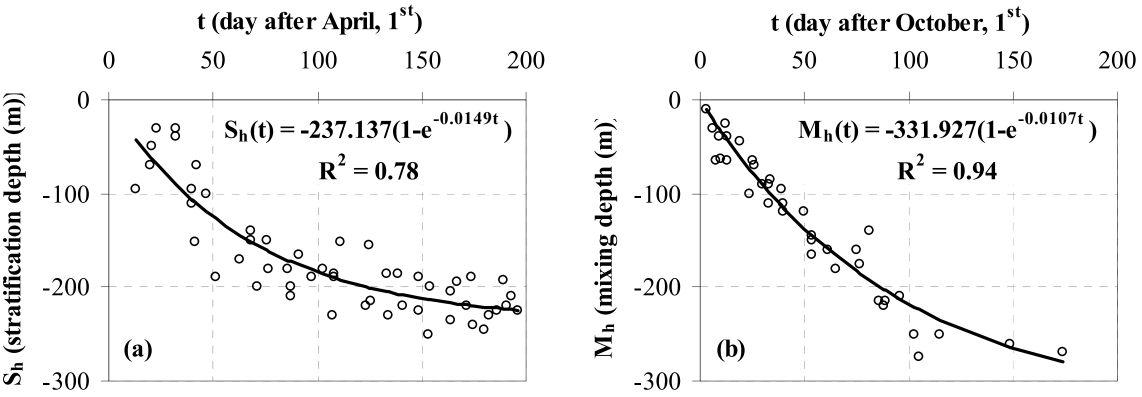


Fig. 5: Composite variations in (a) stratification deepness S_h (m) during summers and (b) mixed layer deepness M_h (m) during winter-spring seasons during the period May 1997-April 2003 in the northern Gulf of Aqaba.

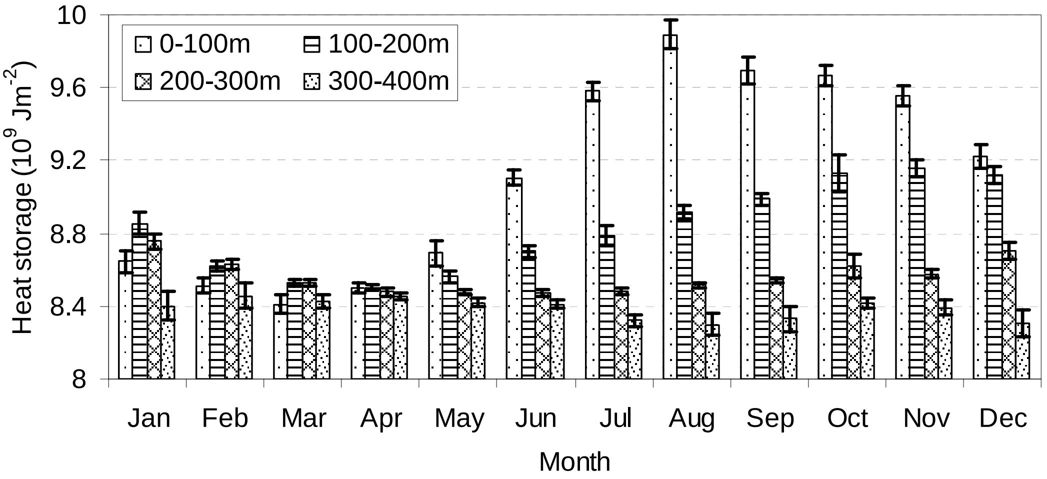


Fig. 6: Monthly average of heat storage (Jm^{-2}) in the 0-100, 100-200, 200-300 and 300-400 m water columns during May 1997-April 2003 at the reference station (S2) in front of the MSS in the northern Gulf of Aqaba.

