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Glacial conditions in the Red Sea

Eelco J. Rohling

Department of Oceanography, University of Southampton, Southampton, United Kingdom

Abstract. In this paper, results from previous studies on planktonic foraminifera, $\delta^{18}O$, and global sea level are combined to discuss climatic conditions in the Red Sea during the last glacial maximum (18,000 B.P.). First, the influence of 120-m sea level lowering on the exchange transport through the strait of Bab-el-Mandab is considered. This strait is the only natural connection of the Red Sea to the open ocean. Next, glacial Red Sea outflow salinity is estimated (about 48 parts per thousand) from the foraminiferal record. Combined, these results yield an estimate of the glacial net water deficit, which appears to have been quite similar to the present (about 2 m yr^{-1}). Finally, budget calculation of $\delta^{18}O$ fluxes suggests that the glacial $\delta^{18}O$ value of evaporation was about 50% of the present value. This is considered to have resulted from substantially increased mean wind speeds over the glacial Red Sea, which would have caused a rapid drop in the kinematic fractionation factor for ^{18}O. The sensitivity of the calculated values for water deficit and isotopic fractionation to the various assumptions and estimates is evaluated in the discussion. Improvents are to be expected especially through research on the glacial salinity contrast between the Red Sea and Gulf of Aden. It is argued, however, that such future improvement will likely result in a worsening of the isotopic discrepancy, thus increasing the need for an additional mechanism that influenced fractionation (such as mean wind speed). This study demonstrates the need for caution when calculating paleosalinities from $\delta^{18}O$ records under the assumption that the modern S:$\delta^{18}O$ relation has remained constant through time. Previously overlooked factors, such as mean wind speed, may have significantly altered that relation in the past.

Introduction

Strong excess of evaporation over freshwater input into the Red Sea results in a net water deficit of about 2 m per year [*Siedler*, 1969; *Morcos*, 1970; *Grasshoff*, 1975]. This drives surface water inflow from the Gulf of Aden through the Strait of Bab-el-Mandab, and causes a mainly salinity-related increase in density within the Red Sea. Dense water is transported out of the Red Sea via subsurface flow into the Gulf of Aden. This simplified representation of the vertical circulation is complicated in summer by wind-induced reversal of the flow through the strait at the very surface (< 40 m), while inflow at intermediate levels and outflow at depth continue (Figures 1, 2) [*Thompson*, 1939; *Patzert*, 1974a, 1974b; *Maillard and Soliman*, 1986; *Souvermezoglou et al.*, 1989].

The Strait of Bab-el-Mandab, the only connection of the Red Sea with the adjacent Indian Ocean, is narrowest near Perim Island, where the main channel is only about 20 km wide and about 300 m deep (Figure 1). Some 140 km basin-inward, just east of Hanish Island, the passage is shallowest, with a maximum depth of 137 m [*Werner and Lange*, 1975], and a width of about 105 km (Figure 1). A grab sample from the sill contained only pieces of living coral, indicating a clean, hard sea bottom without fine sediments [*Werner and Lange*, 1975]. Only over a width of about 11 km is this shallowest passage deeper than 120 m. During the last glacial maximum (LGM), assuming 120-m sea level lowering [*Fairbanks*, 1989], the passage was only 11 km wide and about 17 m deep. In addition, a 120-m lowering of sea level would have reduced the surface area of the Red Sea by about 50% [*Locke*, 1986]. In the sensitivity analysis (discussion),

