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ON THE STERIC SEA LEVEL IN THE RED SEA

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Abstract

Thermal, haline and total steric departures from mean sea level were calculated during winter and summer seasons in six regions representing the whole area of the Red Sea. Thermal and haline components of steric departure are in phase in most regions, although they have different contributions to the total steric departure. The steric sea level in the southern regions of the sea is higher than that in the northern parts by estimated values of about 19 cm in winter and 23 cm in summer. Across the sea, the changes in steric sea level are clearly observed in winter due to the relatively complex circulation pattern characterizing that season. The steric factor is considered to be one of the controlling factors that affect sea level fluctuations in the northern Red Sea during the summer season and in the southern regions in winter.

INTRODUCTION

The benefits of studying the sea level have been understood for a long time. Navigational, coastal defence and engineering problems require a detailed understanding of water movements of every type and scale. Data on sea level variations can be used to draw approximate but valuable conclusions on water interchange between basins and consequently also on water renewal, which forms the basis for all investigations on water pollution.

Among the factors affecting the fluctuations in sea level is the water density. Seasonal variations of the density within the water column, from which steric departures from MSL can be calculated, are dependent on the seasonal variations of thermal and haline structure of that column. PATZERT (1972) discussed the principal causes of sea level fluctuations in the Red Sea, emphasizing the relative

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contributions of steric factor to the sea level fluctuations. He considered the seasonal variations of steric sea level as seasonal variations of monthly mean geopotential relative to the level where there are no seasonal variations (300 m level).

The present work attempts to estimate the steric (thermal and haline) components of sea level fluctuations in the Red Sea during winter and summer seasons, showing deviations along and across the sea calculated from a number of stations rather than one point. A general picture will be given of the variations of mean sea level in the Red Sea and the expected contribution of the steric effect to these variations, showing the effect of regional oceanographic conditions on the calculated steric departures.

MATERIAL AND METHOD

All the available hydrographic data (T °C, S ‰) taken in the Red Sea during the period 1948-1980 were used to reveal the main features of steric (thermal and haline) sea level at different parts of the sea. Data were obtained from the international data center in Moscow. The Red Sea was divided into six regions as shown in Figure 1, which also shows the number of stations taken in

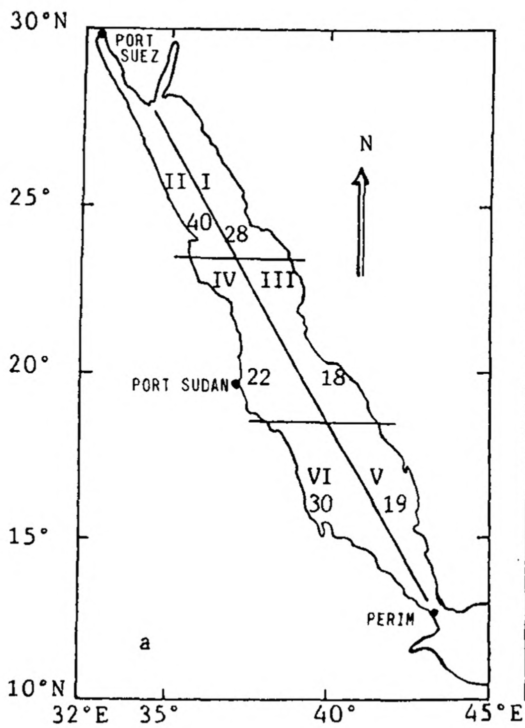


FIG. 1. — Number of stations in different regions (I, II, ..., VI) of the Red Sea.
a: for winter, b: for summer.

each region during winter months (December-February) and summer months

(June-August), with a total number of 157 stations for winter and 78 stations for summer. Due to the lack of data and the uneven distribution of stations over the whole Red Sea in spring and autumn, the analysis was made only for winter and summer seasons.

