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# Water Mass Formation, Overturning Circulation, and the Exchange of the Red Sea with the Adjacent Basins

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## Abstract

The Red Sea experiences strong atmospheric forcing through both wind stress and air–sea buoyancy fluxes. Direct observations and modeling experiment show a robust response that consists of a strong and complicated three-dimensional circulation pattern with intense seasonal variability, involving water masses that are locally formed in the Red Sea or enter it from adjacent basins. Two thermohaline cells are identified related to intermediate (Red Sea Outflow Water—RSOW) and deepwater (Red Sea Deep Water—RSDW) formation processes. Results from numerical simulations indicate that the permanent cyclonic gyre in the northern end of the basin is the most probable location for the RSOW formation to take place, but further investigation with observations and numerical modeling techniques is needed to better understand the processes involved as well as the role of the Gulfs of Suez and Aqaba in the regional thermohaline circulation. The Red Sea circulation is closely linked to the flow pattern in the Strait of Bab-al-Mandab where the exchange of the Red Sea with the Indian Ocean takes place. The exchange is of an inverse estuarine type, which compensates for the strong heat and freshwater fluxes in the basin, but with very strong seasonal and synoptic variability related to remote and local forcing. Although important progress has been achieved during the last two decades in describing and understanding basic processes of the Red Sea dynamics, several features are not yet understood and explained. Further observational and modeling activities are required to improve our understanding of these processes and should be combined in an interdisciplinary approach to improve our monitoring and forecasting capabilities for environmental management and protection.

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## Introduction

The Red Sea is an elongated basin, oriented SE to NW, separating the African and Asian continents (Fig. 1). It extends from 12.5°N to 30°N with an average width of 220 km (Patzert 1974a). The mean depth of the basin is 524 m (Patzert 1974a), but with maximum recorded depths of almost 3,000 m. At its northern end, it bifurcates into two gulfs, the Gulf of Suez with

average depth of 40 m and the Gulf of Aqaba with depths exceeding 1,800 m and a sill at the entrance of approximately 175 m (Neumann and McGill 1962).

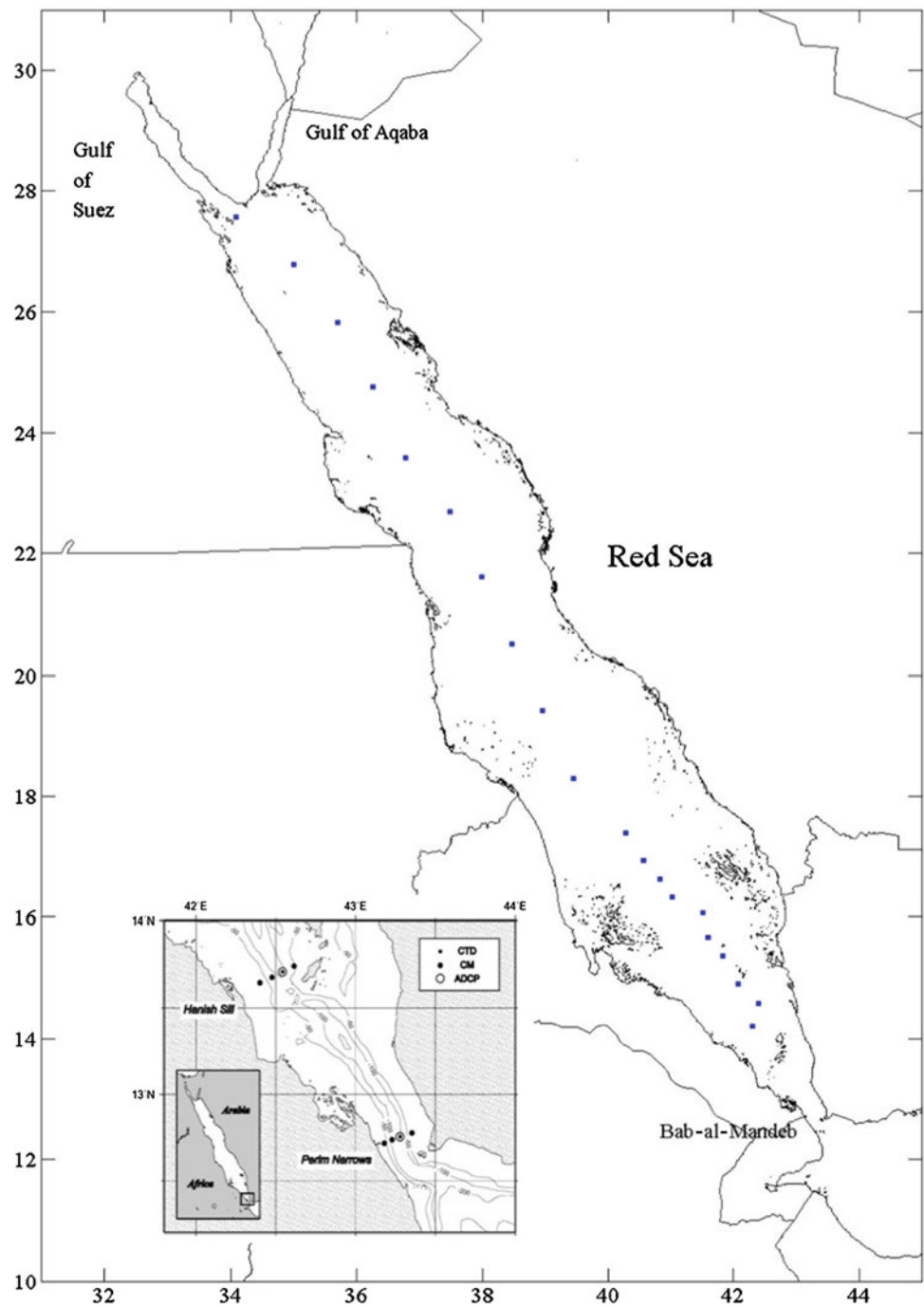
Due to its arid setting, the Red Sea experiences one of the largest evaporation rates in the world's oceans. Combined with very small precipitation and negligible river runoff, it loses approximately 2 m/year of freshwater through its upper surface on an annual basis (Yegorov 1950; Neumann 1952; Privett 1959; Tragou et al. 1999; Bower and Farrar this volume). In order for the Red Sea's average salinity to remain in a steady state, this means that the Red Sea must import freshwater from adjacent basins. The transport through the Suez Canal, which connects the Mediterranean Sea with the Gulf of Suez and the Red Sea, is negligible, and therefore, the only significant connection between the Red

