A comparison of *Globigerinoides ruber* calcification between upwelling and non-upwelling regions in the Arabian Sea

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Shell weights of planktonic foraminifera species *Globigerinoides ruber* in the size range of 300–355 μm were measured from sediment traps in the western and eastern Arabian Sea which represent upwelling and non-upwelling conditions respectively. In the Western Arabian Sea Trap (WAST), *G. ruber* flux ranged from 33.3 to 437.3 $\#/m^2/day$ and shell weights ranged from 6.7 to 14.2 μg. Whereas, in the Eastern Arabian Sea Trap (EAST), flux ranged from 0.7 to 164.6 $\#/m^2/day$ and shell weights ranged from 10.4 to 14.8 μg. Shell weights of *G. ruber versus* flux showed significant correlation at both the sites which reveals that shell calcification mainly depends on optimal growth conditions. Though the WAST and EAST location have distinct difference in pCO_2 and sea surface temperature (SST), the shell weights of *G. ruber* are similar in these two regions which suggest that surface water pCO_2 and SST do not show dominant influence on shell calcification on a seasonal timescale.

1. Introduction

Atmospheric CO_2 dissolves in surface seawater and affects the equilibrium between the species, H_2CO_3, HCO_3^- and $CO_3^=$. The preindustrial value of atmospheric CO_2 was around 280 ppm and has increased sharply to 388 ppm due to increases in fossil fuel combustion, deforestation and land-use change. One third of this excess atmospheric CO_2 is absorbed by the ocean and causes an increase in $[H^+]$ which leads to a lowered pH, and a decrease in $[CO_3^=]$. This makes the seawater less alkaline and is currently referred to as 'Ocean Acidification'. The surface ocean pH has been reported to drop on average by about 0.1 pH units since pre-industrial levels (Byrne *et al.* 2010).

Attempts have been made to reconstruct the carbonate ion history from sediments of the world oceans using the planktonic foraminifera shell weight proxy (Lohmann 1995) and this proxy has been widely utilised (Broecker *et al.* 1999; Broecker and Clark 1999, 2001). Largely, in the above studies, the shell weights of selected planktonic foraminifer species has been successfully utilized in understanding the carbonate ion variations during the Holocene and the LGM. The surface water $[CO_3^=]$ decrease probably leads to a reduction in shell calcification (de Moel *et al.* 2009) and in turn surface water $[CO_3^=]$ has been estimated by using shell weights of planktonic foraminifera (Barker and Elderfield 2002; Naik *et al.* 2010). However, de Villiers (2004) notes that highest foraminiferal shell-weights are observed within the optimum ecological niche of each planktonic species and there are no simple relationships with calcite saturation, temperature or surface nutrient levels. Due to such contradictory findings it is of importance to understand what factors could be influencing shell

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calcification and further what could be the fate of planktonic foraminifera under high CO_2 conditions.

Globigerinoides ruber is a sub-tropical, symbiont-bearing planktonic foraminifera and occurs throughout the year with high abundances during the SW monsoon followed by the north-east (NE) monsoon period (Curry *et al.* 1992; Conan *et al.* 2002; Peeters *et al.* 2002). Here, we compare flux and shell weights of *G. ruber* from two sediment traps from the western and eastern Arabian Sea so as to (1) understand whether optimum growth conditions influence shell calcification, and (2) whether shell calcification is affected by high ambient water pCO_2. We have chosen the planktonic foraminifera species *G. ruber* as it lives throughout the year in the Arabian Sea and represents surface water conditions, and secondly, does not secrete gametogenic calcite (Hemleben and Spindler 1983).

