A 27,000 year record of Red Sea Outflow: Implication for timing of post-glacial monsoon intensification

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Abstract. We reconstruct here the history of the Red Sea Outflow (RSO) over the past 27,000 years from an AMS $^{14}$C-dated high-resolution $\delta^{13}$C record of benthic foraminifera from the inner Gulf of Aden assuming the dominance of circulation over productivity in regulating benthic $\delta^{13}$C. The results reveal that, following a period of suppressed RSO due to shallow sill 24,000-18,000 yr BP, the Red Sea was vigorously flushed for ~2,000 years before a major monsoon intensification caused the cessation of deep water formation from 15,500 to 7,300 yr BP. It appears that the monsoon intensification did lag behind insolation until 15,500 yr BP. Between 15,500 and the present, however, there was no lag in conflict with the previous reports, implying a negligible dampening effect of continental albedo during this period. However, since our analysis is confined to a single depth horizon and our record is sensitive to sea level, it has some limitations as an indicator of monsoon intensity.

Introduction

The Red Sea is connected to the Gulf of Aden by the narrow Strait of Bab-el-Mandeb (sill depth 137 m). Its exchange with the Indian Ocean is dependent on the water balance and seasonally-reversing winds [Maillard and Soliman, 1986]. Excessive evaporation drives an inflow of fresher surface water and an outflow of dense Red Sea water over the sill. This simple two-layered circulation is altered during summer when the inflowing current shifts to mid-depth, embedded between the two outflowing currents.

Intense cooling of salty waters in the northern Red Sea and in the Gulfs of Suez and Aqaba in winter leads to the formation of deep waters with very similar thermohaline characteristics in two different modes [Cemler, 1988]. The lower deep water is formed through mixing of dense outflows from the two gulfs with the upper (~150 m) waters of the northern Red Sea in roughly equal proportions. In the other mode, dense water is injected directly beneath the pycnocline in the northern Red Sea and possibly in the Gulf of Aqaba. The combined rate of deep water production ($0.16 \text{ m}^3 \text{s}^{-1}$) yields a renewal time of 36 years [Cemler, 1988].

The Red Sea Outflow (RSO), probably a mixture of the convectively and isopycnally formed deep waters, advects into the Arabian Sea along 27.2 $\sigma_T$ surface within 500-800 m [Wyrtki, 1971]. However, its rate varies seasonally by an order of magnitude [Maillard and Soliman, 1986] as evident from salinity distribution in the inner Gulf of Aden (Figure 1). It may be noted that even in summer, when the RSO is greatly reduced, the core layer occurs at about the same level, and the influence of RSO is perennially felt down to at least 1 km in the inner Gulf of Aden.

Previous studies have shown that the Red Sea experienced large changes during and since the last glacial maximum (LGM) in response to variations in glacio-eustatic sea level and climate [Almogi-Labin et al., 1991, and references therein; Rohling, 1994]. Very high salinities (~50%) prevailed in both the surface and deep waters at the LGM due to the much lower sea level [Deuser et al., 1976; Thunell et al., 1988]. By contrast, pluvial conditions during deglaciation caused a stagnation of deep waters as manifested by the accumulation of sapropelic sediments [Rossignol-Strick, 1987; Almogi-Labin et al., 1991].

As a result of their short residence time, the Red Sea deep waters are characterised by a much higher $\delta^{13}$C of $\Sigma$CO$_2$ (0.84-1.27‰ vs PDB) than that of the water ($\delta^{13}$C ~ 0‰) with which RSO mixes (Figure 2a). We exploit this contrast for investigating RSO variability associated with the changes in Red Sea hydrography mentioned above. Our approach is based on the simple premise that the periods of rapid ventilation of the Red Sea could be characterised by enrichment of the heavier carbon in bottom waters in the inner Gulf of Aden. This, of course; involves the assumption that the residence time of RSO within the inner Gulf of Aden is short enough to make the changes in $\delta^{13}$C due to mineralization negligible. Data from the inner Gulf of Aden, where RSO is conspicuous by its high $\Sigma$CO$_2$ content (Fig. 2b), provide observational support to this assumption (Figure 2b).

