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Red sea water lens formation in Arabian Sea

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Abstract. Historical CTD data, collected in March-April 1980, in the northwest Indian Ocean, were used to find a young lens of Red Sea water at the stage of its formation. The lens is located in the depth range of 640–830 m. Temperature and salinity values in the core are 11.07 °C and 35.56 ‰, whereas maximum anomalies with respect to background water are 0.75 °C and 0.22 ‰. The temperature-salinity structure as well as the dynamics, energy and vorticity distribution in the lens are analyzed. A probable trajectory of the lens is estimated using T–S analysis, Lagrangian invariants and neutral surface methods. It is shown that the lens was formed as a result of interaction of a cyclonic meander with a tongue of Red Sea Water. We suggest a new physical mechanism of intrathermocline lens formation that could be called the "forced generation" mechanism.

Introduction

Highly saline Red Sea water (RSW) flows out through the shallow Strait of Bab al Mandah, and then, after mixing with the Gulf of Aden water, enters the Arabian Sea in the form of an intermediate salinity maximum. It has a temperature of $T = 11\,°C$, salinity of $S = 35.5$–35.7 ‰ and density of $\sigma_t = 27.15$–27.35 at depths of 600–900 m [*Rochford*, 1964]. The intensity of the winter highly saline water outflow from the Red Sea through the Strait of Bab al Mandah is approximately 10 times greater then in summer. Nevertheless, the seasonal variability of RSW spatial distribution in the Arabian Sea is small due to its large volume in the Indian Ocean [*Gamsakhurdiya et al.*, 1991]. This variability has a surprising correlation with a change of the surface water circulation when the northeast (winter) monsoon wind reverses to the southwest (summer). In winter, the southward propagation of RSW along the Somali coast increases, whereas in summer the eastward propagation of RSW intensifies.

The circulation of waters in northwest Indian Ocean varies on a synoptic scale. It was in the Arabian Sea during the Poligon-67 experiment, initiated by the Soviet oceanographer V. B. Shtockman, that open ocean synoptic eddies were discovered [*Kamenkovich et al.*, 1982].

The major paths of spreading and the mesoscale structure of a tongue of RSW in the Arabian Sea were examined by *Shapiro and Meshchanov*, [1991] on the basis of hydrographic data obtained from 1935 to 1981 and accumulated at the National Oceanographic Data Center B (Obninsk, Russia). It was shown that spreading of RSW occurs partially as highly saline isolated patches (lenses). The historical data collected in different years were used to demonstrate the existence of at least seven RSW lenses which were called Reddies (Red Sea eddies) in accordance with German oceanographer Zenk's suggestion.

Shapiro and Meshchanov [1991] suggested that the most probable mechanism controlling Reddies generation is the instability of the internal hydrological front separating the RSW tongue from surrounding Arabian Sea water masses (this mechanism is similar to the formation of the Mediterranean Water lenses in the North Atlantic). Experimental data presented by *Shapiro and Meshchanov* [1991] could not confirm or refute this hypothesis, because all of the identified Reddies at the moment of measurements had completed their formation, and were completely separated from the main water mass.

This paper presents the results of the analysis of three-dimensional structure and dynamics of a young lens of RSW just at the stage of its formation. We suggest a new physical mechanism for intrathermocline lens formation that could be called the "forced generation mechanism."

Materials and Methods

This paper used CTD data collected in the Arabian Sea in March–April, 1980 during the 22nd cruise of R/V *Academik Vernadsky* (i.e., during the transition from

