

Figure 14.4c Sea surface temperatures (MCSST), total flux, and carbonate, biogenic opal and organic carbon fluxes measured at the eastern trap location.

matter is the aeolian transport from the deserts of the Arabian peninsula and Somalia during the SW monsoon (Sirocko and Sarin, 1989; this volume, Chapter 3). During the NE monsoon aeolian transport also occurs from the Thar Desert. During this season, however, the amount delivered to the Arabian Sea is much less compared to that delivered during the SW monsoon (Chester et al., 1984).

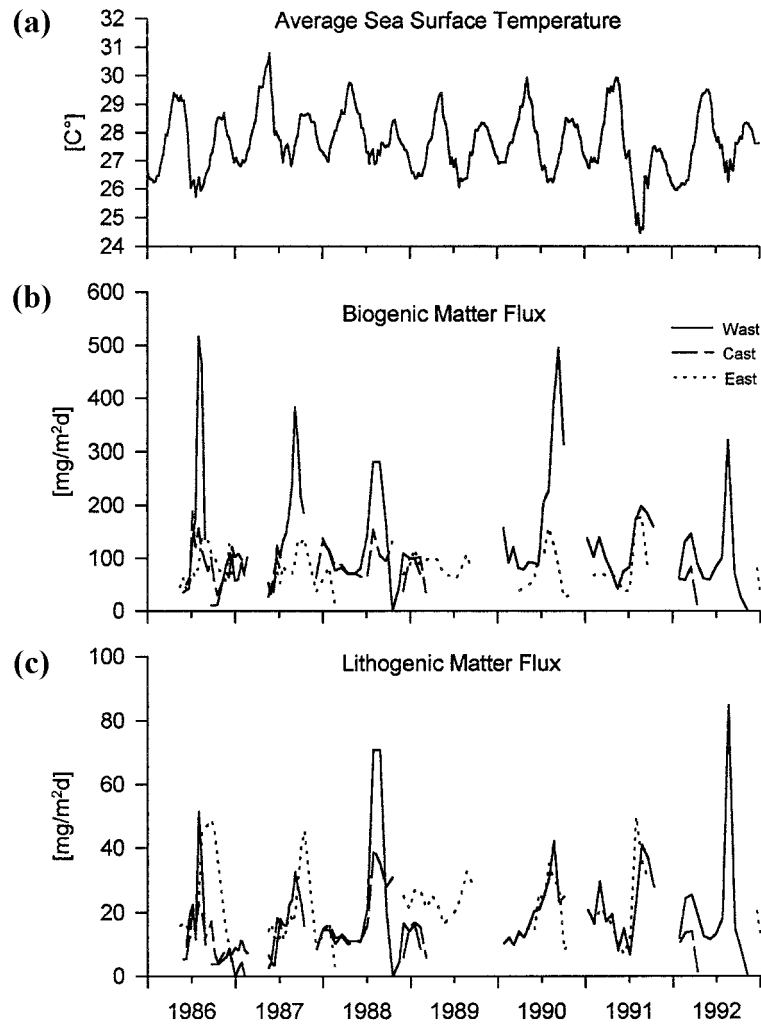


Figure 14.5 (a) Seasonality of average sea surface temperatures in the Arabian Sea from MCSST charts, (b) biogenic matter fluxes and (c) lithogenic matter fluxes at the three trap locations measured at 3000 m water depth from 1986 to 1992.

