

On watermass mixing ratios and regenerated silicon in the Bay of Bengal

D P Rao, V V Sarma, V Subba Rao, U Sudhakar & G V M Gupta

National Institute of Oceanography, Regional Centre, Lawson's Bay Colony, Visakhapatnam-530 017, India

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Regeneration of silicon on mixing in the Bay of Bengal have been computed from six water masses [Bay of Bengal low saline water (BBLs), Bay of Bengal subsurface water (BBSS), northern southeast high salinity water (NSEHS), north Indian intermediate water (NIIW), Indonesian throughflow water (ITW) and Antarctic bottom water (AABW)]. The distribution of watermass fractions showed that BBLs with a maximum of 80-90% in the 40-60 m depth range and BBSS with 50% in the 150-300 m depth range are prominent. In the intermediate layers, NIIW shows a maximum percentage of 40% in 250-700 m depth region while ITW shows a maximum of 60% in 800-1000 m depth region. The deeper layers (below 3000 m) are predominantly occupied by AABW with a maximum of 70%. Silicon regeneration consequent upon watermass mixing has been worked out based on the characteristics of silicon for individual watermass.

Information on watermass structure in Indian Ocean has improved largely due to the pioneering works of Wyrтки¹ and Mamayev². Presence of several watermasses in the subsurface layers of Indian Ocean have been identified³. However, studies on watermass structure in the Bay of Bengal, the northeastern part of the Indian Ocean are meagre. In the present investigation, an attempt has been made to study the percentage composition of different watermasses due to mixing, the mixing ratios and the spreading of deep watermasses utilising the hydrographic data collected in the Bay of Bengal. Further, the removal of silicon in surface waters and its subsequent release at depths is a significant part of the biogeochemical cycle of this element in the oceans. Water column concentrations of these elements are often used to study the mixing processes in the ocean.

Materials and Methods

Hydrographic data collected during *R.V. Gageshani* cruises 181 and 182 in March-April 1987 in the Bay of Bengal (Fig. 1) have been used in this study. Six watermasses viz, Bay of Bengal low saline water (BBLs), Bay of Bengal subsurface water (BBSS), northern southeast high salinity water (NSEHS) in the surface layers and north Indian intermediate water (NIIW), Indonesian throughflow water (ITW) and Antarctic bottom water (AABW) in the deeper layers have been considered in these studies. Percentage composition of watermasses have been computed and their spreading worked out. The watermass end members indicated in Fig. 2 are largely based on the classification of Wyrтки³ and on the salinity distribution pattern⁴. A three end member

mixing model employing potential temperature (θ) and salinity (S) as conservative tracers has been used for the estimation of watermass fractions. A matrix of three linear equations with two conservative parameters is formulated as follows:

$$\begin{aligned}\theta_1 f_1 + \theta_2 f_2 + \theta_3 f_3 &= \theta_A \\ S_1 f_1 + S_2 f_2 + S_3 f_3 &= S_A \\ f_1 + f_2 + f_3 &= 1\end{aligned}$$

Where f 's are the fractions of watermasses 1,2,3; θ and S on the right hand side of the equation represent potential temperature and salinity respectively for a given station A. The end member watermasses 1, 2 and 3 were determined from θ - S curve at every