In each region, average values of T °C, S ‰ and specific volume (α) were calculated at seven selected levels: 0, 25, 75, 100, 150, 200 and 300 m level, taking all available data from different years which were collected during a specified season and at a specified depth. The annual mean values of T °C, S ‰ and specific volume of water of the whole Red Sea were also calculated at the above mentioned levels, using all the available data from the different years (including spring and autumn data). From these average values, 'thermal', 'haline' and 'steric' departures from MSL were calculated using PATTULO et al. (1955) equations:

$$Z_T = g^{-1}\int_{P_a}^{P_o} \left(\frac{\partial\alpha}{\partial T}\right) \Delta T \, dp,$$

$$Z_S = g^{-1}\int_{P_a}^{P_o} \left(\frac{\partial\alpha}{\partial S}\right) \Delta S \, dp,$$

$$Z_\alpha = g^{-1}\int_{P_a}^{P_o} \Delta \alpha \, dp$$

Here Z_T, Z_S and Z_α are thermal, haline and steric departures from MSL, respectively, g is the acceleration of gravity, P_a is the atmospheric pressure, P_o the pressure (depth) where all seasonal effects vanish (300 db), ΔT and ΔS for any depth designate the seasonal departures in temperature and salinity from their long period annual averages $\overline{T}$ and $\overline{S}$. $\Delta\alpha$ is the departure in specific volume (steric departure) due to small ΔT, and ΔS is given by:

$$\Delta\alpha = \alpha(T,S,P) - \alpha(\overline{T},\overline{S},P) = \left(\frac{\partial\alpha}{\partial T}\right)\Delta T + \left(\frac{\partial\alpha}{\partial S}\right) \Delta S + \ldots..$$

where $\frac{\partial\alpha}{\partial T}$ and $\frac{\partial\alpha}{\partial S}$ are to be evaluated at $\overline{T}(P)$ and $\overline{S}(P)$.

MEAN SEA LEVEL

Observations on the mean sea level in the Red Sea are few, data are available only for three stations: Port Suez, Port Sudan and Perim (Fig. 1). The data sets for these three sea level stations (Table 1) are not the same — for Suez: 34 years of records (extracted from SHARAF EL-DIN, 1975 and OSMAN, 1985), for Port Sudan: 37 years (BAGDANOVA, 1974) and for Perim: 6 years (BAGDANOVA, 1974). Because other sea level information from the northern Red Sea is lacking, data from Port Suez are used to represent mean sea level oscillation in the north.

From Table 1, it is clear that mean sea level in the Red Sea is generally higher than the annual mean in winter, and lower in summer, indicating an abso-

Table 1

Monthly mean sea level (cm), Red Sea

Month	Sea Level Stations		
	Port Suez	Port Sudan	Perim
January	11.7	13.0	6.0
February	7.9	9.0	6.0
March	4.7	6.0	5.0
April	5.3	7.0	3.0
May	3.4	5.0	9.0
June	-5.0	-5.0	3.0
July	-10.0	-16.0	-6.0
August	-11.7	-22.0	-12.0
September	-16.2	-14.0	-15.0
October	-7.6	-4.0	-9.0
November	6.8	11.0	-3.0
December	10.3	11.0	3.0
Annual range	28.0	35.0	24.0

lute increase of sea water volume in winter and a decrease in summer. In the northern (Port Suez) and central (Port Sudan) regions of the sea, the level is higher than the annual mean during the period from November to May. Maximum values of mean sea level heights at Suez (11.7 cm) and at Port Sudan (13 cm) were observed in January, approximately four months earlier than that at Perim (9 cm) in the southern Red Sea. In the northern and southern regions of the sea, minimum values were observed in September, when the sea level is lower than the annual mean by 16.2 cm at Suez and by 15 cm at Perim. Mean sea level at Port Sudan reaches its lowest level (– 22 cm) in August. Thus, it is clear that the highest range of mean sea level fluctuation is observed at Port Sudan (35 cm) while the lowest range (24 cm) is at Perim.

According to PATZERT (1972), the predominant factors affecting the sea level fluctuation in the Red Sea are winds, circulation patterns and hydrographic structure of the sea. In the northern and central regions of the sea, evaporation, atmospheric pressure and steric variations are not the controlling factors in the oscillation of the mean sea level in these regions, their net effect is to diminish the rise and fall in the monthly mean sea level. In the southern Red Sea, the atmospheric pressure and steric variations account for almost all of the variations in mean sea level.

