Cyclone Phyan-induced plankton community succession in the coastal waters off Goa, India

Gauns Mangesh*, Kurian Siby, Shenoy M. Damodar, Naik Hema and S. W. A. Naqvi

CSIR-National Institute of Oceanography, Dona Paula, Goa 403 004, India

Effects of the cyclonic storm Phyan, which hit the states of Goa and Maharashtra in western India during 9–12 November 2009, on coastal waters were studied. Mixing induced by the cyclone appreciably affected the vertical thermohaline structure, composition and growth of plankton. The phytoplankton biomass increased by a factor exceeding 4, and a shift in phytoplankton community occurred with diatoms replacing dinoflagellates as the dominant group. A shift in zooplankton dominance from filter-feeders to herbivores and carnivores was also noticed. The results underline the sensitivity of coastal ecosystems to extreme events.

Keywords: Chlorophyll, coastal waters, cyclonic storm, phytoplankton, zooplankton.

SUDDEN climatological events such as tropical cyclones can significantly affect coastal ecosystems. These cyclones can have a substantial effect on the biological productivity in the coastal ecosystems. Despite the short time-span of tropical storms, their effect can be seen for several weeks[1]. Since these disturbances are sudden and unusual climatological events, it is hard to study *in situ* changes in the plankton community. In general, cyclonic winds result in mixing of the surface waters with subsurface waters, thereby entraining new nutrients into the euphotic zone, which in turn enhances, surface productivity. The work of Shiah *et al.*[2] along the continental shelf of the Taiwan Strait has shown that the shelf ecosystem becomes more productive after the cyclone (typhoons) events increasing chlorophyll *a*, nitrate and particulate organic nitrogen concentrations by several fold and resulting in increased primary production, particulate organic carbon concentration and bacterial production roughly twofold. Likewise, studies carried out by Shi and Wang[3] from the Gulf of Mexico, a region hit by hurricane Katrina in August 2005, also showed a prominent phytoplankton bloom roughly four days after the passing of the hurricane. Such episodic events are also known to bring characteristic changes in zooplankton. For example, tropical cyclone-Tiffany along the margin of the southern Northwest Shelf, Australia in January 1998 resulted in

*For correspondence. (e-mail: gmangesh@nio.org)

shifts in copepod-dominated mesozooplankton community. However, it is important to note that most of the data were obtained using various satellite sensors[4,5]. As pointed out by Lin[6], all cyclones do not induce phytoplankton blooms and the associated sea surface temperature (SST) cooling.

The Arabian Sea appears to be experiencing increased occurrence of high-intensity cyclones since 1995, presumably due to a regional climate shift and higher SST[7]. Cyclones in the Arabian Sea are mostly formed during May–June or October–November of the year. Compared to the Arabian Sea, cyclones are formed more frequently in the Bay of Bengal. This is due to the differences in ocean–atmosphere interactions that control cyclone genesis. The warm, low-salinity waters of the Bay of Bengal cause strong vertical stratification, preventing vertical mixing favouring cyclone intensification[8]. In the Bay of Bengal cyclones generally form in April–May and sometimes move across peninsular India and intensify again over the eastern Arabian Sea[3].

Biogeochemical measurements (*in situ* measurements in particular) pertaining to a cyclone are limited, even though these episodic events are known to cause significant impact on the aquatic ecosystem, as the prevailing rough weather conditions during and immediately after the cyclone make *in situ* measurements difficult. However, these measurements are overall crucial to understand their role in global biogeochemical cycles. The present work highlights *in situ* measurements carried out before and immediately after the cyclone Phyan that hit the west coast of India.