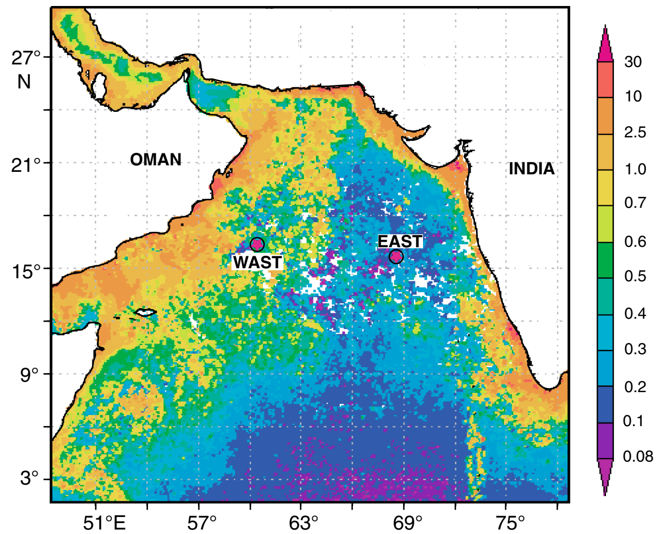

Figure 1. Composite SeaWiFS chlorophyll-*a* concentration (in mg/m^3) image, for June–September 1998 (source: http://gdata1.sci.gsfc.nasa.gov/) with superimposed sediment trap locations.

2. Physical settings

The Arabian Sea is characterised by strong southwesterly monsoon winds during the northern hemisphere summer, which blow across the Arabian Sea, causing offshore Ekman transport and intense seasonal upwelling along the Oman and Somalia margins and the southwest coast of India (Wyrtki 1973; Schott 1983; Shallow 1984; Bauer *et al.* 1991). The upwelling process brings cold, nutrient-rich waters from a few hundred meters depth to the surface and increases the biological productivity in the euphotic zone. These SW monsoon winds and associated upwelling processes make the Arabian Sea one of the highest productive regions in the world oceans (Qasim 1982). During the NE monsoon the upwelling is suppressed but there is a convective mixing due to surface cooling in the northeast Arabian Sea (Madhupratap *et al.* 1996). The western Arabian Sea upwelling is more intense in comparison to its eastern counterpart. The eastern Arabian Sea in contrast is influenced by heavy precipitation during SW monsoon and is also fed by numerous rivers from the Indian subcontinent.

3. Samples and techniques

Planktonic foraminifera samples from two PARFLUX Mark VI sediment traps (Honjo and Doherty 1988) deployed since 1986 at two different locations were used in this study; Western Arabian Sea Trap (WAST) (16°20′N; 60°20′E) placed at 4020 m below sea surface and Eastern Arabian Sea Trap (EAST) (5°37′N; 68°33′E) placed at 2782 m below sea surface (figure 1). EAST and WAST sediment traps were deployed in the year 1993 and 1997 during the cruises SO 91 and SO 119 (Schiebel *et al.* 2004) of RV *Sonne*, respectively. The EAST sediment trap was recovered in January 1995 during the RV *Sagar Kanya* cruise SK 98 whereas the WAST trap was recovered in May 1998 during the cruise SK 135. Samples recovered from the WAST covered the period from June 1997 to January 1998 and that from the EAST were from October 1993 to September 1994 (figure 1; table 1). The WAST sediment trap was programmed to receive consecutive samples at a duration of every 12 days, whereas the sampling days for the EAST trap were variable and ranged from 13 to 27 days. The carbonate compensation depth (CCD) in the Indian Ocean is placed at 4400 m water depth (Banakar *et al.* 1998). Though the WAST trap lies just around this depth in the Arabian Sea, SEM micrographs on the foraminifera shells do not show signs of dissolution.

