Oceanologia (2017) 59, 389—395

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SHORT COMMUNICATION

Estimation of diatom and dinoflagellate cell volumes from surface waters of the Northern Indian Ocean

Rajath R. Chitari, Arga Chandrashekar Anil *

CSIR — National Institute of Oceanography, Dona Paula, Goa, India

Received 14 July 2016; accepted 1 March 2017
Available online 16 March 2017

KEYWORDS
Diatoms;
Dinoflagellates;
Cell volume;
Dona Paula Bay;
Bay of Bengal

Summary Phytoplankton samples collected from the Northern Indian Ocean (Bay of Bengal, northern Arabian Sea, and Dona Paula Bay Goa, west coast of India), were utilized to quantify changes in cell size, cell volume and carbon per cell of diatoms and dinoflagellates. The dataset from the Bay of Bengal also provides inter- and intra-annual variations (April 2008 to March 2010). The variations in cell size and volume were large in regions influenced by the riverine influx or terrigenous inputs. An interregional comparison of commonly available forms (8 species) points out that cell volumes are highest in the North Atlantic and lowest in the Mediterranean. The information provided will be useful in estimation of carbon biomass and biogeochemical studies.

1. Introduction

Trait-based characteristics are increasingly used to predict the phytoplankton community distribution along the environmental gradient (Margalef, 1978; Reynolds, 1988). They are not necessarily taxonomy related but determined based on size and the physiological processes such as growth (light and nutrient assimilation) and loss (sinking and grazing) (Morabito et al., 2007). The cell size is referred as a master trait which places important constraints on many key organismal characteristics and biotic interactions (Barton et al.,

* Corresponding author at: Biofouling and Bioinvasion Division, CSIR — National Institute of Oceanography, Dona Paula, Goa 403004, India. Tel.: +91 8322450404; fax: +91 8322450615.
E-mail address: acanil@nio.org (A.C. Anil).
Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.oceano.2017.03.001

2013 and references therein). Smaller organisms have several advantages over large ones for e.g. a lower sinking rate, which is proportional to cell radius squared (Stokes law) (Smayda, 1970). Higher surface to volume ratio that helps efficient acquisition of limiting nutrients (Ploug et al., 1999; Sherwood et al., 1975) and higher maximum growth rates (Banse, 1976). In contrast, the large size organisms carry the advantage of motility, access nutrient resources unavailable to other organisms; avoid grazing and higher possibility of survival (Reynolds, 2006). The trade-off between these traits represents an ecological strategy to exploit better the available resources (Litchman et al., 2010). Since micro-phytoplankton exhibit a wide range in their size (20–200 μm) and shape, quantification of cell numbers only will not provide accurate information on carbon biomass. Hence, there is a need to convert cell count to cell volume since a large number of small cells are equivalent to few larger cells in terms of carbon biomass (Harrison et al., 2015). Cell size and its carbon content evaluations from cell volume can provide useful inputs to ecosystem applications, modeling and biogeochemistry studies. Phytoplankton cell volume and its associated parameters have been reported from Chinese Sea, Baltic Sea, Mediterranean Sea, Beagle Channel and North of Atlantic (Almandoz et al., 2011; Barton et al., 2013; Olenina et al., 2006; Sarno et al., 1993; Stanca et al., 2013; Sun et al., 2000). However, a similar kind of work from the waters surrounding the Indian subcontinent is lacking. Although Harrison (Harrison et al., 2015) has cited some of the references in this context, published literature is meager. In the Indian waters, the phytoplankton cell volume is measured in a few cases from the mangrove habitat and near coastal sites (Biswas et al., 2010; Mitra et al., 2012; Munir et al., 2015). This study provides information on cell volume and carbon per cell of diatoms and dinoflagellates from coastal and open ocean stations. The dataset is further compared for inter bioregional variations.

2. Material and methods

2.1. Study area

Surface water samples from the Bay of Bengal hereafter referred as "BoB" (XBT program using ships of opportunity) were collected from April 2008 to March 2010 on seven occasions along the Chennai – Port Blair; 81°00′E, 13°00′N to 92°00′E, 11°23′N, and on six occasions (April 2008 to March 2010) along Port Blair to Kolkata; 12°00′N, 93°14′E to 21°00′N, 88°23′E at 22 different stations. The stations are categorized into C-P open ocean (CPOS), Andaman Region (AR), P-K Open Ocean (PKOS) and River Mouth (RM) regions as shown in Fig. 1. From the northern Arabian Sea the surface water samples were collected while on a cruise SSK60 from 25th January 2014 to 1st February 2014 (40 stations covering 6 transects; 20°13′E, 68°90′N to 18°50′E, 69°99′N) and one coastal station located off Goa, Dona Paula Bay (15°27′N, 73°48′E), weekly twice from 1st September to 24th December 2015 with a total 34 samples.

