# 14 Processes Determining Seasonality and Interannual Variability of Settling Particle Fluxes to the Deep Arabian Sea

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## 14.1 INTRODUCTION

Sediment traps are a tool for sampling particulate matter in the water column (see this volume, Chapters 5 through 7). The development of time-series traps has, moreover, enabled us to determine the temporal variations in particle fluxes at intervals from hours to weeks. Such data collected at various oceanic stations have improved our knowledge about oceanic processes such as the mechanisms leading to settling of fine grained particulate matter in the ocean (Honjo, 1978), the coupling between surface processes and sedimentation in the deep sea (Deuser, 1986; Deuser et al., 1990) and degradation of organic matter in the water column (Lee and Cronin, 1984; Wakeham et al., 1984). Long-term sediment trap studies such as the Sargasso Sea experiment (Deuser, 1986; this volume, Chapter 9) or the trap investigations in the northern Indian Ocean (Nair et al., 1989; Haake et al., 1993) can be utilized to study the relationship between climatic variations and sedimentation in the deep sea.

Sediment trap investigations have been carried out in the Arabian Sea since 1986 (Nair et al., 1989; Haake et al., 1993). Here we will give an overview on the influence of climatic processes on sedimentation in the Arabian Sea basin and summarize the information obtained about the sources of organic matter and its decomposition pathways in the water column.

## 14.2 STUDY AREA

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The monsoons are strong atmospheric circulations which have evolved since the Miocene in southern Asia due to the uplift of the Himalayas and which determine the climate of the region (e.g., Molnar et al., 1993). During the northern hemisphere summer, the Tibetian Plateau is heated so that a low pressure cell forms, which reverses the normally occurring Hadley circulation cell and leads to strong SW winds at the surface (SW monsoon: June-September). These winds blow from the sea to the continent and thus bring seasonal rains to a large part of southern Asia. Over the western part of the Indian Ocean a low-level jet stream evolves which flows from south of the equator, touches coastal Kenya and turns SW to the Arabian Sea where it forms the area of maximum wind speed parallel to the Arabian Peninsula (Findlater, 1969). Its second branch turns to the east and blows south of India and into the Bay of Bengal. During the dry NE monsoon (November-March) the winds blow roughly in opposite direction. The overall wind pattern leads to a semiannual reversal of surface water circulation in the northern Indian Ocean from clockwise during the SW monsoon to anti-clockwise during the NE monsoon. During the SW monsoon upwelling occurs along the coasts of Somalia and the Arabian Peninsula as well as spatially along the west coast of India (Wyrtki, 1973). An area of open ocean upwelling has its maximum upward Ekman transport below the Findlater Jet in the western Arabian Sea (Brock et al., 1992). Upwelling and wind-induced mixing result in a cooling of surface waters during both monsoons.

## 14.3 METHODS

Mark VI time-series sediment traps have been deployed since 1986 in the western (16°20’N, 60°30’E), central (14°30’N, 64°45’E) and eastern (15°30’N, 68°45’E) Arabian Sea (Figure 14.1). During most of the sampling period mooring systems consisted of 2 traps each with a shallow trap at depths between 750 m and 1000 m and a deep trap at 3000 m water depth. During some of the years an additional intermediate trap has been deployed at 2000 m depth. During the first one and a half years sampling intervals were about 2 weeks, during the following years they were extended to 3 to 4 weeks. Some of the sampling periods had to be excluded due to malfunctioning traps or disturbance by fish or other swimming organisms.

Sampling cups were filled with seawater from the trap depths with 35 g $l^{-1}$ NaCl and 3.3 g $l^{-1}$ $HgCl_2$ added for preservation and poisoning. Samples were stored at 4°C and processed within 3 days after recovery. Processing consisted of a visual sample description, sieving into > 1 mm and < 1 mm fractions, hand-picking of copepods from the < 1 mm fraction, splitting the fractions into aliquots of 1/4 to 1/64 of the total sample volume, filtering the samples onto preweighed Nuclepore filters (0.4 µm) and drying at 45°C.