At the time of deployment, the sampling cups (13 per trap) were filled with filtered seawater and mercuric chloride ($HgCl_2$, 3.3 g l^{-1}) was added as a preservative to prevent the degradation of organic material and stop bacterial activity in the trap samples to avoid alteration of the samples. After the recovery of the trap, the samples were wet sieved on board through a 1 mm mesh nylon sieve. The fraction <1 mm was split into 16 aliquots using a rotary splitter on board, filtered through 0.4 μm Nuclepore filters, oven-dried at 40°C and weighed. The dried samples were further sieved through a

Table 1. *Sampling periods, flux and shell weights for the western and eastern Arabian Sea sediment traps.*

	WAST				EAST			
Sl. no.	Start date	End date	Flux (#/m^2/day)	Shell weights (µg)	Start date	End date	Flux (#/m^2/day)	Shell weights (µg)
1	01/06/1997	13/06/1997	–	–	18/10/1993	14/11/1993	8.3	–
2	13/06/1997	25/06/1997	33.3	6.7	14/11/1993	11/12/1993	–	–
3	25/06/1997	07/07/1997	158.7	10.2	11/12/1993	24/12/1993	–	–
4	07/07/1997	19/07/1997	66.7	8	24/12/1993	07/01/1993	–	–
5	19/07/1997	31/07/1997	213.3	11.5	07/01/1994	20/01/1994	–	–
6	31/07/1997	12/08/1997	138.7	9.7	20/01/1994	03/02/1994	14.4	12.4
7	12/08/1997	24/08/1997	437.3	11.4	03/02/1994	16/02/1994	0.7	–
8	24/08/1997	05/09/1997	–	–	16/02/1994	02/03/1994	6.2	11.8
9	05/09/1997	17/09/1997	426.7	13.8	02/03/1994	29/03/1994	13.5	12.4
10	17/09/1997	29/09/1997	368	14.1	29/03/1994	25/04/1994	21.5	11.7
11	29/09/1997	11/10/1997	–	–	25/04/1994	22/05/1994	57.6	12.9
12	11/10/1997	23/10/1997	–	–	22/05/1994	04/06/1994	–	–
13	23/10/1997	04/11/1997	–	–	04/06/1994	19/06/1994	–	–
14	04/11/1997	16/11/1997	–	–	19/06/1994	02/07/1994	11.2	12.6
15	16/11/1997	28/11/1997	304	14.2	02/07/1994	16/07/1994	5.2	12.3
16	28/11/1997	10/12/1997	–	–	16/07/1994	29/07/1994	23.6	10.4
17	10/12/1997	22/12/1997	229.3	10.6	29/07/1994	12/08/1994	164.6	14.8
18	22/12/1997	03/01/1998	325.3	11.1	12/08/1994	25/08/1994	10.5	–
19	03/01/1998	15/01/1998	192	9.9	25/08/1994	08/09/1994	–	–
20	15/01/1998	27/01/1998	128	12.5	08/09/1994	21/09/1994	–	–
21					21/09/1994	05/10/1994	–	–

150 µm sieve and the individual species were quantified under a stereo-zoom binocular microscope. Foraminiferal fluxes of *G. ruber* (white) were calculated using the counts, splits, sediment trap aperture and duration of each sample using a standard procedure (Curry *et al.* 1992).

For shell weight measurements, the coarse material was further sieved in the size range of 300–355 µm. Approximately 30 *G. ruber* (white) shells were picked from this size fraction under a stereo-zoom binocular microscope and weighed on a microbalance (1σ precision: ±1.5 µg, n = 10).

4. Results and discussion

In the western Arabian Sea, the flux of *G. ruber* ranged from 33.3 to 437.3 #/m^2/day while in eastern Arabian Sea it ranged from 0.7 to 164.6 #/m^2/day (figure 2a and c). Higher flux values were encountered during the south-west (SW) monsoon, specifically during July–August at both the sites. Foraminiferal fluxes were two-fold higher in the western than the eastern Arabian Sea. The higher flux of *G. ruber* in the western Arabian Sea during SW monsoon is a result of upwelling. The shell weight record for the western Arabian Sea is available from June to January whereas that of the eastern Arabian Sea is from January to August. The gaps in shell weight record occur due to the unavailability of enough shells for weighing. The shell weights of *G. ruber* ranged from 6.7 to 14.2 µg in the western Arabian Sea while they ranged from 10.4 to 14.8 µg in the eastern Arabian Sea (figure 2a and c).