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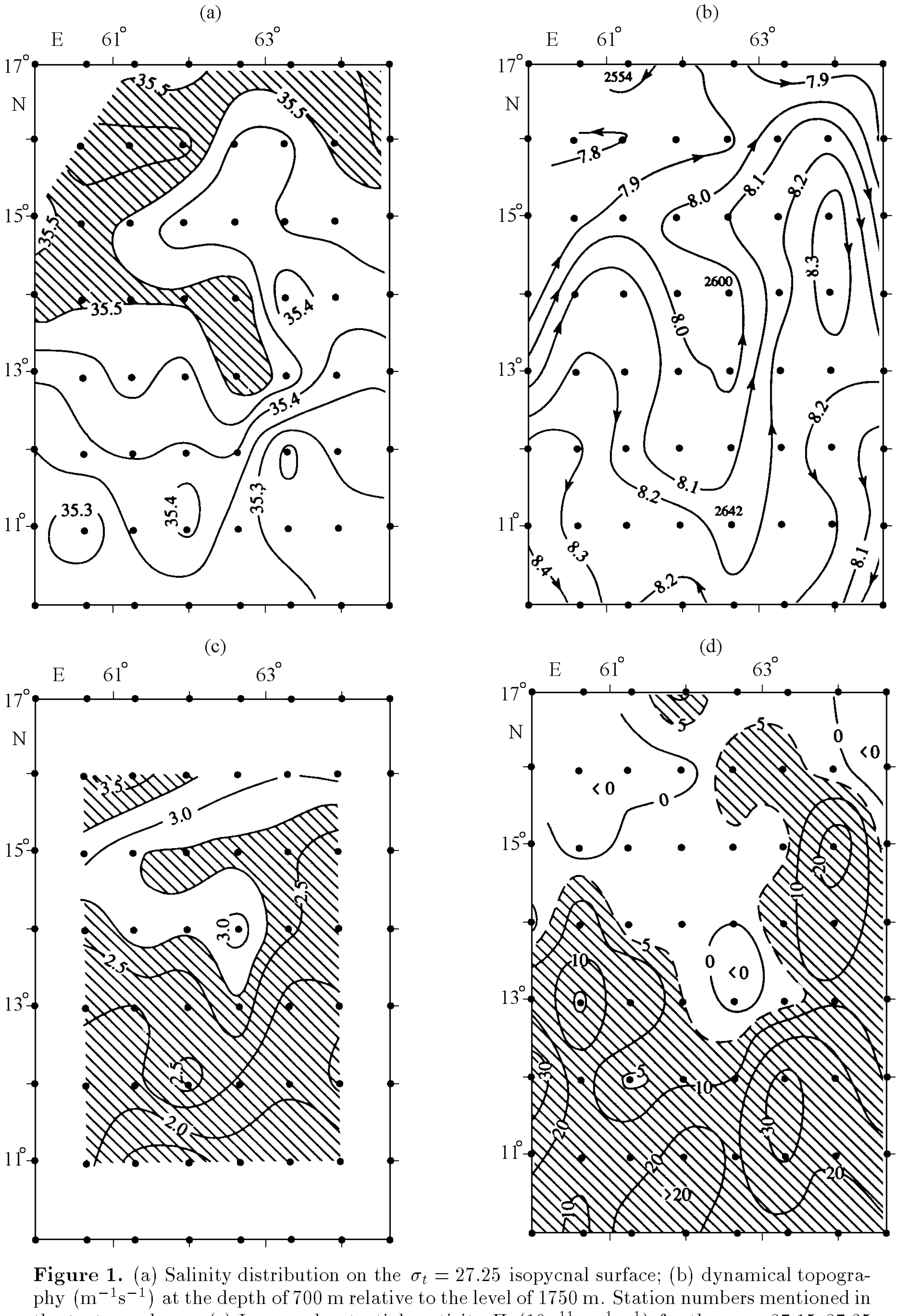

Figure 1. (a) Salinity distribution on the $\sigma_t = 27.25$ isopycnal surface; (b) dynamical topography $(m^{-1}s^{-1})$ at the depth of 700 m relative to the level of 1750 m. Station numbers mentioned in the text are shown; (c) Isopycnal potential vorticity Π $(10^{-11}m^{-1}s^{-1})$ for the $\sigma_t = 27.15$–27.35 layer; (d) δh (m) neutral surface deviation from the $\sigma_t = 27.25$ isopycnal surface.

winter to summer monsoon) [*Shchetinin et al.*, 1981]. The survey was carried out within the region, bounded by 10°–17°N and 58°–68°E, and included 117 hydrographic stations with ISTOK-4 CTD-probe measurements. The measurements were made from the surface down to the depth of 1750 m with 5-m vertical resolution The horizontal grid was regular and covered nm in latitude and 40 nm in longitude. The accuracy of the measurements was 0.02‰ for salinity and 0.01 °C for temperature.