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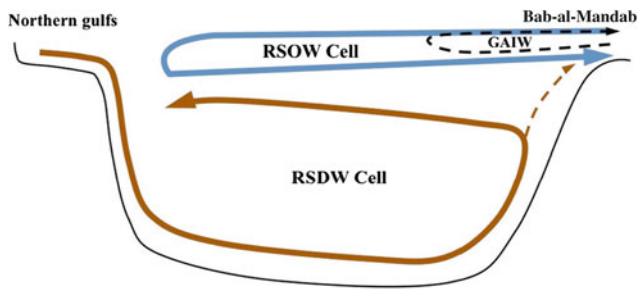
**Fig. 1** Map of the Red. The Bab-al-Mandab Strait geography/topography is presented in the inset, including the locations of the current meter mooring arrays near the Hanish Sill and Perim Narrows deployed by Murray and Johns (1997). The blue dots are the stations occupied along the axis of the Red Sea in the 2001 cruise (Sofianos and Johns 2007)



Sea and the global ocean is the Strait of Bab-al-Mandab located at the southern end of the basin and connecting it to the Gulf of Aden and Indian Ocean. It is a shallow and narrow channel with a sill depth of 137 m (Werner and Lange 1975) and a minimum width of about 25 km.

Long-term observations of the flow and temperature/salinity characteristics at the Strait of Bab-al-Mandab (Murray and Johns 1997) indicate an equivalent annual freshwater flux into the Red Sea of  $2.06 \pm 0.22$  m/year (Sofianos et al. 2002), which is consistent with the most

recent evaporation rate estimates (Ahmad and Sultan 1987, 1989). The latent heat flux associated with the evaporation is very large (about  $160 \text{ W/m}^2$ ); however, the net radiative heat gain nearly balances this loss, so that the annual mean heat loss from the surface of the Red Sea is small,  $O(10 \text{ W/m}^2)$  (Patzert 1974b; Tragou et al. 1999; Sofianos et al. 2002; Ahmad and Albarakati this volume). The main buoyancy forcing that drives circulation in the Red Sea is therefore related to the high evaporation. Additionally, a seasonally changing wind stress pattern influences the Red Sea



**Fig. 2** Schematic representation of the main thermohaline cells in the Red Sea

circulation. The wind field is characterized by two regimes, one in the northern part of the Red Sea and one in the southern part. The former is influenced by the eastern Mediterranean weather systems (Pedgley 1974) and the wind is from the northwest all around the year. In the south, the wind is controlled by the Indian monsoon system and reverses from southeast during winter (October–May) to northwest during summer (June–September).

Due to its limited connection with the world ocean and the excess of evaporation over precipitation and river runoff, the Red Sea acts as a typical concentration basin. An inverse estuarine circulation therefore occurs in the Strait of Bab-al-Mandab, with a relatively fresh surface inflow on the top of a deep outflow of higher salinity water (Fig. 2). Dense water mass formation and an associated overturning circulation within the basin are expected to close the inverse estuarine circulation cell driven by the thermohaline forcing. From the point of view of a physical oceanographer, the Red Sea is an advantageous experimental basin combining several interesting characteristics. It has a relatively simple shape, and its size is moderate. It experiences strong atmospheric forcing of both wind and thermohaline form, with strong seasonal and interannual variability. It is a semi-enclosed basin connected with the world ocean through a very shallow and narrow constriction, the Bab-al-Mandab Strait, whose exchange dynamics can affect processes over the whole basin.

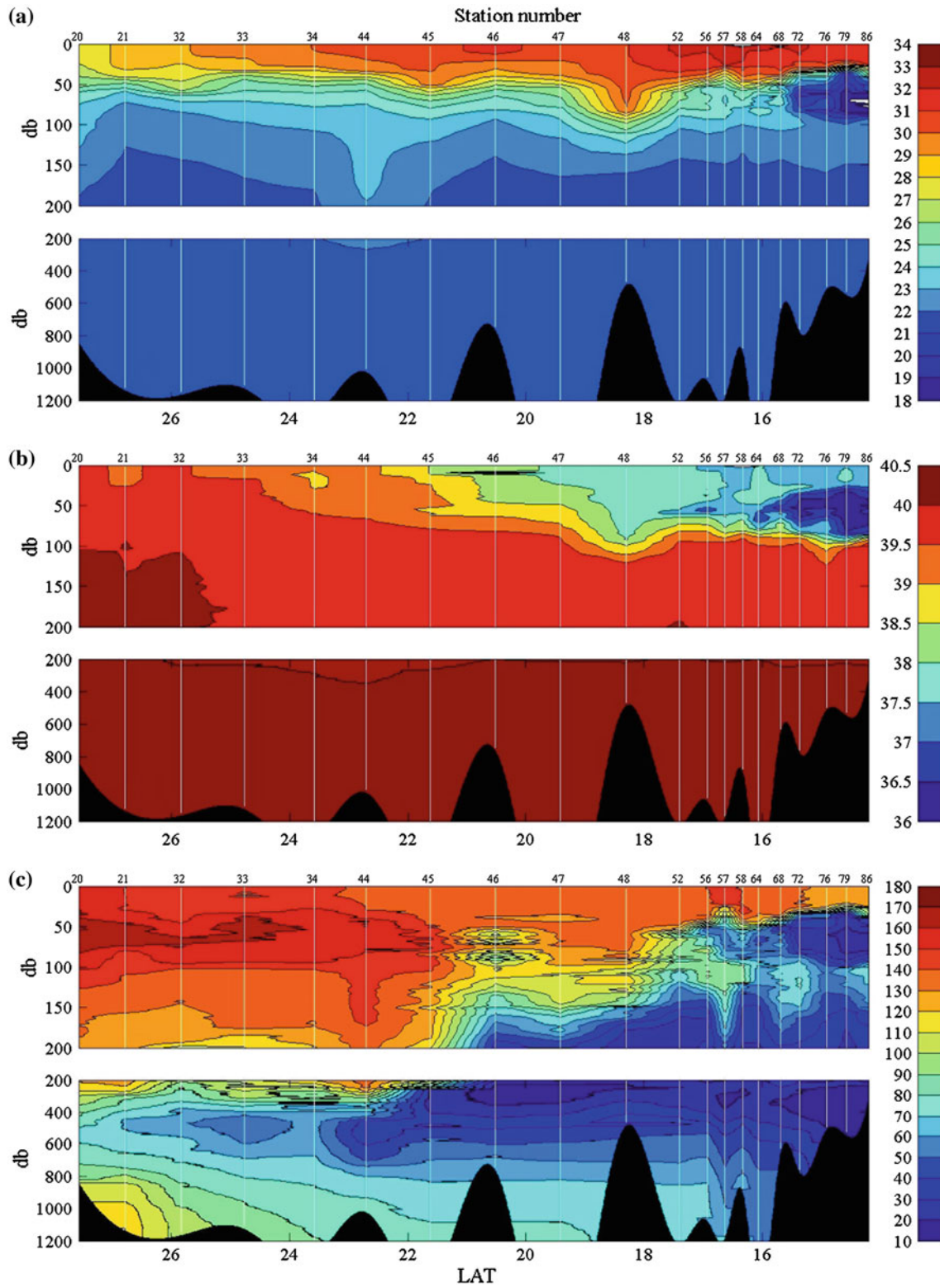
Despite its scientific importance and its ecological and commercial significance, the Red Sea remains widely unexplored and several processes are still not well understood and are highly debated. During the last decades, a series of monitoring expeditions, processes-oriented studies and numerical modeling experiments have shed light on various processes and have allowed an improved understanding to be developed of the basin-wide circulation, water mass formation, thermohaline structure of the basin and its exchange with the Indian Ocean. Our current knowledge of these components is described in this chapter. We start from the identification of the water masses that participate in the Red Sea's general circulation. The next section is devoted to