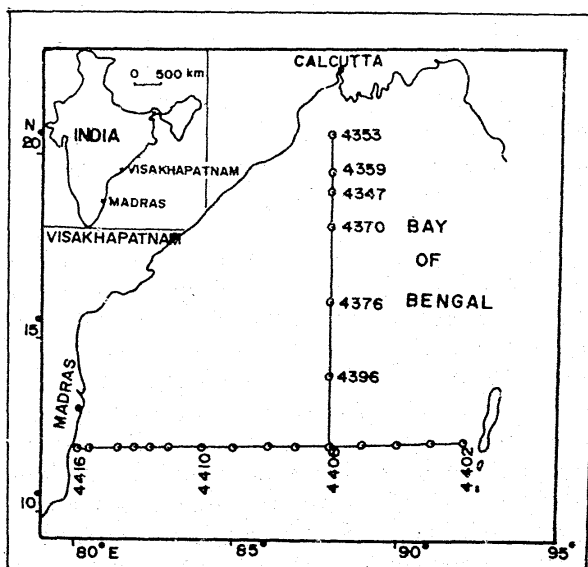


Fig. 1—Station location map

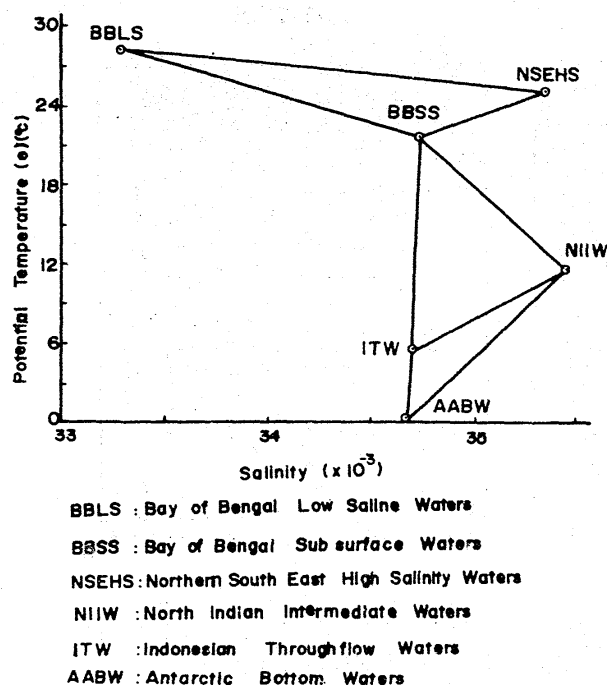


Fig. 2—Watermass end members

station. Inversion method has been used to find out f_1 , f_2 and f_3 .

The concentration of a dissolved substance at any location (C_{obs}) in the oceans will be the sum of fractions resulting from its transportation by various watermasses to that place (C_{mix}) and by biological processes plus sedimentary inputs (C_{reg}) i.e.,

$$C_{obs} = C_{mix} + C_{reg}$$

The sum of the products of the calculated fractions of end member watermass times the respective amounts of silica gives the expected amount C_{mix} of silicon for a given sample. The difference between the observed and expected amounts represent silicon regeneration due to decomposition of particles within the water column or from sediments.

Results and Discussion

The salient features of the distribution of watermasses and the silicon regeneration are discussed below:

Watermass distribution

Bay of Bengal low saline water (BBLs)—In the upper 100 m, the upward sloping of the isotherms (θ) is towards south (Fig. 3a, b). Ranges of θ between 28° and 29°C in the south (12°-14°N) while the surface layer in the north (17°-19°N) ranges between 26°-27°C. The salinity structure shows that the highest salinities ($34-34.5 \times 10^{-3}$) are noticed in the

upper 100 m in the 18°-20°N (Fig. 3d). Thus, the characteristic watermass of BBLs with $\theta = 28.1^\circ\text{C}$ and salinity = 33.25×10^{-3} is predominant in the upper 100 m only. The distribution of this watermass fraction clearly indicates maximum of 80-90% in the northern regions (around 18°-20°N and 88°E; Fig. 4a) in the depths 40-60 m because of higher fresh water discharge⁵.

Bay of Bengal subsurface water (BBSS)—The distribution of θ (Fig. 3b) along 88°E shows a dome like structure in the northern region (around 18°N) in the depth ranges of 100-300 m. Similar distribution of θ is noticed along 12°N (Fig. 3c) from west to east (81°-92°E) except a small hump at 82°E. Potential temperature (θ) ranges between 24° and 12°C in this depth range. High salinities ($34.9-35.0 \times 10^{-3}$) are noticed along 12°N and 88°E in the depth of 100-300 m spreading towards north (18°-19°N). Thus, the characteristics of BBSS centred in the depth range of 100-300 m, is having maximum percentage fraction of 50% around 17°-19°N compared to southern regions (Fig. 4b). This watermass percentage is negligible in the depths of 400-600 m (Fig. 5b), showing the influence of Indian Ocean Common Watermass in the Bay of Bengal.

North Indian Ocean intermediate water (NIIW)—The intermediate waters (300-800 m) showed the salinity ranging from 34.9 to 35.0×10^{-3} and θ ranging from 8°C to 14°C (Fig. 3a). In view of Wyrski's report¹ on spreading of high saline Red Sea and Persian Gulf waters along the west coast of India, the intermediate waters are characterised as NIIW in the present study. The distribution of θ and S shows a dome like structure in the regions 17°-19°N (Fig. 3b, d). Maximum percentage of NIIW (40%) spreads along 12°N (Fig. 4c) in the depth regions of 250-700 m (Fig. 4c) and even to the deeper regions in the northern part along section 88°E. A tongue of high percentage of this watermass with uniform distribution in the study region representing the characteristics of intermediate water as reported by Wyrski¹ is noticed in the present study. The existence of minimum percentage of NIIW in deeper waters may be due to the mixing of Circumpolar Waters at these depth layers.