The change in sea level across the Red Sea is mainly determined by the wind field over the sea (BIBIK, 1968, EDELMAN, 1968). In summer, over the entire Red Sea, the prevailing winds are basically N.N.W. winds, with relatively higher speed northward of about 19°N. These wind conditions result in a piling up of a hot surface water along the African coast and upwelling of relatively cold subsurface water along the Arabian coast. Consequently, during the summer months the sea level along the coast of Africa will be higher than that along the Arabian coast. In winter, the strong S.S.E. winds blow over the southern Red Sea (south of about 19°N), while over the northern parts they are weak and mainly blow from the same direction as in summer. Thus, in the southern Red Sea, under the influence of the prevailing wind conditions, upwelling of more saline sub-surface water will develop along the African coast and piling up of less saline surface water (inflowing into the sea from the Gulf of Aden) along the Asiatic coast. In the northern Red Sea, the situation seems to be the same as in summer. As a result of transverse circulation, the sea level along the Arabian coast is expected to be higher in the southern Red Sea and lower in the northern Red Sea than that along the African coast (BIBIK, 1968).

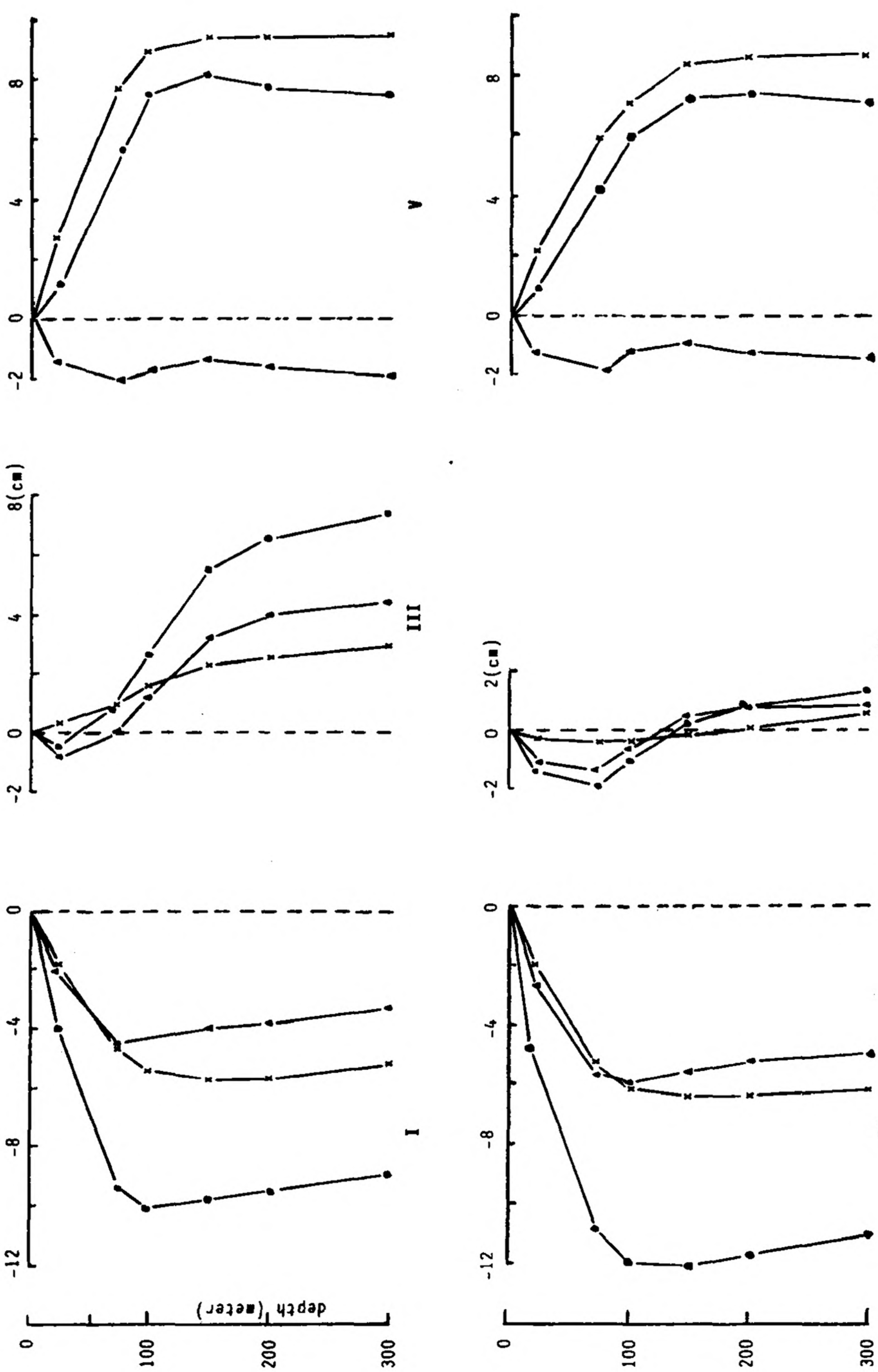
A significant difference in sea level across the Red Sea is therefore expected to occur in the southern parts of the sea during the period from October to December, while in the northern regions (north of about 19°N) it will occur in summer (June-September). During these two periods, the strong S.S.E. winds in the south and N.N.W. winds in the north, with speeds of about 7-9 ms^{-1} (PATZERT, 1972), are expected to produce a considerable piling up of water along the Arabian coast in the southern Red Sea in autumn and early winter and along the coast of Africa in the northern regions of the sea in summer. In late winter and spring, the difference in sea level across the Red Sea is expected to be insignificant due to the weak winds (4.5 ms^{-1}) characterizing these seasons.