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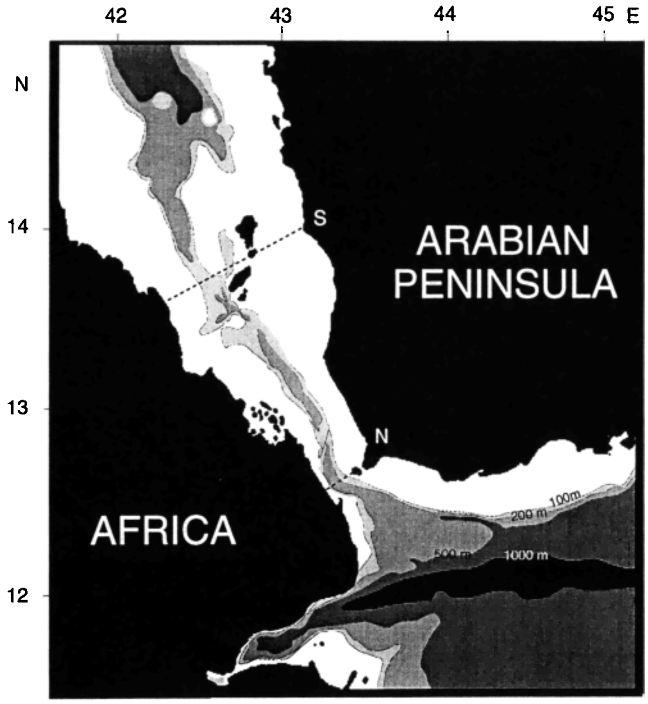

Figure 1. Bathymetry of the passage between the Gulf of Aden and the Red Sea (modified after *Werner and Lange* [1975]). S indicates the shallowest passage near Hanish Island, and N represents the narrowest passage near Perim Island. Depth contours are in meters.

isostatic rebound is argued to have had little effect on the dimensions of the glacial strait.

Given the present-day Red Sea surface area of about 0.44×10^{12} m^2 and a net water deficit of about 2 m yr^{-1}, the volume of present-day excess evaporation (X^p) is about 0.88×10^{12} m^3 yr^{-1} (p indicates present-day value) [*Siedler*, 1969]. Using equations for conservation of mass and salt, the volume of subsurface outflow of Red Sea water (V_{rs}) may be determined according to $V_{rs} = (S_{ga}\,X)/\Delta S$, where S_{ga} is the salinity of surface inflow from the Gulf of Aden and ΔS is the outflow-inflow salinity contrast. Since $S_{ga}{}^p = 36.6$ and $\Delta S^p = 3.1$, $V_{rs}{}^p$ is about 10.4×10^{12} m^3 yr^{-1}, or 0.33 Sverdrup [*Siedler*, 1969]. Recent oxygen isotope measurements show that the modern Red Sea basin enrichment, $\Delta\delta^{18}O$ ($= \delta^{18}O_{rs} - \delta^{18}O_{ga}$), amounts to about $1.7 - 0.8 = 0.9$ parts per thousand [*Andrié and Merlivat*, 1989].

Glacial Conditions

During the LGM, the summer SW monsoon was substantially weakened and the winter NE monsoon intensified [e.g., *Duplessy*, 1982; *Van Campo et al.*, 1982; *Fontugne and Duplessy*, 1986]. Note that, over most of the Red Sea, the winds associated with the winter monsoon are northwesterlies rather than northeasterlies [*Siedler*, 1969; *Pedgley*, 1974]. In combination with the drastic sill depth reduction of 120 m by glacial sea level

