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Geographical differences in seasonality of CZCS-derived phytoplankton pigment in the Arabian Sea for 1978–1986

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Abstract

In situ measurements of phytoplankton chlorophyll in the Arabian Sea were taken largely along temporally and spatially unevenly distributed sections, scarce especially prior to the operation of NASA's Coastal Zone Color Scanner (CZCS). Herein, the CZCS pigment observations between late 1978 and mid-1986 north of 10°N, including the outer Gulf of Oman, are depicted for 14 subregions beyond the continental shelves as daily means, often only five days apart. To eliminate bias from electronic overshoot, the data were reprocessed with a more conservative cloud screen than used for NASA's Global Data Set. The pattern, derived from the older in situ observations, of one period with elevated chlorophyll almost everywhere during the Southwest Monsoon (SWM) and one additional late-winter bloom in the north, is confirmed. The differing nitrate silicate ratios in freshly entrained water in the central and northern Arabian Sea seem to lead to different succession and perhaps to differing vertical fluxes, and during winter favor blooms only in the north. The spatial pigment pattern in the outer Gulf of Oman is not an extension of that of the northwestern Arabian Sea. The seasonal physical forcing explains much of the timing of pigment concentration changes, but not the levels maintained over long periods. From the CZCS observations it is unclear whether the period of high phytoplankton productivity expected during the SWM in the open Arabian Sea lasts for about two or four months. During this entire season, chlorophyll values in the upper layers rarely exceed 1–2 mg m^{-3} outside the zone influenced by the Arabian upwelling. Near 15°N, however, fluxes into sediment traps at 3 km depth indicate an onset of high primary production very soon after the arrival of the SWM and suggest a long period of high production in the open sea. The partial temporal disconnect during the SWM between pigment changes in the upper

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part of the euphotic zone and of fluxes into the traps is disconcerting. For future modeling of plankton production in the open Arabian Sea, the use of two size classes of phytoplankton is recommended. The utility of satellite-derived pigment concentrations (as opposed to temporal changes of pigment) for testing such models is questioned.

1. Introduction

The Arabian Sea is unique among low-latitude seas by terminating at a latitude of 25°N and being under marked continental influence. The resulting monsoon winds reverse their directions seasonally and cause drastic changes of wind stress and wind stress curl. The responses of the surface currents and the adjustment of the pycnocline are rapid because of the low latitude. Depending on season and location, the depth of the pycnocline varies appreciably. The annual range in offshore sea surface temperature (SST) is large relative to that observed offshore in other low-latitude seas. Moreover, the SST has a bimodal cycle with lows during both the wet Southwest Monsoon (SWM) and the dry and cool Northeast Monsoon (NEM). The strong winds of the SWM, which in the central Arabian Sea normally lasts from mid-June through September and into October, affect the western Arabian Sea much more than the eastern part. During this season, upwelling occurs along the western coast and in a zone offshore, as well as in the adjoining Laccadive Sea along the Indian southwest coast and off Sri Lanka. The NEM (in the north, normally November through February) is felt especially in the north where large heat losses cause convective overturn. During the two intermonsoon periods, solar heating and weak winds lead to shallow mixed layers and nutrient depletion, as in most low-latitude waters. (The term intermonsoon herein replaces the “spring” or “fall transitions” of the meteorological literature.) The overall effect of the continental influence is a geographical pattern of seasonally varying upward transport of nutrients into normally nutrient-depleted upper layers, a seasonally changing mean underwater irradiance in the mixed layer, as well as nutrient advection from the western coast. On large scales, this will result in spatial and temporal variability of phytoplankton production and abundance.

The physical processes altering the vertical flux of nutrients normally affect the entire mixed layer and, hence, its phytoplankton. Therefore, the NIMBUS-7 Coastal Zone Color Scanner of NASA (CZCS, late 1978 to mid-1986), which sensed the pigment in the upper-quarter to upper one-third of the euphotic zone, was a useful tool, although it did not recognize the presence or absence of a deep chlorophyll maximum. Also, it did not image the sea during the greater part of the SWM with its heavy overcast over most of the Arabian Sea. Even so, the CZCS provided ample pigment observations for the region, something ships could never have done, and we capitalize on that in this paper.

Temporally and spatially very scarce in situ chlorophyll data for the Arabian Sea that predate the renaissance of field work since the late 1980s were reviewed by Banse (1987). They indicate one bloom period during the SWM in the entire Arabian Sea north of approximately 10°N, including the regions of coastal upwelling. Additionally in the north, a winter bloom (called spring bloom in McCreary et al., 1996), is present that was deduced to be due to new nutrients from convective overturn (see further discussion in Prasanna Kumar and Prasad, 1996). The two intermonsoon seasons with strengthened thermal stratification, especially in the period from March or April to May, exhibit low phytoplankton concentrations. While some relation can be seen or inferred in these data between physical forcing and changes in chlorophyll concentrations, deep mixed layers in climatological data for the Arabian Sea do not regularly coincide with high near-surface chlorophyll values (e.g., Bauer et al., 1991).

McCreary et al. (1996), when modeling the connection between physical forcing and phytoplankton in the Arabian Sea and comparing the results with the climatological pigment data of the CZCS, distinguished blooms initiated by three physical mechanisms, upwelling, entrainment, and detrainment. Upwelling blooms occur with high nutrients in, and with continuing supply to, a shallow mixed layer and, hence, at high underwater irradiance unless the light becomes reduced by self-shading from dense phytoplankton populations. Entrainment blooms are caused by deepening of a mixed layer coupled with erosion (entrainment) of the underlying nutrient-rich water, but the beneficial effect of the increased nutrient supply on division rates is impaired by the lowered mean underwater irradiance in the mixed layer. Detrainment blooms, in initially nutrient-rich but irradiance-constrained water, are due to shoaling of the mixed layer. Their duration should have some relation to the initial nutrient inventory.

For the areas and seasons with slow or absent temporal change of near-surface pigment (cf. figures in the Appendix), McCreary et al. (1996) pointed out that cell growth and death must be approximately balanced. They stressed that even during periods leading to blooms, the gain to the phytoplankton concentration from cell division is primarily negated by the loss from zooplankton grazing, rather than from physical processes. A corollary is that the rate of increase of phytoplankton mass toward a bloom must be much slower than the cell division rate. In other words, where physical processes do not affect concentrations significantly, a temporal change in phytoplankton concentrations is a community phenomenon, but not a question solely of environmentally driven phytoplankton physiology. Longhurst (1995) was the last to make this point on a global scale, as well as specifically for the Arabian Sea.