the identification of water mass formation processes and the pattern of overturning cells circulating the water masses in the basin. Finally, the exchange between the Red Sea and the open ocean, and its variability at various timescales, is presented in the last section.

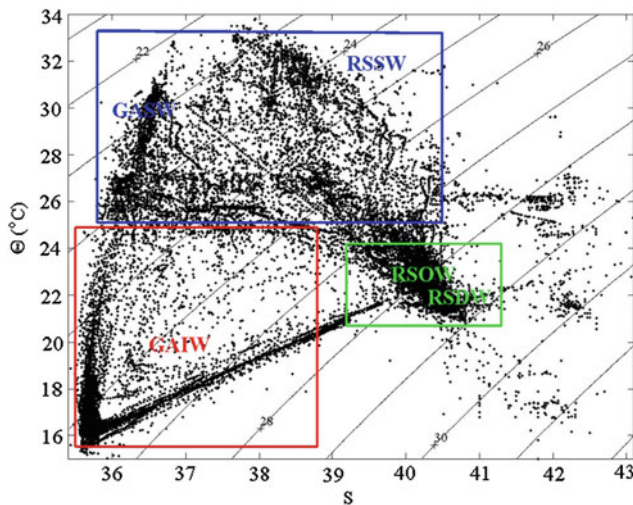
## The Water Masses of the Red Sea

Most of the available observations in the Red Sea have been sporadic in both time and space, making an attempt to construct a picture of the three-dimensional distribution of water mass characteristics in the Red Sea very difficult. The only exception is the area of the Strait of Bab-al-Mandab, which has attracted the interest of several observational efforts (Vercelli 1927; Siedler 1968; Maillard and Soliman 1986; Murray and Johns 1997). Until recent decades, north of the strait, inside the Red Sea basin, most of our knowledge of the distribution of oceanographic properties comes from a handful of expeditions covering very small parts of the basin (e.g., Vercelli 1931a, b; Morcos 1970; Morcos and Soliman 1974; Maillard 1974; Clifford et al. 1997). Some more recent expeditions covering a large part of the basin's hydrography (Quadfasel and Baunder 1993; Sofianos and Johns 2007) enable us to reconstruct a more comprehensive picture of the water mass structure in the Red Sea. Nevertheless, a more intensive and basin-wide observational strategy is still highly needed.

Much of the hydrographic data comes from sections taken along the axis of the Red Sea, such as the data shown in Fig. 3 from a summer 2001 survey (Sofianos and Johns 2007). A compilation of all historical stations collected in the Red Sea is shown in Fig. 4 in the form of temperature–salinity diagrams to identify the water masses. We can identify several water masses, either formed inside the basin, which have high salinities due to its concentration character, or imported from adjacent basins. Two water masses originating in the Gulf of Aden can be identified inside the Red Sea: the Gulf of Aden Surface Water (GASW), in the surface layer, and the Gulf of Aden Intermediate Water (GAIW), at intermediate depths (Fig. 3). They intrude into the basin during the winter and summer period, respectively, and are characterized by low salinities compared to the water masses formed in the Red Sea. The GASW forms the relatively fresh surface layer inflow in the Red Sea that corresponds to the upper part of the inverse estuarine exchange, associated with the fresh water loss from the surface of the sea. It is present only during the winter season and has temperature and salinity characteristics in the range of 25–30 °C and 36.0–36.5. On the other hand, the GAIW is present in the basin only during the summer season and forms an intrusion at intermediate depths, between the surface outflow and the deep outflow. It is identified in the southern half of the basin,



**Fig. 3** a Potential temperature ( $^{\circ}\text{C}$ ), b salinity (psu), and c oxygen ( $\mu\text{mol/kg}$ ) concentration distribution along the axis of the Red Sea during summer 2001 (from Sofianos and Johns 2007). The stations correspond to Fig. 1 positions



