JGOFS (India) – Introduction

The Joint Global Ocean Flux Study (JGOFS) is a core project of the International Geosphere–Biosphere Programme (IGBP), the main international scientific forum addressing issues pertaining to global change. The scientific goals of JGOFS were put together about a decade ago under the auspices of the Scientific Committee on Oceanic Research (SCOR). The main goals of JGOFS are:

- To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, the sea floor, and continental boundaries.
- To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climatic change.

To accomplish these goals a detailed implementation plan with specific scientific objectives have been formulated. One of the key components of this plan is *process studies* in selected *biogeochemical provinces* in the oceans which can significantly influence the global carbon budget. Among the biogeochemical provinces identified by the international JGOFS community, one of them is the Arabian Sea known for its high and seasonally oscillating biological productivity resulting from monsoon-driven circulation. In addition, the northern regions experience enhanced biological productivity in winter which has been attributed to convective overturning associated with winter cooling. One of the goals of the JGOFS programme is to assess the variations in primary and new production and the flux of carbon through the water column during different seasons, especially that arising from the monsoonal circulation. The effect of these physical and biological processes (upwelling, biological productivity) on the CO_2 air–sea exchange fluxes, carbon cycling in the water column and its burial in the sediments is not well understood and is a topic of considerable interest and debate among oceanographers. The international JGOFS community during the past 3–4 years have been conducting major campaigns in this oceanic region, particularly in the monsoon-induced upwelling areas of the western and central Arabian Sea to address the above issues.

The JGOFS (India) programme was seeded during the international symposium on the 'Oceanography of the Indian Ocean' held at the National Institute of Oceanography, Goa, January 1991. The Department of Ocean Development constituted a Steering Committee to generate, monitor and implement JGOFS programme in India. An interdisciplinary, multi-institutional project was formulated for JGOFS-related studies in India with focus on central and eastern Arabian Sea. Broadly the goals of the JGOFS (India) programme are (i) to assess the role of the Arabian Sea in the overall CO_2 air–sea exchange balance by determining the magnitude and direction of CO_2 air–sea exchange fluxes during different seasons; (ii) to determine the primary and new production rates, their spatial and temporal variations, the export flux of carbon from the euphotic zone and its relation to primary productivity, (iii) study of the records of deposition of carbon and other elements in the sediments of the Arabian Sea, particularly in its margin and their relation to water column processes; (iv) to investigate the role of margin sediments in influencing the chemistry of the Arabian Sea interior. Scientists from the National Institute of Oceanography (Goa), Physical Research Laboratory (Ahmedabad), National Chemical Laboratory (Pune) and Centre for Mathematical Modelling and Computer Simulation (Bangalore) are participating in JGOFS (India) programme.

The JGOFS (India) programme is currently in its mid-way. During the last two years it has completed three major sampling expeditions to the eastern and central Arabian Sea. The first cruise (SK-91) was undertaken during the pre-monsoon season, April–May, 1994. This was followed by a winter cruise (SK-99, February–March, 1995) and a monsoon cruise (SK-104, July–August, 1995). All these expeditions by and large followed the same track, however, sampling in the northern latitudes could not be done during the monsoon cruise because of logistical problems. In addition, a fourth expedition is currently underway (August, 1996) and a fifth one is planned for January, 1997.

This special section of *Current Science* contains the first collection of articles of the JGOFS (India) programme, most of the papers deal with the results from the intermonsoon (SK-91) and winter cruises (SK-99). The articles by S. Prasanna Kumar and T. G. Prasad (**page 834**) and by P. M. Muraleedharan and S. Prasanna Kumar (**page 842**) provide a comprehensive overview of the physical oceanography of the central and eastern Arabian Sea, including the near-coastal regions. Their results suggest that during winter, the northern Arabian

Sea surface waters experience densification due to excess evaporation over precipitation and turbulent heat loss in excess of radiative heat gain. This causes sinking and convection which pumps nutrients into surface waters from deeper layers, enhancing biological productivity. These studies demonstrate for the first time through direct observations the effect of winter cooling on the mixed layer dynamics of the northern Arabian Sea and associated enhancement in biological productivity.

The spatial and temporal variations in primary productivity and chlorophyll distribution are addressed in the article by P. M. A. Bhattathiri *et al.* (**page 857**). They observe that during winter the primary production and Chl *a* abundances in the northern latitudes were about a factor of two higher than those during the preceding intermonsoon season, consistent with that expected from changes in circulation. The highest productivity measured in this region (~ 800 mgC m^{-2} d^{-1}) is about a factor of 2–3 lower than that reported for the north western Arabian Sea during the SW monsoon, but is similar to that observed in the north Atlantic during the JGOFS North Atlantic Bloom Experiment.

Fundamental to all biological processes is the nature and availability of solar radiation in the ocean. This important aspect has been studied by T. Suresh *et al.* who measured (February–March, 1995) the photosynthetically available radiation in the eastern and central Arabian Sea. The peak values observed were in the range of 365 to 435 W m^{-2}. In addition, aerosol optical depth measurements yielded values form 0.07 to 0.19. These measurements have great relevance to remote sensing, validation of algorithms and models, and the peculiarity of the Arabian Sea where oscillation of high rates of primary productivity under more or less constant levels of solar radiation take place.