This research used data from 61 hydrographic stations, spaced within the rectangular region bounded by 10°–17°N and 60°00′–64°40′E, and collected from March 17 to April 4, 1980. Vertical profiles of temperature and salinity were averaged over depth with 10 m resolution at depths of 550–1300 m, and with 50-m intervals at depths of 0–550 m and 1300–1750 m. At the levels of 2000, 2500, 3000, 3500 and 4000 m, the data were supplemented with monthly averaged values of T and S from the National Oceanographic Data Center B (Obninsk, Russia) [*VNIIGMI MSTD*, 1981a, 1981b]. This procedure was necessary to calculate the Rossby internal deformation radius.

The existence of RSW at every station was identified in accordance with the method of *Rochford* [1964] whereby the salinity anomalies more then 0.04‰ relative to the upper layers in σ_t range of 27.15–27.35 determine the RSW. To filter out errows due to internal waves, horizontal salinity distributions on isopycnal surfaces were used. Measurements of the internal waves showed that their amplitudes did not exceed 10 m and were much less than characteristic thickness of identified mesoscale objects.

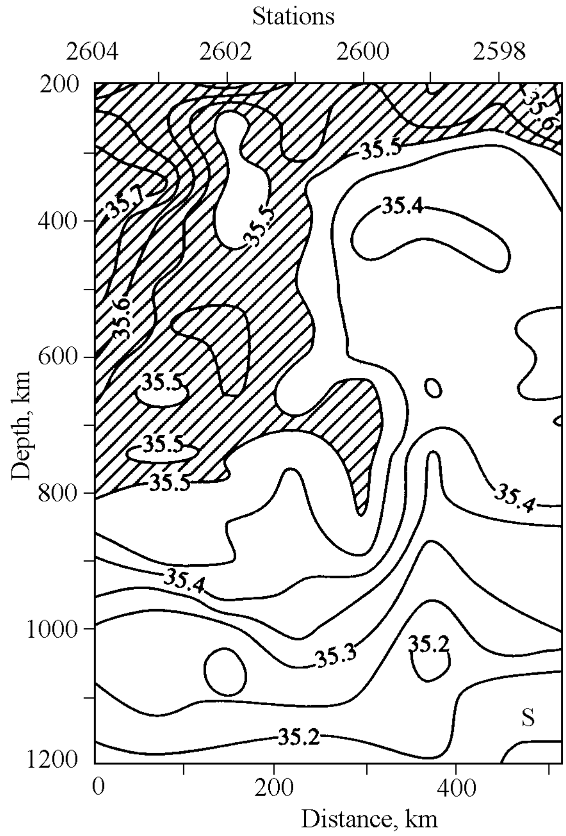

Figure 2. Hydrographic section of salinity (‰) along 14°N through the RSW lens. The area with $S > 35.5$‰ is shaded.

Results

Red Sea waters are located in the northwest and west parts of the study area. It is concentrated near the σ_t isopycnal surface of 27.25 (depth is about 700 m). The core of RSW is well bounded by the 35.50‰ isohaline (Figure 1a). The southwest part of the study area is occupied by the intermediate Arabian Sea water with a salinity less than 35.30‰.

The large-scale RSW tongue consists of several synoptic scale meanders. One of them is located in the center of the study area (Figure 1a). The meander is almost separated from the main core of the RSW, and a highly saline lens is formed. Assume the lens is bounded by the $S = 35.50$‰ isohaline. Then the horizontal scale of the lens is 90 km from north to south and 40 km from east to west. At the station 2600 (14°N, 62°40′E), the lens is located between 640 and 830 m (Figure 2), i.e., its thickness reaches 190 m. The lens core (st. 2600, depth of 665 m) is characterized by a maximum temperature of 11.07 °C and salinity of 35.56‰ (Figure 3), with the corresponding density of σ_t of 27.19.

