Papers

Circulation and winter deep-water formation in the northern Red Sea*

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Abstract

Water mass characteristics and circulation patterns in the Gulf of Aqaba and northern Red Sea were studied for the first time during the r/v 'Meteor' cruise leg 44/2 from February 21st to March 7th 1999 using temperature-salinity profiles and current observations. The deep water in the northern Red Sea had similar characteristics to the well-mixed upper 450 m of water in the Gulf of Aqaba.

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This indicates that the winter mixed waters of the Gulf of Aqaba contribute significantly to deep-water in the northern Red Sea. Mixing in the Gulf of Aqaba is an annually repeated event that starts with the cooling of the surface water during November–December and reaches a maximum, which in most years extends down the entire water column in March–April. Waters deeper than the mixed layer in the Gulf seems to be rather passive and play no specific role in water mass formation in the northern Red Sea. In contrast to the Gulf of Aqaba, the upper 200 m of the northern Red Sea were stratified (21.5–23.5°C, and 40.0–40.3 PSU). Stratification at the Strait of Tiran was weak (21.6–22.0°C, and 40.3–40.5 PSU) and disappeared abruptly in the Gulf of Aqaba (21.4–21.6°C, and 40.6–40.7 PSU). A well-developed cyclonic gyre with a diameter of about 50–60 km and maximum velocity of about 0.4 m s^{-1} was observed in the stratified upper 200 m of the northern Red Sea waters. The gyre may contribute to the preconditioning for intermediate water formation in the northern Red Sea.

1. Introduction

The Red Sea (Fig. 1a) can be considered a miniature world ocean. It features a unique combination of being relatively small but having a rather complex bathymetry. It features several characteristics of a global ocean, such as the role of convective and subductive water mass formation in maintaining meridional thermohaline overturning, air-sea interactions leading to formation events, interactions with adjacent semi-enclosed basins, and the significance of small scale mixing processes (Eshel et al. 1994, Eshel & Naik 1996). Red Sea water is one of the most important intermediate water masses in the Indian Ocean due to its higher temperature and salinity as compared with the water in the interior of the ocean (Eshel et al. 1994, Plaehn et al. 2002). The Red Sea forms a long and narrow trench, oriented roughly NNW–SSE, located between 12°N and 28°N and is about 1930 km long and 270 km wide (Sverdrup et al. 1961, Maillard & Soliman 1986). The sea splits in the north into the western shallow Gulf of Suez and the eastern deep Gulf of Aqaba.

The Gulf of Aqaba (Fig. 1b) is located in the sub-tropical arid zone between 28–29°30′N and 34°30′–35°E. It is about 180 km long and has a maximum width of 25 km. The width decreases at the northern tip to about 5 km (Hall & Ben-Avraham 1978, Hulings 1989). The maximum depth of the Gulf is about 1830 m with a mean depth of about 800 m (Por & Lerner-Seggev 1966, Morcos 1970, Hulings 1989). The Gulf of Aqaba is semi-enclosed and is connected to the Red Sea by the Strait of Tiran, which has a sill depth of about 260 m (Hall 1975). Plaehn et al. (2002), studying the formation of bottom water in the Red Sea by applying a box model, found that the contribution of the Gulf of Aqaba to bottom water

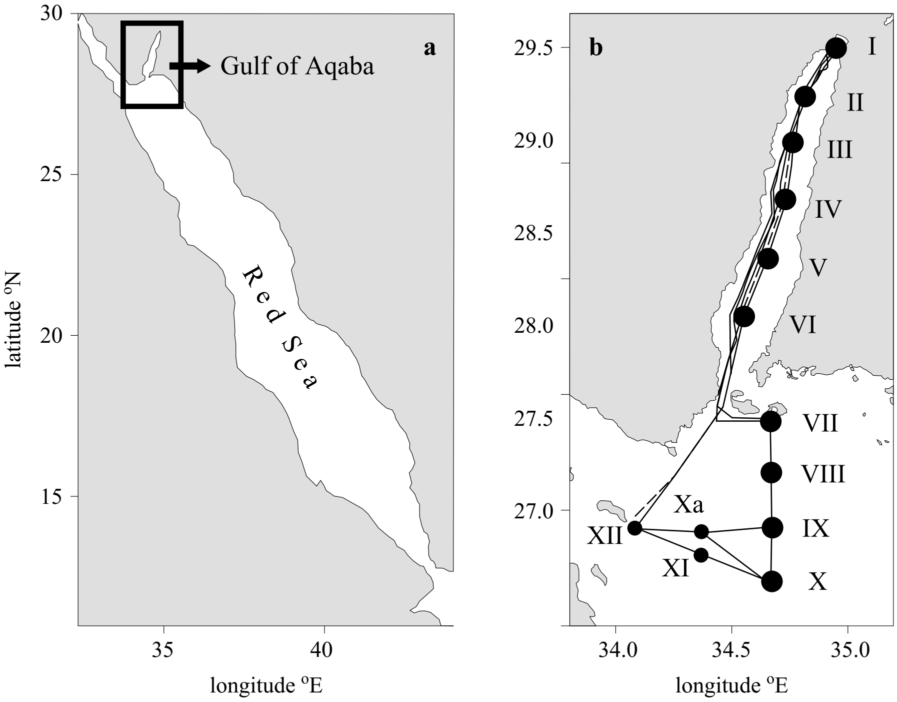

Fig. 1. Study area map (a) and station locations (positions I–XII) and route of current measurements in the Gulf of Aqaba and northern Red Sea, r/v 'Meteor' cruise 44/2 (b)

formation in the Red Sea is at least 1.5 times that of the longer, wider but much shallower and bathymetrically smoother Gulf of Suez. Estimates of the annually averaged rate of Red Sea deep-water formation range from 0.06 to 0.16 Sv (1 Sv = 1×10^6 m^3 s^{-1}) (Wyrtki 1974, Cember 1988). This water forms in the northern Red Sea predominantly during winter, filling the deep basin below the sill depth (approximately 160 m) of Bab el Mandeb Strait with a nearly homogeneous water mass of temperature (~22°C) and salinity (~40.6 PSU) (Neumann & McGill 1961). A second source of somewhat less dense 'intermediate' Red Sea water is believed to be formed, also predominantly in winter, by an open sea convection process, but it is still poorly understood and not sufficiently documented (Cember 1988). The objectives of the present work are to describe the water mass characteristics and circulation regime in the Gulf of Aqaba and northern Red Sea and to further investigate the role of the Gulf of Aqaba in deep-water formation in the Red Sea during spring using CTD and current records generated during the r/v 'Meteor' cruise leg 44/2 (February–March 1999).