STERIC DEPARTURE FROM MEAN SEA LEVEL

Figures 2 and 3 show the thermal Z_t, haline Z_s and total steric departures Z_α within the upper water column (to 300 m depth) for winter and summer seasons in different regions of the Red Sea.

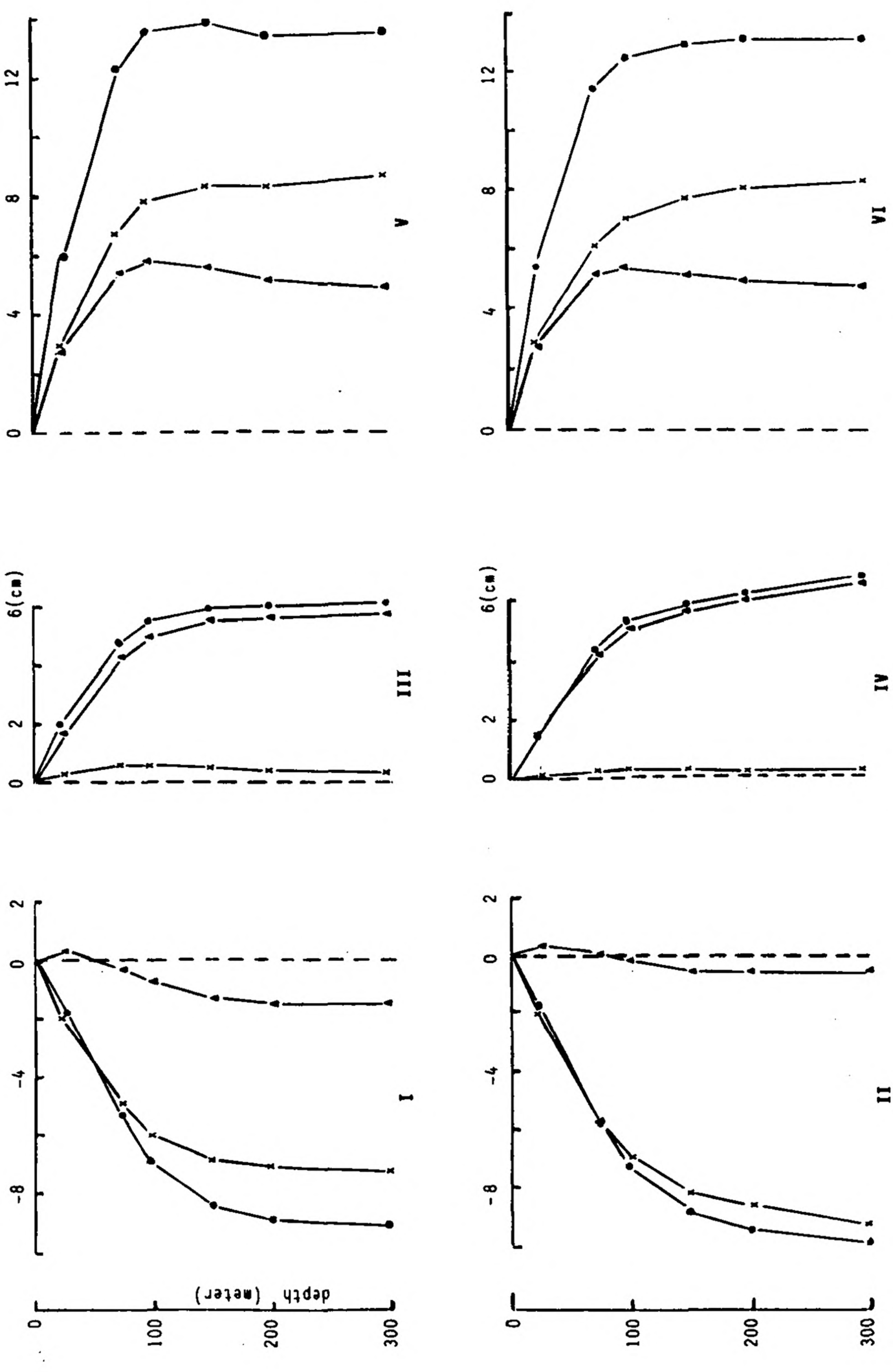
Winter season

Negative thermal departure results when water temperature is lower than the annual mean temperature and vice versa. Figure 2 shows that in most regions the thermal departure occurs mainly in the upper 100 m layer and has negative values. An exception to this is found in the central regions of the sea, where a relatively positive value of about 5 cm is found in the layer between 75-300 m depth in region III. This may be attributed to the formation of a local anticyclone in the central Red Sea, with its center close to the Arabian coast where sinking of warm surface water is taking place. Thermal departures, in the upper 100 m layer, are significant only in the northern regions (about −6 cm in region II) while in both central and southern regions they are negligibly small. The values of Z_t in the regions to the east of the Red Sea main axis are slightly higher than those to the west of it; a difference of about 2 cm occurs in the northern Red Sea. This can be attributed to the existence of a relatively cold and more saline surface current that flows southward mainly along the African side of the sea (ABDALLAH, 1985).



—Δ—Δ— thermal departure, —x—x— haline departure, —·—·— steric departure

FIG. 2. — Thermal, haline and total steric departures from MSL in different regions (I, II, ..., VI) of the Red Sea for winter season.



—Δ—Δ— thermal departure, —x—x— haline departure, —·—·— steric departure

FIG. 3. — Thermal, haline and total steric departures from MSL in different regions (I, II, ..., VI) of the Red Sea for summer season.

A decrease in salinity will be accompanied by a decrease in density which will, in turn, be responsible for the increase in the volume occupied by a given mass of water. Consequently, a negative departure from the annual mean salinity will result in a positive haline departure from MSL and vice versa. In the Red Sea, the haline departure generally increases towards the southern end of the sea and mainly occurs