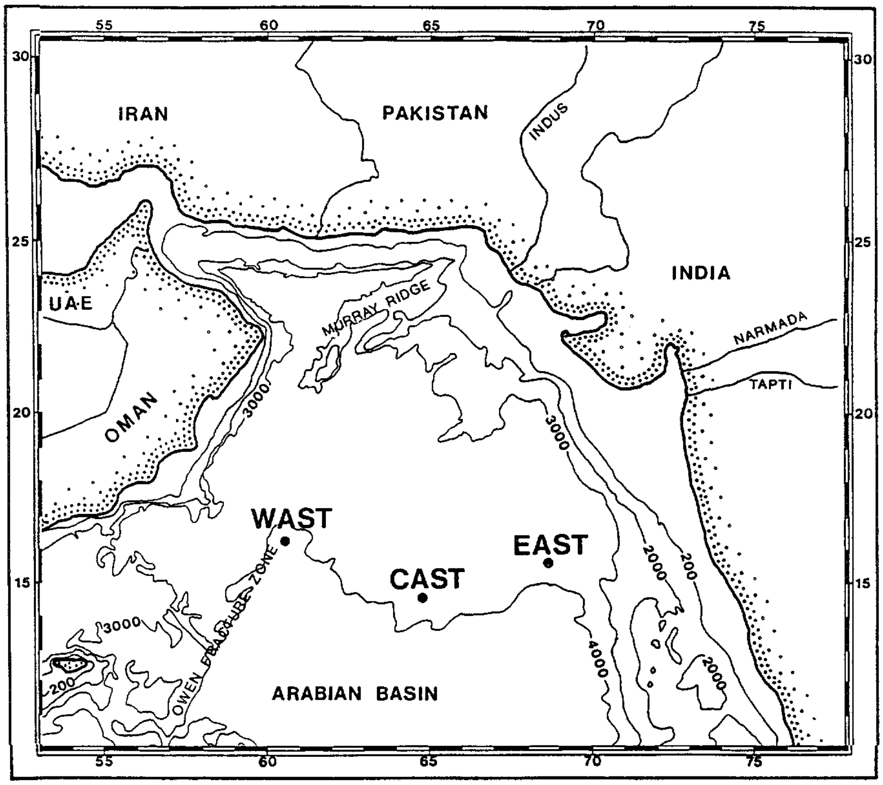

**Figure 14.1** Sites of sediment trap moorings in the western (WAST), central (CAST) and eastern (EAST) Arabian Sea.

## 14.4 SAMPLE ANALYSES

Aliquots of the samples were analyzed for carbonate, organic carbon, total nitrogen, biogenic opal and lithogenic matter (methods in Haake et al., 1993), amino acids and hexosamines (methods in Haake et al., 1992; Rixen and Haake, 1993), carbohydrates (methods in Ittekkot et al., 1984b), fatty acids (methods in Reemtsma et al., 1990), and mineral constituents (methods in Ramaswamy et al., 1991).

## 14.5 RESULTS AND DISCUSSION

### 14.5.1 PROCESSES DETERMINING SEASONALITIES OF BIOGENIC AND LITHOGENIC FLUXES

Particle fluxes measured by traps in intermediate and deep waters of the Arabian Sea basically reveal a semiannual periodicity with maxima during the SW and NE monsoon seasons. These flux maxima coincide with maxima of wind speeds and minima of sea surface temperatures (Figure 14.2). Sea surface temperature charts (Multi Channel Sea Surface Temperature = MCSST, Advanced Very High