The occurrence of a tropical cyclone in the eastern Arabian Sea provided us with an opportunity to study its biogeochemical effects at a coastal time-series site off Goa. A low pressure formed over the Comorin area on 7 November 2009, became well-marked within a day over the Lakshadweep region. This depression slowly moved in a northwesterly direction until 10 November 2009 and then towards north–northeast as it turned into a cyclonic storm named 'Phyan'. This storm moved at ~40 km h^{-1} towards Goa and Maharashtra coast on 11 November 2009 and then weakened into a depression over central Maharashtra (Nasik) on 12 November 2009 (http://www.imd.gov.in/cyclone-phyan.pdf; Figure 1). The passage of the cyclone generated moderately high winds (~85 km h^{-1}) and widespread heavy to very heavy rainfall over Konkan–Goa (5–8 cm) and central Maharashtra (5–13 cm). The meteorological details of Phyan are recorded at India Meteorological Department website (http://www.imd.gov.in/section/nhac/dynamic/cyclone-phyan.pdf).

Prior to the formation of the cyclone, we had carried out regular sampling at the Candolim Time Series (CaTS) station G5 (15°30′36″N; 73°39′0″E) on 4 November 2009 (CaTS-85). Following the cyclone we visited the station again on 17 November 2009 (CaTS 86). Water samples on both field trips were collected with Niskin samplers

fixed on nylon ropes. Subsamples for chlorophyll *a* (Chl *a*) were stored in an ice-box until analysis. These were filtered onto 47 mm Whatman GF/F filter papers, extracted in 10 ml of 90% acetone for 24 h at –20°C and analysed fluorometrically with a Turner Designs 10 AU fluorometer. For pigment analysis, samples were collected and processed following the protocol described by Roy *et al.*[9] and analysed using high performance liquid chromatography (HPLC). Chemotaxonomic relation used for phytoplankton taxonomy was according to Gibb *et al.*[10] and Jeffrey *et al.*[11]. Aliquots of 1.5 ml were preserved with paraformaldehyde (1% final concentration) for picoplankton analyses and analysed on BD FASC Calibur Flow Cytometer following Marie *et al.*[12]. Subsamples (200 ml) fixed with 0.5% Lugol's iodine and preserved with 2% formalin were used for phytoplankton analyses. Then 10–50 ml aliquots were settled in Utermohl's chambers (Hydro-Bios Kiel, Germany) and species-specific cell numbers were counted at 100 and 400× magnification using Olympus IX52 inverted microscope (Tokyo, Japan). Only certain taxa were identified to the species level and the rest to the genus level.

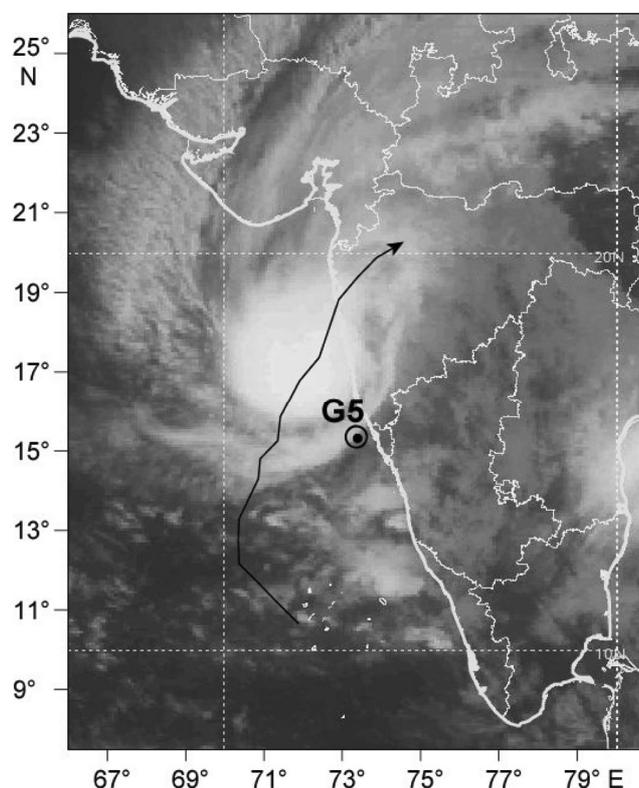Mesozooplankton samples were collected using the Heron Tranter net by vertical haul (close to the bottom to the surface). Mesozooplankton biomass was estimated by the volume displacement method and species composition was analysed with SZM1000 stereoscopic zoom microscope (Nikon, Japan).