2. Material and methods

2.1. Study area

The r/v 'Meteor' cruise 44/2 covered the Gulf of Aqaba and parts of the northern Red Sea near the Strait of Tiran. Six positions (Pos. I–VI) were distributed 25–30 km apart along the axis of the Gulf. The northern Red Sea part consisted of a further seven positions (Pos. VII–XII and Xa) aligned mainly along meridional and latitudinal sections (Fig. 1b). The sampling stations were occupied four times in the Gulf of Aqaba and three times in the northern Red Sea during the period February 21st to March 7th 1999.

2.2. Field data

Meteorological data as well as seawater temperature and salinity near the sea surface and current profiles down to 350 m depth were continuously recorded en route. Seventy-two profiles of salinity and temperature were generated at 52 stations by the CTD (Conductivity, Temperature and Depth meter) Neil Brown Mark IIIb that was attached to a 24-bottle 10 L General Oceanic rosette water sampler. Four of the bottles were equipped with deep-sea reversing electronic thermometers from SIS. When employed, the rosette was lowered and hauled at a speed of 0.5 m s^{-1} in the upper 100 m and at a speed of 1 m s^{-1} deeper. Calibrations of the pressure and temperature sensors were done prior to the cruise at the Institut für Meereskunde (IFM), Kiel University. During the cruise, thermometer readings were used to check the laboratory calibration of the temperature sensor. Salinity samples, typically three per profile, were analyzed after the cruise using an Autosal Salinometer in the IFM.

Currents were recorded using a shipboard Acoustic Doppler Current Profiler 150 kHz (ADCP) covering a range of about 350 m at a bin length of 8 m and a pulse length of 16 m. The number of bins was 60. The profiles were averaged over 2 minutes. A GLONASS/GPS-receiver was used for correction of the ship's motion and a three-dimensional GPS receiver (ADU) for highly accurate heading measurements in order to correct the Schuler oscillation of the gyro-compass.

3. Results

3.1. Weather and meteorological conditions during the cruise

During the cruise the weather conditions in the Gulf of Aqaba was good with a poor cloudiness. The winds blew daily from northerly directions with wind speeds between 18 and 26 knots. Additionally orographic- and katabatic effects forced the wind speed up to 40 knots in some regions of the Gulf of Aqaba, especially in the Strait of Tiran. The average wind speed during the cruise was about 20 knots from northerly directions with a frequency of 92%. Due to the short fetch of about 100 km, the maximum wind sea was about 1.5 meter. The temperatures cooled to 13°C in the morning and raised up to 22°C in the afternoon. Only in the last three days of the cruise the wind became calm because of a low pressure gradient in the area. Therefore see breeze developed in the afternoon with wind speeds up to 8 knots from southerly directions (Brauner 2000).

3.2. Water masses, mixing and stratification

3.2.1. Spatial distribution of the potential temperature, salinity and potential density

The short-term yet intensive investigation of the potential temperature [°C] and salinity carried out during the period of weak stratification in the Gulf of Aqaba and northern Red Sea showed that the potential temperature variationwith depth in the Gulf of Aqaba was clearly different from that in the northern Red Sea (Fig. 2a). The surface water in the latter, with temperatures of 21.5–23.5°C and salinities of 40.00–40.35 PSU (Fig. 2b), was separated from the intermediate water (21.5°C; 40.50 PSU) and the bottom water (21.3°C; 40.53 PSU) by a thermocline centered at about 100 m. The surface temperature in the study area decreased gradually from south to north (from position X to I; Fig. 1b), whereas salinity increased. In the Gulf of Aqaba, well-mixed water was found in the upper 300 m, extending slightly deeper than the sill depth of the Strait of Tiran. A weak thermocline between 350–500 m separated the homogeneous deep-water with a potential temperature of ~20.5°C and a salinity of 40.67 PSU from the surface water. The deep-water in the Gulf of Aqaba that was separated from the northern Red Sea by the sill of the Strait of Tiran was cooler and saltier than the deep-water body observed in the northern Red Sea. The surface water of the Gulf of Aqaba, with temperatures ranging from 22.0 to 21.3°C and salinities from 40.30 to 40.70 PSU from south to north, was also cooler and more saline than the surface water of the northern Red Sea. The two surface water masses were separated by a front slightly north of the Strait of Tiran, referred to as the 'Strait of Tiran front'. The surface water of the Gulf of Aqaba just north of the Strait of Tiran front had the same potential temperature-salinity characteristics of both the intermediate and the deep-water in the northern Red Sea. The surface water salinity (~40.70 PSU) in the northern Gulf of Aqaba (Fig. 2b) was higher than the bottom water salinity (~40.55 PSU) in the northern Red Sea. The behavior of the