The coastal upwelling off the Arabian Peninsula during the SWM has been known for a long time, as has the advection of some of this nutrient-rich water into the open sea. In addition, as noted first by Smith and Bottero (1977; see also Bauer et al., 1991), the increase in strength of the wind away from the Arabian coast (Findlater Jet in Fig. 1) leads to upward advection of water and a rise of the pycnocline (Ekman pumping) to the left (north) of the jet by positive (cyclonic) wind-stress curl in a broad band, which may overlap with the coastal upwelling (see Brock et al., 1991: Plates 5, 8 for 1979). To the right (south) of the jet under negative (anticyclonic) curl, the concomitant deepening of the mixed layer apparent in climatologies based on temperature profiles (e.g., Rao et al., 1989) was emphasized especially by Bauer et al. (1991). The salient biological difference between the two vertically advecting regimes is that

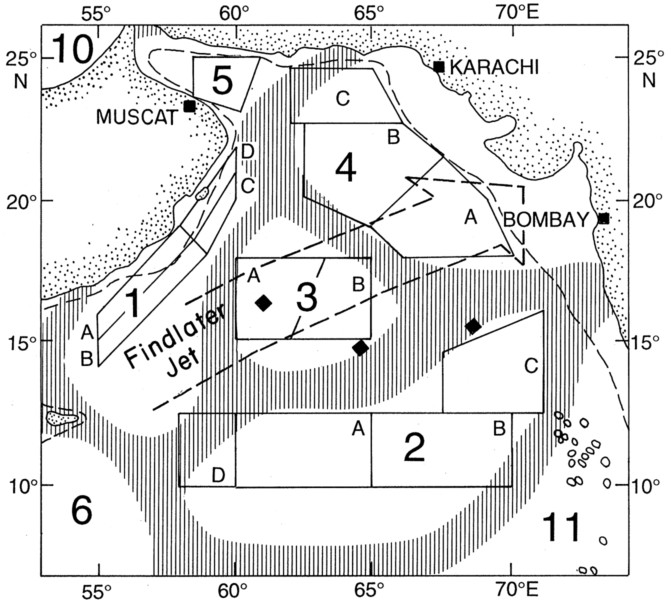

Fig. 1. Arabian Sea with major hydrographic areas separated by hatching (from Colborn, 1975) and boxes used. See the Section A.1.4. for the corner coordinates of the boxes. Broken line, 500-m isobath. General position of the axis of the Findlater Jet superimposed. Three diamonds, western, central, and eastern trap sites of Haake et al. (1993).

under pure downwelling from negative wind stress curl, a nutrient-depleted deep mixed layer would be formed, while pure upward advection and wind-stirring with surface cooling would entrain nutrients into a surface layer that in the central Arabian Sea may be as deep as under downwelling. In both cases, the mean irradiance in the mixed layer will be relatively low and may directly affect phytoplankton cell division rates. However, the intensive physical observations during 1994/1995 suggest that broad upward advection of nutrients coupled with wind-stirring and surface cooling may occur during the SWM also to the right of the Findlater Jet and actually override the effect of Ekman pumping (Lee et al., 2000). These authors note that Bauer et al. (1991) omitted the so-called Delta-term in their model, which is proportional to the local wind stress and causes mixing, as well as horizontal advection. Finally, Young and Kindle (1994) and especially Keen et al. (1997) point out the role of nutrient advection from the Arabian upwelling on open-sea phytoplankton production.

Our paper adds much to the CZCS observations in Banse and English (1993) and Banse (1994). For the first time for the Arabian Sea, it is based on all eight years of CZCS operation. The geographic organization of the presentation is independent of the pigment data since it follows Colborn (1975), who used the seasonal thermal structure as the principal criterion. For the region north of approximately 10°N, where the coverage by the CZCS was good, he recognized five regimes, here called areas (Fig. 1); a sixth, off Somalia, is not discussed. The five areas are represented by 14 boxes, which exclude continental shelves except off Arabia. CZCS images were reprocessed with more stringent (perhaps overly so) criteria than used for NASA's Global Data Sets. The results are depicted in time plots of pigment as means for individual dates in each box for each year, allowing comments on seasonal, regional, and interannual differences. Dates < 5 d apart were generally omitted. The term "chlorophyll" is used loosely, because the CZCS data, as well as chlorophyll *a,* also include its immediate break-down products ("pheopigment") and the influence of dissolved colored material. Moreover, the earlier analyses of ship-collected samples often did not separate chlorophyll *a* and pheopigment.

To look for physical effects on phytoplankton distribution, the CZCS pigment data are qualitatively compared with nutrient data from ships, as well as physical-oceanographic temporal and regional gradients. On the suggestion of M.E. Luther and D.M. Bartolacci (University of Southern Florida), three presumed atmospheric forcing functions are referred to, i.e., wind pseudo-stress acting by wind stirring, wind pseudo-stress curl acting by Ekman pumping (for brevity, called stress and curl herein), and total heat flux (net radiation, sensible plus latent heat) affecting stratification. The values are similar to those in Bartolacci (1996). The SST as such is neglected because outside of the coastal upwelling zone, chlorophyll concentrations in the upper 25 m were not clearly correlated with either SST or the depth of the mixed layer in a station-by-station comparison of in situ pigment for all seasons (Banse, 1987). This depth range is the approximate source of the CZCS-received signal in the open sea. A quantitative spatial–temporal correlation between the climatologies for 1978–1986 of CZCS pigment from the Global Data Set (GDS) and the same presumed atmospheric forcing functions is presented by Bartolacci and Luther (1999). The large-scale spatial averaging in the present study does not lend itself to discussing the occurrence and role of singular hydrographic features like the filaments or eddies with high chlorophyll that extend for hundreds of kilometers from the Arabian upwelling into the open sea.