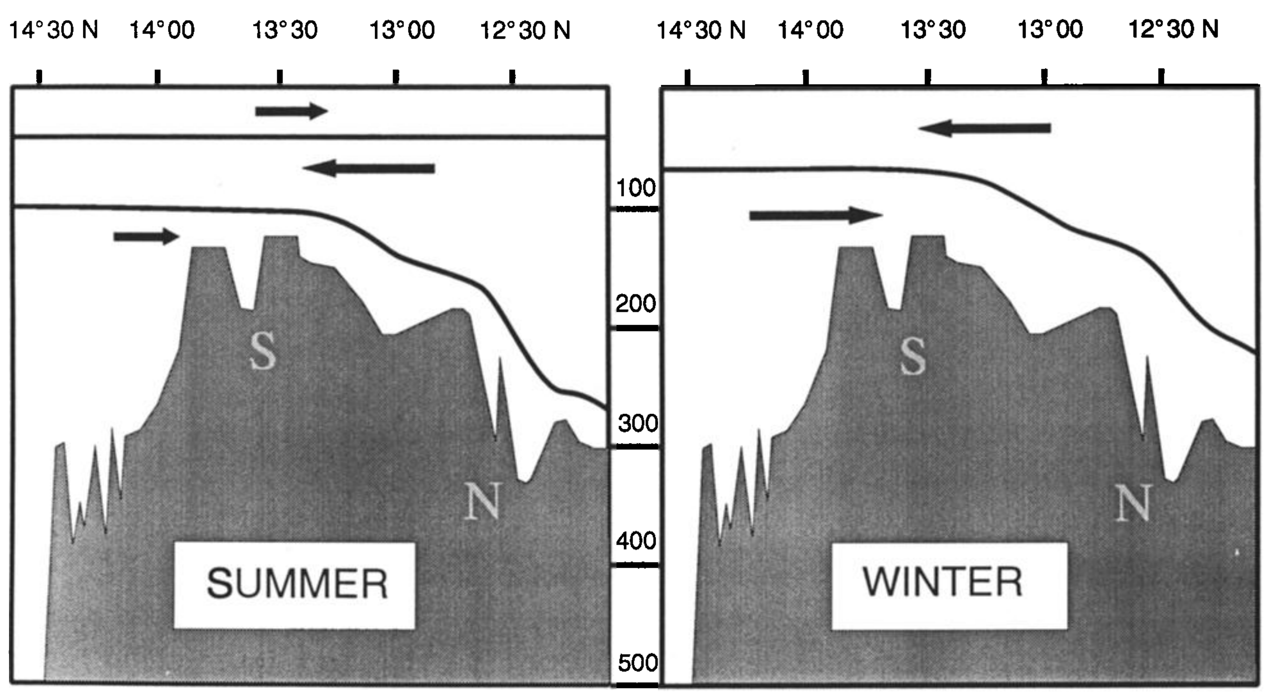

Figure 2. Schematic along-strait profiles showing the modern summer and winter circulation patterns through the Strait of Bab-el-Mandab (modified after *Thompson* [1939], *Patzert* [1974a,b], *Maillard and Soliman* [1986], and *Souvermezoglou et al.* [1989]). S indicates the shallowest passage near Hanish Island, and N represents the narrowest passage near Perim Island. Depth scale is in meters.

lowering [*Fairbanks*, 1989], the weakening of the summer monsoon would have resulted in a far less pronounced seasonal reversal of surface flow in the Strait of Bab-el-Mandab. If strong winds would prevail in a strait with a total depth of only 17 m, one would expect the whole water column to move in the direction determined by the winds until the slope of the sea surface balanced the along-strait wind stress. Then, two-layer flow could be set up with normal inflow at the surface and outflow deeper down. I would argue, therefore, that the glacial exchange between the Red Sea and Gulf of Aden may be considered two-layered, especially for the specific purpose of this study, which concerns the long-term average conditions. In assuming this, I am supported by the conclusions of *Assaf and Hecht* [1974] that even in the present-day configuration, the effects of wind stress on the average current pattern of the strait are rather weak and that a model intending to show only average conditions could possibly ignore them.

As mentioned before, the Strait of Bab-el-Mandab is narrowest on the outward (Gulf of Aden) side and shallowest on the inward (Red Sea) side (Figure 1). This configuration is the opposite of that found in the Strait of Gibraltar, where the Mediterranean Sea is connected to the Atlantic Ocean via a passage shallowest on its outward (Atlantic) side and narrowest on its inward (Mediterranean) side [*Bryden and Kinder*, 1991]. Considering the influence of strait geometry on exchange transport, the Bab-el-Mandab configuration is less complicated than that of Gibraltar, since the narrowest width of a passage only influences exchange if it occurs between the sill and the reservoir containing the denser fluid [*Farmer and Armi*, 1986].