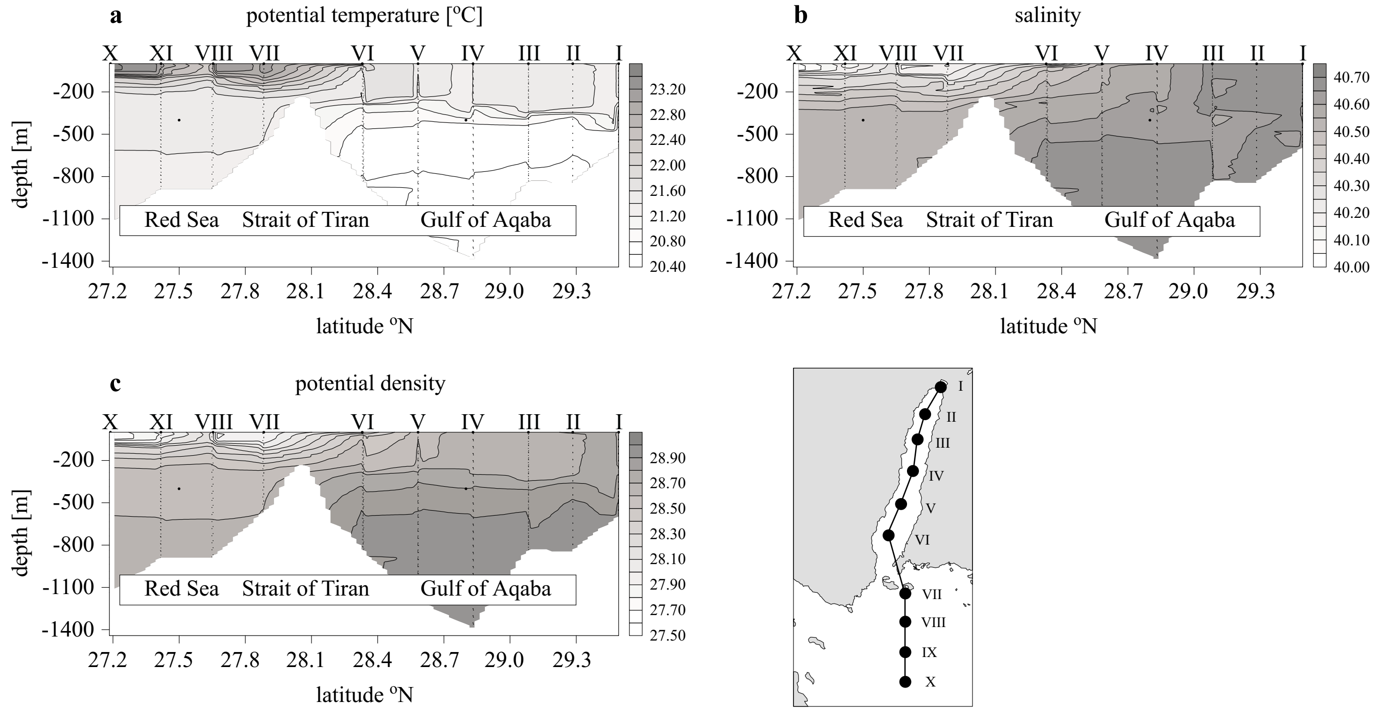

Fig. 2. Long section distribution of the potential temperature [°C], salinity and potential density in the Gulf of Aqaba and the northern Red Sea from February 21st to March 7th 1999, r/v 'Meteor' cruise 44/2

potential density (Fig. 2c) followed basically the potential temperature scale with respect to the stratification and mixing, i.e., salinity played a minor role.

3.2.2. Water mass properties

Water masses can be classified on the basis of their potential temperature-salinity characteristics depicted in θ-S diagrams, introduced by Helland-Hansen (1916). All CTD casts taken from the Gulf of Aqaba and northern Red Sea during the cruise are plotted in a θ-S diagram (Fig. 3). Apparent here is that the upper layer of the Gulf of Aqaba (0–300 m) had the same water mass characteristics of the intermediate and deep waters (500–1300 m) of the northern Red Sea. Moreover, the characteristics of the deep water (500–1400 m) in the Gulf of Aqaba was similar neither to the upper waters in the Gulf of Aqaba nor to those in the northern Red Sea.

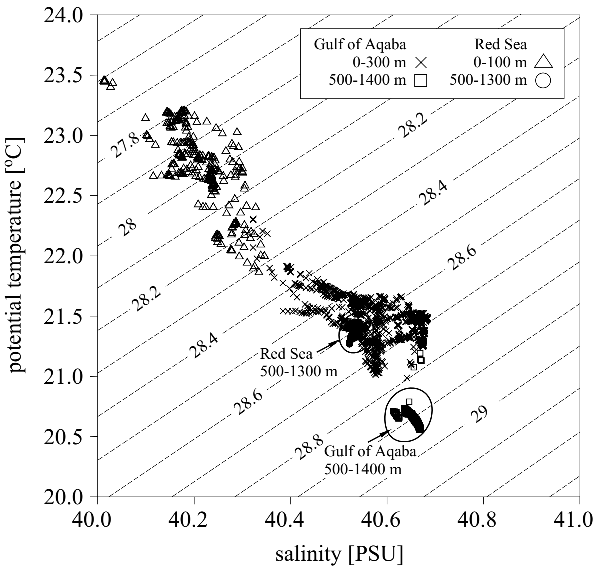

Fig. 3. Potential temperature-salinity (θ-S) diagram in the Gulf of Aqaba and the northern Red Sea during February 21st–March 7th 1999, r/v 'Meteor' cruise 44/2

3.3. Circulation in the Gulf of Aqaba

In order to study the basin scale current pattern along the Gulf of Aqaba axis, four continuous tracks were performed within eight days, on February 26th–27th, February 28th–March 1st, March 1st–2nd, and March 4th–5th 1999 (Fig. 1b). The horizontal current components (Figs 4a and 4b)

