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JOINT GLOBAL OCEAN FLUX STUDY

Results Are Coming In From JGOFS-India Cruises And Collaborative Projects In The Arabian Sea

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The Indian national programme for the Joint Global Ocean Flux Study (JGOFS-India), supported by the Department of Ocean Development in New Delhi, involves researchers and modelers at four laboratories: the National Institute of Oceanography (NIO) in Goa, the Physical Research Laboratory (PRL) in Ahmedabad, the National Chemical Laboratory (NCL) in Pune and the Centre for Mathematical Modelling and Computer Simulation (C-MMACS) in Bangalore. The first three laboratories are responsible for field and laboratory measurements, and the fourth is charged with the task of developing models.

The JGOFS-India research programme has concentrated primarily on the central and eastern Arabian Sea (Figure 1). Field work was carried out during five cruises aboard research vessel *Sagar Kanya*: two during winter monsoon seasons (February 1995 and 1997), one during an intermonsoon period (April-May 1994) and two during summer monsoon seasons (July-August 1995 and 1996). As a general rule, cruises included eight to 10 process-study stations that were at least 48 hours long as well as more frequent sampling for physical and chemical measurements. In the summer of 1995, however, we were unable to complete the open-ocean track because of unfavourable weather.

Conditions during the three seasons were very different. During the winter season, we observed mixed layers that were more than 100 meters deep throughout the northern Arabian Sea as a result of surface cooling. This cooling led to convective mixing and the injection of nutrients into the euphotic zone, substantially enhancing pigments and production.

The intermonsoon period, in con-

trast, was characterised by mixed layers of less than 30 meters depth and oligotrophic conditions. Bacterial and microzooplankton counts were at their highest in this season, however, showing a decoupling from primary production. We surmise that the high bacterial and microzooplankton biomass might be sustained by the dissolved organic carbon (DOC) that builds up after the winter bloom.

During the summer monsoons, we recorded rates of primary production as high as 1.7 grams of carbon per square meter per day ($\text{gC}/\text{m}^2/\text{d}$) in the coastal waters off Southwest India. The high rates are a result of upwelling in this region. Production was also moderately high in the open ocean, reaching $1.7 \text{ gC}/\text{m}^2/\text{d}$ at 15°N , 64°E . The positive wind-stress curl north of the path of the Findlater Jet resulted in a shoaling of the thermocline and an increase in the nutrient input into the euphotic zone.

Mesozooplankton biomass did not vary much between the seasons. It may be that the filter feeders are able to maintain biomass by feeding on microbes during times when phytoplankton are scarce. We found significant seasonal changes in subsurface oxygen and nitrate concentrations, indicating variable extents of denitrification, and attributed these differences primarily to changes in circulation.

Carbonate system parameters also varied considerably in space and time. The most significant finding was that the study region appears to be a perennial source of carbon dioxide to the atmosphere. We found transparent exopolymer particles in high concentrations within the denitrifying layer, which indicates that sufficient organic carbon is available to meet bacterial demand in these waters. These par-

ticles are produced through condensation of dissolved polysaccharides and cannot be detected with a nephelometer.

Measurements of nitrous oxide (N_2O) and methane showed fairly high supersaturations in surface waters, but the sea-to-air fluxes of these gases varied both seasonally and spatially. Radioactive isotopic measurements revealed nearly uniform rates of scavenging via sinking particles in the central Arabian Sea. Thorium-234 measurements suggested that the particle fluxes determined from sediment trap samples could be systematically low and that the estimated carbon supply was incompatible with measurements of production in the water column.

Many of the results from the JGOFS-India cruises in the Arabian Sea have been published in a special issue of *Current Science*, Vol. 71, No. 11 (Dec. 10, 1996). Some copies are available for distribution; those interested should contact M. Madhupratap via electronic mail at madhu@csnio.ren.nic.in

Indo-U.S. Collaborative Study

In addition to the JGOFS-India programme, biogeochemical research in the Arabian Sea is also being conducted as part of a joint Indo-U.S. collaboration supported by the U.S. Office of Naval Research. Principal investigators on this project are Wajih Naqvi of NIO, Louis Codispoti of Old Dominion University, Allan Devol of the University of Washington, Bess Ward of the University of California at Santa Cruz (UCSC) and Tadashi Yoshinari of the State University of New York at Albany.

Under this programme, six cruises have been undertaken since April 1994 aboard research vessels *Sagar Sampada* and *Sagar Kanya* during various sea-

sons. Sampling during these cruises focused on carbon-nitrogen dynamics in oxygen-depleted waters, using a variety of isotopic, enzymatic, microbiological and molecular techniques.

Repeated sampling at fixed stations along a roughly zonal transect off Goa and at three other sites within the denitrification zone (Figure 2) provided a measure of temporal changes in the mid-depth redox environment. We observed substantial variations in the chemical composition of the water column down to a depth of approximately 1 kilometer (km). An important factor contributing to these changes is the production and spreading of the outflow from the Persian Gulf. This outflow seems to serve as a significant source of oxygen for the subsurface waters of the northwestern Arabian Sea, regulating the extent of denitrification in this region.