2.2. Hydrological parameters

From the BoB, vertical temperature profile of the water column was recorded by launching XBT-MK21-T7 probes (Sippican Inc.) at one-degree intervals. From the northern Arabian Sea, the temperature was recorded using CTD (Sea - Bird Electronics, Inc.). In the Dona Paula Bay, surface water temperature was measured in situ. The conductivity of surface seawater from the Bay of Bengal and Dona Paula Bay was measured using Autosal and later converted into salinity (Guildline Autosal 8400B). From the northern Arabian Sea, the conductivity was measured using dual conductivity (SBE4) sensor fitted to CTD.

In all regions, for nutrients, 10 ml of seawater samples were collected into 10 ml cryovials, immediately frozen in

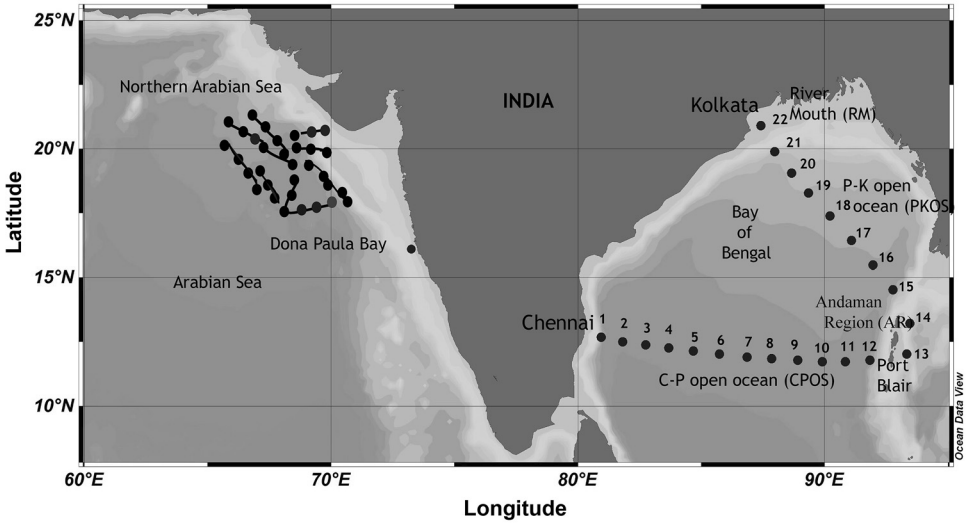

Figure 1 Locations of sample collection from the northern Indian Ocean (Bay of Bengal, northern Arabian Sea, and Dona Paula Bay). In the Bay of Bengal, samples were collected from four different tracks (Chennai to Port Blair open ocean – CPOS; Andaman Region – AR; Port Blair to Kolkata open ocean – PKOS; and River Mouth – RM). From the northern Arabian Sea samples were collected from 40 stations and in the Dona Paula Bay from one station.

liquid nitrogen and then analyzed using Skylar, (San++ segmented flow analyzer) following the method of Grasshoff et al. (1983).

2.3. Estimation of micro-phytoplankton cell volume

From the BoB, three liters of surface water samples were collected separately and preserved with different preservatives. (0.40% of Lugol's iodine, 0.60% buffered formaldehyde and 0.20% glutaraldehyde). The samples were allowed to settle in the laboratory for quantification of diatoms and dinoflagellates through a microscope. From the northern Arabian Sea, only one liter of surface water samples was collected and fixed with 0.40% Lugol's iodine for the estimation of diatom cell volume and a similar procedure was followed as that of BoB. For the estimation of dinoflagellates, thirty-five liters of surface water samples were collected and concentrated to 50.0 ml, using 20 μm nylon mesh. The samples were immediately fixed with 0.40% Lugol's iodine. At the end of the cruise, the samples were brought to the laboratory and concentrated to 35.0 ml and 5.00 ml of this concentrated sample was analyzed for dinoflagellates. For the coastal station of Dona Paula Bay, one liter of surface water was concentrated to 20.0 ml, of which 2.00 ml of sample was dispensed on a 3.80 cm petridish and measured for both diatoms and dinoflagellates.