**Fig. 4** Temperature–salinity (in practical salinity units) characteristics in the Red Sea derived from the NODC dataset with the addition of the 2001 cruise (the red area corresponds to GAIW, the blue area to the surface layers (RSSW and GASW) and the green area to the deep layers, namely the RSOW and the RSDW)

as a subsurface minimum in salinity and temperature which enters the basin with temperature and salinity values near 16.5 °C and 37.5, respectively. As it intrudes farther into the basin, it exhibits strong latitudinal gradients due to horizontal and vertical mixing, with potential temperature increasing to almost 30 °C and the salinity to over 38 (Fig. 3). At the same time, the depth of the salinity minimum gradually decreases, from around 75 m to very shallow depths (Sofianos and Johns 2007). The northern limit of the intrusion appears to be about 22°N. Although the strong circulation features may disperse lenses with GAIW to the northern part of the basin, no clear signal is detected north of 22°N. This latitude is close to latitude estimated from historical data by Smeed (1997) for the northernmost intrusion latitude at the end of the summer season (end of September). The mechanisms controlling the inflow of these water masses to the Red Sea will be discussed in Sect. “Exchange Between the Red Sea and Adjacent Basins”.

The most important, locally formed water masses are the Red Sea Outflow Water (RSOW) and the Red Sea Deep Water (RSDW), the former occupying intermediate layers of the basin, while the latter fills the deep part of the basin. They are both characterized by high salinity values (over 40), being two of the most saline water masses of the world ocean. The RSDW is characterized by very homogeneous temperature and salinity values (Figs. 3 and 4) and fills the basin below the level of 150–250 m (this level deepens to the north and is modified by the strong circulation features present in the basin). On top of this water mass lies the RSOW flowing to the south to form the main core of the Red Sea deep outflow to the Gulf of Aden. The mechanisms involved in the formation of these two water masses are discussed in the next

section. Finally, during summer, the surface waters outflowing from the basin through the Strait of Bab-al-Mandab acquire their characteristics in the Red Sea and are usually referred as the Red Sea Surface Water (RSSW).

The RSOW and RSDW have very similar temperature and salinity characteristics and for a long time they were identified as one water mass. It was only when basin-wide observations measuring other tracers such as oxygen,  $^{14}\text{C}$ , and  $^3\text{He}$  concentrations became available (e.g., Cember 1988; Quadfasel and Baunder 1993; Sofianos and Johns 2007) that it was possible to clearly distinguish between the two water masses. The RSDW is characterized by very low oxygen concentration, due to consumption while it spreads at bottom levels to the south and upwells and then recirculates to the north at higher levels (Fig. 2). The RSOW is a relatively younger water mass that contributes most of the high salinity waters to the outflow through the Bab-al-Mandab into the Indian Ocean. It is also characterized by the relatively higher oxygen concentration levels near 100–150 m in the southern Red Sea (Fig. 3c).

### Water Mass Formation in the Red Sea and the Basin-wide Overturning Circulation

There is a wide agreement between investigators that the origin of the RSDW is located in the northern Gulfs of Suez and Aqaba. Most studies propose the Gulf of Suez as the main source of deep waters in the Red Sea basin (Woelk and Quadfasel 1996; Cember 1988; Maillard 1974; Wyrski 1974). Studies in the Strait of Tiran (Hecht and Anati 1983; Murray et al. 1984; Manasrah et al. 2004), connecting the Gulf of Aqaba with the Red Sea basin, showed that there is also a contribution of waters from the Gulf of Aqaba to the deep layers of the Red Sea.

The deep waters of the Red Sea (deeper than 600 m) are renewed through sinking of dense waters formed in these northern gulfs. The time of this formation as well as the amount of RSDW produced is not well known. It is generally believed that it occurs during the peak of the winter season, when intense evaporation and surface cooling take place. Relatively small amounts of extremely dense water are produced in the gulfs and after mixing with ambient waters at the mouth of the gulfs sink to replenish the deep reservoir of the Red Sea. The RSDW formation rate at the Gulf of Suez, derived by direct observations (Maillard 1974), is on the order of magnitude of  $O$  (0.04 Sv) on annual basis ( $1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$ ). Kuntz (1985), combining historical hydrography, Tritium and  $^3\text{He}$  measurements in a two-dimensional advective–diffusive box model of the Red Sea, estimated the deep-water formation as low as 0.016 Sv. Cember (1988) estimated the formation rate at 0.05 Sv, based on  $^{14}\text{C}$  measurements. Wyrski (1974), based on a

simple vertical advection diffusion model, estimated the deep-water formation at 0.06 Sv, while Woelk and Quadfasel (1996), using a one-dimensional plume model, estimated the Gulf of Suez outflow at 0.058 Sv, over a period of 7 months, but they also proposed that the deep-water formation process are presented only during winters with extreme forcing. The Gulf of Aqaba deep-water outflow is less investigated, although its contribution to the deep layers is thought to be of similar importance. Klinker et al. (1976) estimated the winter outflow from the gulf to the Red Sea at 0.069 Sv, Anati (1976) at 0.05 Sv, while Murray et al. (1984) measured the deep outflow over a period of 2 weeks and calculated a transport of 0.029 Sv. Biton and Gildor (2011), using a numerical model of the Gulf of Aqaba, estimated its contribution to be 0.0185 Sv. Overall, the total contribution from these two gulfs to the deep layers is estimated at the range of 0.05–0.1 Sv.

There are no direct observations available of RSOW formation. Sofianos and Johns (2003), using a numerical model approach, investigated the processes involved in the formation of this water mass. The results of the model simulations suggest that RSOW forms through open ocean convection that takes place in the northern Red Sea during the peak of the winter season. They proposed that it is associated with a cyclonic gyre that is centered at about 25°N. This feature is observed in several different studies (e.g., Clifford et al. 1997; Sofianos and Johns 2007) and seems to be a permanent pattern of the circulation in the northern basin. Inside this gyre, the mixed layer achieves high densities throughout the year, and at the peak of the winter season, the mixed layer has densities close to those of the RSOW layer.