Samples for dimethylsulphide (DMS), total dimethylsulphoniopropionate (DMSP) and total dimethylsulphoxide (DMSO) were collected in 60 ml amber-coloured glass bottles with ground glass stoppers. The samples were kept in dark at 4°C till analysis. The storage time never exceeded 6 h. Analyses of DMS, DMSP and DMSO were done using the purge and trap gas chromatographic technique as detailed in refs 13 and 14. In short, a definite volume of seawater sample was purged with dry nitrogen at 60 ml min^{-1}. The dried stream of gaseous mixture was passed through a cold trap consisting of liquid nitrogen where DMS and other gases were trapped. Later, the trapped gases were flash-evaporated using boiling water and fed to the gas chromatograph where Chromosil 330 separated the gaseous mixture and DMS was detected by the flame photometric detector. Following DMS analysis, 2 ml of 10 M NaOH was added and purged for 20 min to convert DMSP to DMS for analysis by the above method. Later, 0.3 g of cobalt-doped sodium borohydride was added and purged for 20 min to convert DMSO to DMS. Calibration was performed using DMSP standards. The precision of the method was between 6% and 10%.

Subsamples for suspended particulate organic matter (SPOM) were filtered through pre-combusted (450°C for 4 h) GF/F filters (0.7 μm pore size). The filters were exposed to acid fumes (36% HCl) to remove carbonates and air-dried in a clean laminar flow. Two aliquots each of 12 mm diameter were sub-sectioned from each filter and packed tightly in tin cups for the analysis. A Euro-vector elemental analyser coupled to a Thermo-Finnigan Delta V IRMS (in continuous-flow mode) was used for carbon content and isotopic analyses. Isotopic ratio $\delta^{13}C$ is expressed with respect to the Pee Dee Belemnite (PDB) and the precision was better than ± 0.2‰ as determined

Figure 1. Track of Phyan during 9–12 November 2009 that reached study location – G5, off Goa, central west coast of India (satellite picture of the cyclone and track taken from the website: http://www. imd.gov.in/cyclone-phyan.pdf).
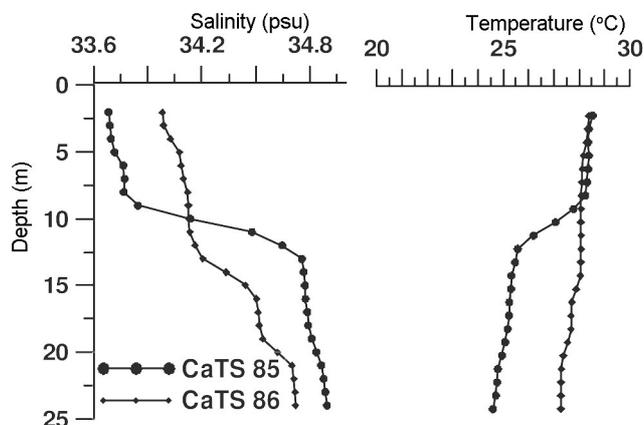

Figure 2. Vertical profiles of temperature and salinity measured by CTD before (CaTS 85; ●) and after (CaTS 86; ◆) Phyan.

Table 1. Changes in depth-weighted integrated phytoplankton abundance before and after the cyclone Phyan

	Diatoms (%)	Dinoflagellates (%)	Synechococcus abundance cells × 10^{10} m^{-3}	Picoeukaryotes abundance cells × 10^{9} m^{-3}	Nanoplankton abundance cells × 10^{9} m^{-3}
Before the cyclone	14.77	85.23	8.49	12.1	1.9
After the cyclone	99.74	0.26	7.21	8.8	8.5

Table 2. List of phytoplankton species before and after the passage of Phyan at station G5 (CaTS location) off Goa, west coast of India