The Arabian Sea is known to be a region with highest particle flux to the deep sea in comparison to the global flux (Honjo *et al.* 2008). Measurements made since 1983 show that the western Arabian Sea in particular contributed to an average organic carbon flux (normalised to 2 km of water depth) of 553 mmol C/m^2/yr and an inorganic flux of 424 mmol C/m^2/yr (Honjo *et al.* 2008). In the eastern Arabian Sea, organic and inorganic carbon flux of 234 and 171 mmol C/m^2/yr have been noted (Honjo *et al.* 2008). The foraminiferal flux is also known to greatly increase during the SW monsoon (Curry *et al.* 1992; Mohan *et al.* 2006). During 1986–1987, Curry *et al.* (1992) noted a *G. ruber* flux of ∼1000 #/m^2/day during the SW and ∼2000 #/m^2/day during the NE monsoon season at the WAST and ∼700 #/m^2/day during the SW monsoon and very low flux during the NE monsoon at EAST. Our study, however, shows a higher *G. ruber* flux during the SW monsoon and lower during the NE monsoon at both the locations.

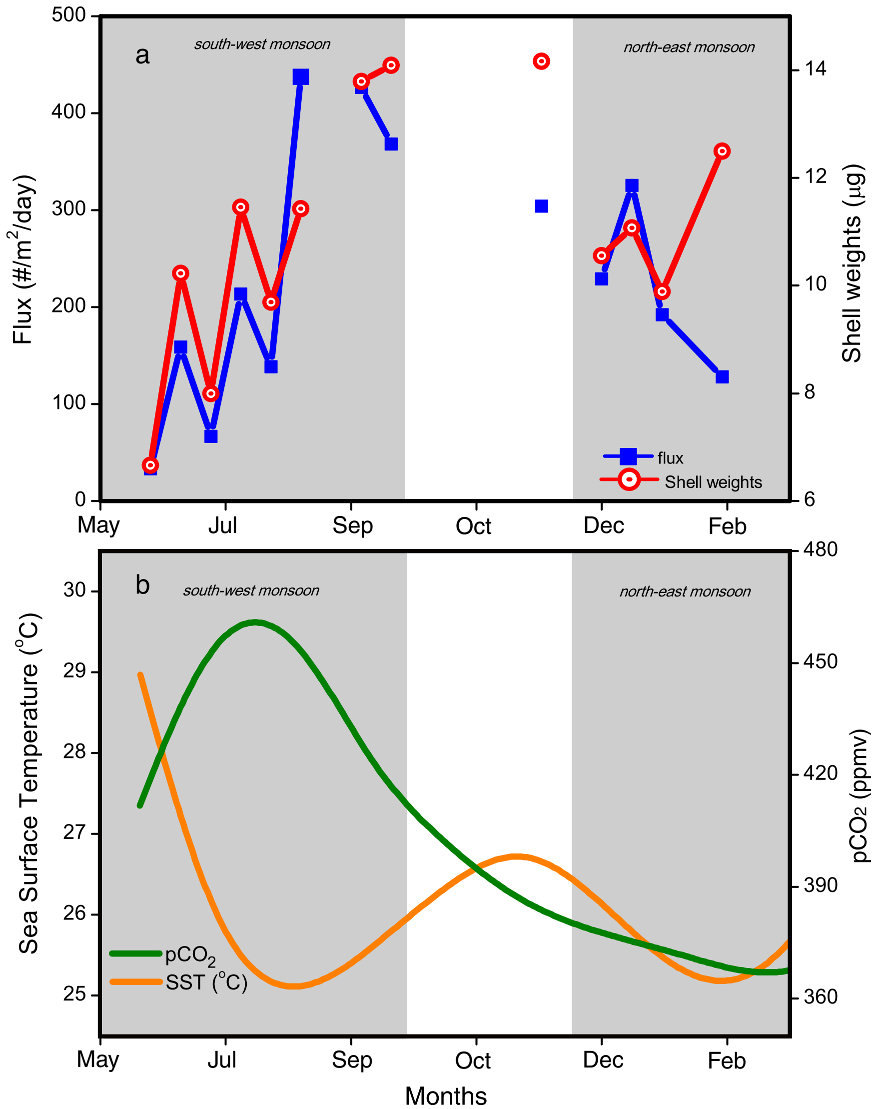

Figure 2. (**a**) Shell weights and flux of *G. ruber* at WAST, (**b**) pCO_2 and SST variation in western Arabian Sea, (**c**) shell weights and flux of *G. ruber* at EAST and (**d**) pCO_2 and SST variation in eastern Arabian Sea.

