Marine Micropaleontology 137 (2017) 16–30

Contents lists available at ScienceDirect

Marine Micropaleontology

journal homepage: www.elsevier.com/locate/marmicro

Research paper

Biogeographic distribution of extant Coccolithophores in the Indian sector of the Southern Ocean

Shramik M. Patil[a], Rahul Mohan[a,*], Suhas S. Shetye[b], Sahina Gazi[a], Karl-Heinz Baumann[c], Syed Jafar[d]

[a] National Centre for Antarctic and Ocean Research, Vasco-da-Gama, Goa 403804, India
[b] National Institute of Oceanography, Dona Paula, Goa 403004, India
[c] Department of Geosciences, Universität Bremen, PO Box 330440, 28334 Bremen, Germany
[d] Flat 5-B, Whispering Meadows, Haralur Road, Bangalore 560 102, India

ARTICLE INFO

Keywords:
Extant Coccolithophores
Southern Indian Ocean
Nutrients
Oceanic fronts
Austral summer

ABSTRACTS

Water samples from nine vertical profiles down to 110 m water depth and 19 samples from the sea-surface were studied for coccolithophore abundance and distribution across oceanic frontal regions of the Indian sector of the Southern Ocean. Sampling was performed along a north-south transect (between 39°S and 65.49°S, ~57.3°E) during the 4th Indian Southern Ocean Expedition (between 31st January and 18th February 2010). Coccospheres and coccoliths were counted separately using a Scanning Electron Microscope (SEM). A total of 39 taxa (including morphotypes, types and subspecies) were recorded as intact coccospheres with abundances reaching up to 750 × 10^3 coccospheres/l. In addition, 85 taxa (including varieties, morphotypes) were counted as coccoliths reaching up to 900 × 10^5 coccoliths/l. *Emiliania huxleyi* was recognized as the most abundant species, accounting for > 86% of the total coccolithophore assemblage at each station. Elevated coccolithophore diversity was observed in the subtropical zone whereas high coccolithophore abundance was observed in the Subantarctic zone. A monospecific *Emiliania huxleyi* assemblage was recorded within and south of the Polar frontal zone. Three assemblages were recognized based on coccolithophore abundance and diversity. The assemblage of the Agulhas Retroflection frontal zone and Subtropical zone is highly diverse (39 taxa) and can be linked to relatively warm, high saline and oligotrophic waters. The Subantarctic zone assemblage is characterized by a reduced number (thirteen) of coccolithophore taxa, whereas the Polar Frontal zone comprises a monospecific *E. huxleyi* assemblage (preferentially morphotypes C and B/C). Multivariate statistics indicated that regions with elevated temperature and low nutrient concentration show high coccolithophore diversity whereas regions with high nutrient concentrations and low temperature show a strongly reduced coccolithophore diversity with abundant monospecific *E. huxleyi* (morphotypes B/C and C) assemblages.

1. Introduction

Coccolithophores are calcified, unicellular, photosynthetic marine microalgae found in coastal and open ocean regions. They are the most important marine carbonate producers dwelling in the upper photic layer of the world oceans (Westbroek et al., 1993) and play a significant role in the marine food web and carbon cycling (Rost and Riebesell, 2004). Coccolithophore abundance and species fluctuations in the oceans are linked to changes in environmental parameters such as Sea Surface Temperature (SST), Sea Surface Salinity (SSS), solar radiation, and nutrient content (Winter et al., 1994). In recent years, increase in SST and decrease in oceanic pH generated appreciable interest in the coccolithophore ecology and biogeography (Orr et al., 2005; Iglesias-Rodriguez et al., 2008; Beaufort et al., 2011). A latitudinal expansion of coccolithophore species such as *Emiliania huxleyi* in the Southern Ocean, south of 60°S latitude was recorded by several authors (Winter et al., 1999; Findlay and Giraudeau, 2000; Cubillos et al., 2007; Gravalosa et al., 2008; Patil et al., 2014; Winter et al., 2014), but the actual cause of this southward expanse is still debated. Thus, detailed knowledge about coccolithophore species diversity, spatial and vertical distribution and their production in this region is needed. In the past decade, studies of plankton and sediment samples on coccolithophore biogeography, taxonomy, ecological preferences were carried out in various regions of the Southern Ocean (SO) (Winter et al., 1999; Findlay and Giraudeau, 2000; Mohan et al., 2008; Gravalosa et al., 2008; Saavedra-Pellitero et al., 2014; Malinverno et al., 2015;

