Enhanced biological production off Chennai triggered by October 1999 super cyclone (Orissa)

N. V. Madhu*, P. A. Maheswaran, R. Jyothibabu, V. Sunil, C. Revichandran, T. Balasubramanian, T. C. Gopalakrishnan and K. K. C. Nair

National Institute of Oceanography, Regional Centre, Dr Salim Ali Road, P.B. No. 1616, Kochi 682 014, India

The results of physical forcings on primary production, its variation and associated hydrography of the southwestern Bay of Bengal during the southwest monsoon (July) and post-cyclone period (November) of 1999 were studied as a part of Marine Research–Living Resources (MR–LR) assessment programme in the Indian EEZ. During the southwest monsoon coastal upwelling was prominent along 11°N (off Karaikal), whereas along 13°N and 15°N the signatures of upwelling were obscure. But in the post-cyclone period, the combined effects of well-mixed northwestern Bay of Bengal coastal waters and the freshwater injection from the land runoff associated with the cyclone brought nutrients to the mixed layer, which enhanced primary production along the southwestern Bay. A maximum of primary production (1229 mgC m^{-2} d^{-1}), chlorophyll-*a* (24.4 mg m^{-2}) and particulate organic carbon (68.7 g m^{-2}) was recorded along the coastal waters off Chennai (13°N) during this period.

MAJOR storms occurring in the world's oceans typically have duration of only a few days, but the physical and biological effects due to this perturbation can last up to several weeks[1–4]. The integrated effect from these storm events has the potential to account for a significant portion of ocean primary productivity, especially in areas where light is unlimited and the upper layer is nutrient-limited[5]. Nitrate, a limiting nutrient in many oceanic environments, can enter the euphotic zone directly as dissolved form through rainfall[6–8]. Alternatively, strong and sustained surface winds could entrain subsurface nutrients into the euphotic zone through wind-mixing[1,9,10]. Coastal upwellings occur mostly along the western coasts of the continents; exceptions to this pattern are found along the northeastern African coast, Somali coast, east coast of Arabia and to some extent in the east coast of India, etc. Upwelling occurs in varying intensities along the west coast and east coast of India during the southwest monsoon. Along the east coast of India, upwelling has been reported earlier at a few positions during the southwest monsoon[11,12].

The Bay of Bengal, which experiences the southwest monsoon during June to September and northeast monsoon during November to February, is a region of severe cyclones during intermonsoon periods (May and October). These cyclones and freshwater influx exert a strong influence on the surface water characteristics of the Bay of Bengal. The Bay of Bengal in general is considered as one of the least studied regions of the world oceans. The objective of the study is to delineate the upwelling areas along the southeast coast of India and the after-effects of freshwater influx induced by a super cyclone on primary production.

As a part of Marine Research–Living Resources (MR–LR) programme, *in situ* measurements were done in the southwestern Bay of Bengal on-board *FORV Sagar Sampada* during the southwest monsoon from 16 July to 10 August 1999 and northeast (November, two weeks after a super cyclonic storm[13] with a wind speed of 260 km/h hit the Orissa coast on 29 October 1999; see Figure 1 for the track of the cyclone) monsoon of 1999. Measurements included conductivity–temperature–depth (CTD) profiles, nutrients (nitrate, nitrite, phosphate and silicate), chlorophyll-*a*, particulate organic carbon (POC) and primary productivity. The samplings were made from seventeen hydrographic stations in three transects along 11°N (off Karaikal), 13°N (off Chennai) and 15°N (off Kavali) with nine primary productivity stations, three each in transects

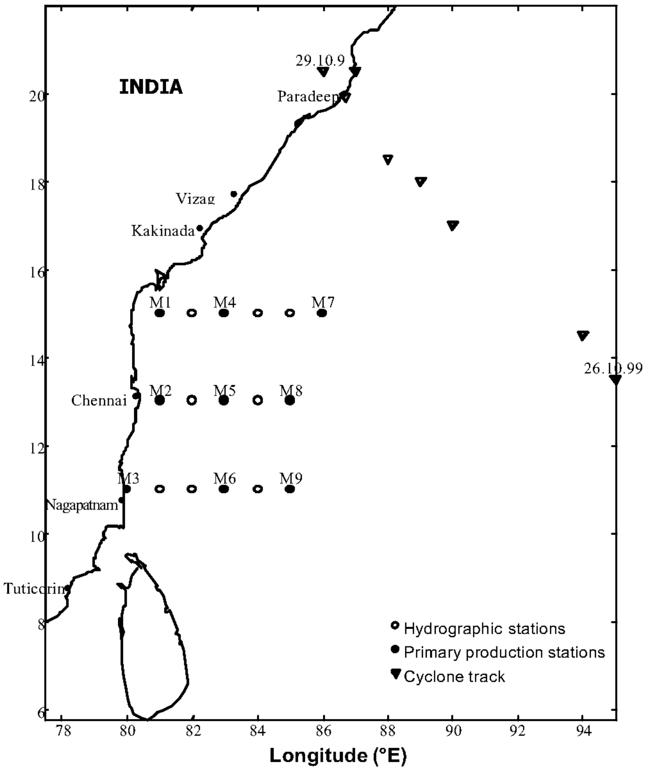

Figure 1. Station locations in July–August and November 1999 and cyclone track. A cyclonic storm centred at 13.5°N, 95°E moved in a northwesterly direction on 26 October 1999 and intensified to a very severe cyclonic storm and further to a super cyclonic storm which hit the Paradeep coast on 29 October 1999. After crossing the coast, it moved in a northwesterly direction and weakened gradually.