Indonesian throughflow water (ITW)—Several reports⁶⁻⁹ showed the Indonesian throughflow transport into the Indian Ocean in the deeper waters on variety of time scales. Thus, the prominent ITW is considered as the significant watermass in the deeper regions i.e., 800-2000 m. Values of θ range from 3° to 7°C and salinities vary from 34.8 to 34.9×10^{-3} in the deeper depths represent the characteristics of ITW in the study region. Similar distributions in θ and S are

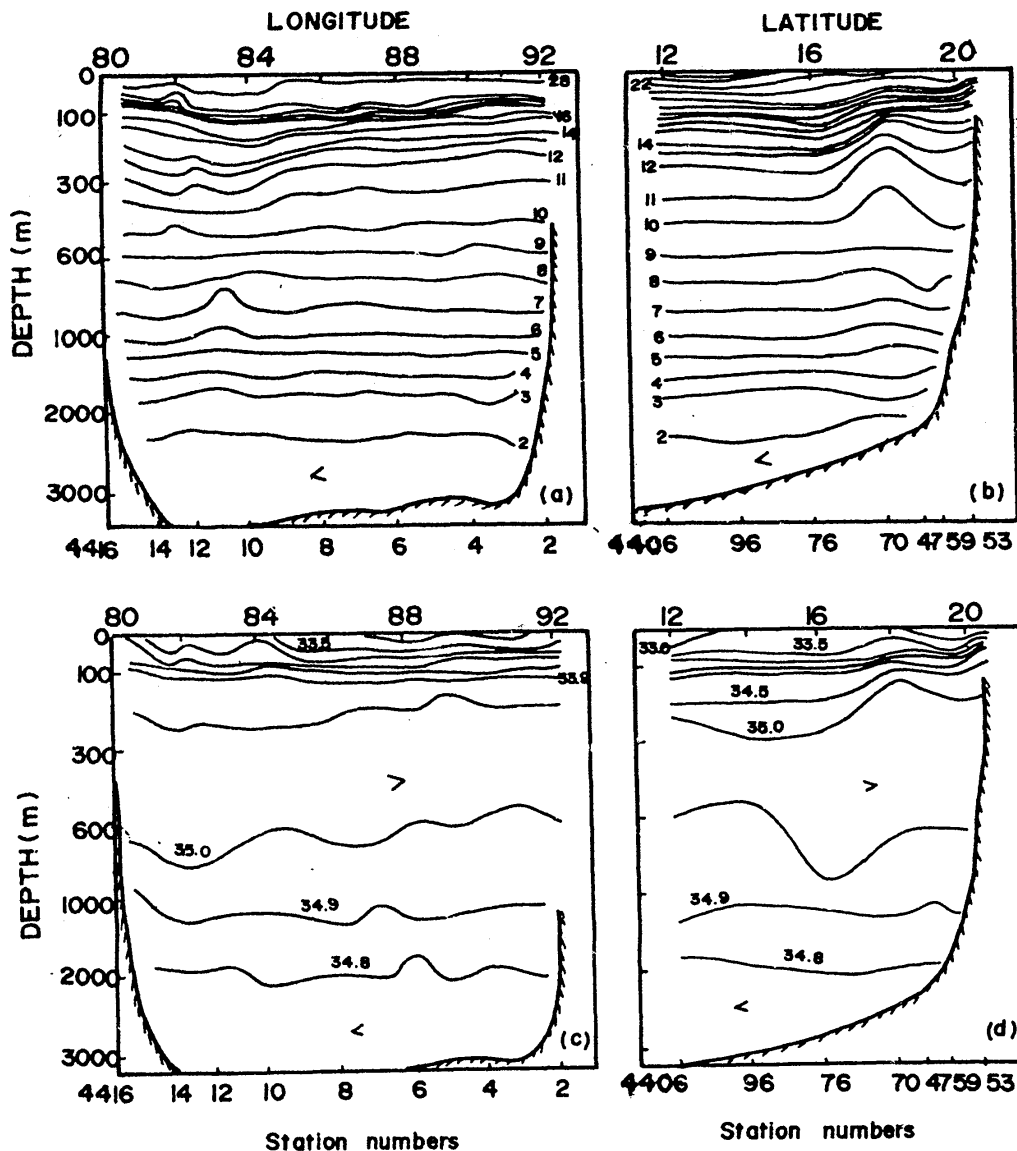


Fig. 3—Distribution of potential temperature θ ($^{\circ}\text{C}$) along (a) 12°N , (b) 88°E and salinity ($\times 10^{-3}$) along, (c) 12°N and (d) 88°E