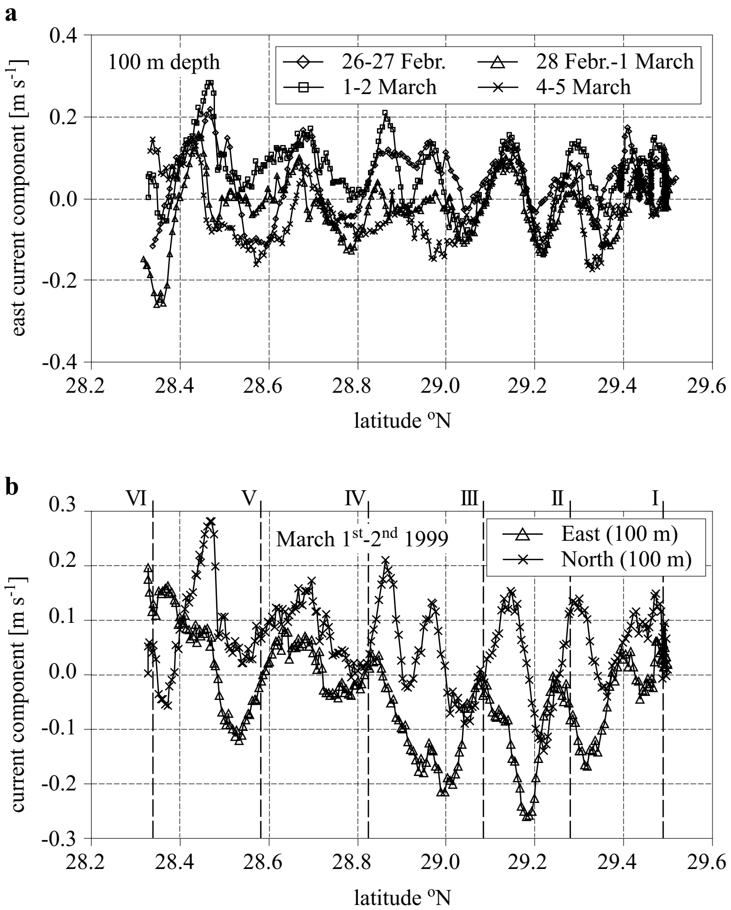

Fig. 4. Distribution of the east current component [m s^{-1}] along the axis of the Gulf of Aqaba at 100 m depth on repeated tracks (a). Distribution of east and north current components (all in [m s^{-1}]) along the axis of the Gulf of Aqaba at 100 m depth during March 1st–2nd 1999, r/v 'Meteor' cruise 44/2 (b)

indicated that the most significant feature was a wave-like variation of the velocity and a phase difference between the east and north current components. These properties of the current field suggest the existence of a wave train, which looks like a chain of cyclonic and anti-cyclonic eddy pairs (Fig. 5). Statistical analysis of the east and north current components at selected depths (40, 100, 150, 200 and 250 m) for all tracks along the Gulf axis revealed weak averaged magnitudes, ranging between −0.05 to 0.03 m s^{-1} with a standard error of 0.002–0.003 and indicating a fluctuating water movement.

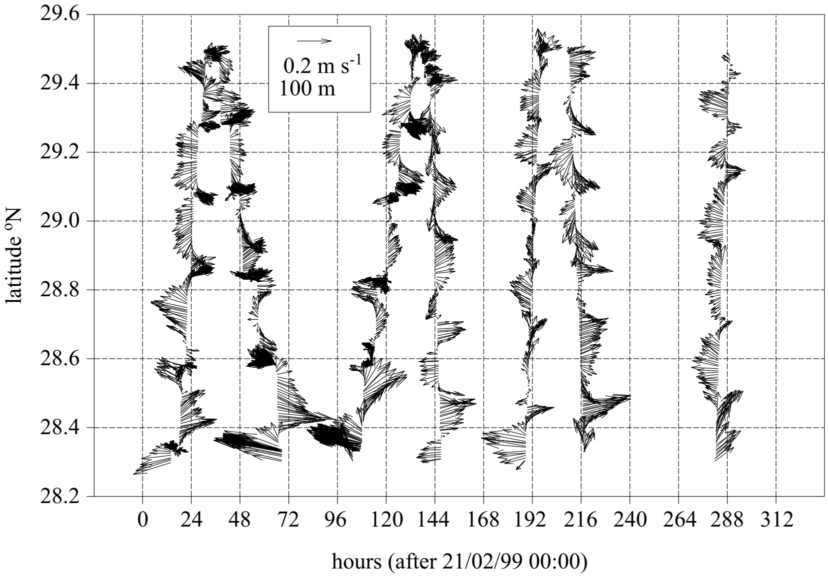

Fig. 5. Time-latitude distribution of the current vectors along the axis of the Gulf of Aqaba at 105 m depth on repeated tracks during February 21st–March 6th 1999, r/v 'Meteor' cruise 44/2

3.4. Circulation in the northern Red Sea

Horizontal current vector distributions in the northern Red Sea during the periods February 21st–24th, February 25th–28th and March 3rd–4th 1999 are plotted against different depths in the upper 275 m (Figs 6–8). These observations covered the area east and southeast of the Southern Sinai Peninsula. A well developed cyclonic gyre with a diameter of about 50–60 km and maximum velocity of about 0.4 m s^{-1} was observed in the upper 215 m depth (Figs 6–8). This gyre was quite stable during all three observational periods.

3.5. Water exchange through the Strait of Tiran

ADCP measurements were used to study the water exchange through the Strait of Tiran; they exhibited a general view of the two-layer exchange between the northern Red Sea and Gulf of Aqaba through the Strait during February 21st–March 4th, 1999 (Fig. 9). Inflow (NNW) into the Gulf of Aqaba occurred in the 35–70 m of the water column over the sill (Fig. 10). This inflow was also clear about 1.5 km to the north and south of the sill (Fig. 9), where the thickness was larger (35–150 m). The SSW outflow into the northern Red Sea observed below 70 m over the sill (Fig. 10) comprised