---

*For correspondence. (e-mail: madhu@niokochi.org)

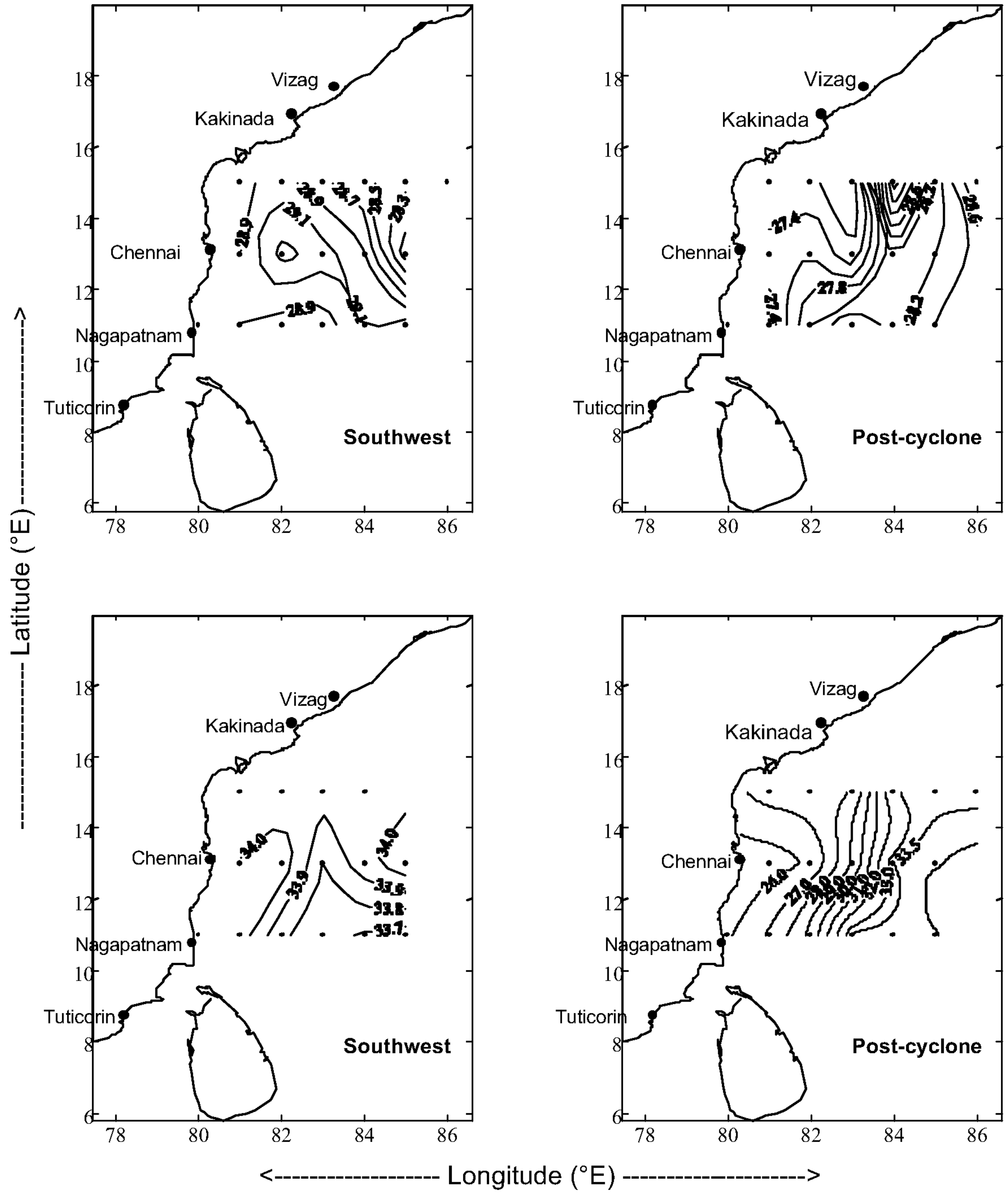

Figure 2. Distribution of sea surface temperature (°C) (top) and sea surface salinity (bottom) in the southwestern Bay of Bengal during southwest monsoon (left) and post-cyclone period (right), 1999. Note the change in contour interval in the bottom right panel.

as shown in Figure 1. The primary productivity stations were grouped into coastal (stations nearest to the coast M1, M2, M3), offshore (stations of longitude 83°E, M4, M5, M6) and open ocean (stations farthest from the coast, M7, M8, M9) in each transect.