Taxon	Before Phyan cells m^{-3}	After Phyan cells m^{-3}	Taxon	Before Phyan cells m^{-3}	After Phyan cells m^{-3}
Dinoflagellates			*Coscinodiscus granii*	+	+
Ceratium carriens	+	ND	*Coscinodiscus wiesellii*	+	ND
Ceratium furca	ND	+	*Coscinodiscus* sp. (70 μm)	++	+
Ceratium fusus	++	+	*Ditylum brightwellii*	ND	+
Ceratium macroceros	+	ND	*Eucampia zodiacus*	++	ND
Ceratium sp.	+	ND	*Guinardia delicatula*	+	++
Dinophysis acuminata	+++	+	*Guinardia flaccida*	+	+
Dinophysis cuadata	++	ND	*Guinardia striata*	++	+++
Gonyaulax sp.	+++	ND	*Hemiaulus* sp.	ND	+++
Chattonella sp (*)	+++*	ND	*Hemiaulus membranaceus*	+++	ND
Gymnodinium sp.	+	ND	*Leptocylindrus danicus*	++	+++
Gyrodinium sp.	+++	++	*Leptocylindrus minimus*	+++	+++
Gyrodinium spirale	++	ND	*Leptocylindrus mediterraneus*	+++	ND
Prorocentrum gracile	++	+	*Lauderia* sp.	ND	++
Prorocentrum micans	+	ND	*Navicula* sp. (<50 μm)	+++	+++
Protoperidinium sp.	ND	+	*Navicula* sp. (>100 μm)	++	++
Silicoflagellates			*Navicula septentrionalis*	++	ND
Dictyocha octonaria	ND	++	*Navicula transistrans*	++	+++
			Nitzschia sp.	++	ND
Diatoms			*Nitzschia longissima*	++	+++
Asterionellopsis glacialis	+	+++	*Odontella mobiliensis*	+	+
Bacteriastrum delicatulum	ND	++	*Odontella sinensis*	++	++
Bacteriastrum furcatum	+	ND	*Pleurosigma* sp.	+	+
Bacteriastrum hyalinum	ND	+	*Pseudonitzschia* sp.	++	+++
Bacteriastrum sp.	++	ND	*Rhizosolenia alata*	++	+
Ceratoneus closterium	+++	+++	*Rhizosolenia* cf. *curvata*	+	++
Cerataulina sp.	+++	++	*Rhizosolenia* cf. *setigera*	++	ND
Chaetoceros aequatorialis	+	ND	*Rhizosolenia styliformis*	+	+
Chaetoceros curvisetus	+	+++	*Rhizosolenia* sp.	++	+
Chaetoceros danicus	ND	+	*Skeletonema costatum*	+	+++
Chaetoceros cf *decipiens*	+	++	*Skeletonema* sp.	ND	++
Chaetoceros diversus	++	ND	*Thalassionema nitzschiodes*	++	+++
Chaetoceros cf *lacinious*	ND	++	*Thallassiosera* sp. (<20 μm)	ND	+++
Chaetoceros lorenzianus	+	+++	*Thalassiosira* sp. (>50 μm)	ND	++
Chaetoceros sp.	+	+++	*Thalassiosira* sp. (<50 μm)	++	+++
Corethron sp.	ND	+	*Thalassiothrix* sp.	++	ND

+++ Most abundant (10^6–10^8 cells m^{-3}). ++ Abundant (10^5 cells m^{-3}). + Rare (10^3–10^4 cells m^{-3}), ND, Not detected. (*) Bloom species.

from repeated measurements on a working standard, ε-amino-n-caproic Acid or ACA ($\delta^{13}C = -25.3‰$) and an in-house sediment standard labelled COD ($\delta^{13}C = -21‰$). A calibration curve made of ACA standards ranging from 6 to 24 μM carbon was used to calculate carbon content in SPOM[15].