in the upper 100 m layer. This indicates a decrease in salinity towards the southern end of the sea under the effect of the less saline water of the Gulf of Aden flowing into the Red Sea through the Strait of Bab El-Mandeb in the upper 50-100 m layer. In the northern regions (I, II), the haline departure (considering the upper 300 m layer) has negative values, around −6 cm, while that in the southern regions (V, VI) has positive ones (about 9 cm). Across the Red Sea, the values of Z_s in the eastern regions are slightly higher than those in the western parts (up to 2 cm), indicating that the salinity along the Asiatic coast is lower than that along the African coast, because the less saline northward moving water that enters the Red Sea from the Gulf of Aden is spreading mainly along the Arabian coast.

The steric departure generally increases towards the southern end of the sea. In the northern regions, the steric departure (considering the upper 300 m layer) has negative values (about −11 cm), while in the central and southern regions the values are positive where the departure reaches a value of about 8 cm in the southern Red Sea (region V). It is clear from Figure 2 that the steric departure in the southern regions is mainly haline with thermal effect opposing the haline effect. In the northern and central regions, both thermal and haline departures have the same sign and comparable contributions to the total steric departures. Thus, during the winter season, the difference in steric sea level (considering the upper 300 m layer) between the southern and northern regions of the Red Sea may be estimated at about 19 cm. This difference in steric sea level can be attributed to the difference in hydrographic structure between northern and southern regions of the sea (in the northern regions the water is relatively cold and more saline while in the southern parts of the sea the water is warm and less saline). With regard to the steric sea level across the Red Sea, it was found that the level in the regions to the east of the main axis of the sea is generally higher than that in the regions to the west of it. A maximum difference of about 6 cm is observed within the upper 300 m layer in the central region of the sea.