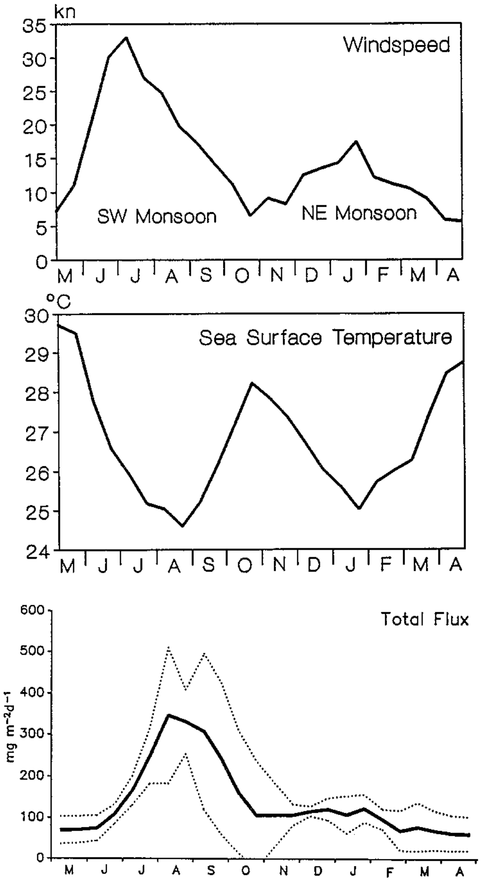

**Figure 14.2** Monthly averages of wind speeds (kn), sea surface temperatures (MCSST data) and total fluxes at the western trap location. The standard deviation of ± 1 sigma is indicated by the dotted line.

Resolution Radiometer = AVHRR data) of the Arabian Sea show that intermonsoons are warm with temperatures between 28° and 30°C whereas the temperatures of the SW and NE monsoons are several degrees lower (Figure 14.3). Maximum cooling occurs during the SW monsoon in the western, and during the NE monsoon in the north-western, Arabian Sea. Centers of coastal upwelling in the SW monsoon are indicated by temperatures below 22°C. A broad area of open ocean upwelling is marked roughly by the 25°C isotherm (Figure 14.3). The cooling of surface waters is accompanied by nutrient entrainment into the mixed layer and increased primary productivity and particle fluxes due to: (i) monsoonal upwelling during the SW monsoon in the western part of the basin, (ii) wind-mixing of cold nutrient-rich subsurface waters into the euphotic zone during both

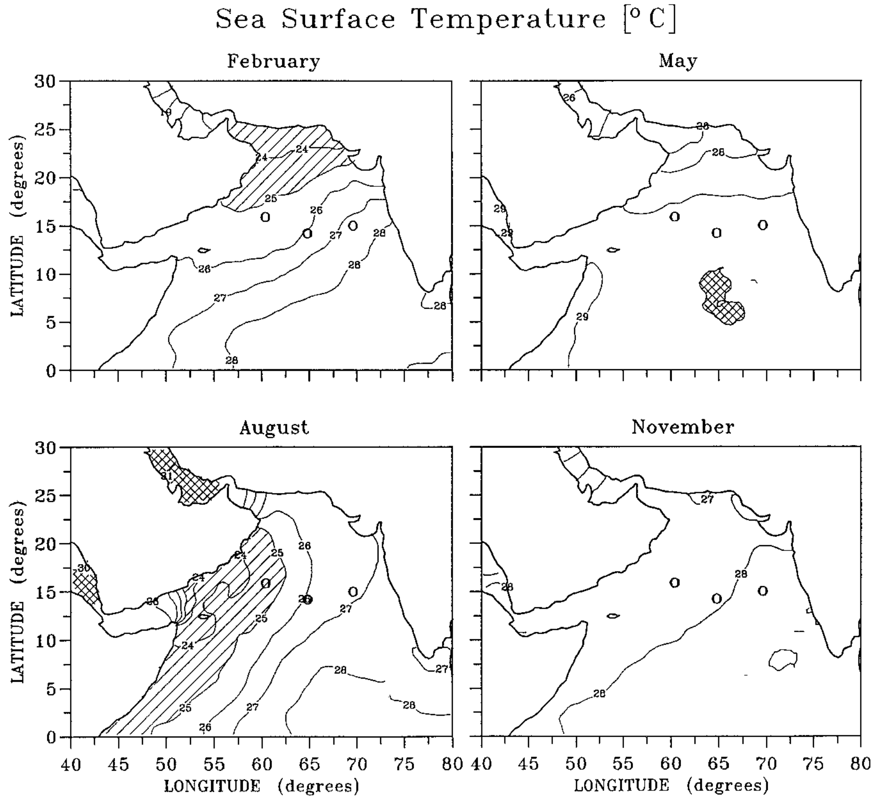

**Figure 14.3** Satellite derived sea surface temperature (MCSST) distributions in the Arabian Sea averaged for four different months from 1986 to 1992. The selected months represent the height of the four different seasons in the region: NE monsoon (February), intermonsoon 1 (May), SW monsoon (August) and intermonsoon 2 (November). Circles represent the three sediment trap locations.

monsoons and, (iii) northern hemisphere winter cooling adding to the wind induced mixing of the NE monsoon (Nair et al., 1989; Haake et al., 1993).