A Sea Bird electronic CTD was used to obtain the temperature and salinity profiles. CTD salinities were calibrated against values obtained with a ship-borne autosal. The analysis of nitrate and silicate was done using an autoanalyser (Technicon). Nitrite and phosphate were measured spectrophotometrically using the method of Murphy and Riley[14]. Primary production was measured by deck incubation method using ^{14}C technique. Samples were collected from seven depths (0, 10, 20, 50, 75, 100 and 120 m) using 1.8 l Niskin sampler. Water samples were collected between 0500 and 0600 h; incubation experiments were conducted for 6 h. Appropriate neutral density filters were used to cover the light bottles to maintain approximate light intensity at various depths from which the samples were taken. Prior to incubation of ^{14}C series, 1 ml of NaH^{14}CO$_3$ was added to each sample (5 μCi per 300 ml sea water). After the desired duration, the samples were filtered through 47 mm GF/F (nominal pore size 0.7 μm) filters with gentle suction. The filter papers used were exposed to concentrated HCl fumes for removing excess inorganic carbon and kept in scintillation vials for later estimation of ^{14}C uptake. Liquid scintillation cocktail was added to the vials a day before analysis, and counted in Wallac scintillation counter. The disintegration per minute (DPM) values were converted into daily production rates (mgC m^{-3} d^{-1}). The daily production rates from various depths sampled were integrated to calculate column production (mgC m^{-2} d^{-1}).

Water samples were also collected from all standard depths as given above for chlorophyll-*a* estimation. One litre of water from each depth was filtered through GF/F (nominal pore size 0.7 μm) filters. Chlorophyll-*a* was estimated spectrophotometrically (Perkin-Elmer UV/Vis)[15] using 10 ml 90% acetone for extraction. For the measurements of POC, one litre of sea water was filtered through combusted GF/F filters and values were estimated using dichromate titration method[16].

During southwest monsoon, sea surface temperature (SST) showed an increase from offshore 28°C to 29.2°C towards inshore, while surface salinity showed an increase of 0.3 (Figure 2, left). SST distribution during post-cyclone period (Figure 2, right), in general showed a reverse trend with warmer waters offshore (28.6°C) and colder waters inshore (27°C). Interestingly, surface salinity distribution showed strong gradients with salinity ranging from 25.8 inshore to 33.8 offshore, over a span of 6° longitude (80°E to 86°E). A comparison with climatology[17,18] shows that the observed values are at least 2–5°C lower. Thermal structure along 11°N (off Karaikal) shows upsloping of isotherms towards the coast, indicating the signatures of subsurface upwelling during the southwest monsoon (Figure 3 *a*). During post-monsoon period, the cyclone and associated precipitation complexes the hydrography along the southeast coast of India. The thermal structure (Figure 3 *b*) shows a stable inversion layer, which is a common feature along the southeast coast of India due to freshwater influx[19]. The vertical distribution of salinity along 13°N (off Chennai) showed the freshwater influx in this area, which was as deep as 50 m near the coast and surfaced to 30 m offshore (Figure 3 *c*).

During the southwest monsoon, along 15°N and 13°N, the nitrate distribution showed an oligotrophic tendency in the upper 50 m (Figure 4 *a* and *c*), except along 11°N where 2 μM was seen to surface from ~30 m to ~20 m towards the coast (Figure 4 *e*). Additional evidence of upwelling observed along 11°N (off Karaikal) is seen when the 20 μM isopleth reaches at about 50 m, but along 13°N and 15°N it was between 80 and 90 m. During post-cyclone, the nutrient enriched land runoff causes the surfacing of 2 μM isopleths along the southeast coast of India (Figure 4, right).

The surface chlorophyll-*a* during southwest monsoon along the coastal, offshore and open ocean stations ranged between 0.16 and 0.38, 0.18–0.23 and 0.14–0.46 mg m^{-3}, and the corresponding column values were 6.7–16.1, 14.6–15.7 and 14.5–15.5 mg m^{-2} respectively. But during the post-cyclone period the surface as well as column-integrated chlorophyll-*a* showed high values at all the stations (Table 1). Maximum surface and column chlorophyll-*a* of 0.97 mg m^{-3} and 24.4 mg m^{-2} were recorded at station M2 (13°N, off Chennai) where the dilution due to freshwater influx was more during November (Figure 3 *c*). The surface chlorophyll-*a* during this period varied from 0.29 to 0.97, 0.3 to 0.49 and 0.22 to 0.29 mg m^{-3} in the coastal, offshore and open ocean respectively, and the corresponding column values were 11.4–24.4, 19.6–20.5 and 13.9–19.2 mg m^{-2} respectively.

Primary production was two to three folds higher during the post-cyclone period compared to that of southwest monsoon along the southeast coast of India. It was maximum at the surface in all the coastal stations (Figure 5), except at 11°N where maximum was recorded at 10 m. In the offshore and open ocean stations, the maximum primary production was observed between the surface and 20 m depth during both the seasons. The average surface primary production along the coastal, offshore and open ocean stations was 8.1, 4.7 and 2.8 mgC m^{-3} d^{-1} respectively during the southwest monsoon and a maximum of 9.4 mgC m^{-3} d^{-1} was recorded at the coastal station (M3), off Karaikal (Table 1). The corresponding average column primary production obtained was 270, 246 and 269 mgC m^{-2} d^{-1} respectively, with a maximum of 457 mgC m^{-2} d^{-1} recorded at the open ocean station M8 (along 13°N). The surface and column primary production was higher during November than during July, particularly along the coastal stations in all the three transects. During the post-cyclone period the average surface primary production obtained was 40.2, 20.9 and 7.4 mgC m^{-3} d^{-1} and the corresponding column primary production was 734, 833 and 528 mgC m^{-2} d^{-1} along the coastal, offshore and open ocean areas respectively. The maximum surface and column values of 69.1 mgC m^{-3} d^{-1} and 1229 mgC m^{-2} d^{-1} were recorded off Chennai. Both the surface and column primary production showed a decreasing trend towards open ocean from the coastal region during the post-cyclone period.