Physical characteristics of the water column were measured using a portable sea bird conductivity, temperature, and depth (CTD, sea bird). Profiles of temperature and salinity before and after the cyclone indicate the occurrence of vertical mixing in the water column (Figure 2). The water was more stratified before the cyclone with the mixed layer depth being only 10 m. After the cyclone, water column was well mixed to the bottom. Following the cyclone the surface water became more saline by ~0.3 and slightly cooler (by 0.2°C). Relative to these changes, the shifts observed in biological parameters were more dramatic.
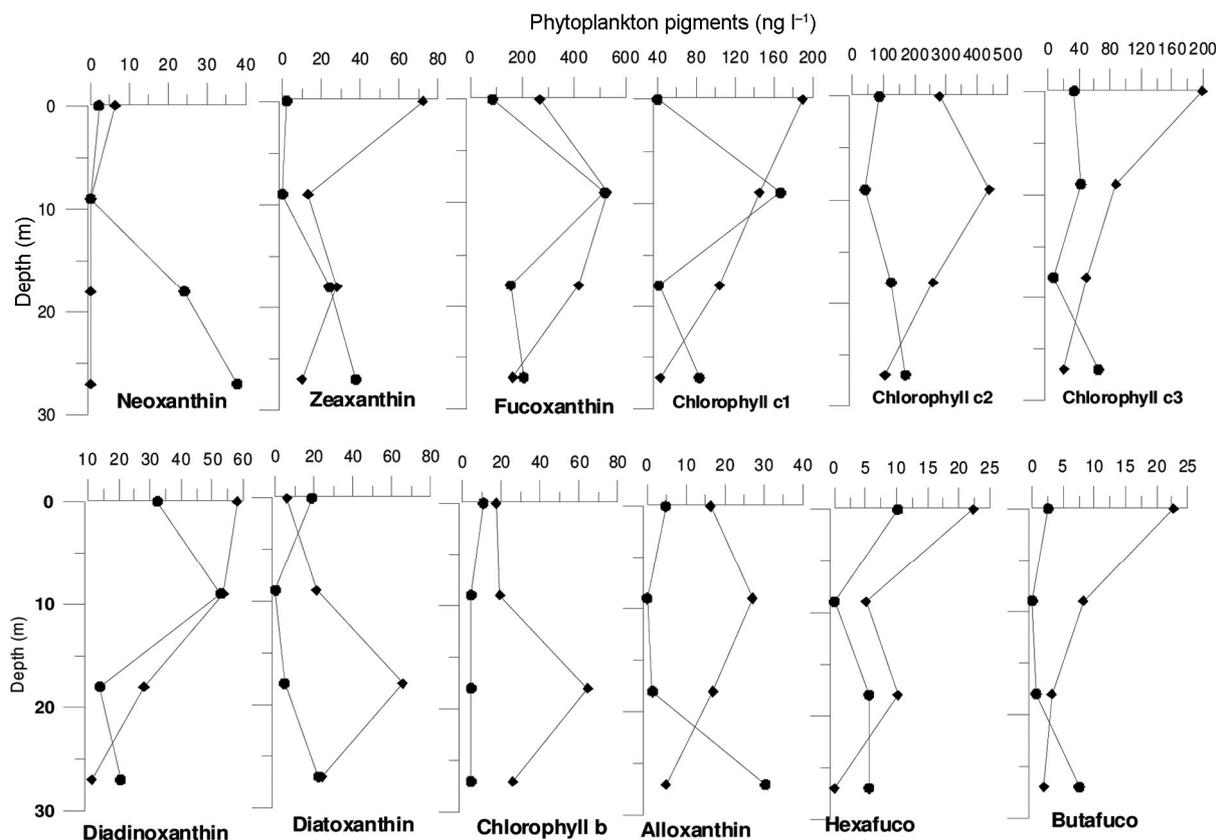
Figure 3. Vertical profiles of phytoplankton pigments before (●) and after (◆) Phyan.

Phytoplankton biomass as well as community composition showed large differences between observations made before and after the cyclone. Phytoplankton biomass (Chl a) in surface waters rose from 0.8 to 3.5 mg m^{-3}, a 4.4-fold increase. Depth-weighted integrated water column phytoplankton biomass calculated following Uye et al.[16] also showed an increase by 54%. Likewise, flow cytometry data showed distinct shifts. After the cyclonic event, depth-weighted integrated abundance of nano-plankton ($\times 10^9$ cells m^{-3}) increased about four-fold from 1.95 to 8.5, while *Synechococcus* and pico-eukaryotes became less abundant (Table 1). This is consistent with the results of pigment analysis by HPLC, which recorded dominance of zeaxanthin (an indicator of pico-phytoplankton such as *Synechococcus* and *Prochlorococcus*) before the cyclone. An increase in other smaller forms mainly belonging to prymnesiophytes, crypto-phytes and cryophytes occurred following the cyclonic event as evident from the marker pigments (19'HF, 19'BF, Chl b, Chl c_3 and alloxanthin; Figure 3), supporting the enhancement of nano-phytoplankton abundance (Table 1).