During the LGM, 120 m of sea level lowering [*Fairbanks*, 1989] would have left a passage across the Hanish Sill only 17 m deep and about 11 km wide. Calculation of maximal outflow then implies that the Froude number for outflow, F_{rs}^2 (= $U_{rs}^2/0.375g'H$), achieved a critical value of 1 at the sill [*Farmer and Armi*, 1986; *Bryden and Kinder*, 1991], so that $U_{rs}^2 = 0.375g'H$, where U_{rs} is the outflow velocity and $g' = g\Delta\rho/\rho_{rs}$, where g is gravitational acceleration, $\Delta\rho$ is the outflow-inflow density contrast and ρ_{rs} is the density of subsurface Red Sea outflow. H is sill depth. Since $\Delta\rho \approx 0.77\times10^{-3}\Delta S$ [*Bryden and Kinder*, 1991], so that $g' \approx 7.4\times10^{-3}\Delta S$, this idealized scenario gives maximum estimates $U_{rs}^{lgm} = 0.22(\Delta S^{lgm})^{1/2}$ m s^{-1}, and $V_{rs}^{lgm} = 15427.5(\Delta S^{lgm})^{1/2}$ m^3 s^{-1} ($4.865\times10^{11}(\Delta S^{lgm})^{1/2}$ m^3 yr^{-1}). The assumption of maximal exchange is evaluated in the discussion.

Conservation of mass and salt, compared to the present, gives $(X^{lgm}/X^{p}) \times (S_{ga}^{lgm}/S_{ga}^{p}) = (\Delta S^{lgm}/\Delta S^{p}) \times (V_{rs}^{lgm}/V_{rs}^{p})$. Note that conservation of mass and salt assumes that the glacial conditions may be considered as steady state (see next paragraph). Introducing a non-dimensional coefficient γ (= X^{lgm}/X^{p}) as a measure of change in excess evaporation relative to the present, and an ice-volume related increase in glacial surface water salinity of 1 ppt (S_{ga}^{lgm} = 37.6), γ^{lgm} may be expressed as a function of ΔS^{lgm}; $\gamma^{lgm} \approx (\Delta S^{lgm})^{3/2}/69$. In addition, ΔS^{lgm} may be estimated from the foraminiferal record. During the LGM, only two planktonic species managed to survive in the Red Sea, namely the warm euryhaline mixed-layer dweller *Globigerinoides ruber* and the cosmopolitan species *Globigerinita glutinata* [*Berggren and Boersma*, 1969; *Ivanova*, 1985; *Locke*, 1986; *Locke and Thunell*, 1988]. Previous studies show a re-entry sequence of planktonic species after the LGM, ascribed to the lowering of the Red Sea salinities from pleniglacial values above the tolerance limit of most species to more favorable levels [*Locke*, 1986; *Locke and Thunell*, 1988]. This interpretation is supported by the presence of chemical precipitates and benthic foraminiferal species indicative of hypersaline conditions in the LGM interval of Red Sea cores [*Ku et al.*, 1969; *Milliman et al.*, 1969; *Halicz and Reiss*, 1981; *Winter et al.*, 1983; *Locke*, 1986; *Almogi-Labin et al.*, 1986; *Locke and Thunell*, 1988]. The chemical precipitates mainly formed indurated hard layers of aragonitic composition serving as a matrix for lutites containing pteropods and foraminifera, and they are indicative of inorganic precipitation of aragonite resulting from supersaturation under presumably hypersaline conditions [*Ku et al.*, 1969]. No salt deposits were found, so that the assumption of steady state involved in using statements of conservation of mass and salt in the glacial scenario seems reasonably valid.

According to their salinity tolerances, the absence of *Globigerinoides sacculifer* and *Globigerinella siphonifera* (upper limits about S = 47 ppt [*Hemleben et al.*, 1989]) and the persistence of *Globigerinoides ruber* (upper limit about S = 49 ppt [*Hemleben et al.*, 1989]) in the glacial Red Sea suggest that $S_{rs}^{lgm} \approx 48$, or $\Delta S^{lgm} \approx 10$. With this value, $\gamma^{lgm} \approx 0.5$. A similar estimate of ΔS^{lgm} has been obtained by comparing changes in the $\delta^{18}O$ records from the Red Sea and Gulf of Aden [*Thunell et al.*, 1988]. The sensitivity of the calculations to variations in ΔS^{lgm} is evaluated briefly in the discussion.

The value of $\gamma^{lgm} \approx 0.5$ indicates that during the LGM, the excess evaporation (X^{lgm}) was reduced by about 50%, relative to the present. However, because of the 120-m sea level lowering, the Red Sea surface area was also reduced by about 50% [*Locke*, 1986]. Therefore, the calculated $\gamma^{lgm} \approx 0.5$ suggests that the water deficit was about equal to the present (2 m yr^{-1}).