In contrast to flux patterns of biogenic matter those of lithogenic matter are similar at all three trap locations (Figure 14.5) suggesting a common source. The western trap collected higher lithogenic fluxes than the central, a feature, which may be explained by a reduction of lithogenic fluxes with increasing distance from the source areas of aeolian material, west of the Arabian Sea. However, the eastern trap which is farther away from the source of the aeolian material, collected more material in 1986 and 1987 and very similar amounts as the western trap in 1990 and 1991. The source area of this lithogenic matter can often be deduced from the clay mineral assemblage. Both, aeolian material and fluvial particles from the Indus are basically illite dominated (Kolla et al., 1981). However, aeolian material has a higher content of palygorskite originating from local sources on the Arabian Peninsula (Kolla et al., 1981). The fluvial material derived from the Narmada and Tapti has a higher smectite content related to weathering on the Deccan Plateau. Based on smectite content Ramaswamy et al. (1991) have estimated that less than 5% of riverine material from the Narmada and Tapti can escape the shelf areas and is transported to the deep sea. Similarly, lithogenic matter transported by the Indus is mainly being deposited on the wide continental shelf and does not influence the deep sea (Sirocko and Sarnthein, 1989). The clay mineral assemblages in sediment trap samples do not show any distinct differences between the three stations. Palygorskite and smectites are almost equally high in the eastern, central and western Arabian Sea (Ramaswamy et al., 1991). The high palygorskite and low smectite contents support the suggestion that the major amount of mineral matter is aeolian in origin and that fluvial contributions are relatively small even in the eastern Arabian Sea (Ramaswamy et al., 1991). The amount of aeolian material reaching the western and eastern Arabian Sea is evidently similar, despite the different distances from the source areas. The reason for this may be the rains. Monsoon rainfalls are extremely low in the western and central Arabian Sea but are almost as high as in the coastal areas in the eastern Arabian Sea (Rixen, in prep.). As rains effectively remove mineral matter, similar amounts of aeolian material can reach the eastern and western part of the basin, though the latter is much closer to the source areas of aeolian material.

Peak lithogenic fluxes in 1986 and 1987 occurred at the eastern site in October/November after the end of SW monsoon. Therefore these peaks are not related to SW monsoon aeolian transport but could be due to resuspension on the Indian continental margin and to riverine transport. Such peaks, decoupled from the flux patterns in the central and western Arabian Sea, could be typical of very weak monsoons.

14.5.2 SOURCES AND DECOMPOSITION OF ORGANIC MATTER

The distribution of individual organic compounds can provide information about the sources of organic matter as well as pathways and intensities of organic matter decomposition. Ratios of individual compounds and statistical analyses of compound distributions have been used to decipher the sources of organic matter (Cowie and Hedges, 1994; Moers and Larter, 1993; Reemtsma et al., 1993). The identification of sources is, however, difficult as only a small portion of the multitude of organic constituents can be identified and quantified. Amino acids, hexosamines, carbohydrates and fatty acids are the major constituents of marine and terrigenous organic matter (Rashid, 1985). In particles caught by sediment traps in deep water, amino acids and carbohydrates can contribute up to 50% to total organic carbon (Ittekkot et al., 1984a, b) whereas the fatty acid contribution is around 1% (Reemtsma et al., 1990). Most of the individual amino acids and carbohydrates and many of the fatty acids are ubiquitous as they are essential for animal and plant life. However, since they are easily degradable organic constituents, their contents and spectral distributions may in many cases reflect degradation rather than the source of the organic matter.

Fatty acids determined in the central Arabian Sea during the SW monsoon are predominantly marine. Minor contributions from long chain fatty acids indicate terrestrial input most probably of aeolian origin (Reemtsma et al., 1990). A relative increase of terrigenous markers from shallow to deep sediment trap is due to their higher stability compared to short chain fatty acids which are largely marine in origin.

Spectral distributions of carbohydrates (Figure 14.6) are very similar to those observed in other trap experiments from the deep marine environment (Ittekkot et al., 1984a, b). They do not suggest any significant contribution of terrigenous material which would be indicated for example by high arabinose or glucose contents

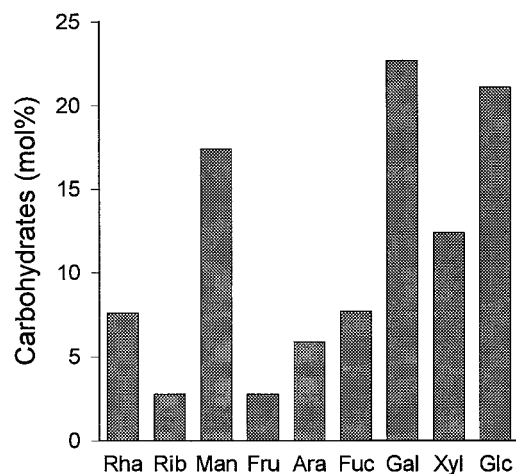


Figure 14.6 Average spectral distribution of carbohydrates (in mol %) of all trap samples collected between May 1986 and November 1987 in the Arabian Sea.