To facilitate reading, the Methods and the entire data base with its first-order description, which would conventionally have formed the broad section on results, were moved into an appendix. This large appendix comprises the methods of processing the CZCS measurements, the variability of the daily pigment means within and between close dates, the time-series plots with all data points (Fig 3), and tabulated monthly means for each box (Table 1). The detailed description and interpretation of the depicted CZCS data are combined with a review of in situ chlorophyll, nutrient, and physical observations, in part from years prior or following the CZCS operation of late 1978 to mid-1986. Thus, the present Results and Discussion only summarize the conclusions, which were principally derived from visual comparison of interannual similarities and differences between spatial and temporal patterns of pigment and environmental forcing. Statistical analyses of the CZCS pigment were eschewed in view of the uneven temporal and spatial coverage (see figures in the Appendix).

The goal of the paper is to proceed beyond the CZCS data and give an overview of the geographic and seasonal differences of the usual mixed-layer pigment distribution, offshore in the Arabian Sea north of 10°N, and discuss some of the causes.

2. Results and discussion

2.1. The pigment time-series

The section proceeds in an approximately south-to-north sequence, i.e., from a maritime (or oceanic) to a more continental setting, treating Area 1 last, which is dominated by coastal divergence and upwelling. Then, general features or particular processes are discussed. Prior to turning to the following text for a particular area or box the reader may wish to glance at the time-series plots in the Appendix where the pigment is depicted on a linear scale. They illustrate the great uniformity or even temporal monotony (see the small standard deviations) over many months in all areas, and in the south for much of the year. The slow temporal change, if any, prevails in spite of daily division rates of phytoplankton of approximately 1 d^{-1} (see Section 2.2.2.) and is a key feature of these tropical-subtropical phytoplankton dynamics. In contrast, Fig. 2, to be referred to presently, with its logarithmic ordinate and compressed abscissa demonstrates clear seasonality of pigment in the entire open Arabian Sea. Seasonality is even more pronounced in the coastal upwelling areas. Note that the means and medians of pigment are often near the lower limit of the satellite's sensitivity of 0.04 mg m^{-3}.

2.1.1. Overview

Fig. 2 shows the median CZCS pigment values for the individual dates of all years in three boxes that represent the major physical regimes of the open Arabian Sea according to Colborn (1975). During both monsoons, as well as during the intermonsoons, the median concentrations increase from the near-oceanic south to the continentally most affected north; Box 4C is closest to the continent and most revealing regarding its effects. Seasonality is present in all regimes even during the periods of low pigment concentrations, although amplitudes differ greatly among regions. Satellite observations during the height of the SWM season are scarce or missing, but high pigment values with high standard deviations, i.e., blooms are seen in all areas by September or October (cf. plots for individual years in the Appendix, Fig. 3). From the scant CZCS data (box means, but see also the standard deviations in the Appendix) and individual, newer in situ observations it appears that the chlorophyll concentrations of the SWM rarely surpass 2 mg m^{-3} in the open sea. In addition in the north (Box 4C), winter blooms occur regularly. The late-SWM and winter blooms in the north are separate events, as also can be gleaned for Area 3 in several years (cf. Appendix, lower-right panel for each box with its linear ordinate). It is unclear whether the winter pigment values in the north may be regularly higher than those of the SWM.

The seasonal pattern of mean pigment concentrations in Area 5 in the Gulf of Oman (see Appendix) is similar in most regards to that of Box 4C, but the actual images show very differing spatial patterns (see Section 2.1.5). The means in Area 1, which extends parallel to the coast of the Arabian Peninsula, deviate only slightly from those in the adjoining Box 3A during the months accessible to the CZCS. However, even during the post-SWM period, the spatial pattern of pigment

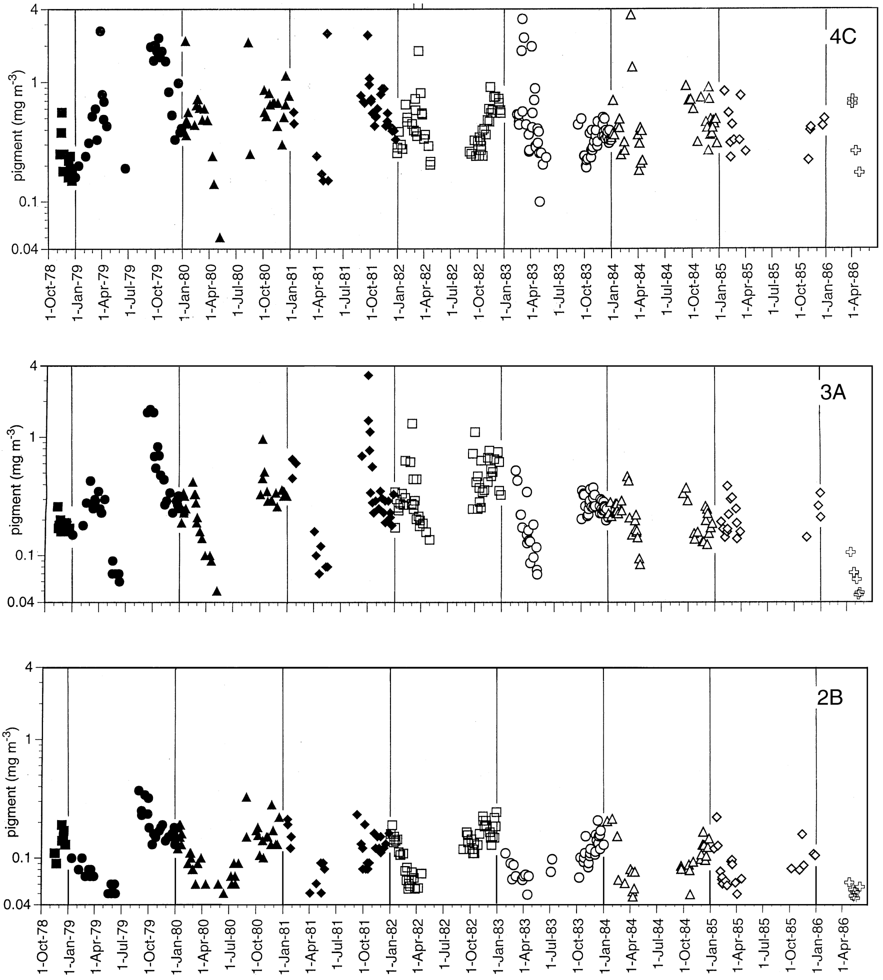

Fig. 2. Medians of pigment for all dates with reprocessed data for the years of operation of the Coastal Zone Color Scanner for boxes 2B, 3A, and 4C.

distribution seen in the actual images differs markedly from that farther offshore. It reflects the hydrographic complexity of coastal upwelling.