noticed along 88°E and 12°N (Fig. 3a-d). From the calculated watermass percentages, maximum of 60% is noticed in the regions of $88^{\circ}\text{--}92^{\circ}\text{E}$ and $18^{\circ}\text{--}19^{\circ}\text{N}$ in the depths of 800-1000 m. A tongue of high fraction of this watermass (50-60%) when compared to NIIW in the depth regions of 600-1000 m, (Figs 4d, 5d) shows the mixing of these two watermasses (ITW and NIIW) in the intermediate layers. The distribution of ITW in the deeper waters showed the spreading of this watermass in the Bay of Bengal.

Antarctic bottom water (AABW)—Potential temperature and salinity distributions show (Fig. 3) that AABW spreads uniformly in the depths of 1500-3000 m both along the longitudinal (12°N) and

meridional (88°E) sections with thermohaline index of $\theta = < 2^{\circ}\text{C}$ and salinities $34.6\text{--}34.8 \times 10^{-3}$. Percentage fraction of AABW showed maximum of 70% at about 3000 m in the regions (Figs 4e, 5e). Wyrski³ reported that the existence of several basins in Indian Ocean prevents the northward flow of AABW. Warren¹⁰ observed the AABW spillage over the 90°E ridge resulting in its higher abundance in the central basin. The results indicated maximum percentage of AABW in deeper layers in the northern regions also ($17^{\circ}\text{--}19^{\circ}\text{N}$) confirming a significant inflow of AABW into the central basin^{10,11} over the deep saddles around 10°S and continued the northward movement into Bay of Bengal along 90°E ridge.