Microscopic analysis of phytoplankton (cells >5 μm) also revealed a prominent community shift (from dinoflagellates to diatoms; Table 1). Pre-cyclone phytoplankton community was numerically dominated by dinoflagellates

and raphidophyte *Chattonella* sp. reaching maximal abundance of 4.28×10^5 cells l^{-1} and was specifically restricted to 9 m below the surface. Interestingly, post-cyclone phytoplankton community was largely dominated by diverse diatoms, with *Leptocylindrus danicus* (36%), *Thallassiosera* sp. (14%), *Pseudonitzschia* sp. (13%), *Chaetoceros curvisetus* (12%) and *Skeletonema costatum* (6%). Table 2 provides detailed phytoplankton species composition. Increase in the concentration of marker pigments such as fucoxanthin, chlorophyll c_1, c_2, diadinoxanthin and diatoxanthin supports the dominance of diatom community after the cyclone (Figure 3). However, peridinin (a marker pigment of dinoflagellate) was also present in the water column after the cyclone.

After the cyclone mesozooplankton biomass and abundance showed 1.5- and 2-folds increase respectively. Table 3 provides details of zooplankton composition (>200 μm in size), before and after the passage of Phyan. Before the cyclone, copepods, viz. *Oncaea* spp. dominated (26%) the mesozooplankton community followed by cladocerans – *Evadne tergestina* (23%) and *Penilia avirostris* (11%). Other groups, including Gastropoda, Pteropoda, Pelycepoda, Chaetognatha, Urochordata, Chordata and Hydrozoa collectively constituted 12% of the community. By contrast, the post-cyclone community was dominated by early stages of *Paracalanus* spp.

Table 3. Zooplankton composition (>200 µm in size) before and after the passage of Phyan

Station – G5 Biomass (ml/100 m^3) Taxon (groups/species)	Before Phyan 44 (Organisms/m^3)	% Composition	After Phyan 59 (Organisms/m^3)	% Composition
Acartia ambo	–	–	9	0.1
Acartia erythraea	19	0.3	19	0.1
Acartia spp.	–	–	66	0.5
Acrocalanus spp.	47	0.8	180	1.4
Centropage tenuiremis	–	–	47	0.4
Centropages alcocki	–	–	19	0.1
Centropages gracilis	–	–	28	0.2
Centropages orsinii	28	0.5	9	0.1
Centropages sp.	9	0.2	28	0.2
Clytemnestra scutellata	190	3.2	–	–
Corycaeus catus	–	–	57	0.4
Corycaeus sp.	332	5.6	882	6.8
Euterpina acutifrons	123	2.1	408	3.1
Labidocera sp.	9	0.2	28	0.2
Microsetella rosea	–	–	9	0.1
Oithona plumifera	9	0.2	38	0.3
Oithona rigida	19	0.3	38	0.3
Oithona sp.	104	1.8	–	–
Oithona spinirostris	–	–	19	0.1
Oncaea sp.	1545	26.2	1612	12.4
Oncea venusta	28	0.5	–	–
Paracalanus aculeatus	95	1.6	–	–
Paracalanus parvus	161	2.7	493	3.8
Paracalanus spp. (early stages)	247	4.2	5746	44.4
Pseudodiaptomus serricaudatus	–	–	891	6.9
Scolecithrix sp.	9	0.2	–	–
Temora discaudata	9	0.2	–	–
Temora turbinata	218	3.7	569	4.4
Evadne tergestina	1365	23.1	436	3.4
Penilia avirostris	626	10.6	104	0.8
Sagitta sp.	104	1.8	284	2.2
Conchoecia sp.	28	0.5	237	1.8
Oikopleura sp.	47	0.8	19	0.1
Diphyes	76	1.3	19	0.1
Lensia	19	0.3	28	0.2
Doliolum sp.	19	0.3	–	–
Decapod larvae	19	0.3	47	0.4
Polychaetes	9	0.2	76	0.6
Pelecypodes	152	2.6	351	2.7
Fish eggs	47	0.8	19	0.1
Medusae	104	1.8	28	0.2
Gastropoda	47	0.8	9	0.1
Pteropods	28	0.5	38	0.3
Fish larvae	9	0.2	19	0.1
Total	5907	100	12952	100