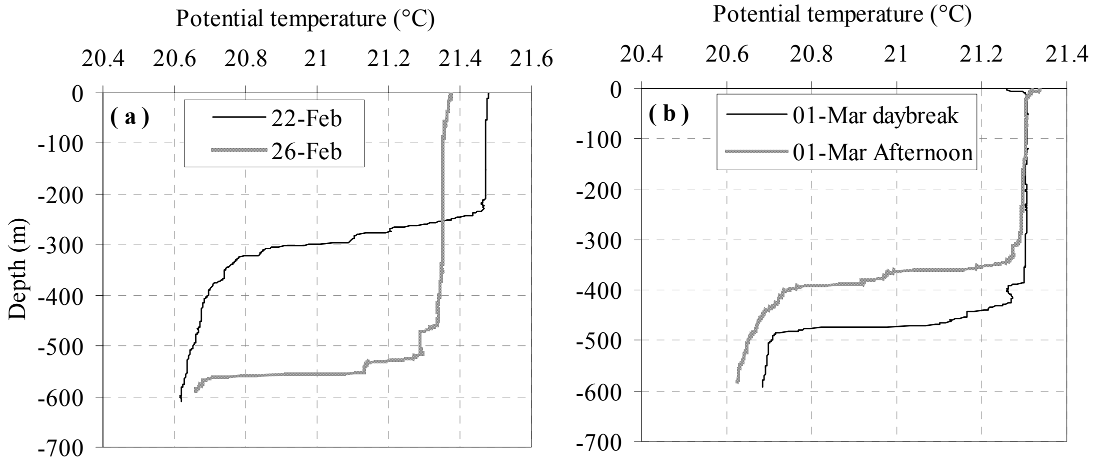
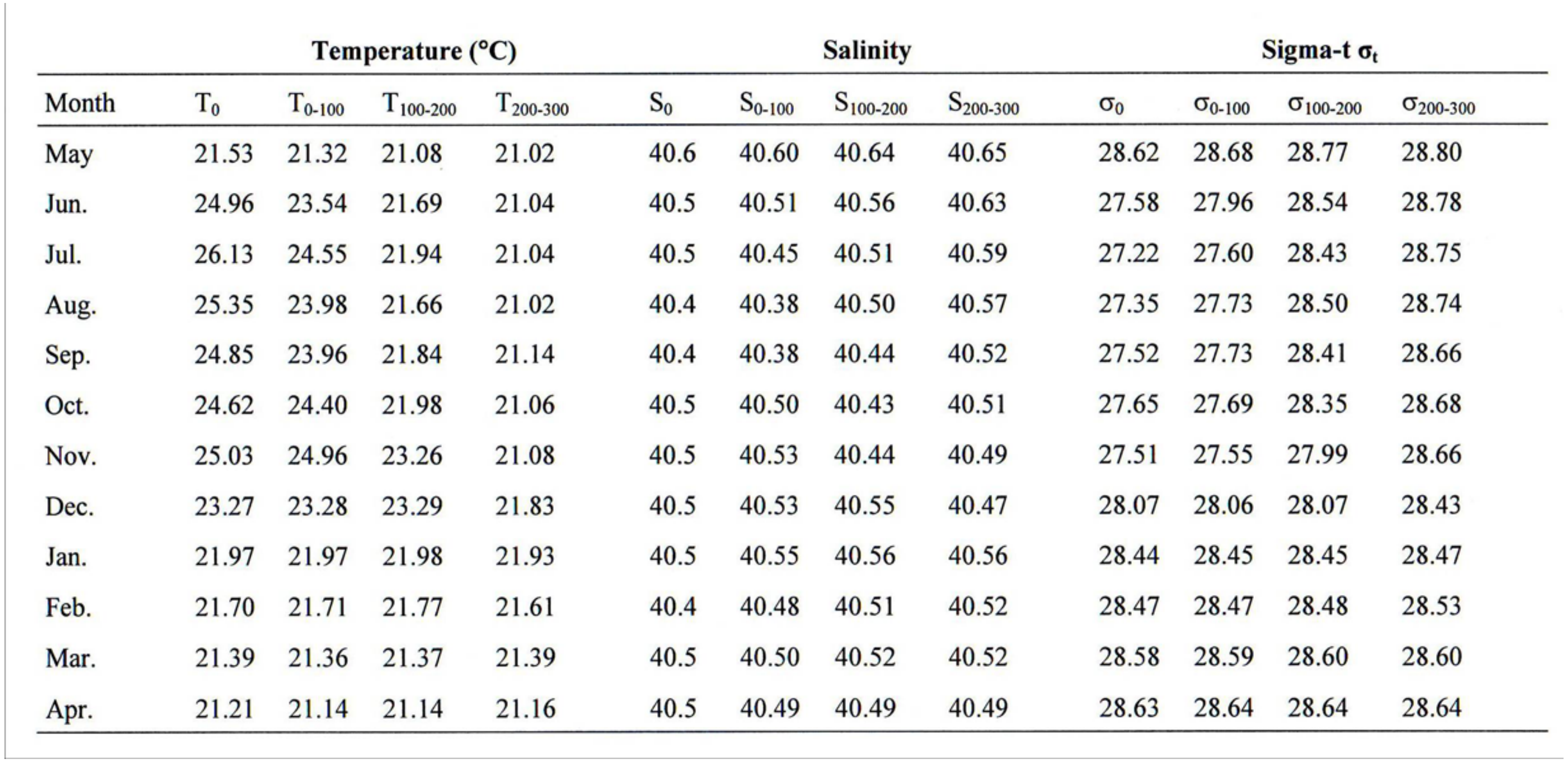


Fig. 7: Potential temperature (°C) profiles measured during R/V Meteor cruise 44/2 (a) February 22nd and 26th1999, and (b) afternoon, and night time of March 1st 1999 in the northern Gulf of Aqaba.