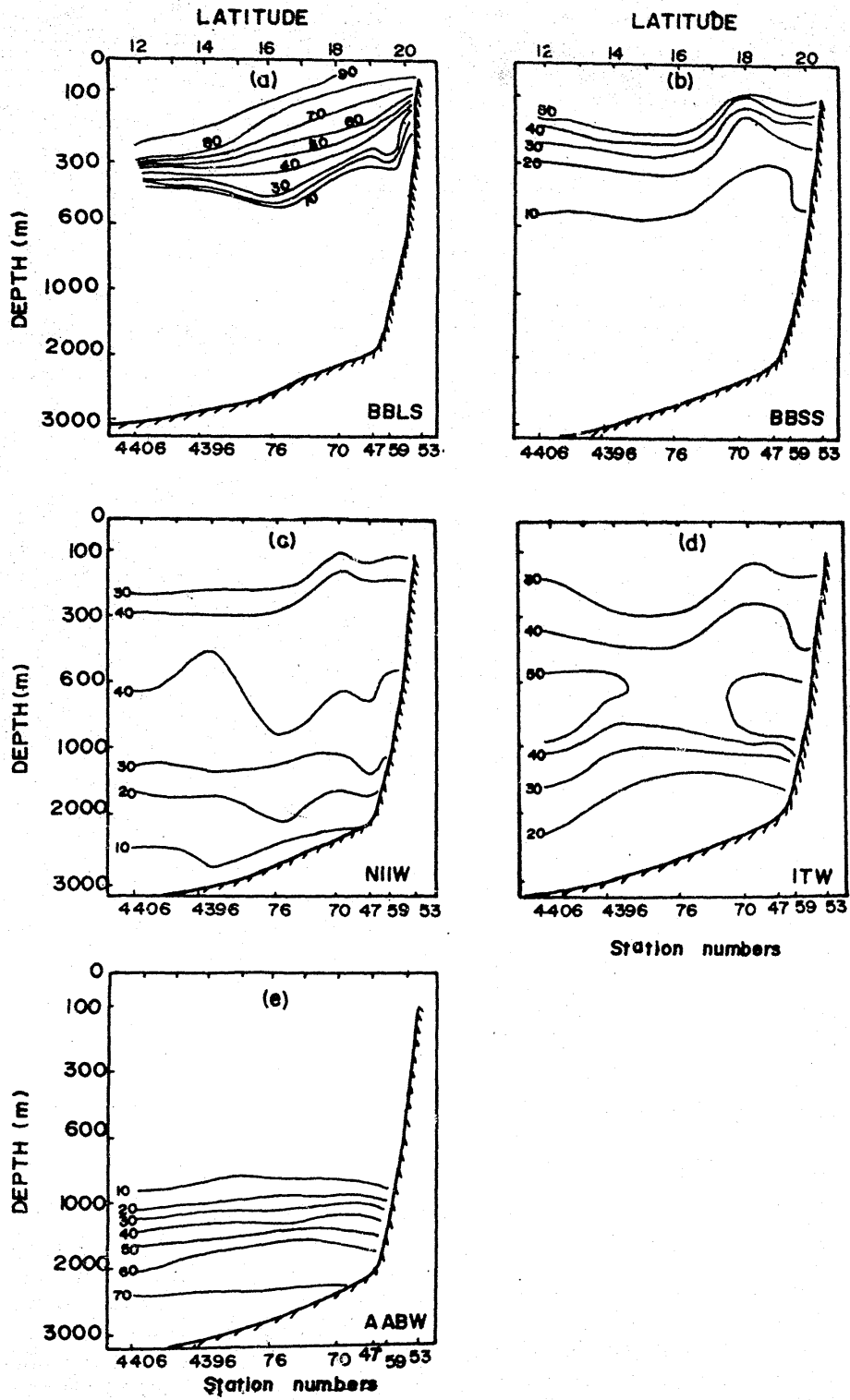


Fig. 4—Distribution of watermass fractions along 88°E

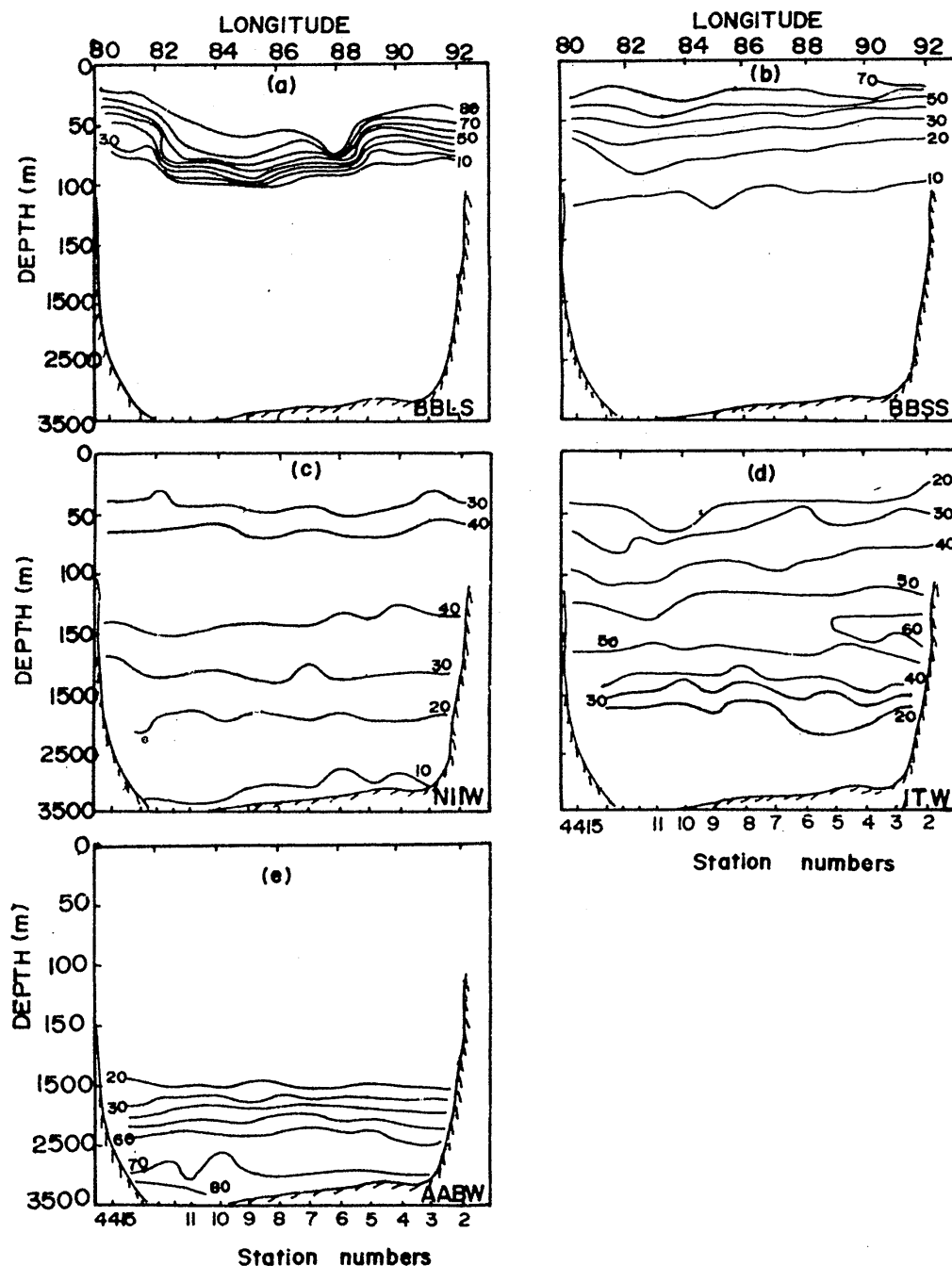


Fig. 5—Distribution of watermass fractions along 12°N

Silicon regeneration

An attempt has been made to know the relative importance of watermass mixing in the regeneration processes with respect to the dissolved silicon in the Bay of Bengal. For this purpose, dissolved silicon data collected at 10 stations along 88°E and 12°N have been used in this study. Calculation of the concentration of silicon due to mixing of watermasses has

been made from the characteristics of silicon for individual watermass. The average concentrations of C_{mix} and C_{obs} along with the calculated C_{reg} (difference between C_{obs} and C_{mix}) in the different depth regions of water column are tabulated in Table 1.

Maximum silicon regeneration of 18-24 $\mu\text{mol.kg}^{-1}$ was observed in the bottom waters in the present study showing the abundance of diatoms in

Table 1—Average concentration of silicon ($\mu\text{mol.kg}^{-1}$) for 10 stations

Depth (m)	C_{obs}	C_{mix}	$C_{\text{reg}} = C_{\text{obs}} - C_{\text{mix}}$
100	13.6 \pm 2.3	8.7 \pm 2.8	4.9
200	46.2 \pm 4.2	42.0 \pm 7.9	4.2
300	56.5 \pm 5.7	52.9 \pm 3.4	3.6
500	70.4 \pm 2.1	64.0 \pm 3.3	6.4
600	77.8 \pm 6.2	66.7 \pm 2.1	11.1
800	88.6 \pm 1.4	78.1 \pm 1.4	10.5
1000	98.0 \pm 5.0	82.4 \pm 2.0	15.6
1200	109.5 \pm 2.5	92.2 \pm 3.0	17.3