Today, there are no major rivers draining into the Red Sea, and precipitation is less than 100 mm yr^{-1} [*Pedgley*, 1974; *Grasshoff*, 1975]. Hence, the total freshwater input compensates for no more than 5% of the water evaporated each year, so that it may be considered negligible. It is not surprising that the glacial water deficit was comparable to that of today (about 2 m yr^{-1}), because with the freshwater input being so small, X is essentially the rate of evaporation ($X \approx E$). At glacial times, increased vigour and persistence of the winter monsoons might have increased evaporation, but this potential may have been countered by enhanced southward transport of moisture collected from the northern Arabian Sea by the intensified northeasterlies [*Duplessy*, 1982].

Comparison of the $\delta^{18}O$ records from the Red Sea and Gulf of Aden shows that the $\delta^{18}O$ of surface water in the Gulf of Aden was about 1.8 ppt enriched during the LGM [*Thunell et al.*, 1988] relative to the present 0.8 ppt, so that $\delta^{18}O_{ga}^{lgm}$ = 2.6 ppt. The glacial Red Sea basin enrichment, $\Delta\delta^{18}O^{lgm}$, was about 2 ppt [*Locke*, 1986; *Thunell et al.*, 1988], compared to its present value of 0.9 ppt [*Andrié and Merlivat*, 1989]. These values, their interrelationships, and the references are listed in Figure 3. The value of $\Delta\delta^{18}O$ can be related to $\delta^{18}O_x$, giving the net isotopic effect of excess evaporation on the seawater as $\delta^{18}O_x = (\Delta\delta^{18}O \times V_{rs}/X) - \delta^{18}O_{ga}$. From this equation, $\delta^{18}O_x^{p} \approx 10$ and $\delta^{18}O_x^{lgm} \approx 5$.

Furthermore, the net isotopic effect involved with the excess of evaporation over freshwater input is described by $X \times \delta^{18}O_x = (E \times \delta^{18}O_e + I \times \delta^{18}O_i)$, where $X = E - I = \gamma X^{p}$; $\delta^{18}O_e$ stands for the $\delta^{18}O$ enrichment of surface waters due to preferential loss of ^{16}O by evaporation, and $\delta^{18}O_i$ stands for the isotopic composition of freshwater input (I). Since I is virtually negligible compared to E, $E \approx X$, so that $\delta^{18}O_e \approx \delta^{18}O_x$. Thus the isotopic budget suggests that $\delta^{18}O_e^{lgm}$ was about 50% lower than $\delta^{18}O_e^{p}$. Such a large difference between $\delta^{18}O_e^{p}$ and $\delta^{18}O_e^{lgm}$ is impossible to explain in terms of temperature changes alone. However, it may well be related to a change from a so-called smooth regime with mean wind speeds below about 7 m s^{-1} to a rough regime with higher mean wind speeds. Such a change would cause a drop of 50% or more in the kinematic fractionation factor for ^{18}O (Figure 4) [*Merlivat and Jouzel*, 1979]. At present, mean wind speed over the Red Sea is about 5 m s^{-1} [*Cember*, 1989].