* Corresponding author.
E-mail address: rahulmohangupta@gmail.com (R. Mohan).

http://dx.doi.org/10.1016/j.marmicro.2017.08.002
Received 28 March 2016; Received in revised form 20 July 2017; Accepted 22 August 2017
Available online 26 August 2017

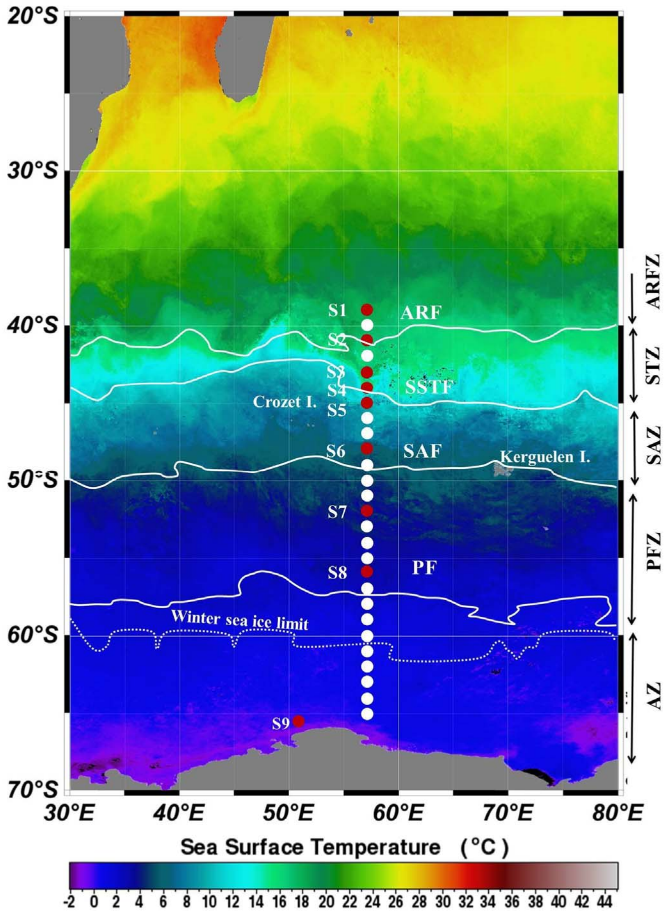

Fig. 1. Location of water samples. Red dots represent vertical profile stations (S1–S9) and white dots represents surface water samples collected during the austral summer of 2010. Location of fronts after Orsi et al. (1995), Anilkumar et al. (2006) and Luis and Sudhakar (2009). ARF, Agulhas Retroflection Front; SSTF, Southern Subtropical Front; SAF, Subantarctic Front; PF, Polar Front. The different oceanographic frontal zones are indicated as, ARFZ, Agulhas Retroflection Frontal Zone; STZ, Subtropical Zone; SAZ, Subantarctic Zone; PFZ, Polar Frontal Zone; AZ, Antarctic Zone. SST image source- SST image source — http://oceancolor.gsfc.nasa.gov/cgi/l3. The white dotted contour is the sea ice extent in November 2009 inferred from monthly HadISST global sea ice data (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_hadisst).

Malinvrno et al., 2016). However, studies on coccolithophores of the Indian sector of the SO still remain relatively scarce.

In this study, vertical and latitudinal distribution and community composition of coccolithophores were examined quantitatively along a N-S transect in the Indian sector of the Southern Ocean (Fig. 1, Table 1). Coccolithophore species diversity and its relationship with the present environmental conditions were studied across the major oceanic frontal regions of the study area. The relationship between species and environmental conditions was assessed by Canonical Correspondence Analysis (CCA) and the obtained results are compared with those published from other sectors of the Southern Ocean. The investigation of coccolithophores in extreme southern latitudes was carried out to verify whether coccolithophores showed any southward expansion, as was previously suggested (e.g., Winter et al., 2014). The probable forcing mechanisms involved and the general response of coccolithophores to the physicochemical characteristics of the southern latitudes and oceanic frontal regions of the Indian Sector of the Southern Ocean are also investigated.