The cell dimensions of diatoms and dinoflagellates from the BoB were measured using an ocular micrometer, calibrated with a stage micrometer. From the northern Arabian Sea and Dona Paula Bay, the cells were measured using image analysis software (Q-Capture Pro 7, Olympus Inc). In all the three sites cells were observed using an inverted microscope (Olympus IX71) at 100 and 200 times magnification. The measured dimension for each taxon was calculated for its cell volume using assigned geometric shape (Hillebrand et al., 1999; Sun and Liu, 2003). The range of cell size and cell volume, its classification according to size classes, the median value of cell volume and the number of cells measured (N) from three different regions are provided in Appendix (1A and 1B). A comparative analysis of the cell volume, 10 species of diatoms and dinoflagellates (which has a minimum number of 8 measurements) is presented in Fig. 2a—g. The rest of the species with cell volume are provided in Appendix 1A.

The carbon per cell was calculated using the equation provided by Menden-Deuer and Lessard (2000). The median volume was converted to carbon per cell using the equation $C = aV^b$ where a and b are 0.288 and 0.811 for diatoms, 0.216 and 0.939 for other protists, and 0.003 and 1 for *Noctiluca scintillans* (Macartney) Kofoid and Swezy, 1921. We also measured cell volume of live and fixed cells. The data is provided in (Appendix 1A and 1B). Studies on phytoplankton cell volume have emphasized that at least a minimum of 10—50 randomly selected cells for each species should be measured. Although we have measured most of the cells up to 25 or more, it was not possible to measure all the taxa since some of them were rare forms and they are measured as they occurred in the samples. The dataset from three different sites of northern Indian Ocean is compared with the published literature from different bioregions to evaluate the variations in the cell size (Appendix 2).

3. Results and discussion

3.1. Hydrological parameters

The BoB, (CPOS and PKOS) comprised of stations that are away from the riverine influence, whereas the AR and RM are closer to the Irrawaddy and Hooghly — Ganga river basins. The variations in Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and nutrients during the observation period are provided in detail in another publication (Chitari et al., 2017). In brief, the SST was low during monsoon (NEM and SWM; 26.1—29.9°C) and relatively higher during the inter-monsoon (SIM and FIM; 28.2—31.0°C). The SSS was relatively high in CPOS (29.2—34.4) when compared to P-K (25.7—34.4). Low SSS, was observed during the SWM, especially in the RM and was relatively high during the SIM and FIM.

Nutrient concentrations in the surface waters of the BoB were below detectable range for the most part of the year, especially during the SIM. In the CPOS, maximum concentrations of DIN and DIP were observed on some occasions during the monsoon and was upto 3.02 and 2.88 μmol L^{-1}. In the PKOS it was on par with CPOS. However, in the AR and RM, it was noticed that the concentration was upto 4.23 μmol L^{-1} for DIN and 3.08 μmol L^{-1} for DIP. The relatively higher nutrient concentration can be attributed to freshwater discharge.

The temperature in the northern Arabian Sea was observed to be low compared to BoB and Dona Paula Bay. The nutrients were higher (Nitrate >2.00 μmol) compared to BoB and both are attributed to winter convective mixing. In the Dona Paula Bay high nitrate (0.40—8.00 μmol L^{-1}) and phosphate (0.01—0.68 μmol L^{-1}) concentration was also observed. The details of hydrological parameters of the northern Arabian Sea (Roy et al., 2015; Sarma et al., 2015) and Dona Paula Bay (Patil and Anil, 2011, 2015) are available in the published literature.