(Hedges et al., 1994, Ochiai et al. 1988). A predominance of marine over terrigenous organic matter is generally observed in sinking particulate matter from the open marine environment. This is even true in the northern Bay of Bengal (Reemtsma et al., 1993) where fluvial material can make up more than 60% of total fluxes (Ittekkot et al., 1991; this volume, Chapter 15). Due to its higher stability terrigenous organic matter may become quantitatively more important in the sediments (Ittekkot, 1988).

Organic carbon, amino acid, fatty acid and hexosamine contents are low during high flux periods (Figure 14.7). This could be due (i) to the lower organic matter content of primary produced material, (ii) to dilution with inorganic matter or (iii) to the stronger decomposition of organic matter in the water column. Reemtsma et al. (1990) found stronger decomposition of fatty acids when fluxes were higher during the SW monsoon period of 1986. Comparing SW, NE and intermonsoons for the whole period between 1986 and 1990 their findings could be confirmed for amino acids and hexosamines (Rixen et al., in prep.). Similarly, biogenic indicators such as the ratio of aspartic acid to β -alanine (Asp/ β -Ala) revealed that organic matter was more labile when total material fluxes were higher, such as during bloom periods (Haake et al., 1992). It is thus likely that organic matter decomposition in the water column is more intense during blooms since the settling material is more labile. Carbohydrate contents did not decrease during high flux periods (Figure 14.7) and may be less affected by decomposition in the water column.

Total organic carbon, fatty acids, amino acids, hexosamines and carbohydrates are being decomposed between the shallow and deep traps (Table 14.1). The loss rates were greatest for fatty acids and smallest for carbohydrates and hexosamines. Whereas the contributions of fatty acids and amino acids to total organic carbon (FA-C%, AA-C%) decreased considerably with water depth, those of carbohydrates and hexosamines (CHO-C %, HA-C %) remained almost constant or increased slightly. Preferential loss of nitrogenous compounds was regularly observed with increasing depth in the water column and in the sediments. This was reflected in the increasing C/N ratios and decreasing contents of AA-C % from fresh plankton to the sediments (Rixen and Haake, 1993). AA-C % can be used in combination with C/N to compare intensities of alteration and diagenetic stage of organic matter of mixed origin and from different environments (Figure 14.8) (Cowie and Hedges, 1994).

The preferential loss of amino acids might be induced by higher activity of the enzyme protease compared to other digestive enzymes such as chitinase or glucosidase so that amino acids are solubilized and made available for bacterial uptake much faster than hexosamines and carbohydrates (Smith et al., 1992). Contents of branched chain fatty acids (Reemtsma et al., 1990) and the

hexosamine galactoseamine (Haake et al., 1992) relatively increase in particulate matter samples between the shallow and deep traps. Both are indicators of the