The articles by S. Sawant and M. Madhupratap (**page 869**), M. Madhupratap *et al.* (**page 863**), N. Ramaiah *et al.* (**page 878**) and M. Gauns *et al.* (**page 874**) discuss various issues pertaining to the abundance and distribution of phytoplankton and zooplankton, bacteria and micro-zooplankton respectively. The abundance of bacteria decreased drastically from intermonsoon to the winter season. The high abundance during the low productive intermonsoon period is probably sustained by the dissolved organic pool that may build up as the bloom tapers off. The standing stock of bacterial carbon during intermonsoon was significantly higher than that of phytoplankton, thus contributing to much of the POC in the region. The mezo-zooplankton abundance studies attest to the Arabian Sea paradox of its general invariance with productivity. This paradox, most likely results from the switch over of the feeding pattern of the mezo-zooplankton, from phytoplankton during productive seasons to microbial loop during oligotrophic periods. This is also attested by the observation that microzooplankton carbon was higher than meso-zooplankton standing stock.

The influence of water circulation and biological productivity on the nutrient and oxygen distribution in the water column are presented by S. N. De Sousa *et al.* (**page 847**). During winter, intense reducing conditions occur in the intermediate waters resulting from sluggish water movement coupled with higher biological productivity. The studies revealed the occurrence of nitrate reduction in all seasons in sub-oxic waters, which is maximum (10 μm) in winter.

The measurements of the air–sea exchange fluxes of the greenhouse gases, CO_2, CH_4 and N_2O are presented in the articles by V. V. S. S. Sarma *et al.* (**page 852**) and Shyam Lal *et al.* (**page 894**). The pCO_2 values in surface waters were generally higher or equal to those in the atmosphere, with values of about 420 μatm during winter and between 360 and 420 μatm during intermonsoon and monsoon seasons. These results suggest that the central and eastern Arabian Sea serve as a source of CO_2 to the atmosphere, typical flux being ~ a few m moles m^{-2} d^{-1}. Analogous to CO_2, this region of the Arabian Sea also supplies CH_4 and N_2O to the atmosphere, with higher fluxes during winter. The next step in these studies should be to have a better understanding of the various water column processes contributing to the production and consumption of these gases which would enable development of models to quantify their air–sea fluxes.

The application of ^{234}Th : ^{238}U disequilibria in the surface waters to derive information on particle and carbon export fluxes and time scales solute–particle interactions are discussed by M. M. Sarin *et al.* (**page 888**). They observe that the residence time of chemically reactive elements like Th in surface waters of the Arabian Sea is about a month. More importantly, these authors observe that the export flux of carbon at 100 m, estimated from (^{234}Th/C) ratios measured in sediment trap materials and ^{234}Th deficiency in the water column is significantly higher than primary productivity. These results raise concern about the source of carbon to the traps and the underlying assumptions in using ^{234}Th as a survey tool for estimating carbon export.

Another important area of study of the JGOFS (India) programme is the sedimentary record, which provide data on the temporal variations in the burial fluxes of several biogenically important elements, and their relation to water circulation and productivity history. A large number of sediment cores from the continental margin of the Arabian Sea have been collected and are being analysed for a number of diagnostic tracers to decipher the environmental history of sediment deposition and their role in regulating the distribution/removal of trace elements in the water column. The article by D. N. Yadav (**page 900**) addresses to one of the issues, viz. cycling of carbon in the sediments mediated through manganese.

Data management and modelling are two other areas of study which were initiated as a part of JGOFS (India) programme last year. The data and results of JGOFS (India) programme are stored and managed at the Indian National Oceanographic Data Centre (INODC) at NIO, Goa. Scientists from the Centre for Mathematical Modelling and Computer Simulation, Bangalore are in the process of developing a coupled basin scale model of the Arabian Sea circulation and biogeochemical cycles.

The results of these process studies hopefully will be incorporated into predictive models. However, long term continuous time series observations using moored data buoys with sensors which measure selected parameters would have to be deployed in the Arabian Sea to fully understand the biogeochemical processes. Ideally this should be supplemented by remote sensing techniques. Future work would thus have to be in this direction. In addition, work similar to the JGOFS could be initiated in the Bay of Bengal, which has its own unique and special oceanographic characteristics and which necessarily has to be investigated if one aspires to predict processes on a global scale.

The JGOFS (India) is funded by the Department of Ocean Development (DOD), New Delhi. We gratefully acknowledge the support, interest and encouragement received from DOD for the programme. Special thanks are due to Prof. V. K. Gaur, the then Secretary of DOD and the current Chairman of the JGOFS (India) Steering Committee whose personal interest has helped considerably in implementing this programme. Dr P. R. Rama Rao, former Secretary, DOD, Dr A. E. Muthunayagam, Secretary, DOD, Mr B. N. Krishnamurthy, Director, DOD, the members of JGOFS (India) Steering Committee, the Technical Evaluation Committee of *ORV Sagar Kanya*, Dr B. N. Desai, former Director of NIO, and Dr E. Desa, Director, NIO all have contributed to the programme and we acknowledge their support and encouragement. The articles in this special section were reviewed by national and international experts in the field, their reviews have helped considerably in improving the manuscripts. On behalf of JGOFS (India) programme, we thank all these reviewers.

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