Direct observations and modeling results agree that the waters formed inside the basin circulate in two basin-wide cells (Fig. 2): (i) an intermediate cell, carrying the RSOW toward the Strait of Bab-al-Mandab to form the main core of the deep Red Sea outflow and (ii) a deep cell recirculating the RSDW in deep layers of the basin, as can be seen from the oxygen distribution of the deep layers in Fig. 3. The interaction of the two cells and related mixing processes are not known. Another shallower cell as shown in Fig. 2 (black dashed line), generated during the summer season and related to the GAIW, is also hypothesized (Sofianos 2000).

The thermohaline forcing seems to be the most important mechanism driving the overall circulation in the Red Sea (Sofianos and Johns 2003). The pattern of the surface thermohaline cell is related to the buoyancy loss (mostly due to the very large evaporation rates), which increases the density to the north and produces a northward pressure gradient associated with the downward sloping of the sea surface, and a return flow at intermediate depths. The simplest theory for the thermohaline driven circulation of the Red Sea is the two-dimensional model by Phillips (1966), involving similarity solutions of a convectively driven model. The model is

driven by a uniform buoyancy loss over the surface of the basin and the circulation is in steady state. The circulation produced by the model is a two-layer flow while the strength of the exchange flow at the sill is in qualitative agreement with the observed winter pattern.

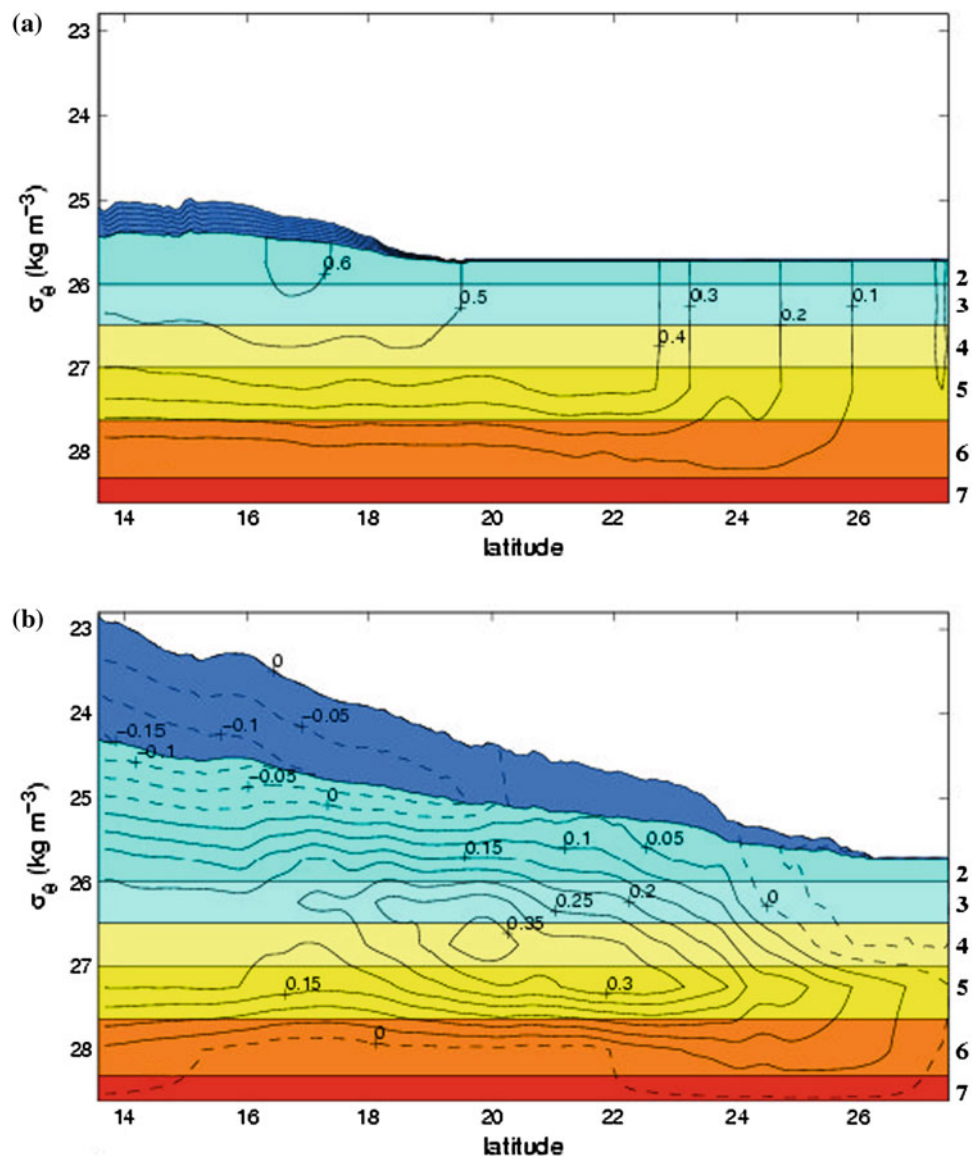
The main seasonal thermohaline cells were also reproduced in numerical modeling simulations (Sofianos and Johns 2002). The meridional overturning cells from this experiment are presented in Fig. 5, plotted on latitude/density coordinates (since the model used is isopycnic). A single broad recirculation cell is present in winter (Fig. 5a) centered at about 17°N. The summer overturning circulation (Fig. 5b) presents two cells, a shallow one in the southern part of the basin and a deeper one centered in the middle of the basin. The shallow cell is associated with the reversal of the surface flow and the GAIW intrusion, in which water entering the basin in the GAIW layer upwells to feed the shallow outflow. The second, deeper, cell connects the intermediate inflow with the RSOW outflow, which is about a half of the strength in summer as it is in winter.

Taking into account the RSOW formation rate and the volume of the lower branch of the surface cell, the renewal time of the layer is on the order of a few years. The simulations showed that about two-third of the total amount of Red Sea deep outflow into the Gulf of Aden (about 0.25 Sv) is formed inside the cyclonic gyre at 25°N, while the remainder is formed north of 20°N latitude by mixing with the surrounding layers. Thus, it can be concluded that the dominant formation region for the RSOW is the northern Red Sea where the vertical structure and the water trapping related to the cyclonic gyre and the strong buoyancy forcing in winter provide a favorable environment for intermediate depth convection. These conclusions are also consistent with tracer distributions of  $^{14}\text{C}$  and  $^3\text{He}$  in the basin (Cember 1988).