The values of POC at the surface and euphotic zone (0–120 m) during both the seasons are presented in Table 1. The average surface POC values during summer monsoon were 0.27, 0.41 and 0.27 g m^{-3} respectively from coastal to open ocean stations and the corresponding column values were 23.1, 24.6 and 20.1 g m^{-2}. The values of

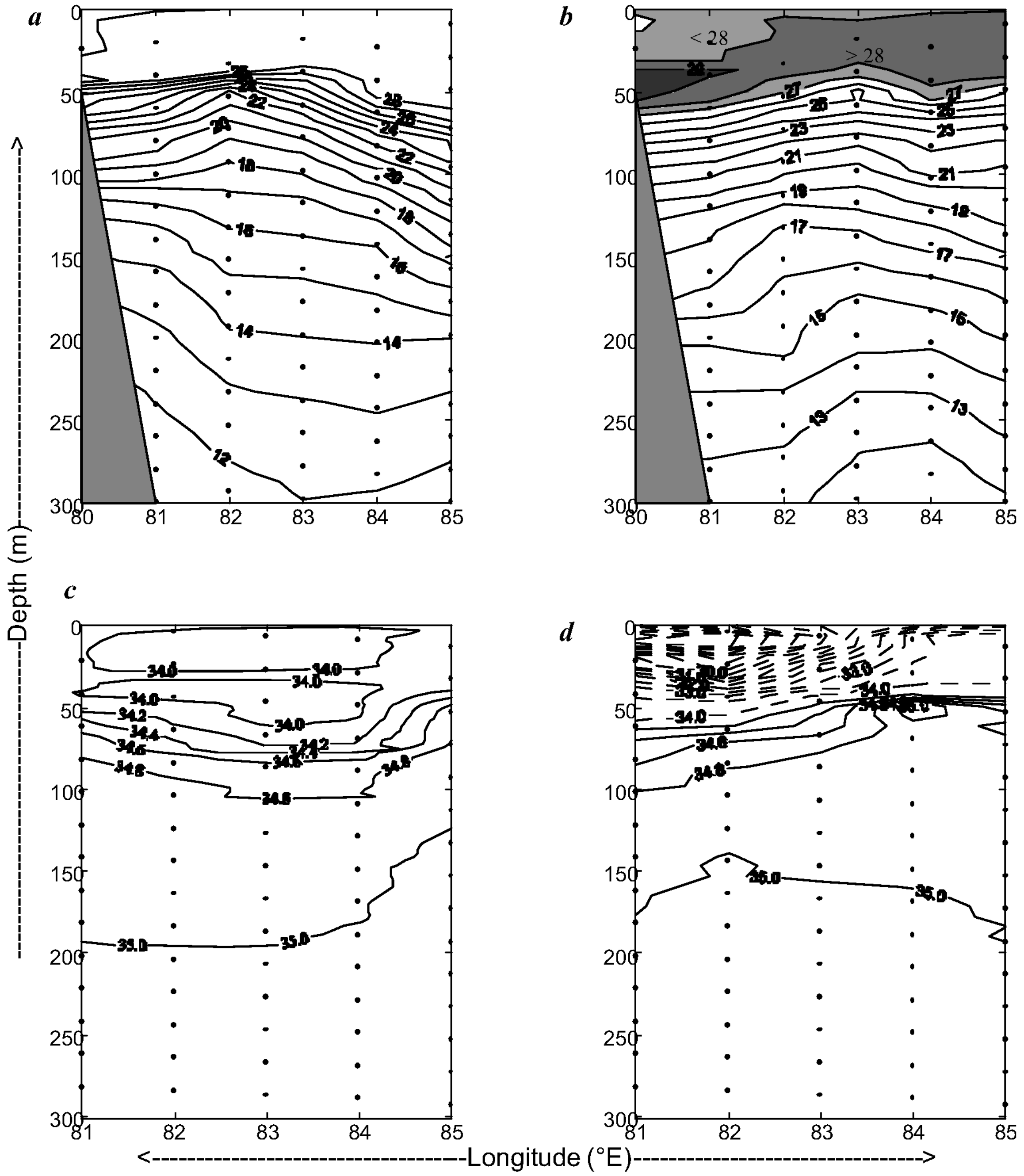

Figure 3. Distribution of temperature (°C) along 11°N during (*a*) southwest monsoon and (*b*) post-cyclone period. Distribution of salinity along 13°N during (*c*) southwest monsoon and (*d*) post-cyclone period. Dashed contours indicate the thickness of the low salinity water under the influence of freshwater discharge. Dark shaded region in (*b*) indicates thermal inversion.

surface and column POC obtained during November show that it was two to three times higher than those obtained during the southwest monsoon season (July), in accordance with higher primary production and chlorophyll values.