1.1. Hydrographical settings of the study region

The Antarctic Circumpolar Current (ACC) is a massive eastwardly flowing current that surrounds the Antarctic continent and comprises various water masses and fronts (Nowlin and Klinck, 1986). The ACC flows eastward due to the intense Southern hemisphere westerly winds and connects all the major oceans (Orsi et al., 1995). Distinct fronts and surface water mass regimes observed in the Southern Ocean in a poleward direction are the Agulhas Retroflection Front (ARF), Subtropical Front (STF), Subtropical zone (STZ), Subantarctic Zone (SAZ), Subantarctic Front (SAF), Polar Frontal Zone (PFZ), Polar Front (PF) and the Antarctic Zone (AZ) (Orsi et al., 1995) (Fig. 1). The Subtropical Front (STF) defines the northern boundary of the ACC (Clifford, 1983; Orsi et al., 1995) which is usually documented between 35°S and 45°S in the study area. The STF shows two different entities, the Northern Subtropical Front (NSTF) and the Southern Subtropical Front (SSTF). Average Sea Surface Temperature (SST) at NSTF changes from about 22 °C to 21 °C while Sea Surface Salinity (SSS) is consistent at ~35.5 (Belkin and Gordon, 1996; Holliday and Read, 1998). At the SSTF, SST changes from 17 °C to 11 °C (and 12 °C to 10 °C at 100 m) and SSS decreases from 35.35 to 35.05 (35.0 to 34.6 at 100 m). The ARF occurs between NSTF and SSTF with SST and SSS ranging from 19 °C to 17 °C and 35.54 to 35.39 (Belkin and Gordon, 1996; Holliday and Read, 1998). At the SAF the temperature ranges between 11 °C to 6 °C at surface and 8 °C to 4 °C at 200 m water depth whereas salinity ranges between 34.0 to ~33.85 at surface and 34.40 to 34.11 at 200 m water depth (Belkin and Gordon, 1996; Orsi et al., 1995). The PF lies between the Agulhas Basin to the north and the Enderby Basin to the south. The PF is defined by the subsurface temperature minimum of 2 °C at the depth above 200 m (Orsi et al., 1995) (Table 2).

The Southern Ocean is also known as a region of intense eddy activity which influences global thermohaline circulation and, thus, affects global climate (Hughes and Ash, 2001). The oceanic fronts in the Southern Indian Ocean split, merge, fluctuate seasonally and vary spatially over regional topographic features. The average SST north of the SAF is generally > 4 °C whereas south of the PF it is < 2 °C (Orsi et al., 1995; Klink and Nowlin, 2001).

2. Materials and methods

2.1. Samples

At the 9 vertical profile stations, samples were collected at 6 different depths (0, 20, 40, 60, 80 and 110 m) using 5 l (capacity) Niskin bottles attached to a CTD rosette (12 bottles) (Sea-Bird Electronics). Additionally, 19 surface water samples were collected using the ship's pumping system at one degree intervals during the 4th Indian Southern Ocean Expedition onboard *Ocean Research Vessel Sagar Nidhi* (between 31st January and 18th February 2010) within the area 39°S to 65.49°S and 57.3°E to 51.09°E (Table 1). The vertical profile observations were made in the oceanic frontal zones identified by using in-situ sea surface temperature and Expendable Bathythermograph (XBD) measurements.

2.2. Defining oceanic frontal locations and zones

The locations of fronts were defined by using a temperature sensor installed on the ship which monitors the in-situ sea surface temperature and by using frequent XBT measurements (every half degree interval). Concerning the criteria used for defining the fronts, we followed Belkin and Gordon (1996), Kostianoy et al. (2004), Anilkumar et al. (2006), and Luis and Sudhakar (2009). Conductivity Temperature Depth (CTD) measurements provided vertical water column temperature and salinity profiles. The temperature and salinity data displayed in Fig. 3 are based on in-situ measurements performed using a Seabird CTD system. In this study, temperature varied between 18.4 °C to −1.4 °C and salinity between 35.48 and 33.56. Stations S1 to S4 were located in the Agulhas Retroflection Frontal zone and Subtropical zone; stations S5 and S6 in the Subantarctic zone whereas, stations S7 and S8 were positioned in the polar frontal zone. The southernmost station S9 was located near the Antarctic coastal region.