3.2. Micro-phytoplankton cell volume

A total of 219 micro-phytoplankton species, 90 diatoms, and 129 dinoflagellates were measured during the study period from three different sites of Indian Ocean (BoB, northern Arabian Sea, and Dona Paula Bay) (Appendix 1A and 1B). Regarding species composition, amongst the diatoms, *Chaetoceros* spp. followed by *Rhizosolenia* spp. were the dominant forms, whereas amongst the dinoflagellate, genus *Tripos* spp. was dominant and this was followed by *Protoperidinium* spp. The higher number of size classes was observed in diatoms especially in the Dona Paula Bay and River Mouth (Hooghly Estuary) when compared to dinoflagellates except for *Pyrocystis pseudonoctiluca* Wyville-Thompson, 1876 in the open ocean. The higher number of size classes observed in diatoms belonged to *Bacteriastrum furcatum* Shadbolt, 1854, *Ditylum brightwellii* (T. West) Grunow, 1885, *Guinardia striata* (Stolterfoth) Hasle, 1996, *Guinardia delicatula* (Cleve) Hasle, 1997, *Leptocylindrus danicus* Cleve, 1889, *Proboscia indica* (H.Peragallo) Hernández-Becerril, 1995, *Rhizosolenia hylina* Ostenfeld, 1901, *Rhizosolenia hebetata* f. *semispina* (Hensen) Gran, 1908, *Rhizosolenia setigera* Brightwell, 1858, *Proboscia alata* (Brightwell) Sundström, 1986 and *Pseudo-solenia calcar-avis*