The seasonal and much of the overall concentration patterns in Fig. 2 are repetitive within each box, in spite of the interannual physical variability expected in a monsoonal climate (e.g., Cadet and Diehl, 1984; Jones et al., 1995). Hence, the use of climatological pigment averages is justified for many purposes. Especially from the plots in the Appendix, however, it is obvious that the second half of 1979 was anomalous with markedly elevated pigment means, a warning for the interpretation of results from expeditions, which normally cannot decide a priori whether they had encountered an average year.

2.1.2. Area 2

This is the most oceanic region and lies south of the Findlater Jet of the SWM. The climatological, seasonal trajectory of the mixed layer depth (MLD) is bimodal, the largest values, which approach 100 m, being attained in July–August (e.g., Hastenrath and Greischar, 1989). The CZCS pigment was low year-round, and even late during the SWM, the medians were < 0.5 mg m^{-3} except in Box 2A during 1979. The lowest means, close to the lower limit of the CZCS, occurred from March or April through June when the tropical, nutrient-poor water above the main pycnocline is further stratified by a relatively shallow seasonal thermocline. The lag between the heating with re-stratification of the water and the attainment of very low pigment levels (Appendix; so also in Area 3) is qualitatively easily understood as the gradual reduction of the nutrient inventory and, hence, of recycling, owing to the unavoidable loss to depth of organic matter by gravity. The counter-effecting upward flux of nutrients by eddy diffusivity is drastically reduced by the seasonal thermocline. The reasons for the length of the lag, varying among years, needs to be studied.

Importantly, only low pigment was found for the first part of the SWM in the two years when the sea was visible. Apparently, the increase of the MLD in the southeastern Area 2 (Box 2B) does not lead to an increase in phytoplankton pigment. Since SST remains fairly high, the mixed layer seems principally deepened by the negative wind stress curl and the associated horizontal advection of nutrient-depleted surface water left by the preceding intermonsoon period (cf. Bauer et al., 1991); relatively little nutrient entrainment from below is to be expected (cf. Wyrtki 1971, Plate 63). Only parts of boxes 2A, 2B, and 2D were visible during two or three years for the first part of the SWM when the low pigment was observed. A salient but open question is whether changes from year to year in visibility to the satellite, i.e., in weather, and pigment levels are correlated. Was there higher or lower pigment during 1981, 1982, 1984 and 1985?

The mixed layer during this time is not deep enough to reduce the mean irradiance for phytoplankton growth drastically, as shown by the well-developed deep chlorophyll maximum (DCM) in the pycnocline during the SWM for the three years with observations (Yentsch, 1965; Bauer et al., 1991; Mantoura et al., 1993); in a fourth year, Gundersen et al. (1998) apparently did not encounter the maximum at the margins of boxes 2B and 2C.

By August or September, CZCS pigment may increase slightly. These somewhat higher values in boxes 2A and B had not been advected from the west. There is little doubt, however, that appreciable phytoplankton production takes place at least in a part of Box 2C prior to September, because the organic flux measured from 1986–1990 at about 3 km depth west of its northern tip is substantial (eastern trap of Haake et al., 1993). Phytoplankton increases north of Box 2C are also indicated for late July/early August 1995 by in vivo fluorescence records (Gundersen et al., 1998; sta. S10 and the end of their N section) and extracted chlorophyll values of 0.5–0.8 mg m^{-3} at these stations, with nitrate and silicate varying from 0.2 to 0.7 and 1 to 2 μM, respectively. Nitrate values in the upper mixed layer between mid-July–November and November–May tended to range from 0.01–0.2 and 0–0.1 μM, respectively.

In summary, considering also the in situ pigment and nutrient observations since the mid-1960s, the upper layer in this meridionally extensive region (Fig. 1) does not show profound effects of the SWM or the NEM on phytoplankton concentrations except for August and September of some years.

2.1.3. Area 3

Box 3A is exposed to the highest monthly mean wind stress of all areas considered here, which during 1979–1985 was markedly higher even than in Box 3B. In the climatological average, the area experiences two periods of deep mixed layers (Colborn, 1975; Banse, 1984). The deepening during the winter period is principally due to cooling of water with relatively high salinity to 24 or 25°C, which may lead to convective overturn. The deepening during the SWM appears to be principally due to a combination of wind stress curl near and under the axis of the Findlater Jet, wind stirring, and evaporative cooling. During both periods, the increased MLD should result in elevated phytoplankton production because of nutrient entrainment. At the same time, the rate of cell division would be lowered owing to the reduced mean irradiance in the deepened mixed layer. The puzzle is that high pigment concentrations do not occur during either period, but as discussed fully in Sections 2.2.3 and 2.2.4, a marked flux peak of planktonic material is regularly observed during the SWM (less so during the NEM) at 3 km depth below the western Box 3A and near, but outside the southeastern corner of Box 3B since mid-1986 (Haake et al., 1993, western and central traps). Thus, phytoplankton concentration as assessed by chlorophyll does not predict production and subsequent flux at this time in this region.

During the winter, the majority of CZCS pigment means were $< 0.5\ \mathrm{m}^{-3}$ and exceeded $1\ \mathrm{mg\ m}^{-3}$ only briefly in February 1982 in Box 3A. Ship-borne collections likewise observed low chlorophyll concentrations (November–January 1994/1995 and March 1995, medians of 0.4 and $0.1\ \mathrm{mg\ m}^{-3}$, respectively). A few high CZCS means, one reaching $4\ \mathrm{m}^{-3}$, were found for the box in the Global Data Set (GDS) for winter 1981 (recall that we did not reprocess all dates) and in situ at the US JGOFS one-year time-series station in Area 3 during 1995 (ca. $0.8\ \mathrm{mg\ m}^{-3}$ from in vivo fluorescence, Dickey et al., 1998). During 1994/1995, nitrate ranged between 1 and 2 μM in the central Area 3 in mid-December, rose by late January to 2 to 5 μM, but by early April had reverted to < 0.1 to 0.2 μM. During the entire time, silicate fluctuated between 1 and 3 μM, without relation to nitrate. Sufficient underwater irradiance should be present in the deep mixed layer of the season to utilize the nutrients, as witnessed by the conspicuous pigment means achieved during the same time in boxes 4B and C to the north.