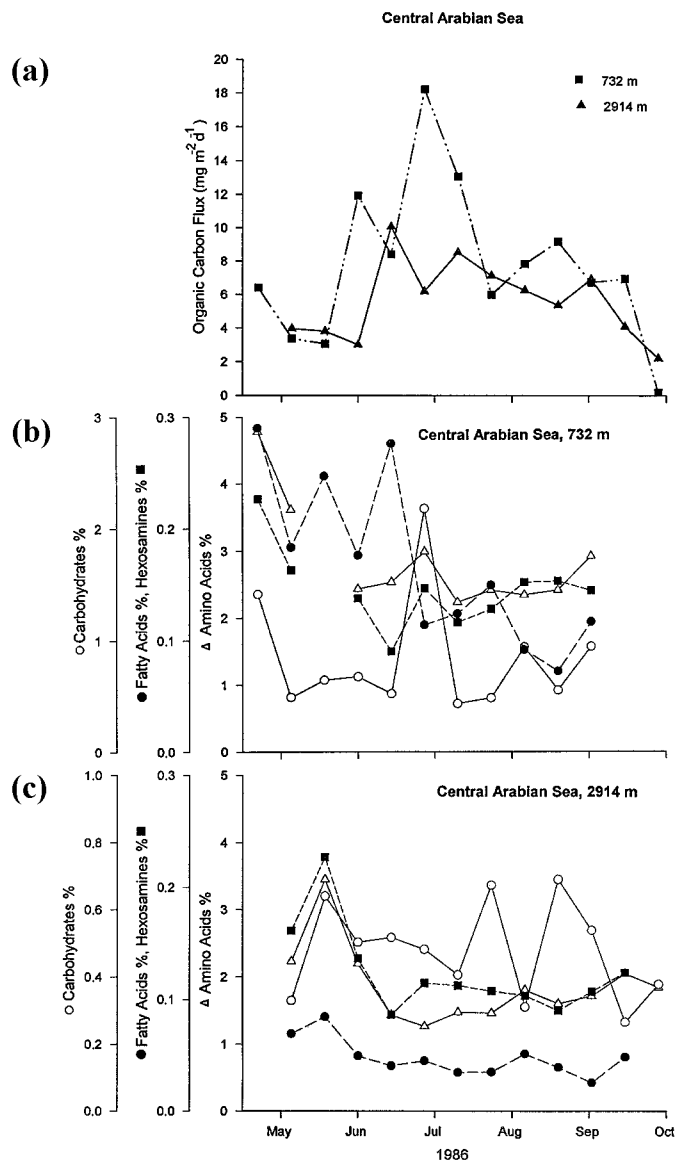


Figure 14.7 (a) Organic carbon fluxes at 732 m and 2914 m water depth between May and October 1986, and percentages of carbohydrates, hexosamines, fatty acids and amino acids in the trap (b) at 732 m and (c) at 2914 m in the central Arabian Sea.

Table 14.1 Total amino acid (AA), hexosamine (HA), carbohydrate (CHO) fluxes measured between May 1986 and October 1987 at the western (WAST), central (CAST) and eastern (EAST) trap locations in the shallow and deep traps. Contents of AA, HA, CHO and fatty acids (FA) are given in mg g^{-1} for the whole period, AA-C %, HA-C %, CHO-C % and FA-C % represent the contributions of the organic constituents to total organic carbon.

	WAST		CAST		EAST	
	1040 m	3020 m	850 m	2900 m	1455 m	2770 m
AA-Flux ($\text{mg m}^{-2} \text{y}^{-1}$)	1277	852	908	399	417	388
HA-Flux ($\text{mg m}^{-2} \text{y}^{-1}$)	107	66	76	43	30	29
CHO-Flux ($\text{mg m}^{-2} \text{y}^{-1}$)	286	180	201	104	124	114
AA (mg g^{-1})	30.3	22.0	36.4	22.5	20.9	17.8
HA (mg g^{-1})	2.6	1.7	3.1	2.4	1.5	1.4
CHO (mg g^{-1})	6.8	4.7	8.1	5.9	6.2	5.2
AA-C %	18.6	16.7	19.9	15.6	14.1	12.9
HA-C %	1.2	1.0	1.3	1.3	0.8	0.8
CHO-C %	3.9	3.3	4.1	3.8	3.9	3.7
FA (mg g^{-1}) *			1.4	0.4		
FA-C % *			1.3	0.5		

* Fatty acid data are for samples collected between May and October 1986.

accumulation of bacterial biomass on sinking particles suggesting that bacteria play a key role in organic matter decomposition.

14.5.3 INTERANNUAL VARIATIONS

The monsoons vary interannually in their intensities; i.e., in their wind speeds, precipitation and timing of arrival and retreat (e.g., Singh, 1994; Khandekar, 1991). Very little research has been done on the NE monsoon as it is much weaker and in most parts not associated with rains. In contrast, the SW monsoon precipitation over India, its duration, amount and seasonal distribution has been studied in detail for a long time. It has been stated that a stronger monsoon on land (i.e., a monsoon with higher amounts of precipitation) must be associated with a stronger Findlater Jet (Findlater, 1969). Systematic investigations of this phenomenon are, however, scarce (Dube et al., 1990).

The precipitation over India is measured at hundreds of rain gauges every year and averaged for the whole country (e.g., Singh, 1994). The deviation of this average from the long term mean precipitation can give an idea of the relative intensity of a monsoon (given as the Monsoon Index, MI). The Monsoon Indices

for 1986 to 1992 (from Singh, 1994) revealed a significantly positive correlation with annual average lithogenic fluxes at the western and central trap sites (Figure