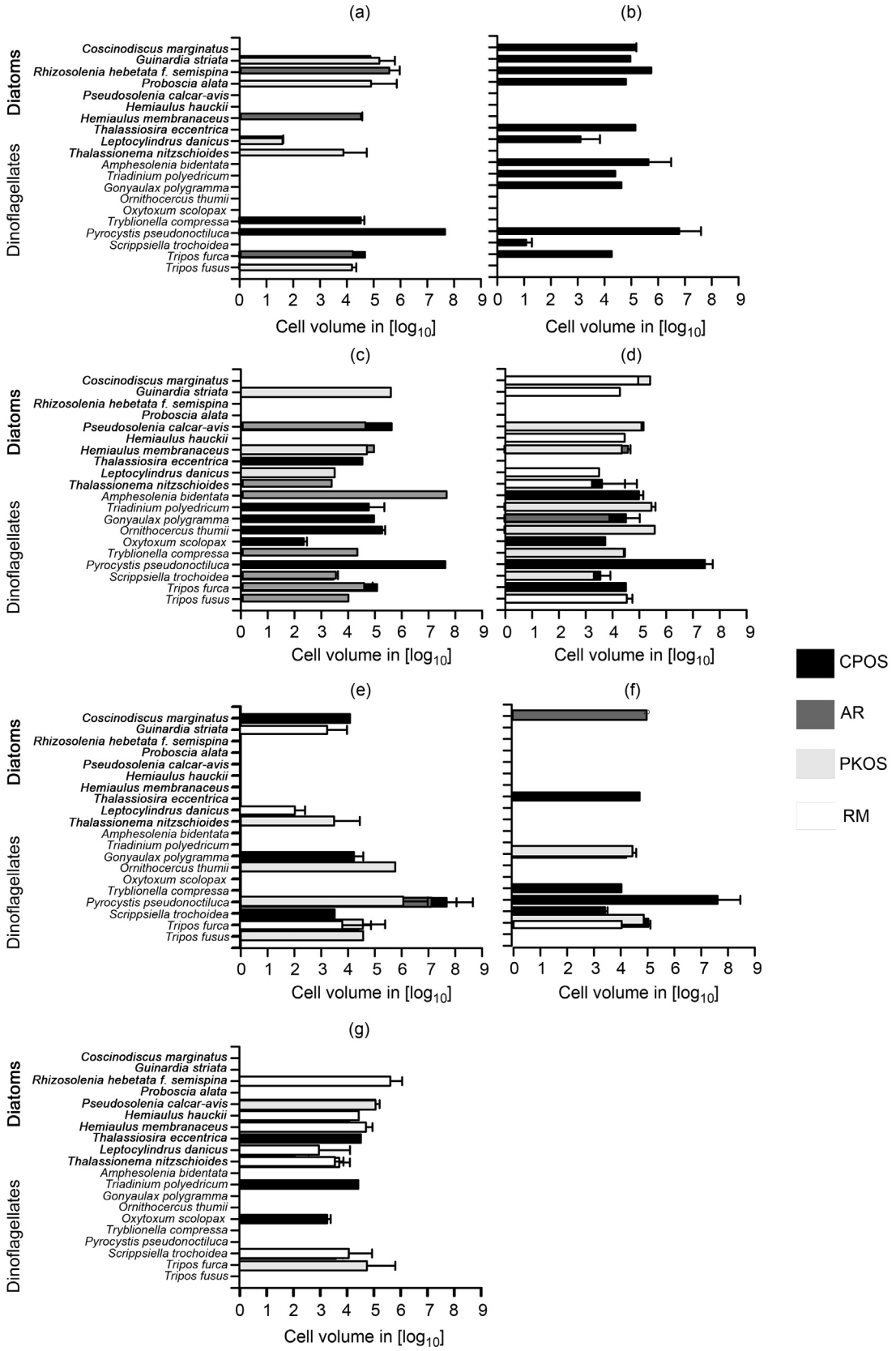

Figure 2 (a–g) Intra- and inter-annual variations in the cell volume (log transformed values) of 10 diatoms and dinoflagellates species from the Bay of Bengal, which had minimum numbers of 8 measurements. The cells measured were from April 2008 to March 2010 (a: April 2008; b: July 2008; c: Sept 2008; d: March 2009; e: July 2009; f: Sept 2009; g: March 2010) along the 4 different tracks (Chennai to Port Blair open ocean – CPOS; Andaman Region – AR; Port Blair to Kolkata open ocean – PKOS; and River Mouth – RM). The regions are denoted in different shades. Species of Diatoms are indicated in bold and Dinoflagellates are indicated in regular font.

(Schultze) B. G. Sundström, 1986. Such a size variation in the Dona Paula Bay and the River Mouth can be attributed to the nutrients and variation in salinity. Finenko et al. (2003) observed diatoms possess a greater degree of plasticity and are dependent on the growth conditions (mainly nutrients and irradiance). Patil and Anil (2015) also observed blooms of these forms in the Dona Paula Bay and are driven mainly by variation in salinity (14—30) and nutrients by freshwater discharge. Similarly, their variations in the Andaman Region can also be attributed to terrigenous inputs and rainfall.

The cumulative variance in the cell volume between similar taxa measured by ocular micrometer and image analysis software showed maximum variations in most complex shapes. In the simplest forms having minimum line parameters, the CV was within a range of 2—3%. However, a maximum variation of 21% was observed in more complex shapes having multiple line parameters such as *Climacodium frauenfeldianum* Grunow, 1868 and then followed by *Chaetoceros* spp. Ehrenberg, 1844 and *Thalassionema frauenfeldii* Tempère and Peragallo, 1910 (Appendix 3).

3.3. Seasonal and spatial variations in microphytoplankton cell volume in the Bay of Bengal

Seasonal variations in cell volume among the diatoms along the BoB was maximum during the SWM (July 2008, September 2008 and July 2009), and minimum during Intermonsoon (April 2008, March 2009 and March 2010). Among the diatoms, variations were observed in *L. danicus*, *G. striata Thalassionema nitzschoides* (Grunow) Mereschkowsky, 1902, *Proboscia alata*, *R. hebetata* f. *semispina*, *Rhizosolenia castracanii* H. Peragallo, 1888 and *Rhizosolenia bergonii* H. Peragallo, 1892 (Fig. 2a—g).

In some of the dinoflagellates, maximum variation was observed during the monsoon and minimum during Intermonsoon (*P. pseudonoctulica*, *Tripos furca* (Ehrenberg) F. Gómez, 2013 and *Tripos fusus* (Ehrenberg) F. Gómez, 2013) and can be attributed due to wind-driven mixing (Fig. 2a—g). Irrespective to the seasons, the Andaman Region and River Mouth showed maximum variations in cell volume when compared to the open ocean sectors of C-P and P-K (Fig. 2a—g). Dinoflagellates are known to be a poor competitor for nitrates and half of them are heterotrophic. Vertical migration in the water column allows them to persist with non-competitive parameters for nitrogen uptake and growth (Eppley and Thomas, 1969; Smayda, 1997). The utilization of energy for mobility could be one of the reasons for minimum variation in cell volume.

3.4. Comparision of cell volumes from the Indian ocean with different regions of the world

The cell volume data from this study is compared with the information available, from Atlantic (Barton et al., 2013; Olenina et al., 2006), Pacific (Sun et al., 2000), and the Mediterranean Sea (Kim and Travers, 1995) and is summarized in Fig. 3. Out of 219 species measured for cell volume from this study, we could compare only 8 species for which the reference data in all the regions were available (Fig. 3, Appendix 2). The maximum cell volume was observed from the waters of North Atlantic and the minimum was observed from the Mediterranean Sea. Larger cell size observed in the northern Atlantic, compared to the Mediterranean could be due to variation in temperature. Smith and Reynolds (2003) observed annual mean SST within a range of 0—25.0°C. In the Mediterranean waters, several authors (Sarno et al., 1993 and Stanca et al., 2013) observed temperature variation from 3.00 to 30.0°C. The temperature variations in the two different regions could be the factor for the variations in the cell volume.