From March onward in the entire Area 3, the decline of CZCS pigment to very low values, almost reaching the lower limit of the CZCS in May and early June, is especially obvious in plots with a logarithmic ordinate as in the Appendix. In both boxes, this decline began about one month later in 1979 than in 1980, but there was no obvious physical correlate.

For the time prior to mid-August, when our reprocessed CZCS data became available again, in situ pigment values $> 1\ \mathrm{m}^{-3}$ seem to be absent in Area 3. Most are well below this level, as found for July in the four years with collections (1963, 1987, 1994, 1995) and implied for 1979–1982 by scattered CZCS observations from May to between late June and 1 August (Brock and McClain, 1992). Owing to the cloud cover of the SWM season coupled with our stringent reprocessing, only 1979 yielded CZCS observations by as early as mid-August (Box 3B) and September (Box 3A). Most importantly, when also considering the first half of October, high pigment means of > 0.8 mg m^{-3} were found only for 1979. Even in 1980 and 1981 with highest values reaching 0.8 m^{-3}, many means were < 0.5 m^{-3}, as holds for all data for the season in 1982–1984 (no data for 1985). The often high standard deviations of the means indicate markedly uneven abundance of phytoplankton with local fields of higher concentrations. While station data of late July provided nitrate and silicate concentrations merely at detection levels in a 60–80 m deep mixed layer, significant nitrate levels were present in Area 3 at least during the mid-SWM of 1995 (see also Wyrtki, 1971; Plate 62, to the same effect for the 1960’s), but silicate was usually quite low and not correlated with nitrate (from inspection).

In the later part of the SWM season, individual in situ measurements and our CZCS means rarely reach 2 mg m^{-3} (for the CZCS, so only for 1979), which is in stark contrast to the much richer blooms near the coast (see also Brock and McClain (1992) and Area 1). Even these higher near-surface, offshore means did not nearly approach those of the CZCS-recorded winter blooms of the open sea in the north.

We did not expect that the SWM would yield only moderately high pigment concentrations in the central Arabian Sea, and even that only in the later part of the season. Depending on the year, at least Box 3A would be under the axis of the Findlater Jet so that high near-surface nutrients, permitting bloom-level accumulation of pigment, might be anticipated. This was not observed.

For interannual variability during the SWM, Brock and McClain (1992) found for the northwestern Arabian Sea, including Area 3, that 1982, a year with less wind relative to 1979–1981 and more stratification (and a very strong El Niño in the Pacific Ocean), yielded the least CZCS pigment among the four years (see for October 1982 also boxes 4B and C in the Appendix). The observations with sediment traps at 3 km depth in and close to Area 3 (western and central trap locations, Rixen et al., 1996), likewise show more flux during intensive monsoons, Rixen et al. (2000) elaborate on this correlation. Because of the central position of Area 3 under the Findlater Jet, the wind stress curl in both boxes must be sensitive to small lateral movements of the Jet axis within the season or among years (for among-year variability of the axis during 1979–1982, see Anderson and Prell, 1992 Fig. 2 (incorrectly ascribed by them to Brock and McClain 1992), but no biological data are available to that effect.

Regarding the physical background of phytoplankton growth during the SWM, especially the relation to the Findlater Jet, the scenario of Bauer et al. (1991) has been mentioned in the Introduction. In it, nutrient supply and, hence, production and distribution of phytoplankton in the central Arabian Sea are governed by the curl of the wind stress and the resulting vertical Ekman flux, the latter down to the right and up to the left of the Findlater Jet. The scenario played a role in the planning of the US JGOFS study (Brown et al., 1991). In fact, in 1995, a deep mixed layer with very low chlorophyll suggests a nutrient-depleted downwelling regime far to the south (Box 2B, cf. Morrison et al. (1998); see also Bartolacci and Luther (1999) for the CZCS years).

The 1995 observations in Area 3 through which the axis of the jet passes, however, indicate a more complex situation. Lee et al. (2000) point out that surface cooling and wind stirring also act and might even override the Ekman-pumping effect. They ran two hydrographic sections with chlorophyll estimated by in situ (in vivo) fluorescence, which traversed Area 3 from the northwestern to the southeastern corners; location E designated in the sections is close to the border between boxes 3A and B. During the first cruise of Lee et al. (2000) in late June/early July, a 60–70 m deep mixed layer with only a slight west–east slope in depth contained little chlorophyll, without detectable nitrate and with < 3 μM silicate (in places close to zero); in the pycnocline, with steep temperature and salinity gradients at the top, a marked chlorophyll maximum was present, as also seen along the same section in late March/early April 1995 (Gundersen et al., 1998, Fig. 9, SI). After two cruises by others between mid-July and mid-September, which observed some nitrate in the mixed layer, Lee et al. (2000) ran the second section in late September/early October. In Box 3A they found a surface column approximately 20 m deep with little nitrate and silicate, but with chlorophyll in places reaching 1.5–2 mg m^{-3}. In Box 3B, a surface layer of about the same depth and similar chemical features, but with slightly higher pigment than in June/July, overlay a continuous chlorophyll maximum (DCM), distinct although patchy in regard to concentrations, with up to 3 mg m^{-3} in a marked halocline. Below, a remnant deep mixed layer extended up to 100 m depth to the depressed thermocline, with nitrate and silicate values $\geqslant 3$ μM (Lee et al., 2000: Figs. 13 and 14). An analogous situation with a somewhat deeper upper mixed layer with 0.3–0.4 m^{-3} chlorophyll and with a thermocline separating the two water columns, was encountered in late September 1986 just east of Box 3A (Mantoura et al., 1993; sta. 5, Fig. 4).

Such a temperature structure appears to be the rule during this time of the year, according to the monthly climatologies for the surface and 50 m in Area 3 (Hastenrath and Greischar, 1989). After the deepening of the mixed layer following the onset of the SWM and the subsequent lowering of the 50-m temperature to 24–26°C by August, this temperature range persists at the 50-m horizon from October through December, while the mean monthly SST increases from October onward. Moreover, the appreciable nutrients in this isolated pool of water (Mantoura et al., 1993; Lee et al., 2000) suggest that the monsoonal deepening of the principal pycnocline to the right of the Findlater Jet is caused not only by the advection of old surface water following Bauer et al. (1991), but at least some time after onset of the SWM involves appreciable injection of deeper water, as postulated by Lee et al. (2000). It is these nutrients that allow the formation of a DCM.