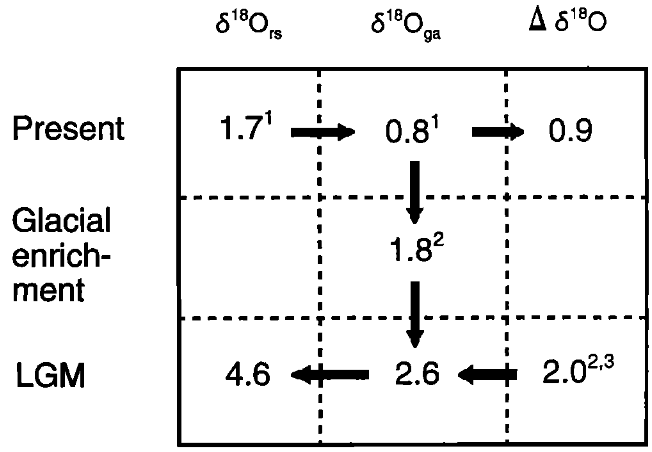

Figure 3. Oxygen isotope value of Red Sea surface water, $\delta^{18}O_{rs}$, Gulf of Aden surface water, $\delta^{18}O_{ga}$, and the Red Sea basin enrichment, $\Delta\delta^{18}O$ (= $\delta^{18}O_{rs} - \delta^{18}O_{ga}$), both at present and during the last glacial maximum (LGM). Also indicated is the glacial enrichment of $\delta^{18}O_{ga}$, the difference between the LGM value and the present-day value. Superscripts indicate the references from which the various values were obtained (1, *Andrié and Merlivat* [1989]; 2, *Thunell et al.* [1988]; 3, *Locke* [1986]). Arrows indicate the way the unknown values were obtained from the other values. Values are in parts per thousand (ppt).

Discussion

General

Substantially increased mean wind velocities may have played an important role in determining not only the Red Sea $\delta^{18}O$ record but also the increased dune activity on the Arabian Peninsula during the LGM. That dune activity has previously been interpreted as evidence of increased aridity [*Sarnthein*, 1978]. Since the summer monsoons are commonly found to have been weakened at glacial times [e.g., *Anderson and Prell*, 1993; *Bigg and Jiang*, 1993; *Sirocko et al.*, 1993], the inferred increased wind speeds are probably suggestive of intensified winter monsoons (increased outflow of air from Asia (see also *Bigg and Jiang* [1993])). SST records based on the distribution of long-chain alkenones also suggest intensified winter monsoons during the LGM

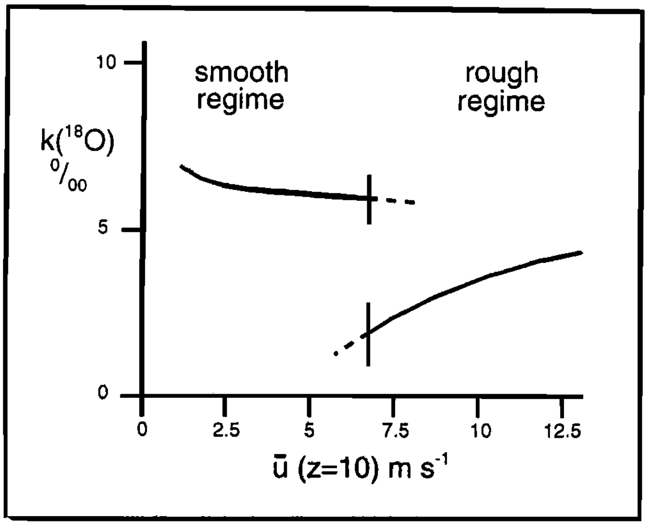

Figure 4. Change in k(^{18}O), the kinematic fractionation factor for ^{18}O, with changing mean wind speed (measured at 10 m above the sea surface). Note the important jump in k(^{18}O) at a mean wind speed of about 7 m s^{-1}, changing from a smooth regime to a rough regime. Modified after *Merlivat and Jouzel* [1979].

[*Ten Haven and Kroon*, 1991], as do previous studies of pollen records [*Van Campo et al.*, 1982] and desert dunes formed during the LGM [*Verstappen*, 1970; *Singh et al.*, 1972; *Goudie et al.*, 1973].

Sensitivity

The discussed model is based on a number of necessary assumptions and approximations. In this section, the influence of possible variations in those assumptions on the model solution will be briefly evaluated.

Concerning the glacial sill depth, H^{lgm}, it is important to consider possible isostatic effects. First, "removal" of the load of a 120-m-thick layer of water from the world ocean would have caused a relative rise of the ocean floor and, through mantle displacement, a related lowering of the adjacent continents. Atolls in the open ocean are especially prone to show exaggerated glacial sea level lowerings due to this process (W. W. Hay and K. Lambeck, personal communication, November 1993). The Gulf of Aden/Red Sea complex, however, is tightly enclosed by continental blocks and has a relatively small surface area. This landlocked character is especially dominant in the Bab-el-Mandab region. As a result, seawater (un)loading effects may be expected to be of minor importance at that site (K. Lambeck, personal communication, November 1993). Second, the mass of the expansive continental ice sheets at full glacial times would, through mantle displacement, have caused the presence of an uplifted area ("peripheral bulge") surrounding the ice sheets. Recent modeling is not yet conclusive about whether, and how much, this peripheral bulge would influence the Strait of Bab-el-Mandab, but as yet, the effect is thought to have been of relatively minor importance at such a distance from the Scandinavian-Barents-Kara Ice Sheet [e.g., *Peltier et al.*, 1978].