The results of the present investigation show the increase of primary production, chlorophyll-*a* concentration and POC, and some variation in physical and chemical parameters between the southwest monsoon and post-super cyclone period 1999 along the southwestern Bay of Bengal. Usually in July the winds are blowing from a southwesterly direction, favourable to upwelling along the east coast of India. In general, the ship drift climatology[20] shows a northerly current along the western boundary during July. Even though the wind direction and current pattern along 13°N and 15°N were favourable to the

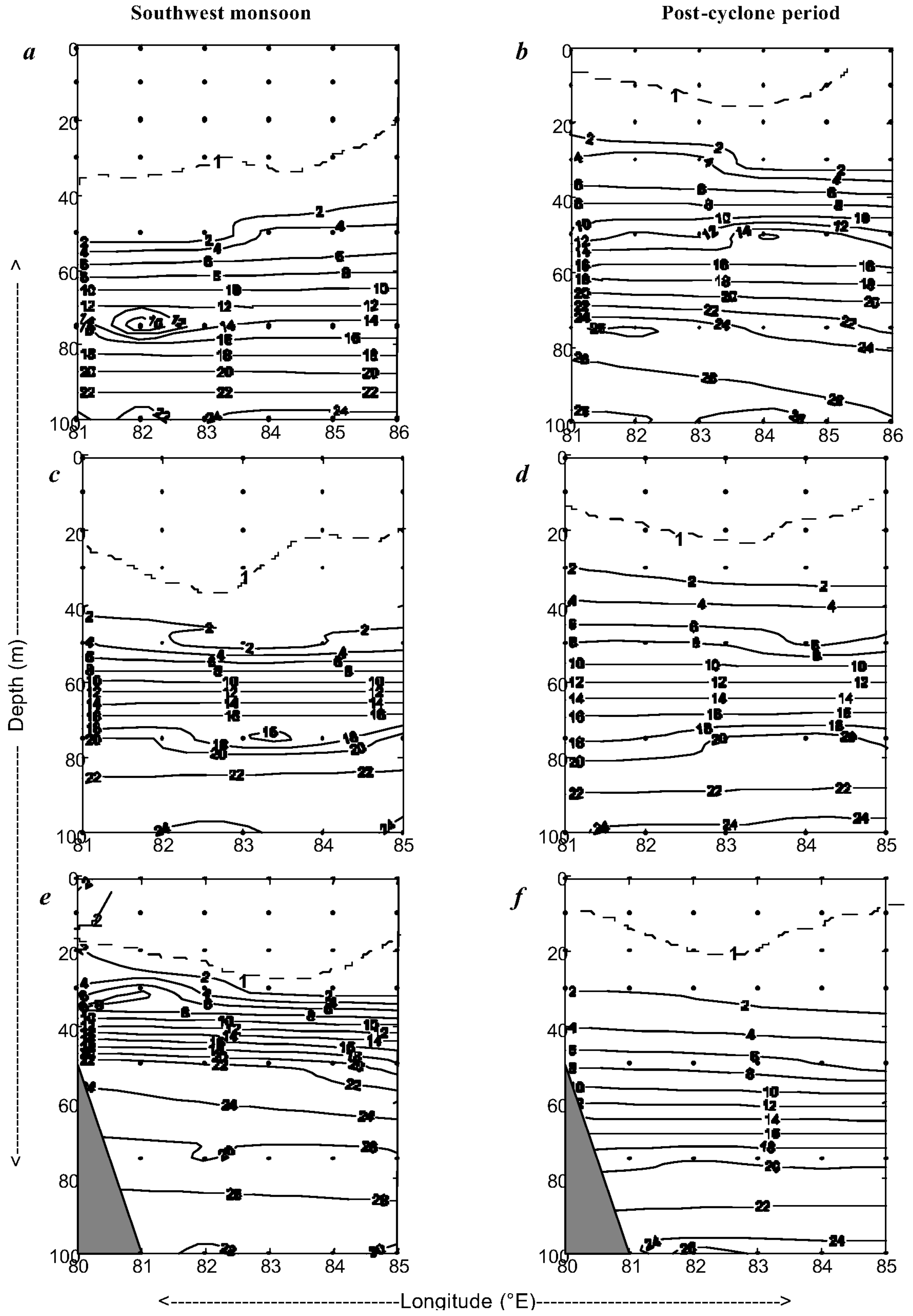

Figure 4. Vertical distribution of nitrate (μM) during southwest monsoon (left) and post-cyclone period (right) 1999 along 15°N (*a*, *b*), 13°N (*c*, *d*) and 11°N (*e*, *f*).

Table 1. Primary production, chlorophyll-*a* and POC in the southwestern Bay of Bengal during southwest monsoon and post-cyclone period 1999

	Primary production				Chlorophyll-*a*				POC			
	Surface (mgC m^{-3} d^{-1})		Column (mgC m^{-2} d^{-1})		Surface (mg m^{-3})		Column (mg m^{-2})		Surface (g m^{-3})		Column (g m^{-2})	
Station	I	II	I	II	I	II	I	II	I	II	I	II
M1	8.7	23.2	326	409	0.16	0.27	11.0	11.4	0.55	0.32	35.5	50.3
M2	6.3	69.1	274	1229	0.38	0.97	16.1	24.4	0.21	0.57	27.4	68.7
M3	9.4	28.2	211	566	0.27	0.52	6.7	10.9	0.04	0.57	6.3	6.2
Offshore												
M4	5.3	11.7	226	1057	0.23	0.48	15.1	20.5	0.52	0.82	31.5	68.1
M5	4	31.7	302	877	0.21	0.30	14.6	19.6	0.49	0.69	24.0	57.7
M6	4.9	19.2	210	565	0.18	0.49	14.9	19.9	0.23	0.25	18.3	90.4
Open ocean												
M7	2.1	3.2	231	423	0.20	0.22	15.5	19.2	0.32	0.95	27.8	48.5
M8	2.8	11.1	457	478	0.14	0.22	14.5	13.9	0.25	0.26	19.3	53.1
M9	3.5	7.9	120	683	0.46	0.29	15.3	16.7	0.25	0.38	14.4	65.4
Coastal												