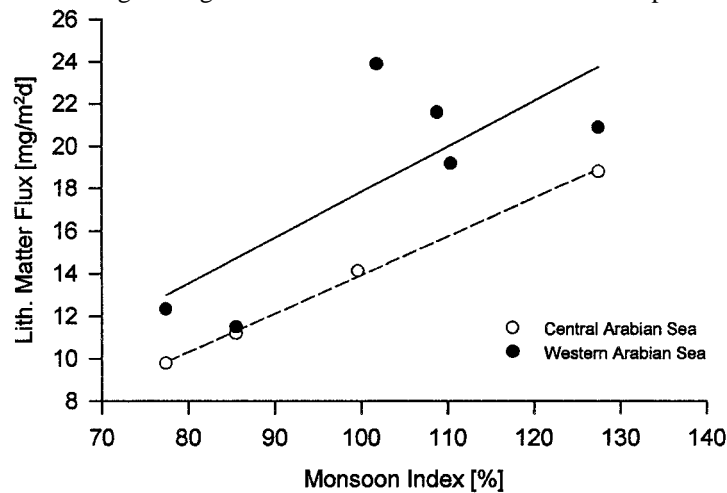


Figure 14.9 Monsoon Index (%) versus annual averages of lithogenic fluxes ($\text{mg m}^{-2} \text{d}^{-1}$) for six years in the western (1986–88, 1990–92) and four years in the central (1986–88, 1992) deep traps.

14.9). Stronger winds during SW monsoons and higher precipitation led to the transport of more dust from the continents to the ocean. In the eastern Arabian Sea there was no relationship between MI and lithogenic fluxes, most probably due to the interference of lithogenic matter of resuspended or fluvial origin which was observed in some of the years of investigation after the retreat of the SW monsoon in October/November (see above). These findings suggest that the total amount of lithogenic matter could be a proxy-indicator of monsoon intensity at locations not affected by near-bottom lateral transport.

14.5 CONCLUSIONS

Monsoon related processes are responsible for the particle flux patterns found in the deep Arabian Sea. The difference between the three stations is large for biogenic fluxes as one of them is influenced by upwelling and, therefore, receives higher amounts of biogenic matter than the other two. Lithogenic fluxes are quite uniform over the basin and consist mainly of aeolian material from desert areas west of the Arabian Sea.

Organic matter in sinking material is of predominantly marine origin throughout the year. During bloom periods the material reaching the deep ocean is more

labile and its decomposition in the deep ocean is, therefore, enhanced compared to the periods of lower fluxes. As amino acids are preferentially degraded, C/N ratios in combination with amino acid carbon percentages can be used to define intensity of alteration and diagenetic stage of organic matter. Tracers of bacterial biomass as well as the difference in stability of amino acids, carbohydrates and hexosamines indicate that bacteria play a key role in organic matter decomposition.

Total annual lithogenic fluxes are positively related to monsoon strength. Its use as a proxy-indicator for SW monsoon intensity in short term studies has to be checked carefully as the lateral transport in the nepheloid layer may alter the accumulation of lithogenic matter in sediments. For long-term studies changes in land vegetation have to be taken into account.

14.6 ACKNOWLEDGMENTS

MCSST data were obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory/California Institute of Technology. Help from Dr. P. Schlüssel and S. Ewald in processing MCSST data is gratefully acknowledged. We thank the mechanical and electronic engineers of the National Institute of Oceanography, Goa, and the University of Hamburg for technical assistance, the officers and crew of the research vessels R/V *Sagar Kanya* and R/V *Sonne* for their help in the deployments and recoveries of the mooring systems. Financial support for the ongoing Indo-German sediment trap program was provided by the Federal Ministry for Education, Science, Research and Technology (BMBF, Bonn), the German Research Council (DFG, Bonn, Grant It 6/1-1, 2, 3), the Council of Scientific and Industrial Research (CSIR, New Delhi) and the Department of Ocean Development (DOD, New Delhi).