Concerning γ^{lgm}, it is important to note that its value depends on those for H^{lgm} and ΔS^{lgm} (Figure 5). Values for γ^{lgm} vary in the range of 0.49 ± 0.19 for H^{lgm} = 17 ± 3 m and ΔS^{lgm} = 10 ± 1 ppt. As mentioned before, it seems that H^{lgm} may be quite accurately estimated, and if ΔS^{lgm} differed significantly from the used value of 10 ppt, then it should have been toward the higher side. *Almogi-Labin et al.* [1991] suggested that Red Sea salinities during the LGM were probably higher than 48 ppt, perhaps even as high as 50 ppt. A change of ΔS^{lgm} to a value higher than 10 ppt would cause γ^{lgm} to assume a value higher than that obtained in this paper (Figure 5).

The calculation of γ^{lgm} was based on the assumption of maximal outflow. Submaximal exchange would give lower outflow rates than the maximal exchange solution. In that case, however, the inflow-outflow interface level in the Gulf of Aden should be sufficiently shallow, or that in the Red Sea sufficiently deep, to override the controls exerted on the exchange by the narrowest and shallowest passages, respectively [see *Farmer and Armi*, 1986]. In this paper, the emphasis is on the sill control on deep outflow. When compared to the sketches of interface shape by *Farmer and Armi* [1986], the present-day interface shape (see *Maillard and Soliman* [1986] schematized in Figure 1) suggests near-maximal sill control, with acceleration of outflow down the sill as a supercritical flow into the deep Gulf of Aden where it settles at its stable depth. Similar controls on outflow were assumed in the LGM scenario because of the strongly reduced depth and width of the passage, and the very high density of glacial outflow that would have caused outflow to accelerate down the sill to great depth in the Gulf of Aden. If submaximal exchange prevailed, however, then γ^{lgm} would assume a value lower than calculated in this paper. A reduction of outflow by about 10% from the maximal value (that is, when $F_n^2 = U_n^2/g'0.375H$ = 0.8 instead of 1.0) would result in a decrease of γ^{lgm} by about 10%.

With only 17 m total depth at the sill, an additional problem would be mixing between inflow and outflow, so that the deep (Red Sea) salinity might have to be higher in order for the mixed water outflow to have a high enough salinity to balance mass and salt. Obviously, the value of $\gamma^{lgm} \approx 0.5$ calculated in this paper is still a pretty rough estimate, to be improved by future research on ΔS^{lgm} especially, and also by more sophisticated modeling of the glacial exchange pattern through the Strait of Bab-el-Mandab. Future models of the glacial exchange through the Strait of Bab-el-Mandab should account for mixing between inflow and outflow, and research on glacial Red Sea deep-water salinities would be helpful to constrain the amount of this mixing.

At this point, I would like to emphasize that the calculation of $\delta^{18}O_e^{lgm}$ does not depend on γ^{lgm}. Instead, it was shown to be virtually equal to $\delta^{18}O_x^{lgm}$, which is a function of $\Delta\delta^{18}O$ and $\delta^{18}O_{ga}$ (both observations), and of the ratio V_n/X. Note that the latter ratio is equal to $S_{ga}/\Delta S$, according to conservation of mass and salt arguments. As mentioned before, new research may show that ΔS^{lgm} should be adjusted relative to the used value of 10 ppt, but if so, then toward a higher value. In that case, the resultant value for $\delta^{18}O_e^{lgm}$ would become smaller than that of about 5 ppt obtained here. In other words, the discrepancy between $\delta^{18}O_e^{lgm}$ and $\delta^{18}O_e^{p}$ would only become stronger, which endorses the conclusion of this study that some previously overlooked factor (such as wind speed) must have influenced fractionation, causing a large difference between $\delta^{18}O_e^{lgm}$ and $\delta^{18}O_e^{p}$ in the Red Sea.