Till date, only 8.00% of the studies have estimated cell volume in the waters surrounding Indian subcontinent (Leblanc et al., 2012). In the Atlantic, Pacific and Arctic

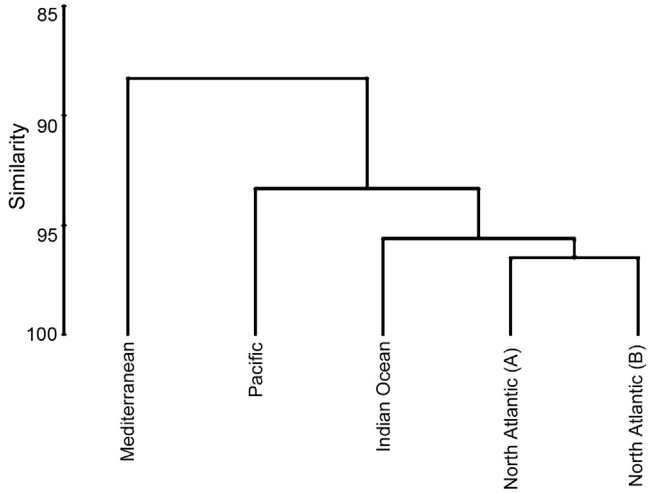

Figure 3 Comparison of cell volume from 4 different geographical regions. These include present dataset, North Atlantic (Barton et al., 2013; Olenina et al., 2006), Pacific Ocean (Sun et al., 2000), and Mediterranean Sea (Kim and Travers, 1995). The eight species which are found to be common in all the 4 regions were clustered using the Bray—Curtis similarity coefficient and group average method (log transformed). The species used for clustering are marked by (*) and is provided in Appendix 2.

region several organized groups such as HELCOM (Helsinki Commission), PEG (Phytoplankton Expert Group), ECS (European Committee for Standardization) have set up standard protocols, to estimate biovolumes using recommended shapes of Hillebrand et al. (1999), and Sun and Liu (2003) for various phytoplankton species (Harrison et al., 2015; Olenina et al., 2006). In the Indian waters, although few datasets are available there is a need to follow the most simple and common protocol to facilitate inter bioregional comparison.

According to Harrison et al. (2015), the diatom cell volumes and carbon estimates are a single largest source of uncertainty. Since larger diatoms are 20,000 times more in its cell volume than the small diatoms. Volumes of big dinoflagellates are 1500 times larger than small dinoflagellates. The ranges in diatom cell volumes are 10 times greater than across dinoflagellates (i.e. >20,000 vs. 1500 times). The Information from the Indian Ocean region provided in this paper adds a number of species from the open ocean and provide their size ranges.

Acknowledgements

We are grateful to the Director of the CSIR — National Institute of Oceanography, for his support and encouragement. We are also thankful to Indian National Centre for Ocean Information Services (Ministry of Earth Sciences) for funding support. Special thanks to Dr. V.V. Gopalakrishna for the support extended during various stages of this work. We appreciate the comments of the anonymous reviewers. We thank Drs. Jagadish S. Patil and Dattesh V. Dessai for their valuable suggestions. We are also thankful to our XBT and Ocean Finder project colleagues for their help during sampling. Rajath R. Chitari acknowledges the Senior Research Fellowship provided by the Council of Scientific and Industrial Research (CSIR) (India).

This is NIO contribution no 6016.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.oceano.2017.03.001.

References

Almandoz, G.O., Hernando, M.P., Ferreyra, G.A., Schloss, I.R., Ferrario, M.E., 2011. Seasonal phytoplankton dynamics in extreme southern South America (Beagle Channel, Argentina). J. Sea Res. 66 (2), 47–57, http://dx.doi.org/10.1016/j.seares.2011.03.005.

Banse, K., 1976. Rates of growth, respiration and photosynthesis of unicellular algae as related to cell size a review. J. Phycol. 12, 135–140.

Barton, A.D., Finkel, Z.V., Ward, B.A., Johns, D.G., Follows, M.J., 2013. On the roles of cell size and trophic strategy in North Atlantic diatom and dinoflagellate communities. Limnol. Oceanogr. 58 (1), 254–266, http://dx.doi.org/10.4319/lo.2013.58.1.0254.