(44%), with a drastic increase in abundance by a factor of 23, whereas the abundance of *Oncaea* spp. dropped by 50% after the cyclone. Abundances of harpacticoids and ostracods also showed 3- and 8-fold increase respectively, after the cyclone. Most harpacticoids are benthic copepods forming one of the largest meiofaunal groups in marine sediments. Turbulence caused by the cyclone possibly re-suspended harpacticoids (and other benthic forms) into the water column, rich in suspended detritus, as seen from the particulate organic carbon (POC) data along with required nutrients for autotrophic forms. A 1.5-fold increase in turbidity in the water column, resulting from fine and large particles was observed based on measurements of water column POC before (CaTS 84; 22 October 2009; 25–38 µM) and after the cyclone (CaTS 86; 28–68 µM), while δ^{13}C of suspended particulate organic matter varied within a narrow range (20.3 ± 1‰) indicating marine origin of the organic matter. Previous measurements of POC from the same location by Maya *et al.*[17] in November 2007 reported much lower concentrations (10.4–25 µM) and lower δ^{13}C (–22‰ to –23.6‰). The higher POC concentration observed in the present

study could be a combination of higher productivity and re-suspension of sediments following the cyclonic event. A similar two-fold increase in POC was reported in the continental shelf of the southeast China Sea after the passage of tropical cyclone 'Herb' during 1996. Shiah et al.[2] also attributed this increase to wind mixing, re-suspension and terrestrial run-off, which resulted from the passage of the cyclone. The higher suspended load could affect filter feeders by clogging their gills and decreasing filtering efficiencies and therefore, an overall decrease in their population. Thus, the post-cyclone period was characterized by a decrease of suspension feeders such as *Penilia avirostris* and *Evadne tergestina* (from 1991 organisms m^{-3} (contributing ~40% to total zooplankton population) to 540 organisms m^{-3} (3% of total zooplankton); Table 3), which form important members of the crustacean zooplankton in coastal waters of tropical and subtropical regions[18]. Greater abundances of herbivores (major forms such as *Paracalanus* spp., *Temora turbinate*; *Euterpina acutifrons*) were documented (by a factor of ~10) in the present study after the cyclone. Usually such shifts in community structure are seen along the coast of Goa on a seasonal scale (M. Gauns, unpublished) as the coastal waters of the eastern Arabian Sea are greatly influenced by monsoonal cycle. During the southwest monsoon, when nutrient concentrations are fairly high, diatoms dominate the phytoplankton community. As nutrient concentrations in the water column decrease after the monsoon, cyanobacteria become the dominant autotrophic group[19]. The seasonal biological rhythm may be altered by extreme conditions like the tropical cyclones, which modify physico-chemical characteristics of the water column, mainly due to nutrient enrichment of the euphotic zone. Nitrate concentration in surface water was close to the detection limit prior to the cyclone. Turbulence caused by cyclone must have brought up nutrients from near bottom waters, possibly also entraining interstitial waters that are rich in phosphate and ammonium. Additional supply is expected from land run-off and also directly from heavy rainfall associated with the cyclone. Rainwater samples, collected on 6 and 11 October 2009 on the terrace of the National Institute of Oceanography, Goa showed moderately high dissolved nutrient concentration (NO$_3^-$ 7.5 and 4.2 μM