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Figure 1. Vertical sections of salinity in the southern Red Sea and inner Gulf of Aden during two seasons [Wyrtki, 1971].
Material and Methods

The core RC9-167 (Lat. 11°50.3′N, Long. 43°21.2′E; depth 650 m) was raised from the Tadjura Trench just outside the entrance to the Red Sea. This site, located close to the Meteor Sta. 43 (Figure 2b), is currently bathed by RSO throughout the year, and it seems reasonable to assume that, unless the Red Sea experienced climatic conditions vastly different from today’s, it received RSO in the past as well during the time span of our study.

Hand-picked shells of the benthic foraminifer Cibicidoides subhaidingeri were analysed at Lamont-Doherty Earth Observatory following standard procedures [Naqvi et al., 1994]. Analytical precision was ±0.03‰ for δ13C and ±0.06 ‰ for δ18O. Radiocarbon dating at the National Ocean Sciences AMS Facility, Woods Hole Oceanographic Institution, using Globigerina omariae or G. ruber at five levels provided excellent chronological control (Table 1). Radiocarbon ages (14C yr BP) were first adjusted by 400 yr to correct for the apparent age of surface water and then converted into calendar years (yr BP) using the data of Bard et al. [1990] and Stuiver and Pearson [1993].

Results and Discussion

Stable isotope data are plotted versus age in Figure 3. Although C. subhaidingeri has not been previously utilised for paleohemical work, the δ13C of several other species of this genus is very close to that of the ambient bottom waters [Curry et al., 1988]. The core-top δ13C (0.85‰) suggests that this species also provides reliable records of the bottom water δ13C. Although it has been reported that the Cibicidoides δ13C may be significantly lower than the bottom water δ13C in areas of high productivity [Mackensen et al., 1993], this effect may not significantly obscure the Cibicidoides δ13C signal in RC9-167 because the site is located well outside the upwelling zone [Wyrski, 1971].

Given the wide thermaline fluctuations expected from the RSO changes, the δ18O record (Figure 3) is remarkably smooth. This is probably because the high temperature of RSO (Figure 2b) causes a decrease in foraminiferal δ18O that may just compensate for the effect of high δ18O of RSO due to its high salinity. The δ18O curve, on the other hand, exhibits several unusual features. Although significant changes in the oceanic δ18O inventory occurred over the glacial-interglacial transition [Curry et al., 1988], recent work [Boyle et al., 1993] suggests that the glacial to interglacial shift in δ18O in the upper waters of the NW Arabian Sea was much smaller than the global mean. Therefore, the changes observed in RC9-167 could be regarded as local, attributable to fluctuations in the Red Sea-Indian Ocean exchange.

The δ13C values near the base of the record (>24,000 yr BP) compare well with those observed within the upper Holocene.

Table 1. AMS 14C ages

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>14C Age (14C yr BP)</th>
<th>Calib. Age (yr BP)</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>117-119</td>
<td>4980±35</td>
<td>5300</td>
<td>G. ruber</td>
</tr>
<tr>
<td>167-169</td>
<td>8670±50</td>
<td>9910</td>
<td>G. ruber</td>
</tr>
<tr>
<td>247-249</td>
<td>12350±50</td>
<td>14680</td>
<td>G. ruber</td>
</tr>
<tr>
<td>271-273</td>
<td>13600±100</td>
<td>16320</td>
<td>G. sacculifer</td>
</tr>
<tr>
<td>317-319</td>
<td>16850±75</td>
<td>20520</td>
<td>G. ruber</td>
</tr>
</tbody>
</table>
(Figure 3) indicating that substantial outflow from the Red Sea occurred until the early isotopic stage 2. The decrease in δ¹³C around 24,000 yr BP was probably caused by much lower sea level; the δ¹³C minimum exactly corresponds to the LGM 21,600 yr BP. Nevertheless, the decrease in δ¹³C during the LGM was about half of that seen during the humid deglacial period, supporting the view that even the peak glacialism some dense water continued to trickle out of the Red Sea [Rahling, 1994].