1500	112.3 \pm 0.5	105.3 \pm 1.5	7.0
2000	127.3 \pm 9.0	113.2 \pm 3.7	14.1
2500	136.8 \pm 3.9	119.5 \pm 1.7	17.2
3000	147.7 \pm 3.4	123.0 \pm 1.1	24.7

the Antarctic region south of the Indian Ocean¹². Further, the dissolution of riverine opal also contribute to the regeneration of silicon in the Bay of Bengal. The lower value noticed in the present investigations may be in accordance with the decrease in sinking the opal fluxes in the Bay of Bengal reported by Ittekot *et al.*¹³. An interesting observation from the present investigations is a relatively lower value of regenerated silicon ($10\text{-}15 \mu\text{mol.kg}^{-1}$) in the water column at depths of 800-1000 m. Indonesian region is rich in dissolved silicon¹ as well as diatoms production¹². Hence the observed regenerated silica maxima in the Bay of Bengal is due to the influx of particles transported by Indonesian flow. In the present investigations, the depth of regenerated maxima (800-1200 m) is coinciding with the highest percentage of ITW and NIIW in the same depth region.

Thus quantitative results through three end member approach indicate the spreading of deep watermasses in the study region. Further, the regenerated silicon contributed by watermass mixing and biogeochemical processes within the water column was found to be less than that occurring near the bottom.

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