I, Southwest monsoon; II, Post-cyclone period.

upwelling, the signatures of upwelling were obscure. Shetye *et al.*[21] suggested that wind forcing over the western boundary of the Bay of Bengal is not felt at all because the longshore wind stress and freshwater discharge are sufficiently strong to overwhelm the upwelling processes. But the southwestern boundary of the Bay, where the present studies were made, receives comparatively less river discharge compared to the northwestern boundary. However, along 11°N, relatively high productivity and chlorophyll-*a* were recorded in the coastal waters during the southwest monsoon (Figure 5). This was primarily due to the subsurface upwelling of nutrient-rich water, which makes the coastal region very productive (Figure 4*e*). During the southwest monsoon, the column chlorophyll-*a* and primary production values were 8 mg m^{-2} and 289 mgC m^{-2} d^{-1} along the continental shelf, 9.6 mg m^{-2} and 369 mgC m^{-2} d^{-1} along the continental slope and 8.2 mg m^{-2} and 240 mgC m^{-2} d^{-1} along the open ocean waters in the southeast coast of India. Comparing the present results of the column chlorophyll-*a* and primary production with those of Nair[22], the values reported were 13.7 mg m^{-2} and 295 mgC m^{-2} d^{-1} along the continental shelf, 16 mg m^{-2} and 315 mgC m^{-2} d^{-1} along the continental slope and 18.6 mg m^{-2} and 220 mgC m^{-2} d^{-1} along the offshore waters respectively of the east coast of India. The southeast coast of India is found to be less productive during the southwest monsoon, where the average values of column chlorophyll-*a*, primary production and POC were 13.7 mg m^{-2}, 262 mgCm^{-2} d^{-1} and 22.7 g m^{-2}, respectively.

During November, the coastal waters of the southwestern Bay of Bengal are rather complex with cyclonic, torrential rain and associated land runoff. Thickness of the freshwater pool varies from 40 to 50 m (Figure 3*c*) in the study area, which brings nutrients into the coastal waters, and which are further carried offshore (Figure 4*b*, *d* and *f*). Shetye *et al.*[21], using the ship-drifted charts given by Cutler and Swallow[20], observed a well-defined equatorward western boundary current in the Bay, which intensified in November. This western boundary current carries well-mixed, nutrient-rich waters from the northwestern Bay, where the cyclone mostly hits. The surface and column primary production and chlorophyll-*a* along the coastal waters of southwestern Bay of Bengal during the post-cyclone period were found to be fairly high (Figure 5), especially in the coastal station M2 (13°N, off Chennai). Here, the column primary production and chlorophyll-*a* recorded were 1229 mgC m^{-2} d^{-1} and 24.4 mg m^{-2}. But the undetectable levels of nitrate with high primary production and chlorophyll-*a* concentration in the surface layers may be due to the rapid biological uptake.

The Bay of Bengal is usually considered less productive compared to the Arabian Sea[22]. Although many major river systems bring in large quantities of nutrients, narrow shelf, heavy cloud cover and less light penetration have been attributed as the main reasons[23,24]. The primary production and chlorophyll-*a* were maximum in the surface layers at all stations during both the seasons (Figure 5). As stated by Radhakrishna *et al.*[23], this is primarily due to the low incident radiation reaching the sea surface in the Bay of Bengal, whereas in the Arabian Sea the chlorophyll-*a* maximum was generally seen in subsurface layers (40 m) as observed during JGOFS[25]. Our studies