Conclusions

The calculations in this paper suggest that the net water deficit in the Red Sea during the last glacial

ΔS^{lgm}	9	9	9	10	10	10	11	11	11
H^{lgm}	γ^{lgm}	V_{rs}^{lgm}	X^{lgm}	γ^{lgm}	V_{rs}^{lgm}	X^{lgm}	γ^{lgm}	V_{rs}^{lgm}	X^{lgm}
14	0.293	$1.077\ 10^{12}$	$2.578\ 10^{11}$	0.343	$1.135\ 10^{12}$	$3.019\ 10^{11}$	0.396	$1.191\ 10^{12}$	$3.483\ 10^{11}$
15	0.325	$1.194\ 10^{12}$	$2.859\ 10^{11}$	0.380	$1.259\ 10^{12}$	$3.348\ 10^{11}$	0.439	$1.320\ 10^{12}$	$3.863\ 10^{11}$
16	0.358	$1.316\ 10^{12}$	$3.149\ 10^{11}$	0.419	$1.387\ 10^{12}$	$3.689\ 10^{11}$	0.484	$1.455\ 10^{12}$	$4.255\ 10^{11}$
17	0.392	$1.441\ 10^{12}$	$3.449\ 10^{11}$	0.459	$1.519\ 10^{12}$	$4.040\ 10^{11}$	0.530	$1.593\ 10^{12}$	$4.661\ 10^{11}$
18	0.427	$1.570\ 10^{12}$	$3.758\ 10^{11}$	0.500	$1.655\ 10^{12}$	$4.401\ 10^{11}$	0.577	$1.736\ 10^{12}$	$5.078\ 10^{11}$
19	0.463	$1.703\ 10^{12}$	$4.075\ 10^{11}$	0.542	$1.795\ 10^{12}$	$4.773\ 10^{11}$	0.626	$1.882\ 10^{12}$	$5.507\ 10^{11}$
20	0.500	$1.839\ 10^{12}$	$4.401\ 10^{11}$	0.586	$1.938\ 10^{12}$	$5.155\ 10^{11}$	0.676	$2.033\ 10^{12}$	$5.947\ 10^{11}$

Figure 5. Variations in the calculated values for γ^{lgm}, V_{rs}^{lgm}, and X^{lgm} for changes in the values of ΔS^{lgm} (9, 10, and 10 ppt), and H^{lgm} (from 14 to 20 m).

maximum was of the order of 2 m yr^{-1}, as it is at present. This seems logical with repect to the fact that even today, freshwater input into the basin is negligible. This conclusion may be stated more accurately after further research on the glacial salinity contrast between the Red Sea and Gulf of Aden, and on the exchange of water masses through the glacial Strait of Bab-el-Mandab.

Budget calculation of $\delta^{18}O$ fluxes, independent of the reconstructed value of the net water deficit, shows that the glacial $\delta^{18}O$ enrichment of surface waters due to preferential loss of ^{16}O by evaporation was about half of the present value, namely about 5 ppt versus about 10 ppt, repectively. Sensitivity analysis shows that this is a genuine discrepancy, which cannot be explained as the result of the assumptions or estimates involved in the calculation. Rather, the explanation should be found in some mechanism that caused a change in the fractionation. I propose that there may have been a distinct increase in mean wind speed over the basin (> 7 m s^{-1}), which would have caused a drop of 50% or more in the kinematic fractionation factor for ^{18}O. At present, mean wind speed over the Red Sea is about 5 m s^{-1}. Such an increase would presumably be related to intensified winter monsoons, for which independent evidence has been reported in the literature.

The present study demonstrates the need for caution when calculating paleosalinities from $\delta^{18}O$ records under the assumption that the modern S:$\delta^{18}O$ relation has remained constant through time. Previously overlooked factors, such as mean wind speed, may have significantly altered that relation in the past.

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E. J. Rohling, Department of Oceanography, University of Southampton, Highfield, Southampton SO9 5NH, United Kingdom

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