With the onset of deglaciation ~18,000 yr BP, a sharp increase in δ¹⁸O occurred as an active water exchange between the Red Sea and the Gulf of Aden was re-established. The δ¹³C values between 16,000 and 17,000 yr BP are amongst the highest observed in the core, providing the first evidence of vigorous flushing of the Red Sea during the early deglaciation.

The most conspicuous feature of the RC9-167 data set is the large (0.6‰) negative excursion in δ¹³C during the deglaciation. This might arise from changes in both productivity and circulation associated with a more intense summer monsoon. The enhanced productivity could have led to a greater nutrient regeneration (δ¹³C decrease) at intermediate depths throughout the NW Indian Ocean. However, such a change in δ¹³C would extend to the RC9-167 site only when it ceased to be bathed by RSO. Thus, the lower δ¹³C of the Arabian Sea intermediate water could have amplified the negative δ¹³C shift arising primarily from a change in circulation. Alternatively, the elevated productivity might have caused a negative shift in the δ¹³C of Cibicidoides relative to bottom water [Mackensen et al., 1993]. This mechanism may account for a strong negative spike in Cibicidoides δ¹³C observed in another Gulf of Aden core (MD76-135, depth 1895 m) at about the same time (Figure 4). This is because the analysis of benthic foraminifera in this core shows a deglacial decrease in cadmium [Boyle et al., 1995], providing evidence against a basin-wide mid-depth enrichment of nutrients. Moreover, the core site is too deep and too far from the Bab-el-Mandeb for this feature to be directly related to changes in RSO. By contrast, the excursion in RC9-167 cannot be attributed to the same phenomenon because unlike MD76-135, RC9-167 is located well outside the upwelling zone. Near the latter site, the upwelling indicator Globigerina bulloides has a uniform dwcore abundance, indicating that, relative to the Holocene, upwelling in the inner Gulf of Aden could not have been more intense during the glacial and deglacial stages [Locke and Thunell, 1988]. Notably, the duration of δ¹³C excursion in RC9-167 is much longer. It is thus far more likely that this feature was caused by a change in circulation. The available information from the Red Sea supports this view. As stated earlier, massive freshwater inputs into the Red Sea during deglaciation caused a marked freshening of the upper water column that triggered the cessation of deep water formation. At that time, the Red Sea waters below the sill depth would have been isolated from the surface layer by strong density gradients and the export of dense water, required for the maintenance of salt balance, would not occur. In such a case, the surface waters flowing into the Red Sea would return at shallow depths, missing the RC9-167 site. Such a change in the Red Sea-Gulf of Aden exchange [Locke and Thunell, 1988], is supported by our results since the δ¹³C at our core site approached the values typical of the Arabian Sea at comparable depths. (In the event of the cessation of RSO, the Antarctic Intermediate Water would have penetrated further north in the Arabian Sea, and so the δ¹³C of the Arabian Sea intermediate water itself probably did not vary greatly [Zahn and Pedersen, 1991]).

Two additional points may be made here. First, while the stagnation of deep waters in the Red Sea would have led to a depletion of O₂ and a decrease in δ¹³C, it could not have produced the δ¹³C decrease outside the basin. Secondly, hyper-saline conditions continued to prevail within the deep waters of the Red Sea during the deglaciation [Thunell et al., 1988; Almogi-Labin et al., 1991]. This requires an abrupt climate change since a gradual freshening of the Red Sea surface waters driven by a slowly-intensifying monsoon should have led to a gradual decrease in deep water salinity and a shoaling of RSO until the surface waters became too buoyant to sink. Thus, while it may be argued that the rapid change inferred from our record ~15,500 yr BP may be due to the fact that we have sampled a single depth, the available information from the Red Sea makes this scenario quite unlikely. Most importantly, this transition is remarkably coeval with the major glacial/interglacial change observed in several western Arabian Sea cores [Sirocko et al., 1993]. For example, in the core 74KL, collected from the East Sheba Ridge, there occurred extremely rapid (~300 yr) and pronounced shifts, centred around 13,060 ¹³C yr BP, in planktonic δ¹⁸O and dolomite and CaCO₃ contents of sediments; these were attributed to changes in summer monsoon strength [Sirocko et al., 1993]. Based on an independent climate proxy (monsoon-driven changes in RSO), our results also indicate that an abrupt intensification of monsoon circulation occurred ~13,000 ¹³C yr BP (15,500 yr BP).