Every organism is adapted to specific optimum environmental conditions which include temperature, salinity, depth habitat, etc., under which it is able to flourish (Schmidt *et al.* 2006). We can logically assume that an increase in flux of a foraminiferal species is an indicator of optimal conditions for that species growth. In order to understand whether optimum growth conditions control shell calcification, we compared *G. ruber* shell weights and fluxes. We observe significant correlations between *G. ruber* shell weights and fluxes in the western ($r^2 = 0.58$; $n = 13$; $p = 0.001$) and the eastern ($r^2 = 0.60$; $n = 9$; $p = 0.0046$) Arabian Sea (figure 3a and b). However, the correlation in the eastern Arabian Sea is weaker as it is highly dependent on a single data point which falls in the upwelling period. The increase in shell weights of *G. ruber* coupled with the increase in its flux (figure 2a and c) suggests that shell calcification is enhanced when conditions are favourable for this species to grow. This finding implies that shell calcification primarily depends upon optimum growth conditions and is in line with results of de Villiers (2004). Conan (2006), reported shell weights of *G. ruber* from a western Arabian Sea sediment trap (Site 905, lying further south of the present study location) to be in the range of 9–14.7 µg (250–355 µm size fraction) with lower shell weights during the upwelling season and no relationship with the flux. Our findings are thus in contrast, with higher shell weights during the upwelling season and significant correlation with flux.

We also examined the possible influence of factors such as ambient water pCO_2 and sea surface

