The Arabian Sea: carbon cycle response to strong, predictable physical forcing

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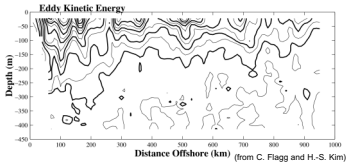
Abstract

At the time the JGOFS expeditions to the Arabian Sea were organized in the early 1990's, first-order issues such as whether or not the Arabian Sea was a sink or a source for atmospheric carbon dioxide were still unclear. Did high rates of primary productivity and large concentrations of sedimentary carbon make it a sink or were these processes overwhelmed by outgassing of carbon dioxide arising from the warming of deeper waters reaching the sea surface via upwelling and mixing? We now have answers to these questions, as well as understanding of many other important processes affecting the carbon cycle in the Arabian Sea. These include seasonality in microbial loop processes, bacteria and total organic carbon; the response of primary productivity to simultaneous atmospheric input of iron and upwelling of nitrogen; the role of physical forcing in the distribution of biological properties and the oxygen minimum zone; potential control of phytoplankton blooms and vertical flux by large-bodied grazers; and strong seasonality in export flux to the seabed. When the Arabian Sea Process Studies ended in 1997, more than 80 research cruises had been carried out, with cruises mounted by Germany, India, Pakistan, UK and USA focused on the northern Arabian Sea while the Netherlands tackled the Somali Current system.

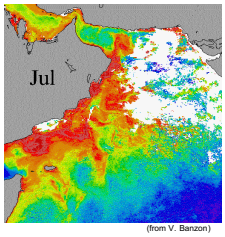
The Arabian Sea Process Study, the first JGOFS study to investigate an annual carbon cycle, discovered pronounced seasonal and spatial variability. Carbon dioxide outgassing due to upwelling during the SW Monsoon (313 mmol C/m^2/month) was roughly half the carbon exported to depth (562 mmol C/m^2/month) in that season. The areal extent of the Arabian Sea acting as a carbon sink is approximately twice the size of the Arabian Sea acting as a carbon source for the atmosphere. The largest pool of carbon, total organic carbon (TOC), was in greatest concentration in the SW Monsoon season (11.5 mol C/m^2).

Strong physical forcing from the Findlater Jet during the SW Monsoon resulted in a dramatic eddy field between the coast and 600 km offshore.



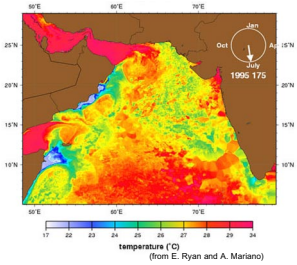
(from C. Flagg and H.-S. Kim)

Distributions of biological properties (chlorophyll *a*)…



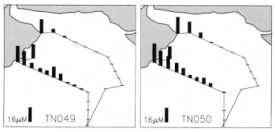
(from V. Banzon)

physical properties (sea-surface temperature, SST)…



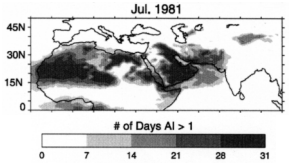
(from E. Ryan and A. Mariano)

and associated variables such as nutrients all showed the importance of mesoscale surface forcing in shaping the ocean's response during the SW Monsoon.



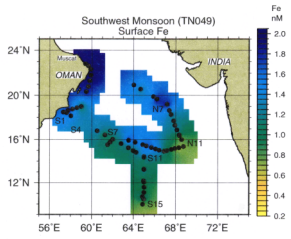
Average inorganic nitrogen concentrations ($NO_3 + NO_2 + NH_4$) in the 0-25 db layer during the SW Monsoon (from Morrison *et al.*, 1998).

The coincidence of upwelling-favorable winds and dust in the atmosphere during the SW Monsoon,



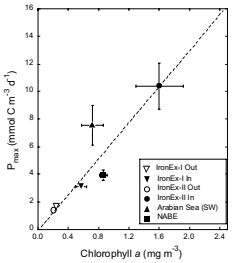
Index of atmospheric dust in the global dust belt as identified by the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. The scale shows the number of days during the month of July, 1981 when the AAI equals or exceeds 1.0. The authors used a threshold of 1.0 in order to supress the almost constant background of blowing dust over much of this region (from Prospero *et al.*, 2002).

result in elevated upper layer concentrations of iron, nitrate and silicate north of approximately 15˚N.



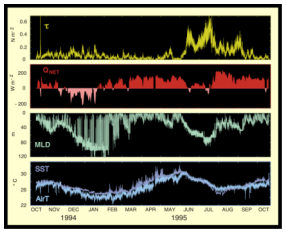
Contoured mixed layer distribution of Fe concentration for cruise TN049, July 17 - August 15. (from Measures and Vink, 1999). Note the congruence of the dust field over the northern Arabian Sea and the area of elevated surface iron concentrations.

This annually recurring, predictable set of circumstances result in phytoplankton populations that fix more carbon per unit chlorophyll *a* than phytoplankton in any other natural, oceanic environment.



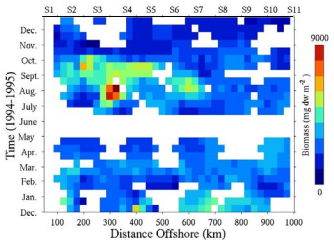
The correlation of maximum primary productivity and chlorophyll *a* biomass measured in a variety of environments (data provided by R. Barber).