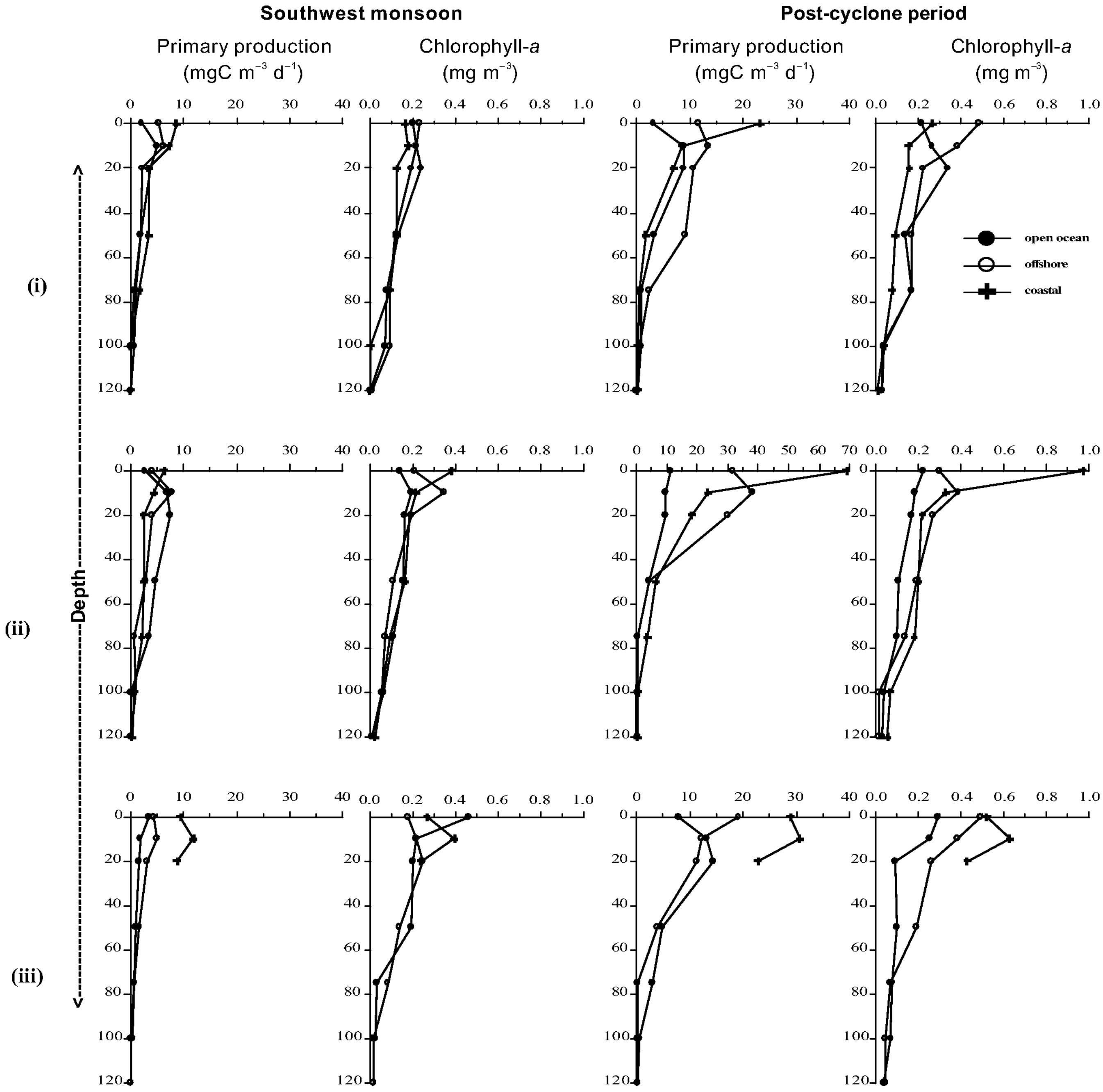

Figure 5. Vertical distribution of primary production and chlorophyll-*a* along (i) 15°N, (ii) 13°N and (iii) 11°N during southwest monsoon and post-cyclone period 1999 in southwestern Bay of Bengal at coastal, offshore and open ocean stations. See Figure 1 for station location.

reveal that in November the southeast coastal waters of India become biologically highly productive, with an average chlorophyll-*a*, 17.4 mg m^{-2}; primary production, 699 mgC m^{-2} d^{-1} and POC, 56.5 g m^{-2}. Comparing the earlier results of average primary production value of 440 mgC m^{-2} d^{-1} (inshore) and 300 mgC m^{-2} d^{-1} (offshore) during December 1991 along the east coast of India[26], the present average primary production values in November are very high (coastal, 734 mgC m^{-2} d^{-1}, offshore, 833 mgC m^{-2} d^{-1} and open ocean, 528 mgC m^{-2} d^{-1}). The increased biological production along the southeast coast, especially off Chennai was primarily due to the combined effect of nutrient-enriched land run-off and equatorward western boundary current along with a complementary effect of the super cyclone which hit the Orissa coast on 29 October 1999. This is supported by the results obtained from the IRS-P4 OCM-derived chlorophyll-*a* images along the Orissa coast during the post-cyclone period (6 November 1999)[27] further up the east coast, but needs more investigation.