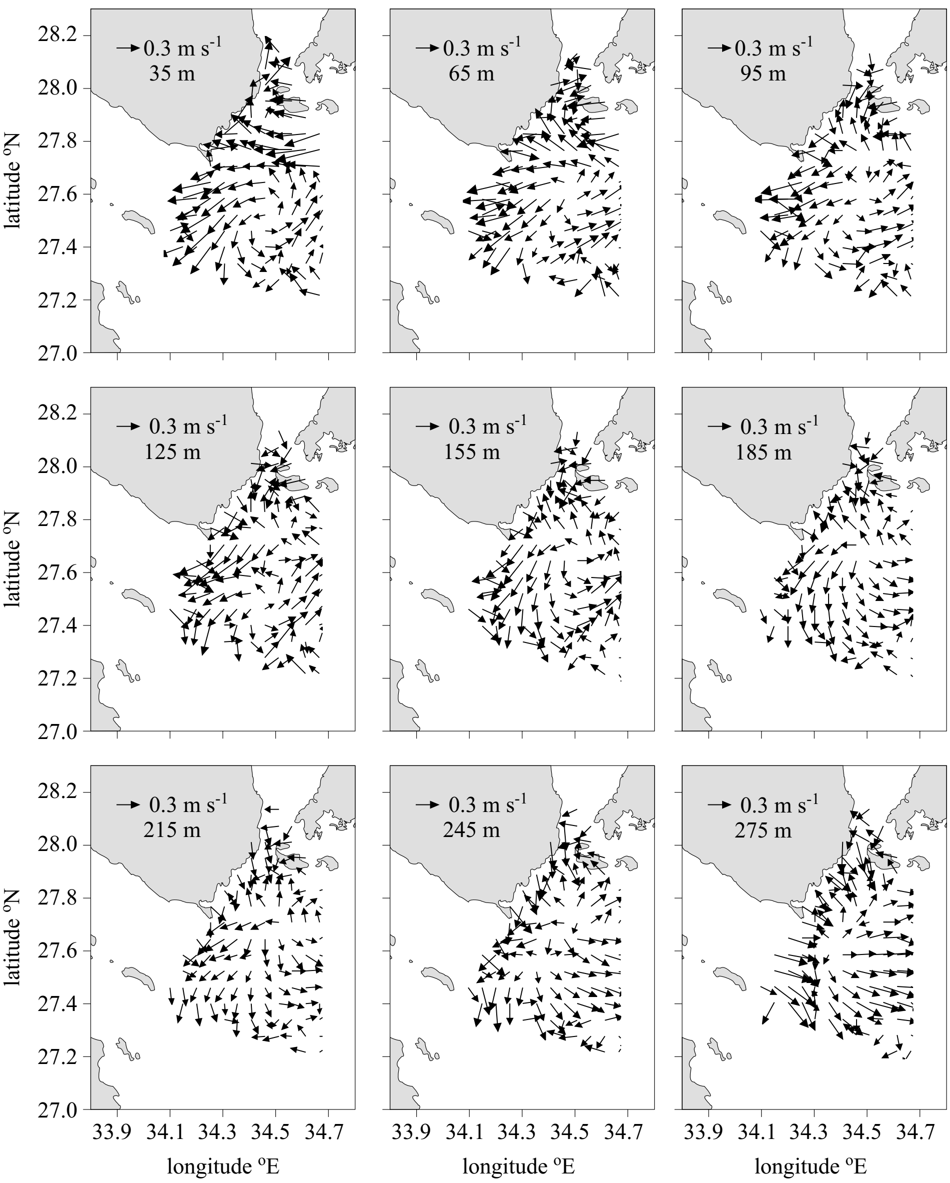

Fig. 6. Distribution of the horizontal current vectors in the northern Red Sea at different depths in the upper 275 m during February 21st–24th 1999, r/v 'Meteor' cruise 44/2