Seasonally reversing monsoon winds cause vigorous coastal upwelling and an eddy field in the SW Monsoon and strong convective mixing during the NE Monsoon.

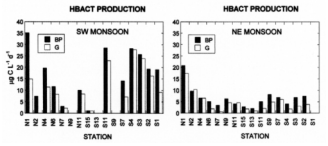


Annual (October 1994 – October 1995) sea-surface forcing and response at a mooring located at 15.5ºN, 61.5ºE in the Arabian Sea. From top to bottom, hourly values of wind stress (τ; yellow), daily average net heat flux (W m^{-2}; red/pink), mixed layer depth (meters, based on the depth at which temperature is 0.1ºC cooler than the surface; green), sea-surface temperature (ºC; dark blue), and air temperature (ºC; light blue). Figure redrawn from Weller *et al.*, 2002.

Zooplankton biomass, heterotrophic bacteria production,

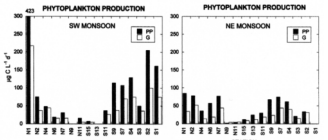


Annual distribution of integrated ADCP biomass in the upper water column (20-120 m) during daytime as a function of along track distance on the south line and time. Gaps in the distribution resulted when along-transect locations were not sampled. No cruises took place in May and most of June (from Ashjian *et al.*, 2002).



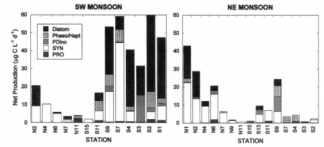
Spatial distributions of daily heterotrophic bacteria production (BP) rates and grazing losses to protists (*G*) from dilution experiments in the surface mixed layer. Rates are determined from FCM-measured changes in the heterotrophic bacteria community (from Brown *et al.*, 2002).

primary production and protistan grazing all showed peaks within 600 km of the coast during the SW Monsoon. The biological response to convection during the NE Monsoon was smaller in magnitude, and spatially more widespread in the study area; both the phytoplankton and zooplankton community compositions were different in the NE Monsoon compared with the SW Monsoon.



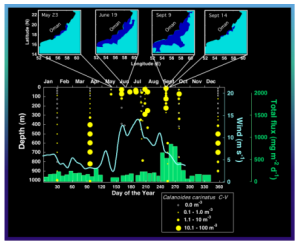
Spatial distribution of total community daily primary production rates (PP) and grazing losses to protists (G) from dilution experiments in the surface mixed layer. Rates are based on the sum of HPLC-measured monovinyl and dvinyl chlorophyll *a*. Stations N1-N3 and S1-S4 were within 400 km of the coast (from Brown, *et al.*, 2002).

Diatoms dominated primary production in the coastal upwelling area and associated eddy field during the SW Monsoon. Stations affected by convection during the NE Monsoon (~N1-N3; ~S6-S10) showed primary production dominated by *Synechococcus* spp., diatoms and *Phaeocystis* spp. Strong contrasts between the SW and NE Monsoon seasons were obvious in community composition of picoplankton, phytoplankton and mesozooplankton (Garrison *et al.*, 2000; Brown *et al.*, 2002; Campbell, *et al.*, 1998; Smith, 2001; Latasa and Bidigare, 1998).



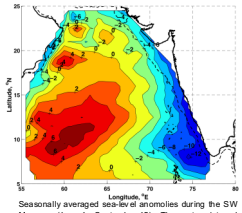
Spatial distribution of net phytoplankton carbon production (*P-G*) and component taxa (from Brown *et al.*, 2002).

Total export flux and carbon export flux were highest at the termination of the SW Monsoon season.



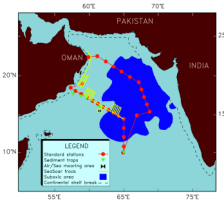
Arabian Sea: annual (1995) cycle of wind speed (light grey line) measured by a mooring positioned at 15° 30´N, 61° 30´ E (redrawn from Weller *et al.*, 1998); of total particulate flux (green bars) measured by a sediment trap at 858 meters positioned at 17° 13´ N, 59° 36´ E (redrawn from Honjo *et al.*, 1999); of vertical distribution of the copepod *Calanoides carinatus* stage V (yellow circles) collected throughout the northern Arabian Sea from Somalia to Oman (Somali data provided by M. Baars; June data for Oman derived from samples collected by M. Wood; remainder collected by S. Smith). Insets at the top show sea-surface temperature off Oman obtained by the advanced very high resolution radiometer (AVHRR) at various times during the upwelling season in 1995. Darker blue depicts the area of cool sea-surface temperatures (redrawn from Smith *et al.*, 1998). Note how quickly the sea-surface warms following cessation of upwelling-favorable winds in September.

The spatial distribution of the intensity of the eddy field, decreasing from southwest to northeast in the Arabian Sea,



Seasonally averaged sea-level anomolies during the SW Monsoon (June 1 - September 15). The contour interval is 2 cm (from Kim *et al.*, 2001).

and the geographical position of the oxygen minimum zone (OMZ)…



suggest the possibility that reduced eddy energy allows enhanced settlement of organic particles in the northeastern Arabian Sea. Particles arising from upwelling production could be carried offshore and eastward until reduced eddy energy (and coagulation perhaps) creates conditions for particles to settle into the subsurface OMZ.

Acknowledgements. Arabian Sea JGOFS participants generously shared their ideas and data throughout the expedition and continue to do so. Most of the figures in this poster can be found in the five special issues of *Deep-Sea Research II* (volumes 45,46, 47, 48, 49) devoted to the Arabian Sea Expedition.