14.7 REFERENCES

- Allredge, A. L. and M. W. Silver (1988) "Characteristics, dynamics and significance of marine snow", *Prog. Oceanogr.*, **20**, 41-82.
- Borole, D. V., M. M. Sarin and B. L. K. Somayajulu (1982) "Composition of Narmada and Tapti estuarine particles and adjacent Arabian Sea sediments", *Indian J. Mar. Sci.*, **11**, 51-62.
- Brock, J. C., C. R. McClain and W. W. Hay (1992) "A southwest monsoon hydrographic climatology for the northwestern Arabian Sea", *J. Geophys. Res.*, **97**, 9455-9465.
- Chester, R., E. J. Sharples and G. S. Sanders (1984) "The concentration of particulate aluminum and clay minerals in aerosols from the northern Arabian Sea", *Journ. Sed. Petrol.*, **55**, 37-41.
- Cowie, G. L. and J. I. Hedges (1994) "Biochemical indicators of diagenetic alteration in natural organic matter mixtures", *Nature*, **369**, 304-307.
- Curry, W. B., D. R. Ostermann, M. V. S. Guptha and V. Ittekkot (1992) "Foraminiferal production and monsoonal upwelling in the Arabian Sea: Evidence from sediment traps", in C. P. Summerhayes, W. L. Prell and K. C. Emeis (eds) *Upwelling Systems: Evolution Since the Early Miocene*, Geological Society Special Publication No. 64, 93-106.

- Degens, E. T. and V. Ittekkot (1984) "A new look at clay-organic interactions", in E. T. Degens, W. A. Krumbein and A. A. Prashnowsky (eds) *Festband Georg Knetsch*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg No. 56, 229–248.
- Deuser, W. G. (1986) "Seasonal and interannual variations in deep-water particle fluxes in the Sargasso Sea and their relation to surface hydrography", *Deep-Sea Res.*, **33**, 225–246.
- Deuser, W. G., F. E. Müller-Karger, R. H. Evans, O. B. Brown, W. E. Esaias and G. C. Feldman (1990) "Surface-ocean color and deep-ocean carbon flux: how close a connection?", *Deep-Sea Res.*, **37**, 1331–1344.
- Deuser, W. G., E. H. Ross and R. F. Anderson (1981) "Seasonality in the supply of sediment to the deep Sargasso Sea and implications for the rapid transfer of matter to the deep ocean", *Deep-Sea Res.*, **28**, 495–505.
- Dube, S. K., M. E. Luther and J. J. O'Brien (1990) "Relationship between interannual variability in the Arabian Sea and Indian Summer monsoon rainfall", *Meteorol. Atmos. Phys.*, **44**, 153–165.
- Findlater, J. (1969) "A major low-level air current near the Indian Ocean during the northern summer", *Quart. J.R. Met. Soc.*, **95**, 362–380.
- Haake, B., V. Ittekkot, V. Ramaswamy, R. R. Nair and S. Honjo (1992) "Fluxes of amino acids and hexosamines to the deep Arabian Sea", *Mar. Chem.*, **40**, 291–314.
- Haake, B., V. Ittekkot, T. Rixen, V. Ramaswamy, R. R. Nair and W. B. Curry (1993) "Seasonality and interannual variability of particle fluxes to the deep Arabian Sea", *Deep-Sea Res.*, **40**, 1323–1344.
- Hedges, J. I., G. L. Cowie, J. E. Richey, P. D. Quay, R. Benner, M. Strom and B. R. Forsberg (1994) "Origins and processing of organic matter in the Amazon River as indicated by carbohydrates and amino acids", *Limnol. Oceanogr.*, **39**, 743–761.
- Honjo, S. (1978) "Sedimentation of materials in the Sargasso Sea at a 5,347 m deep station", *J. Mar. Res.*, **36**, 459–492.
- Honjo, S., S. J. Manganini and J. J. Cole (1982) "Sedimentation of biogenic matter in the deep ocean", *Deep-Sea Res.*, **29**, 609–625.
- Ittekkot, V. (1988) "Global trends in the nature of organic matter in river suspensions", *Nature*, **332**, 436–438.
- Ittekkot, V. (1993) "The abiotically driven biological pump in the ocean and short-term fluctuations in atmospheric CO₂ contents", *Global Planet. Change*, **8**, 17–25.
- Ittekkot, V. and R. Arain (1986) "Nature of particulate organic matter in the river Indus, Pakistan", *Geochim. Cosmochim. Acta*, **50**, 1643–1653.
- Ittekkot, V., E. T. Degens and S. Honjo (1984a) "Seasonality in the fluxes of sugars, amino acids and amino sugars to the deep ocean: Panama Basin", *Deep-Sea Res.*, **31**, 1071–1083.
- Ittekkot, V., W. G. Deuser and E. T. Degens (1984b) "Seasonality in the fluxes of sugars, amino acids and amino sugars to the deep ocean: Sargasso Sea", *Deep-Sea Res.*, **31**, 1057–1069.
- Ittekkot, V., R. R. Nair, S. Honjo, V. Ramaswamy, M. Bartsch, S. Manganini and B. N. Desai (1991) "Enhanced particle fluxes in Bay of Bengal induced by injection of freshwater", *Nature*, **351**, 385–387.
- Khandekar, M. L. (1991) "Eurasian snow cover, Indian monsoon and El Niño/Southern oscillation - a synthesis", *Atmosphere-Ocean*, **29**, 636–647.
- Kolla, V., J. A. Kostecki, F. Robinson, P. E. Biscaye and P. K. Kray (1981) "Distribution and origin of clay minerals and quartz in surface sediments of the Arabian Sea", *J. Sed. Petrol.*, **51**, 563–569.
- Lee, C. and C. Cronin (1984) "Particulate amino acids in the sea: Effects of primary productivity and biological decomposition", *J. Mar. Res.*, **42**, 1075–1097.