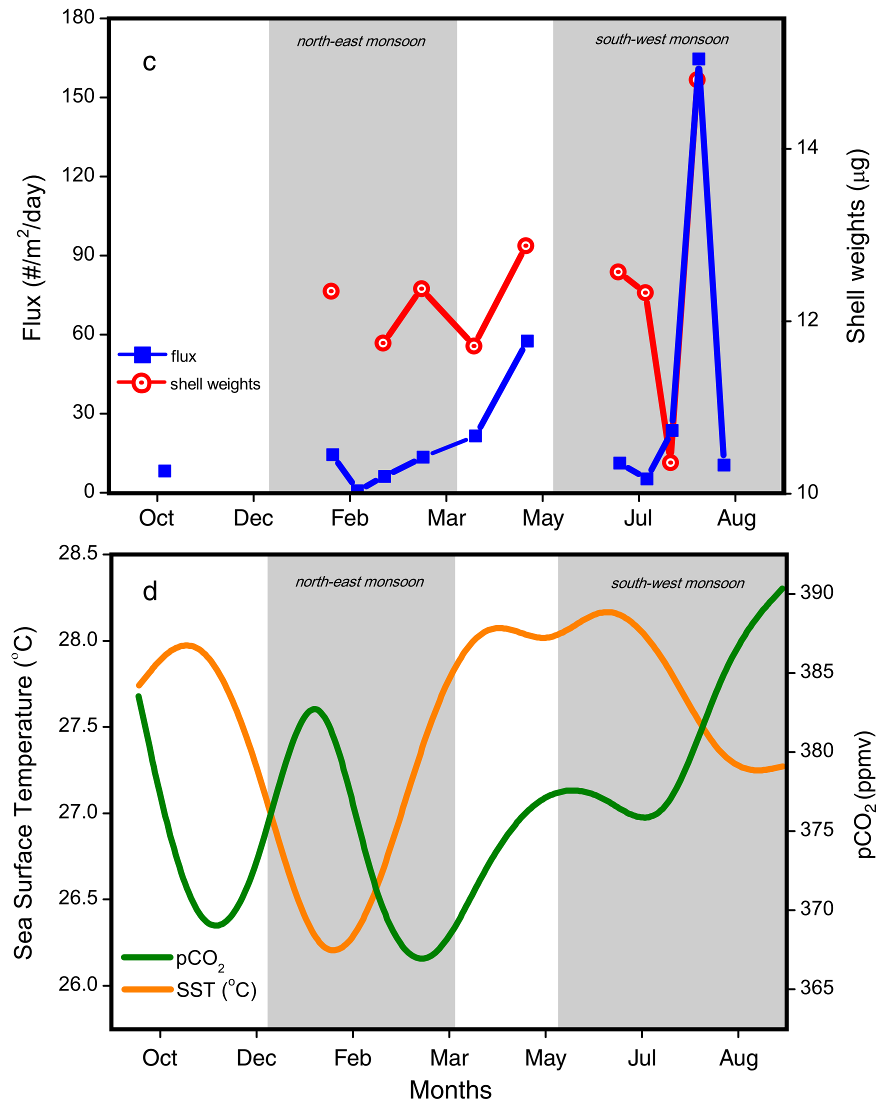

Figure 2. *(Continued)*

temperature (SST) on shell calcification at both these sites. The pCO_2 and SST were calculated for the months wherein the flux and shell weight data are available and the values are monthly averages for the years 1970–2000, obtained from the database of Takahashi *et al.* (2009). The calculated pCO_2 values of surface waters in the western Arabian Sea ranges from 366 ppm during the non-upwelling period to 464 ppm during the upwelling period, whereas, those on the eastern side range from 365 to 390 ppm (figure 2b, d). We have compared 30-year averages of pCO_2 and SST to shell weight data of a single year because *in-situ* measurements were not made at the time of sample collection. However, the averages depict a general pattern of pCO_2 and SST variations in a year. This is also supported by the data of Lendt *et al.* (2003), from the western Arabian Sea, collected in the same year as the sediment trap samples of 1997–1998. SSTs were lower during the monsoon season whereas the pCO_2 values were highest during the same period reaching a maximum of ∼650 µatm (Lendt *et al.* 2003). During the SW monsoon, the pCO_2 in the western Arabian Sea attains much higher values compared to the eastern Arabian Sea due to intense upwelling of sub-surface CO_2 enriched waters. The SSTs in the western Arabian Sea show a larger variability from 25° to 30°C as compared to the eastern side which range from 26° to 28°C (figure 2b, d) (Takahashi *et al.* 2009). Our observation shows that there is no covariance between pCO_2 and shell weights or SSTs and shell weights. In the WAST, shell weights averaged 10.7 µg for the SW monsoon and 11 µg for the NE monsoon. The average pCO_2 for the same periods are 440 and 372 ppmv, respectively. This indicates that the shell weight differences are negligible for a pCO_2 change of 68 ppmv.