Area 3 is almost identical with the "Central Basin" modeled by McCreary et al. (1996). A small entrainment bloom was calculated for the climatological June and a large and a short entrainment bloom for September and late February, respectively (op. cit., Figs. 4, 8a and b). The modeled September and winter blooms showed more than two months of lag relative to the wind effect because of light limitation from a large MLD, but no lag regarding the heat flux as indicated by the rise of SST. While the CZCS cannot address the principal months of the SWM, the four available years of in-situ observations do not support the model-predicted SWM blooms. The calculated winter bloom is neither well supported by the CZCS nor the in situ data. The model by Keen et al. (1997) (their sta. 4, about 150 km west of Box 3A) suggests, as have other authors before, the role of advection from the Arabian upwelling far into the open sea. It remains to be seen, however, whether 30 μM of ammonium plus nitrate, calculated for late July/early August, can be observed even in a filament extending from the coast.

Finally, Brock and McClain (1992) reported on the CZCS pigment west and northwest of Area 3 in a box in the positive curl region of the SWM, oriented parallel to Box 1A with its upwelling and overlapping it, as well as much of Box 1C, and reaching to the northwestern and southwestern tips of boxes 3A and 4B, respectively. With a reprocessing method different from ours and that of the Global Data Set, they obtained seasonal means between 1.5 and 3.7 mg m^{-3}, averaged from late July/mid-August to the end of September/early October for each of 1979 to 1982. Obviously, areas of even higher concentrations are included in these means, which suggests that the open Arabian Sea regime as derived here for Area 3 does not extend to the west during the SWM.

2.1.4. Area 4

Aside from the Gulf of Oman (Area 5), Area 4 is the region most influenced by the surrounding land, as indicated by the large annual range of SST, which is principally due to the cold and dry NEM. During winter, the sea surface isotherms in the northwestern Arabian Sea trend east–west in contrast to those of the SWM, which approach a north–south direction (Wooster et al., 1967; Hastenrath and Lamb, 1979). Box 4A, the most southern and eastern box of the Area, will differ from the northern- and westernmost Box 4C in both periods for that reason alone.

The MLD is greatest during winter in Box 4C, from convection reaching ca. 120 m in February (Banse, 1984), which holds similarly in Box 4B (only about 80 m for Box 4B in Hastenrath and Greischar (1989)), but it is least deep in Box 4A. Seasonal heating shoals the MLD in March, more so in Box 4C than in Box 4A. During the SWM, SST declines but at the same time, the principal pycnocline and the associated nutrient reservoir rise in the north (Box 4C) to about 40 m, presumably from geostrophic adjustment to the current near the shelf (cf. the sea level changes for Karachi in Banse, 1968). Again, the change is least pronounced in the southeast (Box 4A). During October, the upper layer once more becomes thermally stratified by the second annual heating period.

As already noted, the fall (late SWM) and winter (late NEM) phytoplankton blooms in Area 4 are separate events. For Box 4C, the intervening period of low pigment, usually from December into January or February, is especially conspicuous when means are plotted on a linear ordinate (Appendix, last panel of each box). The CZCS concentrations in all boxes of Area 4 during this slack time stayed in the range from 0.2 to mostly 0.5 (up to 0.8) mg m^{-3}, except for a few daily means near 4 mg m^{-3} in boxes 4A and 4B in January 1981 (only two successive days with observations from Box 4C for this month). These were among the highest means in the entire data set. The apparent offshore “bloom” in Box 4C in early January 1980 was an anomaly caused by a lobe of coastal water extending far into the box that was not present on the other January dates, including the first days of the month (from the GDS). In 1981, however, a large and intensive bloom occurred over much of the northern Arabian Sea, growing from mid-January onward and waning by the end of the month.

Later in winter in Box 4C, which is the box farthest to the north and west, blooms with mean concentrations of 1–3 m^{-3} seemed to be present in five out of six years with adequate CZCS observations, presumably due to the regularly formed deep mixed layer. In the entire Area 4, many periods with pigment means of 0.5 to 1.5 mg m^{-3} with large standard deviations, i.e., blooms, lasted for 2–8 weeks. Even during January, however, nitrate and silicate values did not rise greatly, medians being 3 and 1.5 μM, respectively, in boxes 4A and B (no data for Box 4C). In Box 4C, the pigment decrease of the Spring Intermonsoon occurred only by April although according to the climatology, the seasonal thermocline forms during March (Banse, 1984, Fig. 1).

As suggested by the great temporal irregularity in occurrence of these blooms also in Box 4B, the causal sequence may not be as straightforward as sufficient cooling causing overturn of the water column and entrainment of nutrients. This would be accomplished by February, and subsequent seasonal stabilization would lead to augmented biomass (detrainment blooms). Possibly instead, occasional one- or two-week long episodes of mixed-layer heating may occur already during the usual period of deep mixing, explaining some of the high pigment values in mid-winter. Such irregular physical initiation of bloom is difficult to document without, at least, sequences of good SST data. Also, the nutrient injection from convection by cooling would be followed by a recognizable pigment increase only after some time because of the interval needed for the phytoplankton population to grow significantly in the face of grazing. By then, the SST signature of the event may well have been erased by heating. General biological implications of the winter production were discussed by Madhupratap et al. (1996).

Notice for the winter blooms under often clear skies (from visual inspection of images), that the day–night difference in the heat budget might lead to nocturnal deepening and day-time shoaling of the mixed layer. Hence the daily phytoplankton dynamics may be similar to those described by Woods and Onken (1982) for a hypothetical temperate ocean. Models for phytoplankton production in the Arabian Sea, so far, have not considered the problem. The depth of this diel cycle of deepening and shoaling, however, will be greatly reduced where the layer above the thermocline is stratified due to advection of low-salinity water as in the eastern Area 2 during the NEM. The diel cycle of stratification from heating also might be reduced or vanish under the cloudy sky and strong wind of the SWM (for 1995, see Gardner et al., 1999).