Table 1: Monthly mean temperature (^{o}C), salinity and the density σ_t at the surface water and in the segments 0-100, 100-200 and 200-300 m of the water column between May 1997 to April 1998 at the southern part of the Jordanian sector of the Gulf of Aqaba (Manasrah, 1998)



	Temperature (°C)				Salinity				Sigma-t σ_t			
Month	T_0	T_{0-100}	$T_{100-200}$	$T_{200-300}$	S_0	S_{0-100}	$S_{100-200}$	$S_{200-300}$	σ_0	σ_{0-100}	$\sigma_{100-200}$	$\sigma_{200-300}$
May	21.53	21.32	21.08	21.02	40.6	40.60	40.64	40.65	28.62	28.68	28.77	28.80
Jun.	24.96	23.54	21.69	21.04	40.5	40.51	40.56	40.63	27.58	27.96	28.54	28.78
Jul.	26.13	24.55	21.94	21.04	40.5	40.45	40.51	40.59	27.22	27.60	28.43	28.75
Aug.	25.35	23.98	21.66	21.02	40.4	40.38	40.50	40.57	27.35	27.73	28.50	28.74
Sep.	24.85	23.96	21.84	21.14	40.4	40.38	40.44	40.52	27.52	27.73	28.41	28.66
Oct.	24.62	24.40	21.98	21.06	40.5	40.50	40.43	40.51	27.65	27.69	28.35	28.68
Nov.	25.03	24.96	23.26	21.08	40.5	40.53	40.44	40.49	27.51	27.55	27.99	28.66
Dec.	23.27	23.28	23.29	21.83	40.5	40.53	40.55	40.47	28.07	28.06	28.07	28.43
Jan.	21.97	21.97	21.98	21.93	40.5	40.55	40.56	40.56	28.44	28.45	28.45	28.47
Feb.	21.70	21.71	21.77	21.61	40.4	40.48	40.51	40.52	28.47	28.47	28.48	28.53
Mar.	21.39	21.36	21.37	21.39	40.5	40.50	40.52	40.52	28.58	28.59	28.60	28.60
Apr.	21.21	21.14	21.14	21.16	40.5	40.49	40.49	40.49	28.63	28.64	28.64	28.64

Table 2: Location and bottom depths of the investigated stations in the northern Gulf of Aqaba.

Station	Latitude (N)	Longitude (E)	Bottom depth (m)
S1	29° 30.201′	34° 57.876′	430
S2	29° 27.503′	34° 57.225′	570
S3	29° 24.157′	34° 56.559′	640

Table 3: Parameters of the approximated fitting functions of the mixed/stratified layer deepness change with time during the years 1997-2002 in the northern Gulf of Aqaba.

	Stratification depth (m) $S_h(t_1^*) = a(1 - e^{-bt_1})$				Mixing depth (m) $M_h(t_2^*) = c(1 - e^{-dt_2})$			
Year		**a**	**b**	**R^2**		**c**	**d**	**R^2**
1997	S_h1	-249.4	0.012	0.88	M_h1	-827.3	0.003	0.85
1998	S_h2	-232.1	0.010	0.89	M_h2	-457.5	0.007	0.98
1999	S_h3	-244.7	0.016	0.95	M_h3	-501.5	0.008	0.99
2000	S_h4	-271.4	0.012	0.91	M_h4	-532.2	0.007	0.90
2001	S_h5	-273.5	0.012	0.87	M_h5	-1299.2	0.002	0.98
2002	S_h6	-210.2	0.033	0.88	M_h6	-380.9	0.009	0.95

*: t_1 is the day's number after April 1st.