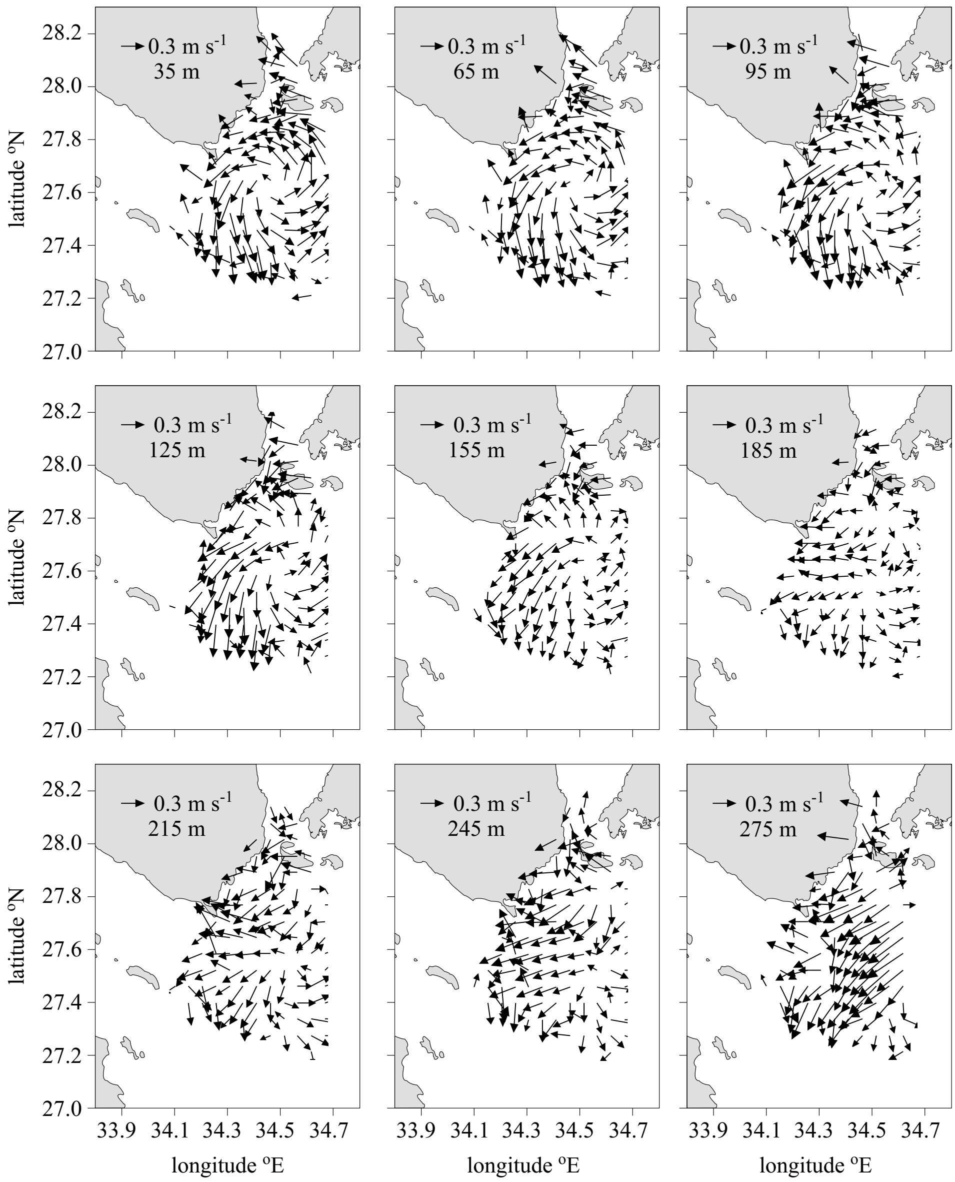

Fig. 7. As in Fig. 6 during February 25th–28th 1999, r/v 'Meteor' cruise 44/2

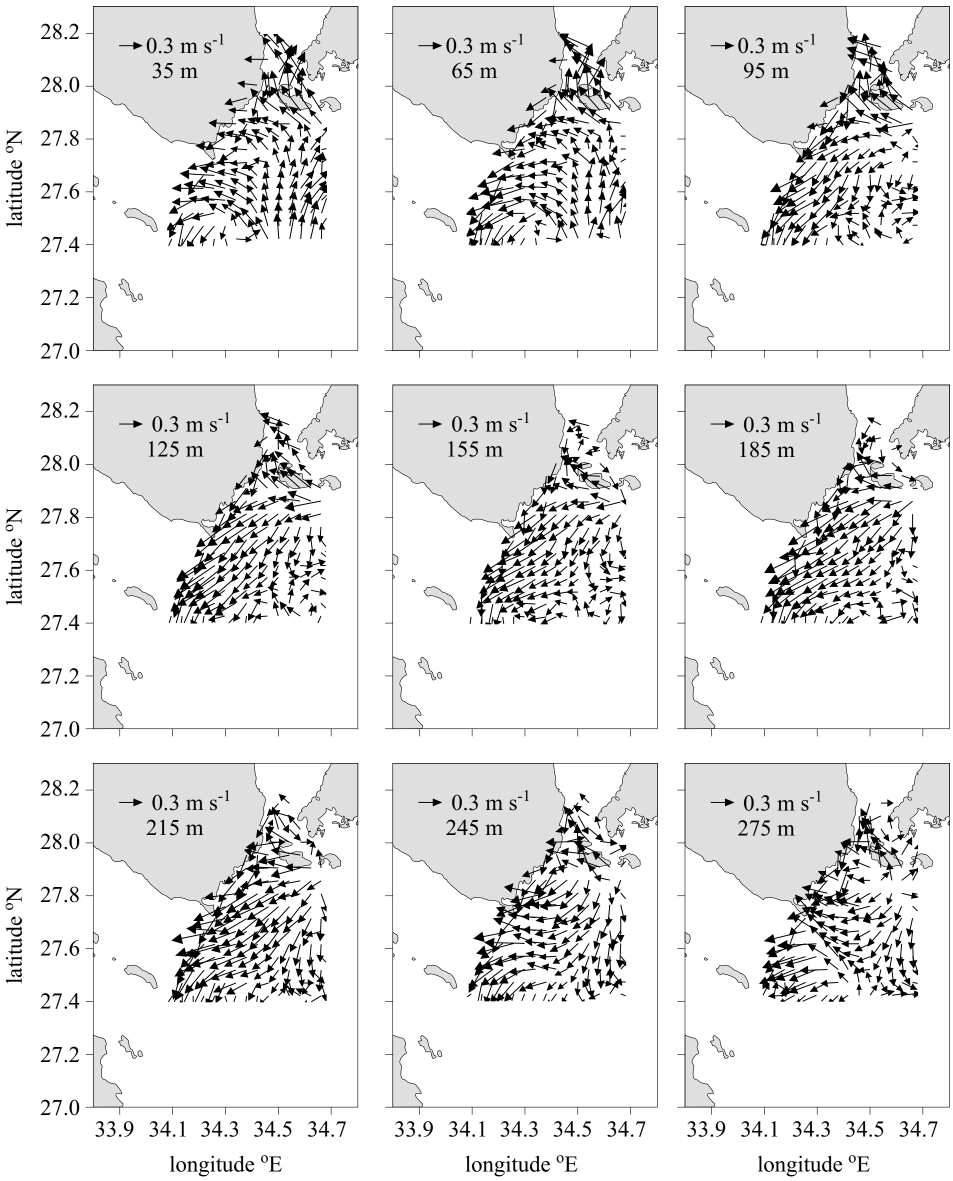

Fig. 8. As in Fig. 6, during March 3rd–4th 1999, r/v 'Meteor' cruise 44/2

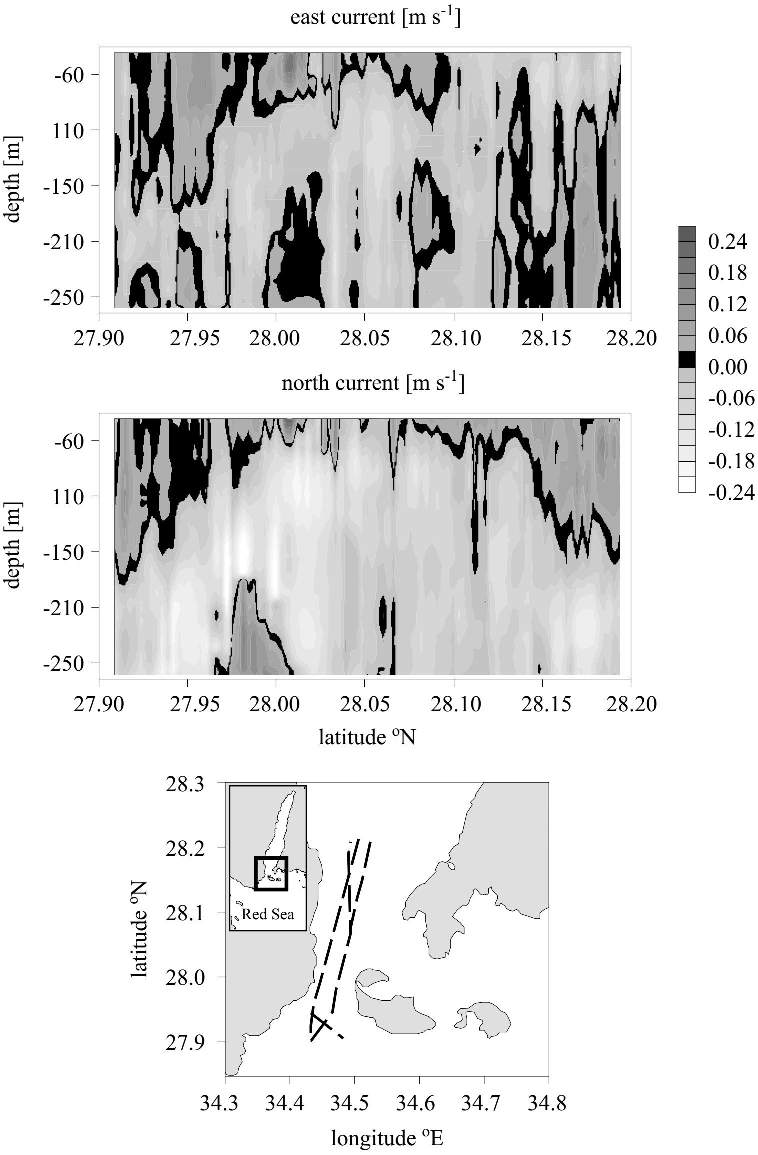

Fig. 9. Vertical section distribution of the east and north current components [m s^{-1}] through the Strait of Tiran during February 21st–March 4th 1999, 'Meteor' cruise 44/2

a thick layer penetrating deeper (< 200 m) about 1.5 km south and north of the sill (Fig. 9). The strength of the outflow to the northern Red Sea increased linearly with depth, reaching up to about 1 m s^{-1} at 200 m depth (Fig. 10d).