The temperature and salinity distributions in the lens center (st. 2600) were compared with the typical profiles of temperature and salinity, averaged over all 61 stations. Maximum anomalies reach values of 0.38 °C and 0.12‰ at the level of 750 m. Relative to the background station 2642 (11°N, 62°40′E), the values have their maximum at the depth of 800 m, and are 0.22‰ for ΔS and 0.75 °C for ΔT. A patch of the low-salinity water with $S < 35.4$‰ is located above the lens of the RSW as slightly higher (400–450 m). Density field analysis shows that the lens does not have the lentil-like isopycnal anomalies typical of the North Atlantic lenses. All anomalies are small and positive between the lens and the background. At the depth of 700 m, $\Delta\sigma_t$ equals 0.04 (between st. 2600 and 2642).

The lens is clearly expressed in the salinity field in vertical sections (Figure 2). It is not so clear in the temperature field and almost invisible in the density field. This situation is typical for the other RSW lenses, earlier observed in the Arabian Sea [*Shapiro and Meshchanov*, 1991]. A characteristic feature of the observed lens is a thin (about 20–30 m) and narrow area which still is connected to the lens core with the main tongue of RSW (Figures 1a, 2). It means that in the Arabian

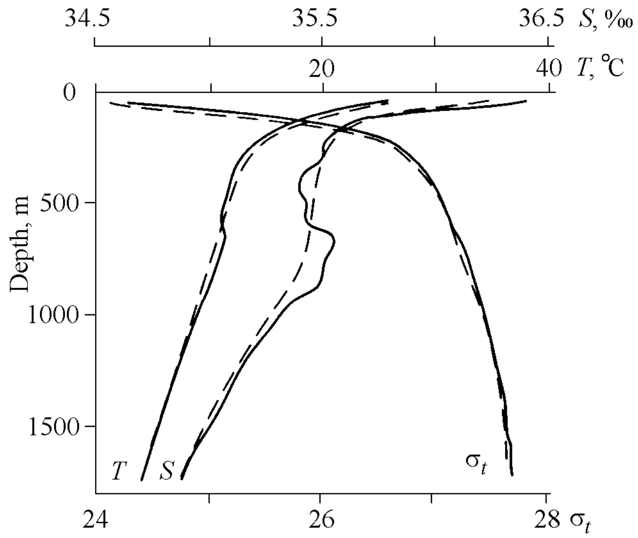

Figure 3. Vertical profiles of salinity, temperature and σ_t density at the st. 2600 (solid lines) and mean study area profiles (dotted lines).

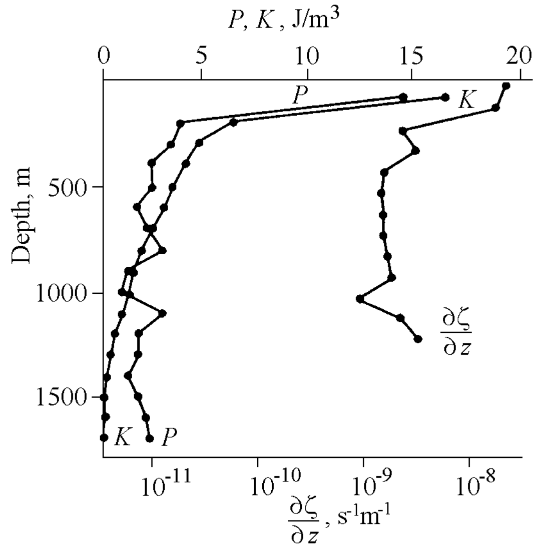

Figure 4. Vertical profiles of $d\zeta/dz$ (ζ is relative vorticity), spatial density of kinetic (K) and available potential (P) energy in the RSW lens.

Sea, a young lens was identified, and the process of its formation was not finished.