**: t_2 is the day's number after October 1st.

Table 4: Statistical comparison between the means of potential temperature (°C), salinity, and density σ_θ at stations S1, S2, and S3 in the upper 300 m during February 2000 -August 2001; where, SD is the standard deviation, SE is the standard error, SSq is the total sum of the square, DF is the degrees of freedom, MSq is the mean of the square, F is the F-ratio or the variance ratio = MSq (stations or factor)/MSq (within cells or error), CI is the 95% confidence interval and p is the probability

Potential temperature (°C)	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**
S3	91	0.0143	0.1016	0.01065	-0.0069 to 0.0355
S2	91	0.0035	0.1156	0.01213	-0.0206 to 0.0276
S1	91	-	0.0977	0.01024	-0.0382 to 0.0025
Salinity	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**
S3	91	0.0011	0.0377	0.00396	-0.0067 to 0.0090
S2	91	-	0.0318	0.00334	-0.0083 to 0.0050
S1	91	0.0005	0.0347	0.00365	-0.0067 to 0.0078
Density σ_θ	**n**	**Mean**	**SD**	**SE**	**95% CI of Mean**
S3	91	-	0.0440	0.00461	-0.0126 to 0.0057
S2	91	-	0.0432	0.00453	-0.0114 to 0.0066
S1	91	0.0058	0.0362	0.00380	-0.0017 to 0.0134

Potential temperature					
Source of variation	SSq	DF	MSq	F	p
Stations (factor)	0.0486	2	0.0243	2.19	0.1136
Within cells (error)	2.9932	270	0.0111		
Total	3.0418	272			
Salinity					
Source of variation	SSq	DF	MSq	F	p
Stations (factor)	0.0004	2	0.0002	0.17	0.8472
Within cells (error)	0.3284	270	0.0012		
Total	0.3288	272			
Density σ_θ					
Source of variation	SSq	DF	MSq	F	p
Stations (factor)	0.0047	2	0.0023	1.37	0.2549
Within cells (error)	0.4607	270	0.0017		
Total	0.4654	272			

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التغيرات الموسمية السنوية للبناء الحراري – الملوحي لمياه البحر في شمالي خليج العقبة، البحر الأحمر

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ملخـص

تمت دراسة التغيرات الزمنية والمكانية لدرجة حرارة وملوحة مياه البحر في ثلاثة مواقع من الجزء الشمالي لخليج العقبة لمدة ست سنوات "أيار 1997-نيسان 2003". أظهرت النتائج أن التطبقَ الحراري هو الميزة السائدة في طبقات المياه العليا خلال فصل الصيف (أيار- كانون1). وظهر أقوى تطبق حراري خلال شهر آب وتجاوز عمق 250 متراً. سادت ظروف الخلط في عمود الماء خلال فصول الشتاء والربيع (كانون2- نيسان)، وسجل أقصى عمق للخلط خلال آذار-نيسان، حيث تجاوز أعمق نقطة جمع عينات (450 متراً). الاختلافات المركبة لعمق التطبق مع الوقت أثناء فترة الصيف وعمق الخلط مع الوقت أثناء فترة الشتاء-الربيع لاءمت علاقة أسية مشتركة. ووجد أن سرعة بناء التطبق الحراري وسرعة انهدامه (خلط المياه) كانت سريعة نسبيا (3.5 متر/يوم) في بداية فترة الصيف وفترة الشتاء-الربيع، على الترتيب، ثم انخفضتا عند نهايات فترة الصيف وفترة الشتاء-الربيع لتصل إلى 0.24 و0.52 متر/يوم، على الترتيب. من ناحية أخرى، هنالك ظاهرة مثيرة للاهتمام ومتكررة خلال أوقات الصيف والتي تبين أن طبقة مياه ذات ملوحة أعلى تعلو طبقة ذات ملوحة أقل. ويمكن أن تعزى هذه الظاهرة إلى التبخر العالي وإلى التيارات البحرية في الطبقات الوسطى من عمود الماء المحملة بمياه ذات ملوحة منخفضة وقادمة من البحر الأحمر إلى الخليج. التغيرات السنوية والموسمية للملوحة في شمالي خليج العقبة خلال فترة الدراسة كانت ضئيلة جداً وتراوحت بين 40.12-40.75 PSU. أما التغيرات في درجة الحرارة فقد كانت واضحة وتراوحت بين 20.02-27.99م°. ويستنتج من ذلك أن الحرارة هي العامل المسيطر في عمليات الديناميكا الحرارية لمياه البحر في شمالي خليج العقبة، في حين أن الملوحة لها تأثير ضئيل. لا يوجد أي اختلافات جوهرية معنوية مكانية فيما بين المواقع الثلاثة لقيم درجة الحرارة، الملوحة والكثافة في عمود الماء من السطح إلى 300 متر.

الكلمات الدالة: درجة حرارة ماء البحر، الملوحة، الكثافة، التطبق، الخلط، خليج العقبة، البحر الأحمر.

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