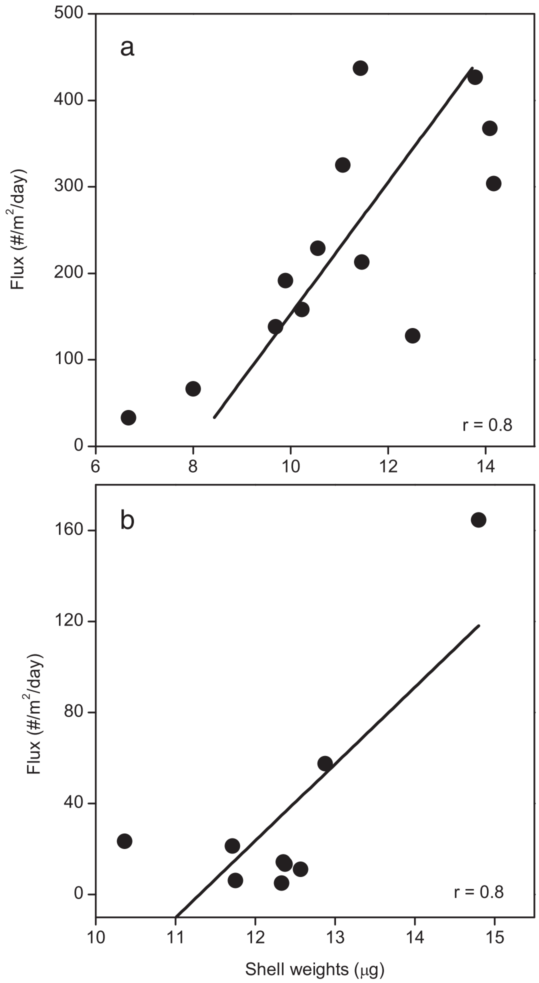

Figure 3. Correlations between *G. ruber* shell weights and *G. ruber* flux at (**a**) WAST and (**b**) EAST.

Likewise in the EAST, shell weights/pCO_2 averaged 12.5 μg/382 ppmv and 12.2 μg/372 ppmv for the SW and NE monsoon, respectively. Since shell weights are seen to be influenced by the higher flux during upwelling, we have calculated flux-weighted averages of shell weights for the two sites, WAST and EAST, which were 12 and 13.2 μg, respectively.

Although pCO_2 and SST are distinct between WAST and EAST, the flux weighted shell weight averages are similar which corroborates the fact that pCO_2 and SST may not have a dominant control on shell calcification. Beer *et al.* (2010) have demonstrated that surface water $[CO_3^=]$ does not exert a dominant control on *G. ruber* and *G. bulloides* shell weights in the western Arabian Sea which is in line with our findings. They have also shown that *G. ruber* is negatively correlated to surface water $[CO_3^=]$. They reasoned it to the fact that, across an upwelling zone, temperature, salinity, alkalinity, $[CO_3^=]$, [DIC], light, nutrients, and food supply vary in conjunction with one another. Therefore shell weights may depend on other factors and still be correlated to $[CO_3^=]$ though it is not a dominant control. However, the present study shows that shell weights are correlated to flux of *G. ruber* and hence, optimal growth conditions are the possible factors in controlling shell calcification.

Further, the different morphotypes of *G. ruber*, namely *G. ruber* sensu stricto (s.s.) and *G. ruber* sensu lato (s.l.) could probably influence the relationship between flux and shell weights. *G. ruber* s.s., is a surface dweller and *G. ruber* s.l., a sub-surface dweller. So during periods of intense upwelling the sub-surface dweller may dominate (Wang 2000) and may cause a bias in shell weights. This could be the possible reason for stronger correlations between flux and shell weights in the upwelling (WAST) region in comparison to the non-upwelling (EAST) region.

5. Conclusions

Planktonic foraminifer *G. ruber* flux and shell weights were measured from the sediment trap samples from the western and eastern Arabian Sea. *G. ruber* flux and shell weights exhibit significant positive correlation during SW and NE monsoons in the western and eastern Arabian Sea suggesting that optimum growth conditions for *G. ruber* prevailed during monsoons which were the primary influence on shell calcification. Strikingly, there was no distinct difference in shell weights of *G. ruber* between the western and eastern Arabian Sea. The lack of influence of elevated CO_2 and lowered SST as a result of intense upwelling in the western Arabian Sea, on *G. ruber* shell weights suggests that temperature or carbonate ion may not be the primarily control on *G. ruber* shell calcification in these regions on a seasonal timescale. Our study proposes that it is further necessary to elucidate the exact factors which promote shell calcification of a particular foraminiferal species during the monsoon season.

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