It is known that Gulf Stream rings and eddy lenses of the North Atlantic have horizontal scales comparable to the Rossby internal deformation radius L_R [*Kamenkovich et al.*, 1982; *Shapiro*, 1986]. To determine this radius in the Arabian Sea study area, we calculated the Brunt-Väisälä frequency $N(z) = \sqrt{g\, d\sigma_t/\rho_0\, dz}$, using density profiles averaged over 61 stations. The Rossby radius of the first internal mode was obtained as $L_R = 1/\sqrt{\lambda_1}$, where $\lambda_1 = 1.89 \times 10^{-4}\mathrm{km}^{-2}$ is the first eigenvalue of the linear operator

$$\frac{d}{dz}\left[\frac{f^2}{N^2(z)}\frac{dp}{dz}\right] + \lambda p = 0, \quad \frac{dp}{dz} = 0 \quad at z = 0, -H.$$

Here f is the Coriolis parameter, and $H = 4\mathrm{km}$. The calculated value 73 km of the L_R Rossby deformation radius of is in good agreement with the horizontal scale of the RSW lens in the study area.

Figure 1b presents the dynamic topography at the depth of 700 m with respect to 1750 m. A narrow stream is the characteristic feature of the study area. It crosses the region from southwest to northeast and probably belongs to southern and southeastern periphery of the large cyclonic gyre occupying the northern part of the Arabian Sea [*Shchetinin et al.*, 1981]. The survey also revealed a system of two self-connected eddy structures (cyclonic meander — anticyclonic eddy) with opposite rotation (Figure 1b). A pair of eddies is observed from the surface down to the depth of 1500 m. The maximum geostrophic velocity of the rotation reaches $12\,\mathrm{cm\,s^{-1}}$ at 700 m. Due to direct measurements at the buoy station, conducted about 100 km southwest away from the study area, the barotropic component of the velocity was considerably less and was about 3–$4\,\mathrm{cm\,s^{-1}}$ at 1500 m.

The lens is located in the center of the cyclonic meander. This is clear from the comparison of Figure 1a and Figure 1b. Maximum velocities in the meander (20–$25\,\mathrm{cm\,s^{-1}}$) are found near the surface. Below the depth of 500 m, velocities do not exceed $10\,\mathrm{cm\,s^{-1}}$. The existence of a warm saline lens of RSW water at intermediate depths does not produce the anticyclonic water rotation, i.e., relative vorticity $\zeta = (\partial v/\partial x) - (\partial u/\partial y)$ does not change sign with depth. The vertical profile of $d\zeta/dz$ at st. 2600 illustrates the dynamical influence of the RSW lens on the current structure in the cyclonic meander. The total cyclonic vorticity ζ increase toward the ocean surface is slow, and the values of $d\zeta/dz$ do not exceed $0.15 \times 10^{-2}\mathrm{m}^{-1}\mathrm{s}^{-1}$ at levels of 400–800 m, i.e., exactly at depths of the lens location. Low values of $d\zeta/dz$ at intermediate depths are caused by the anticyclonic contribution of the RSW lens to the total cyclonic vorticity of the meander.

Vertical profiles of the spatial density of kinetic (K) and available potential (P) energy in the cyclonic meander are also presented in Figure 4. They were calculated from:

$$K = \frac{\rho_0}{2}\left(\bar{u^2} + \bar{v^2}\right), \quad P = \frac{g^2}{\rho_0 N_0^2}\frac{\bar{\sigma_t'^2}}{2}\,\mathrm{J\,m^{-3}},$$

where bars denote values averaged over all stations inside the meander; $\sigma_t' = \sigma_t - \bar{\sigma}_t$; u, v are zonal and meridional geostrophic velocity components; and ρ_0

and N_0 are the mean values of the density and Brunt-Väisälä frequency. The values of K and P are of the same order, and decrease smoothly with depth, as they usually do in the synoptic eddies [*Kamenkovich et al.*, 1982]. The local maximum of $P = 3\ \mathrm{J\,m^{-3}}$ at the depth of 800 m is due to an available potential energy concentration inside the lens. Potential energy exceeding the kinetic is typical for young lenses [*Kamenkovich et al.*, 1982].