We measured the activities of the respiratory electron transport system (ETS) and nitrate reductase (NR) at a number of stations. These analyses provide a measure of the overall respiration potential and reduction of nitrate by microorganisms. The highest NR activities were usually associated with the secondary nitrite peak in the water column, but maximum levels of NR and ETS were often vertically separated.

Characterisation of the suspended particles that comprise the pronounced intermediate nepheloid layer associated with denitrification forms another important component of our work. Basing

our sampling on light transmission profiles, we carried out intensive sampling within the upper 1 km of the water column at a number of stations. Total bacterial counts revealed that the intermediate nepheloid layer was invariably associated with an intense mid-depth peak in bacterial biomass. This finding supports the view that bacterial proliferation in low-oxygen waters may be the principal cause of the enhanced turbidity characteristic of these waters. Most of these bacteria are expected to be denitrifiers; evidence for this is being sought through application of specific molecular probes developed at UCSC.

We are carrying out analyses of the natural abundance of nitrogen isotopes in nitrate and molecular nitrogen (N_2) and nitrogen and oxygen isotopes in N_2O at several locations. We observed a marked depletion of nitrogen-15 (^{15}N) relative to nitrogen-14 (^{14}N), the more abundant stable isotope of nitrogen, in the N_2 within the denitrifying layer along with increased levels of ^{15}N in the nitrate.

These variations in the ratio of ^{15}N to ^{14}N were accompanied by large increases in the ratio of dissolved nitrogen to argon, which provides evidence of intense production of N_2 through denitrification. Measurements of isotopic composition revealed enrichments in both ^{15}N and oxygen-18 (^{18}O) relative to the more common oxygen-16 (^{16}O) in the N_2O found in the second-

ary nitrite maximum zone that are by far the largest reported from any natural environment. This denitrifying layer, however, appears to be effectively isolated from the atmosphere by an overlying layer with high concentrations of N_2O that is less rich in these heavier isotopes.

We have also made the first measurements of both $^{15}N/^{14}N$ and $^{18}O/^{16}O$ ratios in N_2O from an intense upwelling zone off the southwest coast of India where some of the highest concentrations of N_2O ever found at the sea surface and saturations up to 950% were observed. These revealed that while N_2O emitted from the eastern-boundary environments is moderately depleted in ^{15}N , it is enriched in ^{18}O relative to the atmosphere.

These results have two important implications for the global cycling of N_2O , which is an important greenhouse gas. The scarce data on the ratio of isotopes in the stratosphere suggests a large downward flux of N_2O rich in ^{15}N and ^{18}O into the troposphere, and it has been suggested that exchanges with the ocean, where light N_2O may be produced through nitrification, could help achieve the isotopic mass balance. However, our results show that the oceans cannot counteract enrichment of the heavier and rarer isotopes, particularly ^{18}O , in the stratospheric N_2O . Thus there must be additional sources and/or sinks of N_2O in the atmosphere.

Second, the isotopic ratios in the upper layers of the Arabian Sea are difficult to explain conventionally, through production by either nitrification or denitrification. A coupling between the two processes through some common intermediates may be important for the enhanced production of N_2O in this region and similar environments. ♦

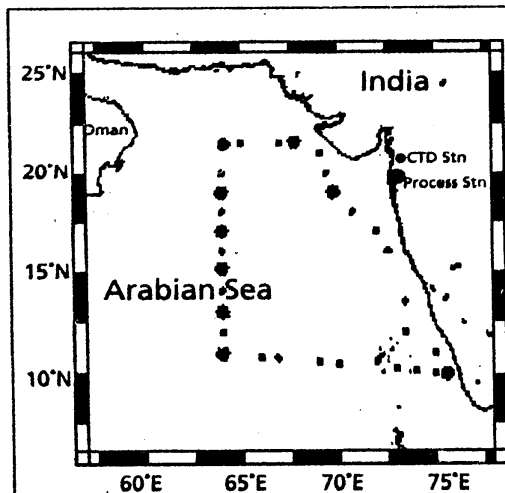


Figure 1: JGOFS-India stations in the Arabian Sea.

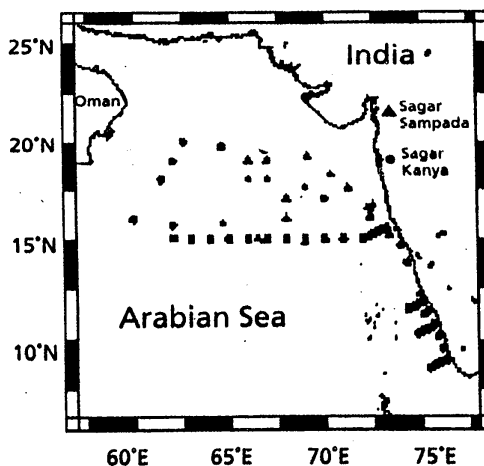


Figure 2: Indo-U.S. study stations in the Arabian Sea.