Biogenic material dominates over lithogenic material in sinking particles in the Arabian Sea and makes up more than 80% of the total fluxes in almost all samples. Carbonate is the major biogenic component and contributes more than 50% of the total flux. Despite the similar general flux patterns with monsoonal maxima and intermonsoonal minima the magnitude of biogenic fluxes differed significantly among the three locations. In the western Arabian Sea biogenic fluxes are more than three times higher than at the other two locations in most years (Figure 14.4). The major biogenic constituents are calcareous frustules made up mainly of coccolithophorids and foraminifers (Curry et al., 1992). The only exceptions are the SW monsoon peak fluxes in the western Arabian Sea (Figure 14.4). Associated with these peaks, biogenic opal can reach maxima of more than 40% of the total material and was made up mainly of *Rhizosolenia* sp. - a diatom typical of upwelling conditions (Takahashi et al., in prep.). This upwelling induced opal peak occurrred once every year with a temporal shift of about one to one and a half months from year to year. It was usually preceded by a carbonate peak indicating a coccolithophorid bloom (Haake et al., 1993). The coccolithophorid bloom developed with the beginning of the monsoons when nutrient entrainment at the base of the mixed layer brought phosphate and nitrate but relatively little silicate into the euphotic zone. Nutrient profiles with detailed sampling of the upper 200 m show that phosphate and nitrate concentrations increased immediately below the mixed layer whereas silicate concentrations remained low to a depth of approximately 150 m (Haake et al., 1993). Thus, only the upwelling of waters from greater depths can lead to sufficient entrainment of silicate for a diatom bloom. A dominance of calcareous primary producers almost throughout the year has been also observed in other tropical and subtropical regions (e.g., Honjo et al., 1982; Deuser et al., 1981).

Biogenic and lithogenic matter was transported into the deep ocean in the form of biologically formed large particles such as macroaggregates or fecal pellets (e.g., Alldredge and Silver, 1988). Biological productivity is, thus, a prerequisite for the transport of fine lithogenic matter into the deep ocean as the sinking speeds of individual mineral grains are too low to overcome turbulence (Degens and Ittekkot, 1984). Lithogenic matter in addition to organism frustules can, on the other hand, enhance particle densities and, hence, the sinking speeds of aggregates (Ittekkot, 1993).

In the Arabian Sea productivity and lithogenic matter supply are enhanced at about the same time as the monsoons not only increase primary productivity but also the supply of lithogenic material from land. Lithogenic matter is being transported via rivers into the northern and eastern parts of the Arabian Sea. These rivers have their maximum discharges during the SW monsoon in August/ September. The major contributing rivers are Indus, Narmada and Tapti (Borole et al., 1982; Ittekkot and Arain, 1986). A more important source for lithogenic