To determine the main core location and a probable trajectory of the RSW lens, the distribution of isopycnal potential vorticity

$$\Pi = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + f\right)\left(\rho_0 \frac{dz}{d\sigma_t}\right)^{-1} \mathrm{m^{-1}s^{-1}}$$

was calculated and analyzed together with the spatial distributions of thermocline (Figure 1a) and dynamical (Figure 1b) characteristics in the study area.

The Π parameter is the Lagrangian invariant, which contains its value in a moving water particle. Together with the potential density σ_θ (or close value of σ_t) distribution, it facilitates estimation of the lens trajectory [*Kostyanoy and Shapiro*, 1989]. The map of the isopycnal potential vorticity Π (in $10^{-11}\mathrm{m^{-1}s^{-1}}$) in the range of $\sigma_t = 27.15$–27.35 is presented in Figure 1c. The RSW lens is characterized by a Π value of $3.1 \times 10^{-11}\mathrm{m^{-1}s^{-1}}$ which substantially exceeds the values of Π for surrounding water. The main water mass with the potential vorticity $\Pi > 3 \times 10^{-11}\mathrm{m^{-1}s^{-1}}$ is located in the northwest corner of the study area and in the area of the main RSW tongue.

It is known from *McDougall* [1984] that adiabatic displacements of the particles occurs along the neutral surfaces in case of the stable stratification. The neutral surface equation can be written in the form of $\rho(\mathbf{r}_0, \mathbf{r}) - \rho(\mathbf{r}, \mathbf{r}) = 0$, where $\rho(\mathbf{r}_0, \mathbf{r})$ is in situ density of a water particle mentally moved from the point with coordinates $\mathbf{r}_0 = (x_0, y_0, z_0)$ to the point with coordinates $\mathbf{r} = (x, y, z)$; $\rho(r, r)$ is the background density at point $\mathbf{r}$. Hence, it is possible to define the trajectory of RSW in another way similar to *Kostyanoy and Shapiro* [1989]: as the line of intersection of neutral and potential (or σ_t) isopycnal surfaces. The neutral cross-lens surface deviation δh (m) from σ_t isopycnal surface of 27.25 is shown in Figure 1d. It is clear that the unshaded area to which values $\delta h < 5$m correspond defines the "permitted" path of the RSW lens movement.

Analysis of the horizontal temperature and salinity distributions shows that the lens has T–S parameters close to values at the northwest corner of the study area, and the salinity distribution on the σ_t isopycnal surface of 27.25 is a good tracer of the lens movement (Figure 1a)

Thus, three different ways of determining the formation and trajectory of RSW lens yield the same results (Figures 1c and 1d). These results are in a good agreement with the pattern of geostrophic velocities at the level of 700 m. This allows us to conclude that the influence of a large cyclonic meander on the RSW tongue near 16°N, 61°E led to the formation of the RSW lens and its forced movement south to a distance of about 200 miles.

Discussion

It is believed that the most probable mechanisms of the Mediterranean Water lens formation in the North Atlantic are the influence of the bottom topography and the baroclinic instability of subsurface currents. The analysis presented in this paper demonstrated that in principle, different mechanism of mesoscale lenses formation were possible and could be called the "forced generation" mechanism. The young RSW lens was shown to be formed by external force: A large cyclonic meander that, during the interaction with the RSW tongue in the Arabian Sea, captured the lens and moved it south to a distance of about 200 miles away from the main core.

A similar situation was observed in the South Atlantic in the Scotia sea, where the young lens formed as a result of the deep meandering of the south branch of the antarctic circumpolar current [*Emel'yanov and Shapiro*, 1989].

The situation when RSW lenses formation and evolution are strongly connected with synoptic meanders or eddies is probably quite typical for the Arabian Sea. The salinity distribution on the $\sigma_t = 27.25$ isopycnal surface, using data collected during the Poligon–67 experiment (March–April, 1967, R/V *Faddey Bellingshausen*), shows the RSW lens location at 12°30′N, 63°30′E (a detailed description of this lens was presented in *Shapiro and Meshchanov* [1991]). The comparison of the salinity field with the Poligon–67 dynamical topography [*Kamenkovich et al.*, 1982] shows that, as in the present situation, the RSW lens location coincides with the center of an intensive cyclonic eddy.

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