The renewal timescale of the deep cell, involving RSDW, is, in contrast to its surface counterpart, on the order of decades. Based on  $^{14}\text{C}$  and  $^3\text{He}$  data from the GEOSECS Indian Ocean Expedition, Cember (1988) estimated a deepwater residence time of about 36 years. Woelk and Quadfasel (1996) used hydrographic data in a one-dimensional plume model and long-term atmospheric forcing to estimate a bulk residence time of the deep waters 73 between 40 and 90 years. They also proposed that the formation of deep waters is episodic and can take place only under extreme meteorological conditions (“convection winters”). These extreme years occur at a timescale of 4–7 years. The influence of this wintertime atmospheric forcing variability on the RSOW formation has not been fully investigated.

The RSDW layer circulation is relatively sluggish and it can be only traced by the oxygen depletion (Sofianos and Johns 2007) as it recirculates to the south in the lower branch and northward at mid-depths. There is little evidence for RSDW escaping through the bottom of the Strait of

**Fig. 5** Meridional overturning volume fluxes (in Sv) on latitude/density coordinates for **a** December and **b** June, from MICOM simulation (Sofianos and Johns 2002). Colors indicate different isopycnal model layers, and contours indicate the overturning cells (note that the two panels have different contour intervals). During the winter regime (**a**), RSOW is formed mainly in the northern Red Sea north of 23°N and flows southward toward the strait (on the left side of the figure) at densities ( $\sigma_\theta$ ) of between 26.5 and 27.8 kg m<sup>-3</sup>. During the summer regime (**b**), inflow of GAIW at intermediate densities ( $\sigma_\theta = 24.5 - 26.0$  kg m<sup>-3</sup>) partly upwells into the southward-flowing RSSW south of about 20°N, and the remainder continues northward to supply sinking of RSOW between 22 and 26°N



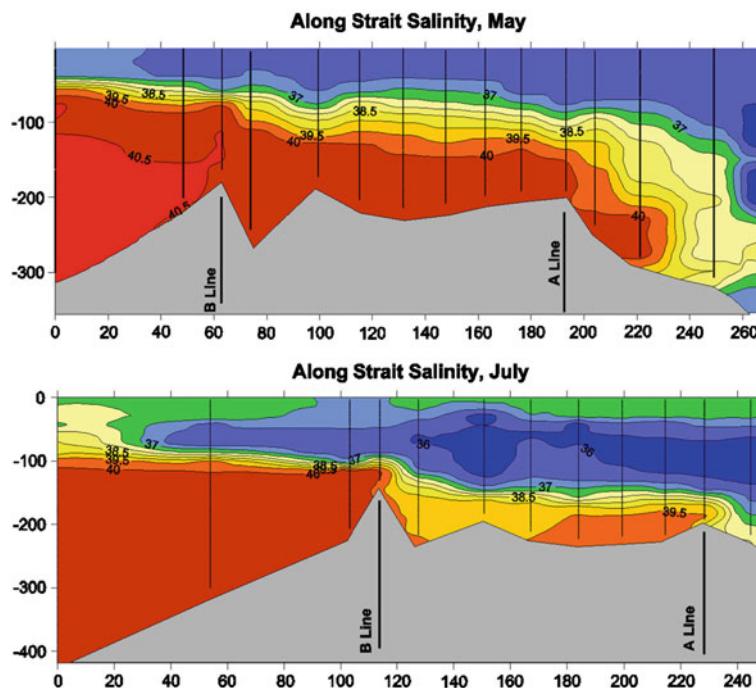
Bab-al-Mandab, and thus, we can assume that this layer upwells into the base of the RSOW layer at a rate approximately equal to its formation rate. The contribution of this cell to the Red Sea outflow is minor compared to that of the RSOW formed by the intermediate depth convection, but it nevertheless plays an important role in the ventilation of the deep parts of the Red Sea.

### Exchange Between the Red Sea and Adjacent Basins

The circulation pattern and water mass formation processes inside the Red Sea are reflected in its exchange with the adjacent basins. In winter, an inverse estuarine exchange flow dominates the circulation at the Strait of Bab-al-Mandab,

with a relatively fresh surface inflow and a deep outflow of water with higher salinity. The diverse stratification in the strait during winter and summer seasons can be readily depicted in the salinity profiles in the strait. Two salinity sections corresponding to the winter and summer exchange patterns, from cruises in the Bab-al-Mandab (Murray and Johns 1997) are presented in Fig. 6. The winter pattern consists of two layers, with a relatively fresh layer on top of a hypersaline lower layer, while in summer, the stratification changes to a three-layer system with a very fresh layer at intermediate depths between two layers with much higher salinity. An Italian expedition on board the AMIRAGLIO MAGNAGHI carried out current measurements along the Strait of Bab-al-Mandab during summer (Vercelli 1931a, b) and for the first time demonstrated the presence of a three-layer exchange during this season, with surface and deep

**Fig. 6** Along strait salinity transects during May 1995 (*upper panel*) and July 1996 (*lower panel*), from along-strait hydrographic sections taken during the Murray and Johns (1997) Bab-al-Mandab study. The May section occurred during the late phase of the winter two-layer exchange pattern, but is still representative of winter conditions. The July section occurred near the time of the maximum seasonal inflow of low-salinity GAIW to the Red Sea. Line A corresponds to the Perim Narrows location and Line B to the Hanish Sill location



outflows and an intermediate inflowing layer. This summer exchange pattern was supported by later observations (Sewell 1934; Thompson 1939; Maillard and Soliman 1986) and quantified by long-term direct observations at the Strait of Bab-al-Mandab (Murray and Johns 1997).