1. Walsh, J. J., Whiteledge, T. E, Barvenik, F. W., Wirick, C. D., Howe, S. O., Esaias, W. E. and Scott, J. T., *Limnol. Oceanogr.*, 1978, **23**, 659–683.
2. Dagg, M. J., *Continent. Shelf Res.*, 1988, **8**, 167–178.
3. Furnas, M. J., Okaichi, T., Anderson, D. M. and Nemoto T., in *Red Tides: Biology, Environmental Science, and Toxicology*, Elsevier, 1989, pp. 273–276.
4. Gagan, M. K., Chivas, A. R. and Herczeg, A. L., *J. Sediment. Petrol.*, 1990, **60**, 456–470.
5. Di Tullio, G. R. and Laws, E. A., *Deep-Sea Res.*, 1991, **38**, 1305–1329.
6. Paerl, H. W., *Nature*, 1985, **315**, 747–749.
7. Willey, J. D. and Paerl, H. W., *Mar. Biol.*, 1993, **116**, 329–334.
8. Paerl, H. W. and Fogel, M. L., *ibid*, 1994, **119**, 635–645.
9. Pant, A. and Desai, B. N., in *Oceanography of the Indian Ocean*, Oxford and IBH, New Delhi, 1992, pp. 81–90.
10. Malone, T. C., Pike, S. E. and Conley, D. J., *Deep-Sea Res.*, 1993, **40**, 903–924.
11. Lafond, E. C., *Proc. Indian Acad. Sci., Sect. B*, 1957, **46**, 1–47.
12. Murty, C. S. and Varadachary, V. V. R., in Proceedings of the Symposium on the Indian Ocean, March 1967, Bulletin of National Institute of Science of India, 1968, vol. 38, pp. 80–86.
13. *INTERFACE, A Bulletin from the NRSA Data Center*, 1999, vol. 10.
14. Murphy, J. and Riley, J. P., *Anal. Chim. Acta*, 1962, **27**, 31–36.
15. Strickland, J. D. H. and Parsons, T. R., in *A Practical Handbook of Sea Water Analysis*, Bull. Fish. Res. Board Can., 2nd edn, 1972, vol. 167, p. 310.
16. Wakeel, El. and Riley, J. P., *J. Cons. Perm. Int. Explor. Mer.*, 1957, **22**, 180–183.
17. Wyrtki, K., *Oceanographic Atlas of the International Indian Ocean Expedition*, National Science Foundation, Washington DC, Amerind Publishing Co Pvt Ltd, New Delhi, 1988.
18. NODC World Ocean Atlas 1998 Grads image, http://www.cdc.noaa.gov/cgi-bin/GrADS.pl.
19. Pankajakshan, T., Gopalakrishna, V. V., Muraleedharan, P. M., Reddy, G. V. and Nilesh, A., in PORSEC-Proceedings, 2000, vol. 1, pp. 458–465.
20. Cutler, A. N. and Swallow, J. C., Tech. Rep. No. 187, Wormely, England, 1984, 36 charts, p. 8.
21. Shetye, S. R., Shenoi, S. S. C., Gouveia, A. D., Michael, G. S., Sundar, D. and Nampoothiri, G., *Continent. Shelf Res.*, 1991, **11**, 1397–1408.
22. Nair, P. V. R., *Cent. Mar. Fish. Res. Inst. Bull.*, 1970, **22**, 56.
23. Radhakrishna, K., Bhattathiri, P. M. A. and Devassy, V. P., *Indian J. Mar. Sci.*, 1978, **7**, 94–98.
24. Qasim, S. Z., *ibid*, 1977, **6**, 122–137.
25. Bhattathiri, P. M. A., Pant, Aditi, Sawant, Surekha, Gauns, M., Matondkar, S. G. P. and Mohanraju, R., *Curr. Sci.*, 1996, **71**,857–862.
26. Gomes, H. R., Goes, J. I. and Saino, T., *Continent. Shelf Res.*, 2000, **20**, 313–330.
27. Nayak, S. R., Sarangi. R. K. and Rajawat, A. S., *Curr. Sci.*, 2001, **80**, 1208–1212.

ACKNOWLEDGEMENTS. We thank the Director, National Institute of Oceanography (NIO), Goa for providing facilities for the study. We are grateful to Dr M. Madhupratap and Dr S. Prasanna Kumar, NIO, Goa, Mr P. Venugopal, NIO, RC, Cochin and Mr A. K. Sudheer, PRL, Ahmedabad for their valuable suggestions and encouragement. This investigation was carried out under the MR-LR programme funded by Department of Ocean Development, Govt. of India, New Delhi.

Received 5 July 2001; revised accepted 19 March 2002

Assessment of large-scale deforestation in Sonitpur district of Assam

Shalini Srivastava, T. P. Singh, Harnam Singh, S. P. S. Kushwaha* and P. S. Roy

Indian Institute of Remote Sensing, Dehradun 248 001, India

The study highlights the deforestation and encroachment in the moist deciduous and other forest areas in Sonitpur District of Assam. The time series analysis of satellite imagery was carried out. Satellite images of 1994, 1999 and 2001 and intensive ground truthing were used for forest type mapping and change detection. Alarming rate of conversion of well-stocked forests into cultivable land was noticed. The spatial distribution of forests showed progressive decline from 1994 to 2001 through 1999. The loss of forest cover was more pronounced between 1999 and 2001 than between 1994 and 1999. This coincides with increased levels of insurgency in lower Assam. An overall loss of 232.19 km^2 of forests was noticed in the Sonitpur District between 1994 and 2001. The study demonstrates unique potential of remote sensing and geographical information system for forest cover assessment and monitoring.

TROPICAL regions around the world are currently experiencing rapid, wide ranging changes in the land cover. The changes in the land cover, in particular the tropical deforestation, have attracted worldwide attention because of their potential effects on soil erosion, run-off and carbon dioxide level[1]. Large-scale deforestation has been reported in India in the past[2]. Forest cover in India has more or less stabilized after 1980 due to ban on clear felling. However, forest degradation and small-scale deforestation still continue. The loss of forest cover in India for the period between 1990 and 2000 is 380.89 km^2, annually as reported by FAO[3] and 1889 km^2 between 1991 and 1999 as reported by Forest Survey of India[4].

The state of Assam falls in the tropical climate belt in the northeastern region of India. The state is well known for its rich flora and fauna. Out of 15,000 flowering plants reported from India, 5000 grow in this region. The forest areas form a network of habitat patches in the primarily agricultural landscape of Assam. These forests fall in one of the two mega biodiversity hot spots identified in India, viz. the Western Ghats and the Eastern Himalayas. Recorded forest area is 3.07 million ha, which constitutes 39.15% of the geographical area of the state. According to the legal classification, reserved forests constitute 59%, protected forests 13% and unclassed forests 28% (ref. 4). Agriculture occupies a significant place in the economy of the state and forms the major occupation of the people. The average density of population per

---

*For correspondence. (e-mail: shalini_srivastava@hotmail.com)