Biswas, H., Dey, M., Ganguly, D., De, T.K., Ghosh, S., Jana, T.K., 2010. Comparative analysis of phytoplankton composition and abundance over a two-decade period at the land–ocean boundary of a tropical mangrove ecosystem. Estuar. Coasts 33 (2), 384–394, http://dx.doi.org/10.1007/s12237-009-9193-5.

Chitari, R.R., Anil, A.C., Kulkarni, V.V., Narale, D.D., Patil, J.S., 2017. Inter- and intra-annual variations in the population of *Tripos* from the Bay of Bengal. Curr. Sci. 112 (6), 1219–1229, http://dx.doi.org/10.18520/cs/v112/i06/1219-1229.

Eppley, R.W., Thomas, W.H., 1969. Comparison of half-saturation constants for growth and nitrate uptake of marine phytoplankton. J. Phycol. 5 (4), 375–379, http://dx.doi.org/10.1111/j.1529-8817.1969.tb02628.x.

Finenko, Z.Z., Hoepffner, N., Williams, R., Piontkovski, S.A., 2003. Phytoplankton carbon to chlorophyll *a* ratio: response to light, temperature and nutrient. Mar. Ecol. J. 2, 40–64.

Grasshoff, K., Erhardt, M., Kremiling, K., 1983. Methods of Seawater Analysis. Verlag Chemie, Weinheim, 419 pp.

Harrison, P.J., Zingone, A., Mickelson, M.J., Lehtinen, S., Ramaiah, N., Kraberg, A.C., Jakobsen, H.H., 2015. Cell volumes of marine phytoplankton from globally distributed coastal datasets. Estuar. Coast. Shelf Sci. 162, 130–142, http://dx.doi.org/10.1016/j.ecss.2015.05.026.

Hillebrand, H., Dürselen, C.D., Kirschtel, D., Pollingher, U., Zohary, T., 1999. Biovolume calculation for pelagic and benthic microalgae. J. Phycol. 35 (2), 403–424, http://dx.doi.org/10.1046/j.1529-8817.1999.3520403.x.

Kim, K.T., Travers, M., 1995. Utilité des mesures dimensionelles et des calculs de surface et biovolume du phytoplancton: comparaisons entre deux écosystèmes differents. Mar. Nat. 4, 43–71.

Leblanc, K., Arístegui, J., Armand, L., Assmy, P., Beker, B., Bode, A., Breton, E., Cornet, V., Gibson, J., Gosselin, P.M., Kopczynska, E., Marshall, H., Peloquin, J., Piontkovski, S., Poulton, A.J., Quéguiner, B., Schiebel, R., Shipe, R., Stefels, J., van Leeuwe, M.A., Varela, M., Widdicombe, C., Yallop, M., 2012. A global diatom database: abundance, biovolume and biomass in the world ocean. Earth Syst. Sci. Data 4 (1), 149–165, http://dx.doi.org/10.5194/essd-4-149-2012.

Litchman, E., de Tezanos Pinto, P., Klausmeier, C.A., Thomas, M.K., Yoshiyama, K., 2010. Linking traits to species diversity and community structure in phytoplankton. Hydrobiologia 653 (1), 15–28, http://dx.doi.org/10.1007/s10750-010-0341-5.

Margalef, R., 1978. Life-forms of phytoplankton as survival alternatives in an unstable environment. Oceanol. Acta 1 (4), 493–509.

Menden-Deuer, S., Lessard, E.J., 2000. Carbon to volume relationships for dinoflagellates, diatoms, and other protist plankton. Limnol. Oceanogr. 45 (3), 569–579, http://dx.doi.org/10.4319/lo.2000.45.3.0569.

Mitra, A., Zaman, S., Ray, S.K., Sinha, S., Banerjee, K., 2012. Interrelationship between phytoplankton cell volume and aquatic salinity in Indian sundarbans. Natl. Acad. Sci. Lett. 35 (6), 485–491.

Morabito, G., Oggioni, A., Caravati, E., Panzani, P., 2007. Seasonal morphological plasticity of phytoplankton in Lago Maggiore (N. Italy). Hydrobiologia 578 (1), 47–57, http://dx.doi.org/10.1007/s10750-006-0432-5.