- Moers, M. E. C. and S. R. Larter (1993) "Neutral monosaccharides from a hypersaline tropical environment: Applications to the characterization of modern and ancient ecosystems", *Geochim. Cosmochim. Acta*, **57**, 3063–3071.
- Molnar, P., P. England and J. Martinod (1993) "Mantle dynamics, uplift of the Tibetan Plateau, and the Indian Monsoon", *Rev. Geophys.*, **31**, 357–396.
- Nair, R. R., V. Ittekkot, S. J. Manganini, V. Ramaswamy, B. Haake, E. T. Degens, B. N. Desai and S. Honjo (1989) "Increased particle fluxes to the deep ocean related to monsoons", *Nature*, **338**, 749–751.
- Ochiai, M., M. Ogino, K. Sasaki and T. Okazawa (1988) "Behaviour of particulate carbohydrates and amino acids in the estuary of the Tama river", *Mar. Chem.*, **25**, 265–278.
- Ramaswamy, V., R. R. Nair, S. J. Manganini, B. Haake and V. Ittekkot (1991) "Lithogenic fluxes to the deep Arabian Sea measured by sediment traps", *Deep-Sea Res.*, **38**, 169–184.
- Rashid, M. A. (1985) *Geochemistry of Marine Humic Compounds*, Springer, Berlin, 300 pp.
- Reemtsma, T., B. Haake, V. Ittekkot, R. R. Nair and U. H. Brockmann (1990) "Downward flux of particulate fatty acids in the Central Arabian Sea", *Mar. Chem.*, **29**, 183–202.
- Reemtsma, T., V. Ittekkot, M. Bartsch and R. R. Nair (1993) "River inputs and organic matter fluxes in the northern Bay of Bengal: Fatty acids", *Chem. Geol.*, **103**, 55–71.
- Rixen, T. and B. Haake (1993) "Fluxes and decomposition of organic matter in the western Arabian Sea: Amino acids and hexosamines", in V. Ittekkot and R. R. Nair (eds) *Monsoon Biogeochemistry*, Mitt. Geol.-Paläont. Inst. Univ. Hamburg 76, 113–130.
- Sirocko, F. and M. Sarnthein (1989) "Wind-borne deposits in the Northwestern Indian Ocean: Record of Holocene sediments versus modern satellite data", in M. Leinen and M. Sarnthein (eds) *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, NATO ASI Series C., 282, Kluwer Acad. Publ., Dordrecht, 401–433.
- Singh, N. (1994) "Optimizing a network of rain-gauges over India to monitor summer monsoon rainfall variations", *Internat. J. Climatol.*, **14**, 61–70.
- Smith, D. C., M. Simon, A. L. Alldredge and F. Azam (1992) "Intense hydrolytic enzyme activity on marine aggregates and implications for rapid particle dissolution", *Nature*, **359**, 139–141.
- Wakeham, S. G., C. Lee, J. W. Farrington and R. B. Gagosian (1984) "Biogeochemistry of particulate organic matter in the oceans: Results from sediment trap experiments", *Deep-Sea Res.*, **31**, 509–528.
- Wyrtki, K. (1973) "Physical oceanography of the Indian Ocean", in B. Zeitzschel (ed) *The Biology of the Indian Ocean*, Springer, Berlin, 18–36.