Results of modelling suggest that the two primary factors determining monsoon strength are insolation and continental albedo [Manabe and Hahn, 1977; Prell and Kutzbach, 1986]. In view of the smooth changes in insolation (Figure 3), it is obvious that the abrupt change in monsoon strength should be driven mainly by albedo changes. The strong influence of the seasonal Eurasian snow cover on monsoons is well established [Barratt et al., 1989]. Perhaps a threshold was reached whereby the increasing insolation prevented the Tibetan snow cover from lasting well into the spring and summer months. A suddenly snow-free plateau during spring and summer might have resulted in an abrupt increase in the summer monsoon strength ~15,500 yr BP.

Unlike the onset of the warm humid phase, the transition from humid to arid conditions is less abruptly recorded in RC9-167. This may imply that the decrease in summer monsoon precipitation was relatively gradual in response to diminishing summer insolation (Figure 3). Alternatively, the post-glacial increase in the area of the Red Sea would require an increasingly larger freshwater flux to produce the same degree of stagnation. Nevertheless, the termination of stagnation ~7,300 yr BP in RC9-167 closely

Figure 4. Comparison of Cibicidoides δ¹³C in RC9-167 (filled circles, left scale, this work) and MD76-135 (142°77N, 50°31'E) (open circles, right scale [Curry et al., 1988]). Age model for MD76-135 is from Boyle et al. [1995].
correlates with the event (8,050 yr BP) that marked the end of the humid interval in 74 KL. [Sirocko et al., 1993].

A noteworthy observation is that a shift in δ13C to high values corresponding to the Younger Dryas (YD) is absent in Figure 3, implying that the YD cooling/aridity was not severe enough to re-establish deep convection in the Red Sea. The humid interval, represented by the uninterrupted stagnation of Red Sea deep waters for ~8,000 yr, appears to be a break with the period of elevated summer insolation in the northern hemisphere that peaked ~11,000 yr BP (Figure 3) [Berger, 1978]. This is in conflict with the results of earlier workers [Van Campo et al., 1982, Prell, 1984, Clemens et al., 1991] who suggested that the monsoon response could lag behind the solar forcing by a few thousand years as a result of the ice sheet overprint or the effect of cross-equatorial transport of latent heat. For example, based on abundance of G. bulloides in a bulk 14C-dated core (V14-88), collected from the Owen Ridge, Prell [1984] suggested that the summer monsoon peaked ~9,000 14C yr BP. However, subsequent work involving paired 14C and thorium-230 (230Th) dating of corals has shown that 14C ages may be significantly younger than those obtained by the 230Th method [Bard et al., 1990], and this might largely account for the time lag derived from the 14C method. In comparison, the more reliable 14C AMS ages on planktonic foraminifera obtained by us have been corrected for this offset. While it is well recognised that the continental albedo had been responsible for the weak summer monsoon during the LGM [Manabe and Hahn, 1977; Duplessy, 1982], our results indicate that this effect abruptly waned ~15,500 yr BP, possibly due to a rapid change in the seasonal snow cover over the Tibetan Plateau. Therefore, the evolution of humid conditions seems to have closely followed the astronomical forcing.

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References

Almogi-Labin, A., C. Hemleben, D. Meischner, and H. Erlenkeuser, Paleoenvironmental events during the last 13,000 years in the central Red Sea as recorded by pteropods, Paleoceanography, 6, 83-98, 1991.


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