From Table 1 and Figure 2, it is clear that the effect of water density (taking the average steric departure in the upper 100 m) upon the recorded departure in mean sea level in the northern Red Sea is to diminish the rise in sea level that occurs during the winter season by about 1 cm/10 m of the water column, while in the central regions the effect is negligibly small. In the southern regions, the steric sea level is in phase with the recorded mean sea level, the steric departures have values around 0.8 cm/10 m of the water column.

Summer season

The total steric departure increases generally in summer, basically due to the increase of water temperature and most of the departures occur in the upper layers of the sea (to 100 m).

Thermal, haline and total steric sea levels generally increase towards the southern end of the Red Sea (Fig. 3), so that the steric sea level (considering the upper 300 m layer) in the southern regions is higher than that in the northern parts by about 23 cm. It is clear from Figures 2 and 3 that in the central regions there are marked differences between the magnitudes and modes of variation with depth of the steric departure that were observed in summer and winter seasons. These differences can be attributed to the seasonal changes in wind and current fields in the Red Sea. In summer, the wind over the whole Red Sea and surface current are generally directed towards the Gulf of Aden. During the winter season, convergence of wind and surface current takes place in the central Red Sea near about 19°N (PATZERT, 1972).

Thermal and haline departures in different parts of the sea have the same sign, but they have different contributions to the total steric departure. In the northern regions, the steric departure has negative values and mainly haline, while in the central regions it is mostly thermal and has positive values. The steric departure, in the southern regions of the sea, also has positive values and both thermal and haline components have a comparable contribution to the total steric departure from MSL.

The variation of steric sea level across the Red Sea during summer is apparently insignificant due to the relatively simple current regime characterizing that season. This relatively simple current field helps in diminishing transverse differences in water properties (T °C, S‰, ..., etc.) from which the steric departure is calculated.

In summer, the steric departure in the northern Red Sea is in phase with the recorded departure from MSL, while in the central and southern regions it is out of phase. The steric departure in the northern regions (taking the average values in the upper 100 m layer) has values around 0.8 cm/10 m of the water column. In central and southern regions, the effect of density is to diminish the fall in sea level that occurs in summer time by about 0.6 cm and 1.2 cm/10 m of the water column, respectively.

SUMMARY and CONCLUSIONS

The thermal, haline and total steric departures from MSL were calculated during winter and summer seasons in six regions representing the whole area of the Red Sea. A general picture of the variations of the mean sea level in the Red Sea and the regional and seasonal changes of its steric sea level were also discussed.

The mean sea level in the Red Sea is generally higher than the annual mean in winter and lower in summer. A significant difference in sea level across the sea is therefore expected to occur in the southern parts of the sea during the period from October to December, while in the northern regions (north of about 19°N) it will occur in summer (June-September).

The steric sea level generally increases towards the southern end of the Red Sea. Considering the upper 300 m layer, the steric sea level in the southern regions is higher than that in the northern parts of the sea by an estimated value of about 19 cm in winter and 23 cm in summer. Thermal and haline components of the steric departure from MSL in most of the regions of the sea are in phase but they have different contributions to the total departure.

The steric departure from MSL shows seasonal changes, especially in the central and southern regions of the Red Sea, with higher values in summer and lower values in winter. The annual range of steric departure from MSL (considering the upper 300 m layer) has values around 7 cm in the southern regions and 5 cm in the central region (IV). Seasonal variations of steric sea level in the northern regions are insignificant. This is because the increase in temperature during the summer season is accompanied by an increase in salinity and, consequently, diminishes the seasonal changes in steric sea level in these regions. Across the sea, the steric sea level in winter season in the regions to the east of the Red Sea main axis is generally higher than that in these regions to the west of it. In summer, the variation in steric sea level across the sea is negligibly small.

The effect of water density (steric factor) upon the recorded mean sea level varies regionally and seasonally. In the northern regions, the effect of density is to diminish the rise in winter and to increase the fall in sea level that occurs during the summer season, while in the southern regions the opposite patterns are encountered. Regarding the central regions, the effect of water density upon the recorded mean sea level is to decrease the fall in sea level that occurs in summer, while in winter the effect is negligible. Thus the steric factor is considered to be one of the controlling factors that affect the fluctuations in sea level in the northern Red Sea during the summer season and in the southern parts of the sea in winter.

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