The biological situation during the early SWM along the northern edge of Box 4C and the northeastern edges of boxes 4B and C ("Northern Basin" in McCreary et al., 1996) is unclear. The upsloping pycnocline near the continental slope with very nutrient-rich water at about 30 m depth (Banse, 1984) under the strong wind should provide a good nutrient supply (cf. McCreary et al., 1996; Fig. 6b[d]). Coupled with a sufficient mixed-layer irradiance, this should lead to a strong bloom at the onset of the SWM. McCreary et al. (1996, Fig. 6a[d]) predicted a substantial, sustained rate of primary production, but only low pigment values throughout the season. As indicated, in situ data are not available until late August.

For September to November, after the cloud cover opened enough to permit CZCS observations, somewhat elevated pigment concentrations were found in the three years with data. Enhanced pigment means, however, were absent from Box 4A, although it is situated under the climatological axis of the Findlater Jet. A number of medians $> 2\,\mathrm{mg\,m^{-3}}$ was recorded in boxes 4B and C, in part with very high standard deviations from large fields of 4–5 $\mathrm{mg\,m^{-3}}$, raising to 7–8 mg toward Area 5 (Appendix, Section A.2). The majority of means for the aftermath of the SWM were $\leqslant 1.0\,\mathrm{mg\,m^{-3}}$ or well below in Box 4C and near $0.6\,\mathrm{mg\,m^{-3}}$ or well below in Box 4B from August (first data) to the end of the year. The SWM blooms in the two boxes are not accompanied by a deepened mixed layer, in contrast to those in areas 2 and 3. Also noteworthy is the interannual variability of pigment during the late or post-SWM in boxes 4B and C.

Median nitrate values for late July and late August 1995 were 0.1 and 0.05 μM, and silicate concentrations (both months) 2 μM, but it cannot be ascertained whether the low levels were the consequence of blooms or had prevented them in the first place. Recall that the top of the pycnocline during the period is quite shallow, and poorly oxygenated water is observed immediately below.

Thus, even in boxes 4A and B, which are to the left (north) of the average Findlater Jet of the SWM, this season was not particularly distinguished in terms of high chlorophyll or nutrients during the few years of observations. The winter medians of pigment were higher than those of the SWM, and both were separated by lower values.

It remains to be seen whether the median and cumulative production of the NEM is higher or lower than that of the SWM. In earlier publications, the north appears as quite rich in terms of chlorophyll during winter (November–April, Krey and Babenerd, 1976), and the integrated primary production of the NEM (October–January) north of 15°N equals that of the SWM (Qasim, 1982, Table 8). A considerable fraction of the material used was collected in October/early November 1963 (Ryther et al. (1966) for productivity; see also, for chlorophyll, Banse and Orellana, unpublished review). During the 1963 cruise, however, the hydrography between Oman and Iran/Pakistan was clearly still in the mode of the SWM (Ryther and Menzel, 1965). The omission of these productivity and pigment values, i.e., a different temporal grouping of observations, would change the picture drastically (see also Banse (1984), for the same point).

2.1.5. Area 5

During 1979–1985, the seasonal pattern and strength of the wind stress varied greatly from year to year. Neither in winter nor summer were they in step with the nearby Box 4C, as also seen from the change in strength and direction of the climatological wind, with the strong winds during the SWM passing by the Gulf (Hastenrath and Lamb, 1979). On average during winter and spring, the vertical structure of temperature is similar to that of the adjoining Box 4C (cf. Colborn, 1975).

Presumably owing to this similarity, the same early-winter lull and the decline of pigment concentrations toward June seem to be present, although the means in Area 5 were about twice as high as in Box 4C. Likewise, a large bloom may occur in late winter, with daily mean values appreciably higher than in the adjoining Box 4C, one mean reaching 10 mg m^{-3}. The temporal coverage by the CZCS was not sufficient to allow a statement about regularity of these winter blooms, although they can be surmised to be regular in occurrence because of the exposure of the Gulf to the NEM.

The few available pigment images for the SWM season, however, showed an almost straight, pronounced color front across the mouth of the Gulf of Oman, with relatively poor water in the Gulf, which also appears in a few of the seasonal means in Brock and McClain (1992, Pl. 3) (cf. the along-Gulf section of chlorophyll in vivo fluorescence of October 1986 in Owens et al., 1993). The late- and post-SWM blooms of CZCS pigment, when they occur, may last into December, but the differences among years in the concentrations during this period were striking. The fall of 1982, a year with a weak SWM over the Arabian Sea, was special not only by the absence of a bloom during September and October in the Gulf, but also by the presence of a feeble increase of pigment means as late as mid-November.

Chlorophyll in situ values for the SWM support the pattern of the CZCS data. Aside from the mentioned fluorescence section in early October with < 0.25 mg m^{-3} pigment (0.01–0.02 μM nitrate, Mantoura et al., 1993) and another such section in July with 0.5–0. 6 mg m^{-3} pigment (from the US JGOFS Data Archive), Barlow et al. (1999) reported 0.15 mg m^{-3} chlorophyll at a station in August.

Thus, the spatial phytoplankton distribution in the Gulf of Oman is certainly not an extension of the Arabian Sea, although ultimately, the water above the pycnocline derives from there (cf. the hydrographic comments in Böhm et al., 1999).

2.1.6. Area 1

The boxes in Fig. 1 were located so that most of the belt was avoided, which is affected by electronic overshoot after the satellite passed over the desert. The boxes were to let us look for onshore–offshore gradients and differentiate between the northern part of Area 1 with strong coastal upwelling, largely north of 15°N, and the southern part with relatively less upwelling.

During the NEM and the Spring Intermonsoon, Area 1 is similar to the other areas in respect to wind stress and curl, but during the SWM it deviates considerably from those north of the Findlater Jet owing to the coastal divergence of water and the resulting upwelling. By its SST signature, which includes seaward advection from the site of actual upwelling, the region affected by the coastal upwelling appears to be 100–200 km wide. The upwelling starts in May or June and extends into September or October. It was described by Currie (1992) in detail for the zone covered by our boxes and beyond.