**a**

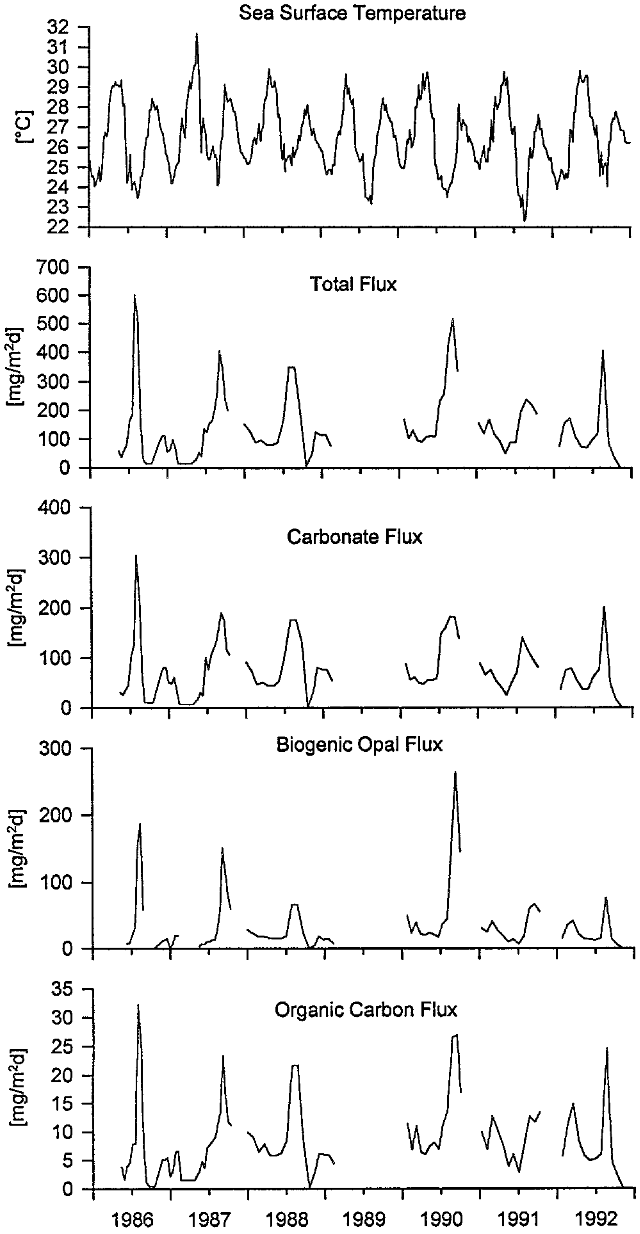

**Figure 14.4a** Sea surface temperatures (MCSST), total flux, and carbonate, biogenic opal and organic carbon fluxes measured at the western trap location.

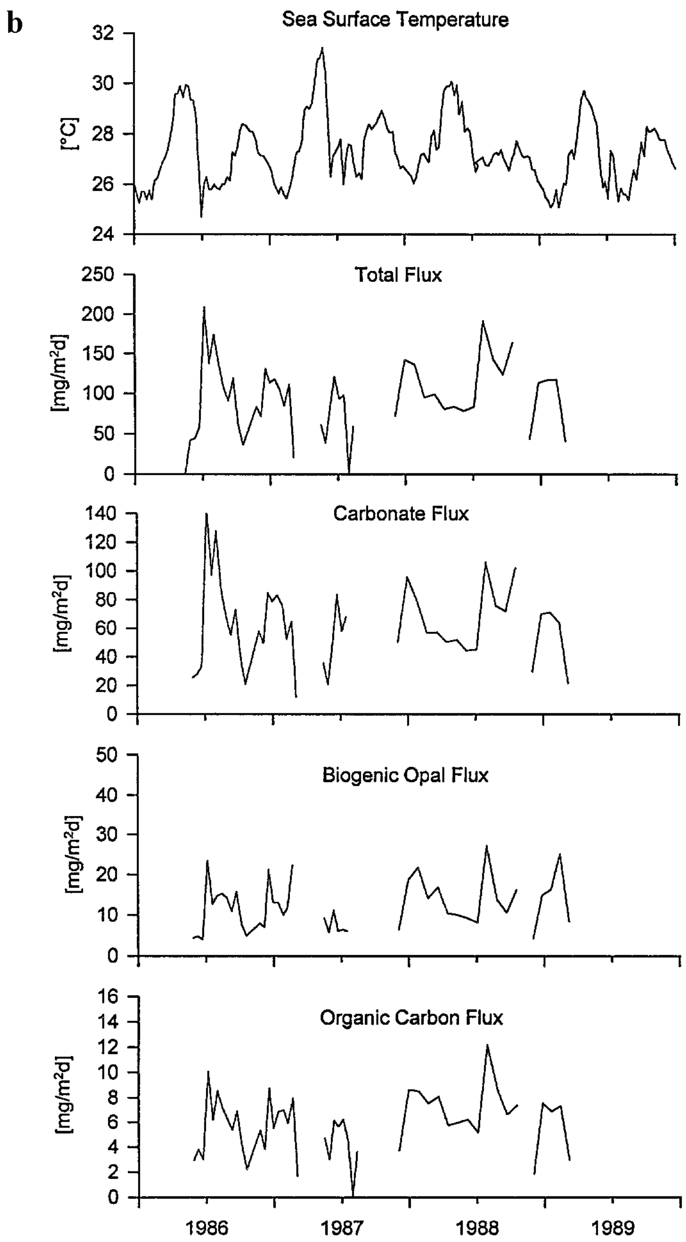

**Figure 14.4b** Sea surface temperatures (MCSST), total flux, and carbonate, biogenic opal and organic carbon fluxes measured at the central trap location.