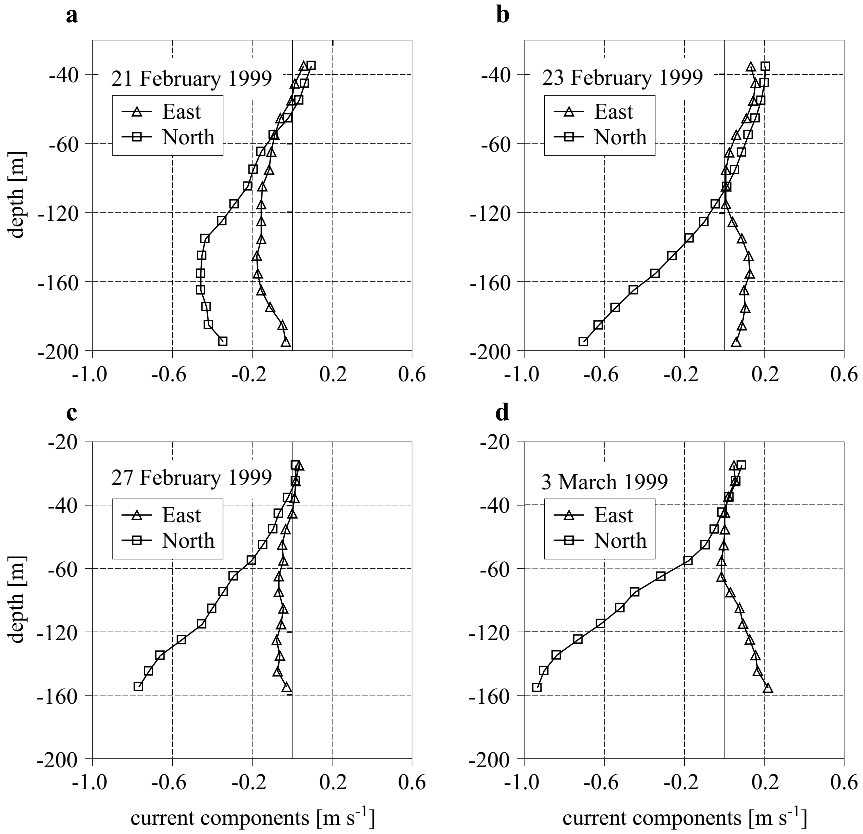

Fig. 10. The east and north current components (all in [m s^{-1}]) profiles at the sill of the Strait of Tiran measured on different dates during r/v 'Meteor' cruise 44/2

4. Discussion and conclusions

4.1. The role of the Gulf of Aqaba in deep-water formation in the northern Red Sea

Results of the present investigation obtained form the spatial distribution of the potential temperature and salinity (Fig. 2) along the main axis of the Gulf of Aqaba and in the northern parts of the Red Sea during spring 1999 strongly suggest that the Gulf of Aqaba is an important source of deep-water formation in the northern Red Sea. This is in good agreement with previous studies (e.g. Maillard 1974, Woelk & Quadfasel 1996, Plaehn 2002). Maillard (1974) concluded that the main convective flow is created by the mixing of the dense Gulf of Aqaba and Gulf of Suez waters, which are far colder and saltier than the Red Sea deep-water with the northern Red Sea subsurface water. According to Plaehn (2002), the deep-water masses in the

Red Sea can be separated into two parts. The upper part is dominated by the inflow from the Gulf of Suez, while the lower part is formed mainly by the dense outflow from the Gulf of Aqaba, marked by a chlorofluorocarbon CFC-12 anomaly, and found at the bottom of the Red Sea. Using a box model, the authors estimated that the Gulf of Aqaba waters contributed to bottom-water formation in the Red Sea with an intensity at least 1.5 times greater than that of the waters in the Gulf of Suez. The potential temperature-salinity (θ-S) diagram (Fig. 3) reveals four main water types; the upper water of the northern Red Sea with a potential density σ_θ ∼27.8–28.3, θ ∼22–23°C and salinity ∼40.1–40.3 PSU, the upper water of the Gulf of Aqaba with σ_θ ∼28.35–28.8, θ ∼21–22°C and salinity ∼40.3–40.7 PSU, the deep water of the northern Red Sea that appears as a dense cluster in the center of the second type with σ_θ ∼28.6, θ ∼21.3°C and salinity ∼40.5–40.6 PSU, and the deep-water of the Gulf of Aqaba below 450 m separated from the northern Red Sea by the sill of the Strait of Tiran with σ_θ ∼28.9, θ ∼20.5°C and salinity ∼40.6–40.7 PSU. The similarity in water type between the deep northern Red Sea and upper Gulf of Aqaba can either facilitate the mixing of these two water types or be a result of this process. It is likely to occur as a result of the cooling and sinking of surface waters in the Gulf of Aqaba which starts every November and continues till April (Badran 2001). The Strait of Tiran appears to play a channeling role, leaving the deep water of the Gulf of Aqaba rather isolated and less actively involved in the exchange process between the Gulf of Aqaba and the Red Sea proper, until they are vertically mixed with the upper water later in spring. The upper water of the northern Red Sea can be best understood in terms of the convection of warmer southern Red Sea water and the less saline waters of the Gulf of Suez.

4.2. Circulation in the Gulf of Aqaba, northern Red Sea and across the Strait of Tiran

4.2.1. Gulf of Aqaba

The chain of cyclonic and anti-cyclonic eddy pairs characterizing the water circulation along the main axis of the Gulf of Aqaba during the winter – spring season with a diameter for each pair of about 20 km, equal to twice the Rossby radius, are recorded in such detail for the first time, thanks to the intensive sampling program of the 'Meteor' Cruise. In a previous study (Berman et al. 2000), the authors, using a numerical model, reported the occurrence of three eddies in the northern half of the Gulf of Aqaba. The northernmost gyre was anti-cyclonic with a diameter of 18 km during winter, but change to cyclonic with a diameter of 10 km during spring.