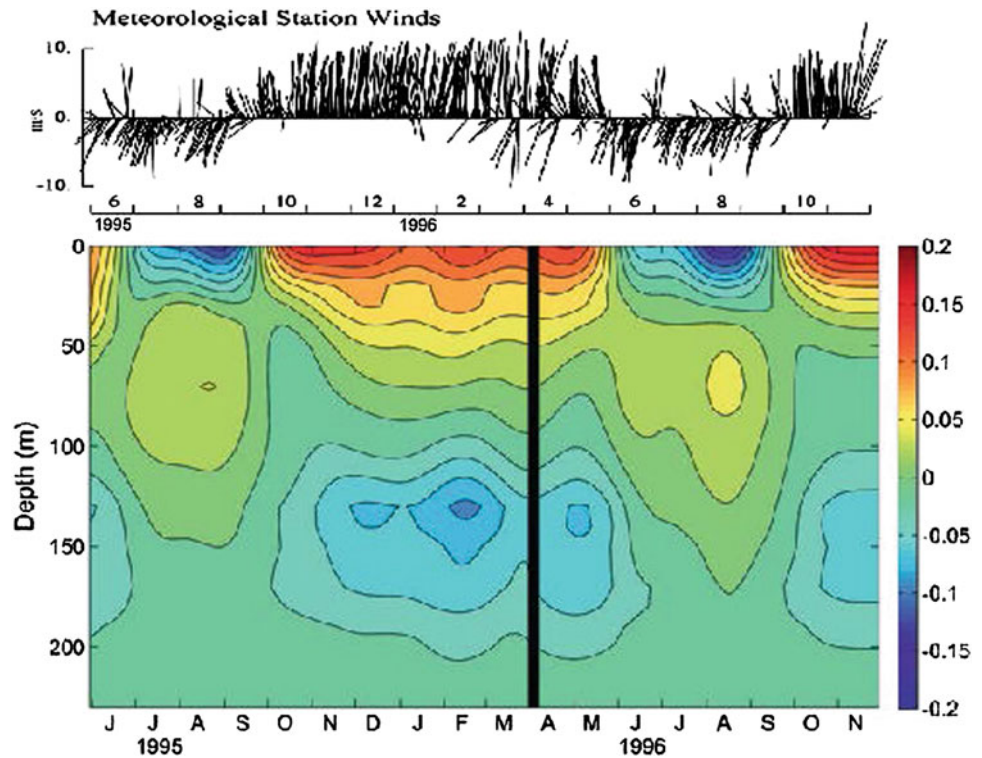
Direct observations and indirect methods were employed in order to estimate the strength of the exchange flow and its seasonal variability. The most comprehensive study was an 18-month observational effort in the Bab-al-Mandab Strait by Murray and Johns (1997). The observations were obtained from a long-term deployment of current meter and acoustic Doppler current profiler (ADCP) moorings located at the Hanish Sill and Perim Narrows (Fig. 1). The mooring arrays were deployed in two 9-month settings, from June 1995 to March 1996 and from March to December 1996. The volume transport profile for the Perim Narrows derived from these observations, obtained by integrating the along-strait flow across the width of the channel, is presented in Fig. 7 (Johns and Sofianos 2012). It has been filtered with a 60-day low-pass filter to emphasize the seasonal cycle. The basic seasonal pattern of the exchange, two layers in winter (October–May) and three layers in summer (June–September), is clearly revealed. Based on this data, the monthly mean transport of the three layers was estimated (Sofianos et al. 2002) and is presented in Fig. 8, together with other historical estimates. The strength of the winter exchange achieves its maximum during February when the RSOW layer has an outflow rate of more than 0.6 Sv. This outflow becomes very weak in summer with a minimum of 0.05 Sv during August. During August, the strongest three-layer

exchange is present in the strait, when the GAIW intrusion reaches a rate of about 0.3 Sv.

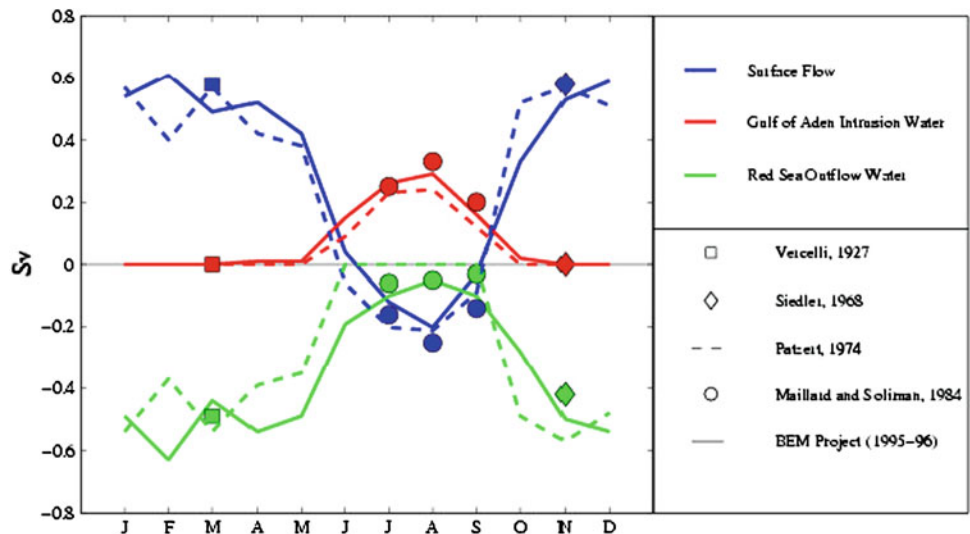
The mechanisms controlling the seasonal variability of the exchange flow in the Strait of Bab-al-Mandab are highly debated. Based on the obvious coincidence of the reversal of the wind field in the southern Red Sea with the reversal of the surface flow (Fig. 7), Patzert (1974a) hypothesized that the variable wind stress and the associated changes of the sea level in the southern Red Sea and the Gulf of Aden control the surface circulation in the region throughout the year as well as the exchange flow in the Strait of Bab-al-Mandab. To explain the three layer system and the associated GAIW intrusion at intermediate depths during summer, Patzert proposed that the northwest winds and a drop in the sea level at the northwestern Gulf of Aden due to wind-induced upwelling forces a shallow surface layer outflow from the Red Sea. The same mechanism displaces the subsurface isopycnals upward, producing an opposite pressure gradient at intermediate depths that induces the intermediate intrusion of the GAIW. A different mechanism controlling the seasonal exchange flow between the Red Sea and the Gulf of Aden, based on the buoyancy fluxes over the Red Sea basin, was proposed by Sofianos (2000) using a modified version of the Phillips (1966) model. This model was also able to explain the summer season subsurface intrusion. Modeling experiments performed by Sofianos and Johns (2002) verified the relevance of the Patzert wind-driven mechanism. They also showed that the combination of the two forcing mechanisms, that is, wind stress and buoyancy flux, can reproduce the seasonal pattern and the amount of the inflowing water masses.