respectively). This is consistent with observations from other areas showing significant DIN supply to surface waters directly through rainfall[20]. Naqvi et al.[21] also reported ~4 μM NO$_3^-$ in rainwater and high DIN inputs into the study region via land run-off through the nearby Mandovi–Zuari estuarine system. Availability of approx. 0.5 μM NO$_3^-$ (after meeting the demand from autotrophs) in the surface waters at the time of the post-cyclone sampling suggests that nutrient enrichment of surface waters did occur following the cyclone (Figure 4). As a result, phytoplankton biomass as indicated by chlorophyll *a* concentration increased several fold after the cyclone, largely contributed by nano- and micro-phytoplankton (diatoms and dinoflagellates). It has been demonstrated previously that cyclones cause entrainment of new nutrients to the mixed layer in the open ocean through vertical mixing, greatly enhancing biological productivity[5,22]. Our results show a similar effect in coastal waters, although the nutrient enrichment source(s) may be different. Conversely, the dominance of *Synechococcus* and pico-eukaryotes before the cyclone may be related to an appreciable concentration of phosphate (which is never completely depleted from surface waters in the region) and low DIN concentration given the high-potential phosphate uptake capacity of these forms relative to other photosynthetic and heterotrophic micro-organisms[23]. A possible explanation for the observed decrease in *Synechococcus* and pico-eukaryotes may be active grazing by herbivorous mesozooplankton, as their abundance increased drastically after the cyclone. An indication of grazing is also provided by measurements of DMS, DMSP and DMSO. Before the cyclone the DMS, DMSP and DMSO concentrations (column values 0–25 m) were 104, 206 and 277 nM respectively. After the cyclone, the concentrations increased to 153, 730 and 1139 nM respectively. These increases again support the idea of increased primary production induced by the cyclone. It may be noted that the high integrated concentration of DMSO may be due to active grazing by zooplankton[24]. This is further supported by the presence of phaeophorbide in the samples (Figure 3), an indicator of active grazing on nanoplankton by zooplankton[25].

The community shift from non-diatoms to diatoms can be attributed to the introduction of new nutrients in the euphotic zone through entrainment of interstitial water as well as precipitation and run-off related to cyclone-induced mixing and rainfall. Higher growth rates of diatoms compared to other phytoplankton groups favour their predominance, once favourable conditions are created (high nutrients, especially silicate). Additionally, turbulence may reintroduce phytoplankton seed that had sunk down previously.
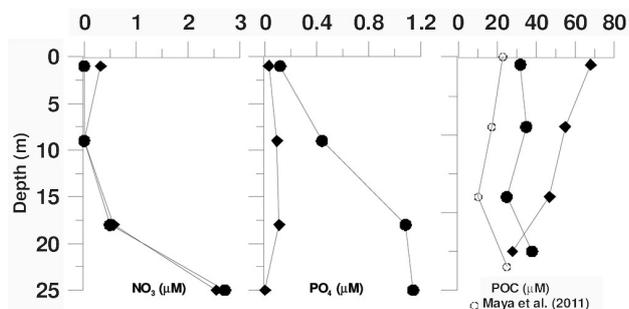

Figure 4. Vertical profiles of nutrient concentration and particulate organic carbon before (●) and after (◆) Phyan.

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Conservation of *Cremnoconchus* Blanford 1869, an iconic freshwater gastropod genus from the Western Ghats, India

N. A. Aravind[1,*], Roshmi Rekha Sarma[1] and N. A. Madhyastha[1,2]

[1]Ashoka Trust for Research in Ecology and the Environment, Royal Enclave, Srirampura, Jakkur Post, Bengaluru 560 064, India
[2]'Inchara', Srinivasa Nagara, Chitpadi, Udupi 576 101, India

Freshwater ecosystems in the Western Ghats are fragile and highly susceptible to environmental disturbances. The freshwater biota is particularly vulnerable because even the slightest change in habitat can lead to extinction. Freshwater gastropods are an important and diverse group in the freshwater ecosystem, accounting for about 20% of all metazoan animal recorded extinctions. The Western Ghats in India harbours an endemic genus of freshwater mollusc, *Cremnoconchus*. To date, 12 species of *Cremnoconchus* are known, and they are recorded only from the spray zones of waterfalls in the Western Ghats biodiversity hotspot. They are point endemic and confined to the western escarpments of the Ghats between 300 m to

*For correspondence. (e-mail: aravind@atree.org)