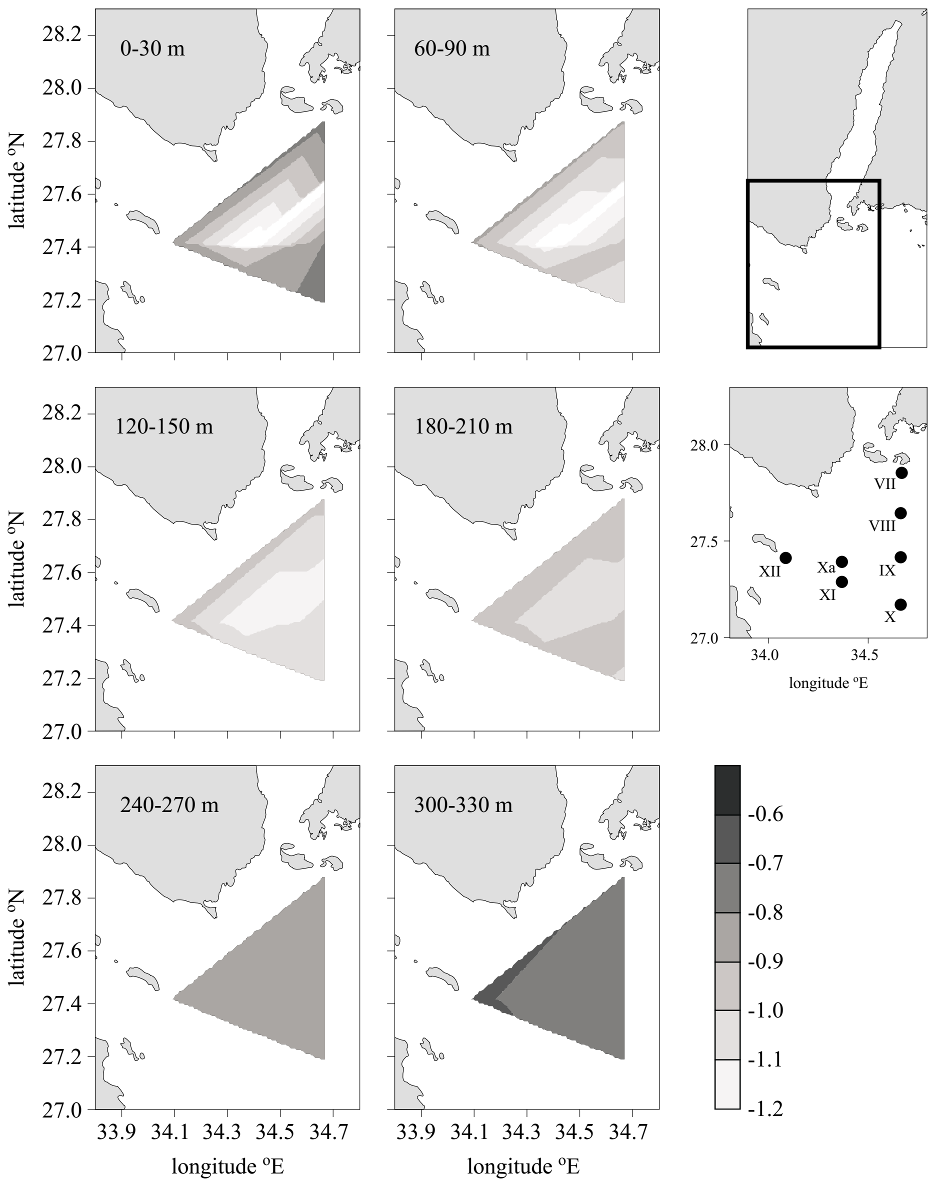

Fig. 11. Horizontal distribution of the geopotential anomaly [m^2 s^{-2}] at different depths in the northern Red Sea, referenced to 600 dbar pressure level, r/v 'Meteor' cruise M44/2

4.2.2. Northern Red Sea

Not very different from the Gulf of Aqaba, the circulation in Red Sea surface water is characterized by a number of horizontal gyres or eddies distributed along its main axis (Quadfasel & Baudner 1993). Some of these may be semi-permanent and in the northern Red Sea mainly cyclonic, particularly in winter, as indicated by drifter trajectories (Clifford et al. 1997). Our records have clearly disclosed a well-developed cyclonic gyre with a diameter of 50–60 km and a velocity of up to 0.4 m s^{-1} in the stratified upper 200 m waters of the northern Red Sea (Figs 6–8). Not only was the gyre recorded by the ADCP, it was also confirmed by the horizontal distribution of the geopotential anomaly [m^2 s^{-2}] at different depths in the northern Red Sea referred to the 600 dbar pressure level (Fig. 11). The baroclinic pressure gradient combined with a depression in the sea surface subjected to geostrophic adjustment revealed the northern Red Sea cyclonic gyre. This gyre may very well be linked with the aforementioned intermediate water formation process in the northern Red Sea. It very likely plays a major role as a necessary preconditioning for intermediate water formation. The outflowing water of the Gulf of Aqaba is likely to merge with the deeper parts of the cyclonic eddy observed southeast of the Sinai Peninsula (Fig. 9). The inflow to the Gulf of Aqaba in the upper 70 m with a maximum velocity not exceeding 0.2 m s^{-1} is not capable of compensating for the strong outflow in the lower layer. Therefore, one should expect lateral variation of the interface between the in- and outflow across the sill of the strait. Wind forcing may contribute significantly to this effect. All previous studies (Assaf & Kessler 1976, Klinker et al. 1976, Paldor & Anati 1979, Murray et al. 1984) agreed on the general circulation pattern in the Straits of Tiran. However, they differed considerably in estimating the rate and magnitude of water exchange between the Gulf of Aqaba and the Red Sea.

In conclusion, the winter well mixed upper waters of the Gulf of Aqaba play a major role in deep-water formation in the northern Red Sea through the strait of Tiran. A well developed cyclonic gyre in the northern Red Sea in favor of this process is likely to contribute to the preconditioning of the intermediate water formation.

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