Munir, S., Zaib-un-nisa Burhan, T.N., Morton, S.L., Siddiqui, P.J.A., 2015. Morphometric forms, biovolume and cellular carbon content of dinoflagellates from polluted waters on the Karachi coast, Pakistan. Indian J. Geo-Mar. Sci. 44 (1), 19–25.

Olenina, I., Hajdu, S., Edler, L., Andersson, A., Wasmund, N., Busch, S., Göbel, J., Gromisz, S., Huseby, S., Huttunen, M., Jaanus, A., Kokkonen, P., Ledaine, I., Niemkiewicz, E., 2006. Biovolumes and size-classes of phytoplankton in the Baltic Sea HELCOM Balt. Sea Environ. Proc. No. 106, 144 pp.

Patil, J.S., Anil, A.C., 2011. Variations in phytoplankton community in a monsoon-influenced tropical estuary. Environ. Monit. Assess. 182 (1–4), 291–300, http://dx.doi.org/10.1007/s10661-011-1876-2.

Patil, J.S., Anil, A.C., 2015. Effect of monsoonal perturbations on the occurrence of phytoplankton blooms in a tropical bay. Mar. Ecol. Prog. Ser. 530, 77–92, http://dx.doi.org/10.3354/meps11289.

Ploug, H., Stolte, W., Epping, E.H.G., Jorgensen, B.B., 1999. Diffusive boundary layers, photosynthesis, and respiration of the colony-forming plankton algae, *Phaeocystis* sp. Limnol. Oceanogr. 44, 1949–1958, http://dx.doi.org/10.4319/lo.1999.44.8.1949.

Reynolds, C.S., 1988. Functional morphology and the adaptive strategies of freshwater phytoplankton. In: Sandgren, C.D. (Ed.), Growth and Reproductive Strategies of Freshwater Phytoplankton. Cambridge Univ. Press, 388–433.

Reynolds, C.S., 2006. The Ecology of Freshwater Phytoplankton. Cambridge Univ. Press, Cambridge, 396 pp.

Roy, R., Chitari, R., Kulkarni, V., Krishna, M.S., Sarma, V.V.S.S., Anil, A.C., 2015. CHEMTAX-derived phytoplankton community structure associated with temperature fronts in the northeastern Arabian Sea. J. Mar. Syst. 144, 81–91, http://dx.doi.org/10.1016/j.jmarsys.2014.11.009.

Sarma, V.V.S.S., Delabehra, H.B., Sudharani, P., Remya, R., Patil, J. S., Desai, D.V., 2015. Variations in the inorganic carbon components in the thermal fronts during winter in the northeastern Arabian Sea. Mar. Chem. 169, 16–22, http://dx.doi.org/10.1016/j.marchem.2014.12.009.

Sarno, D., Zingone, A., Saggiomo, V., Carrada, G.C., 1993. Phytoplankton biomass and species composition in a Mediterranean coastal lagoon. Hydrobiologia 271 (1), 27–40, http://dx.doi.org/10.1007/BF00005692.

Sherwood, T.K., Pigford, R.L., Wilke, C.R., 1975. Mass Transfer. McGraw-Hill, New York, 677 pp.

Smith, T.M., Reynolds, R.W., 2003. Extended reconstruction of global sea surface temperatures based on COADS data (1854–1997). J. Climate 16 (10), 1495–1510, http://dx.doi.org/10.1175/1520-0442-16.10.1495.

Smayda, T.J., 1997. Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. Limnol. Oceanogr. 42 (5 (part 2)), 1137–1153.

Smayda, T.J., 1970. The suspension and sinking of phytoplankton in the sea. Oceanogr. Mar. Biol. Annu. Rev. 8, 353–414.

Stanca, E., Cellamare, M., Basset, A., 2013. Geometric shape as a trait to study phytoplankton distributions in aquatic ecosystems. Hydrobiologia 701 (1), 99–116, http://dx.doi.org/10.1007/s10750-012-1262-2.

Sun, J., Liu, D., Qian, S., 2000. Estimating biomass of phytoplankton in the Jiaozhou bay, I. Phytoplankton biomass estimated from cell volume and plasma volume. Acta Oceanol. Sin. 19 (2), 97–110.

Sun, J., Liu, D., 2003. Geometric models for calculating cell biovolume and surface area for phytoplankton. J. Plankton Res. 25 (11), 1331–1346, http://dx.doi.org/10.1093/plankt/fbg096.