**Fig. 7** The wind time series from a meteorological station located at the Strait of Bab-al-Mandab and the transport-per-unit-depth profile at the Perim Narrows section, after low-pass filtering with a 60 day filter to emphasize the seasonal exchange pattern through the strait ( $units\ 10^4\ m^2\ s^{-1}$ ). Positive transports correspond to inflow to the Red Sea from the Gulf of Aden. The masked-out area (*black bar*) corresponds to the period when moorings were serviced midway through the experiment. (From Johns and Sofianos 2012)



**Fig. 8** Monthly mean transport (in Sv) for the three layers: surface (*blue*), GAIW (*red*), and RSOW (*green*). *Solid lines* represent the layer transport monthly mean values derived from Murray and Johns (1997), the *dashed lines* represent the seasonal layer fluxes estimated by Patzert (1974b), and other symbols represent various historical estimates



Averaging the volume transport of the three layers over the annual cycle, we can estimate the average strength of the exchange flow in Bab-al-Mandab. The annual mean RSOW outflow, which is a good measure of the overall strength of the exchange, was estimated at 0.36 Sv, and showed a large annual cycle ranging from over 0.6 Sv during the peak of the winter (February) to less than 0.1 Sv during the peak of the summer season (Fig. 8). The reversal of the surface flow and the intrusion of the GAIW were found to last for 4 months (June–September) when an average of 0.22 Sv of the GAIW enters the Red Sea basin.

In addition to the seasonal variability, the exchange experiences strong fluctuations at shorter timescales, including tidal (dominantly semidiurnal) and synoptic timescales ranging from a few days to several weeks. Transport variations through the strait on synoptic timescales (days to weeks) appear very strong, reaching values nearly twice as large as the mean rate of the exchange through the strait driven by annual evaporation over the Red Sea (Johns and Sofianos 2012). A very interesting feature is the large-amplitude variability of the transport through the strait that occurs at high frequencies that can reach amplitudes of up to

1 Sv (comparable in magnitude to the total inflow/outflow exchange through the strait). The largest amplitude variability occurs near periodicities of 5–6 days, which corresponds to the Helmholtz frequency of the Red Sea, as determined by the surface area of the Red Sea and the characteristics of the strait (Johns and Sofianos 2012).

The synoptic transport variability appears to be driven by two primary forcing mechanisms: wind stress variability over the strait and variation in the large-scale barometric pressure over the Red Sea. A simple two-layer linear model of the response of the strait to the local wind and changes of the atmospheric pressure over the Red Sea was developed by Johns and Sofianos (2012) and was able to reproduce the essential features of the observations (explaining about 70 % of the observed transport variance). The response to barometric pressure forcing over the Red Sea is fundamentally barotropic, whereas the response to along-strait winds is nearly barotropic at high frequencies and tends toward a two-layer exchange at low frequencies.

Processes related to the density structure and the flow in the Strait of Bab-al-Mandab, as well as the characteristics of the strait and frictional processes, can limit the exchange flow and the associated dynamics inside the Red Sea. The direct and detailed observations at the strait gave the opportunity to investigate these processes and evaluate the possibility of hydraulic control (Farmer and Armi 1988; Armi and Farmer 1988) in the exchange flow. It was found (Pratt et al. 1999, 2000) that the mean exchange flow is not hydraulically controlled in either the winter (two-layer) or summer (three-layer) exchange regimes. On the other hand, it was proposed that hydraulically critical flow could be an intermittent feature, influenced to a great extent by the tides and the strong synoptic variability. A detailed discussion of processes involved in the exchange flow in the Strait of Bab-al-Mandab is given by Smeed (2004).

There are no long-term observations at the mouth of the Gulf of Suez and the mouth of the Gulf of Aqaba. The few observational studies (Maillard 1974; Murray et al. 1984) were carried out for relatively short periods, and the exchange patterns were not studied in detail and at relevant timescales. Systematic monitoring of the two gulf mouths are of great importance for understanding the response of these regions to atmospheric forcing as well as for quantifying the contribution of the gulfs to the Red Sea thermohaline circulation.

## Summary and Discussion

Due to its shape, size, and the intense atmospheric forcing of both wind and buoyancy flux, the Red Sea is a very advantageous experimental basin from a physical oceanographic viewpoint. It can be thought of as a miniature global ocean, with strong thermohaline and wind-driven circulation

components, shelf and open ocean water mass formation and a strong and robust overturning circulation. Its exchange through the narrow and shallow Bab-al-Mandab strait with the Indian Ocean presents strong variability on a wide range of timescales and involves a variety of process that need further investigation. The outflow of the Red Sea is one of the most saline water masses of the world ocean, and it can be traced far from its source into the equatorial and southern subtropical regions of the Indian Ocean.

Despite its ecological importance and the advances in our understanding of the dynamics of the Red Sea made during the last decades, this sea nevertheless remains widely unexplored and processes controlling its circulation are still obscure and highly debated. Several aspects of the dynamics in the region remain poorly or only partly understood, such as the detailed nature of the water mass formation processes both in the open Red Sea and adjacent northern gulfs, the patterns and seasonal variability of the surface and deep circulation, and the controlling mechanisms of the strait exchange. Furthermore, while a coherent picture of the mean state of the basin is starting to emerge from the combination of various observational and modeling studies, the interannual variability has been largely neglected and only recently has attracted the attention of the oceanographic community (e.g., Alraddadi 2013). Long-term monitoring observations, complemented by numerical modeling techniques, are needed to understand the sensitivity of the circulation and water mass formation to wind and thermohaline forcing, and its connection with global- and regional-scale climate variability.

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