From November until May, means stayed generally below, or even well below 1 mg m^{-3}, as elsewhere in the open Arabian Sea, with a mild increase in late winter especially in the north. Contrary to expectation, no striking differences in pigment were seen between the western and eastern, or the northern and southern pairs of boxes. The northern pair in the months at the close of the year tended to have somewhat higher ($\leqslant 2$ fold) pigment values than the southern pair; also in May, the two northern boxes seemed to harbor slightly higher pigment concentrations than the southern pair. There was much temporal coherence in occurrence of the few blooms (means > 1 mg m^{-3}) observed between mid-January and mid-March of 1981,1982 (northern pair only), 1983, and 1984 (northern pair only). These blooms were lacking in Area 3, but possibly coincided with high pigment values in Box 4B.

The highest pigment means of up to 5 mg m^{-3} were observed once images became available during September. The decline from September into October was equally obvious in all boxes, and a bloom in late November 1979 was present in all four. In situ chlorophyll values in the boxes will not be reviewed, because the greatly variable advection from near-shore and the resulting rapid spatial change, as well as the fast local time change in a bloom with potentially small grazing rates, makes a comparison with medians or ranges from the few CZCS observations not meaningful. Apparently, the highest SWM pigment data beyond the shelves of the Arabian Sea tend to be found here and off Somalia, but even they rarely surpass 2 mg m^{-3}. During the 1985 SWM in the surf zone of southern Oman, however, > 10 mg m^{-3} chlorophyll were observed, and in a bay near 17°N, > 20 mg m^{-3} occurred several times, largely accompanied by > 10 μM nitrate (Savidge et al., 1990).

Partly in our boxes, but especially toward the Arabian coast, Brock and McClain (1992) depicted large fields with CZCS pigment between 4 and 11 mg m^{-3} for the late phase of the SWM of 1979–1981, and even > 11 mg m^{-3} in a relatively small area in 1982. The averages for their shelf region were between 5 and 6 mg m^{-3} for the four years. We wish to caution, however, that some of these readings might be biased by sensor hysteresis (cf. the straight lines down-scan from capes south of 20°N in Banse and English (1993, Fig. 1B) and the enhanced pigment to the north of similar lines in 3 of 4 temporally averaged images off Ras Madraka near 19°N in Brock and McClain (1992, Plate 3).

2.2. Pigment time-series and evidence from sediment traps

This section probes major issues of integration of the data on pigment concentrations with other in situ observations and biological-oceanographic concepts. It will also point out that at present, the temporal relation between near-surface pigment *concentration* and the *rate* of export (flux) to depth in the region is somewhat obscure.

2.2.1. Background

Normally in stratified, nutrient-poor water as in most of the Arabian Sea during much of the year, the fraction of daily phytoplankton production leaving the photic zone and, in part, reaching great depth is quite small (Buesseler, 1998). It depends on the structure and function of the food web (e.g., Wassmann, 1998). An increased fraction tends to be associated with an increase of phytoplankton abundance or even a bloom, which follow a disturbance of the common near-equilibrium between the rates of phytoplankton cell division and consumption, and may be caused by, e.g., nutrient entrainment into the photic zone. A fractional increase of export to depth occurs especially if the disturbance leads to an increase in the division rate of large-celled phytoplankton that cannot easily be consumed by the prevailing very small zooplankton (see also Section 2.2.2). The increase of phytoplankton abundance usually goes hand-in-hand with an enhanced rate of total phytoplankton production, which is the product of concentration × cell division rate. By the same token, a greatly increased flux of plankton-derived material into sediment traps may be taken as evidence for increased primary production coupled with a disturbed equilibrium. Aggregation of phytoplankton cells, which may occur especially in blooms, or other mass mortality also could lead to flux maxima. All processes might change in importance with season.

The first point to be discussed is the relation between an increase of pigment in Area 3, which means increased phytoplankton production, with the timing of high flux at depth. Previously, the SWM was thought to cause the principal signal in the annual plankton cycle in the central, open Arabian Sea and, hence, of export of biogenic matter to depth. Yet, the chlorophyll concentration in the upper part of the euphotic zone does not indicate a strong effect of the SWM, especially until August, while sediment traps do. Three km below the surface in and near Area 3, the western and central sediment traps of Nair et al. (1989) collected for 6 and 4 yr between mid-1986 and 1992 and 1990, respectively (Rixen et al., 1996). According to Haake et al. (1993) and Rixen et al. (1996), heavy sedimentation of biogenic material begins in late June to mid-July. A third, eastern trap, located west of the northern tip of Box 2C (Fig. 1), also shows a marked SWM signal with similar timing. Thus, a material build-up of CZCS pigment or in situ chlorophyll to, say, 1 mg m^{-3} does not precede the appearance of higher fluxes at depth.

The median travel time from the surface of the sedimenting material is not known. By flux data with coarse temporal resolution, we estimate an interval of 2–3 weeks for a 2-km depth difference in the central Arabian Sea (from Nair et al., 1989, Fig. 3). Honjo et al. (1999) suggested about a week, or possible two, from more frequent sampling than used by the former authors in the same general region. Since the average flux of particulate organic carbon (POC) near 15°N at all three sites (Nair et al., 1989) peaks from late July through most of August, export from the surface must start early in the SWM. By the time of pigment buildup in September, the multi-year average flux at 3 km depth is already on the decline at the western and central traps, but not yet in the east. Annual POC flux minima occur at the three sites in October/November, while there is still appreciable pigment in the surface layer. A secondary peak of POC flux in March is seen at the western trap (about half the peak rate of the SWM), but not at the two other sites, and is preceded and accompanied by no or only a small pigment increase in Box 3A in spite of a deep mixed layer during the winter. Finally, the cumulative POC flux from December through March at the central and eastern sites is not much lower than during the SWM, although the pigment concentrations differ somewhat (all flux data from inspection of Fig. 2, Rixen et al. (2000). As indicated, this does not point to an obvious temporal connection between phytoplankton concentration in the upper euphotic zone and the export flux to great depth at these three sites.

In contrast, Honjo et al. (1999), with a more frequent sampling schedule, could associate four events of flux in 1995 at depth closely in time with near-surface pigment peaks at mooring sites MS-3 and MS-4, located northwest and southeast, respectively, of the western trap of Nair et al. (1989). Two of the pigment occurrences appear to have been due to transient eddies (cf. Dickey et al., 1998, Fig. 7), but the two others seem to have been the normal NEM and SWM pigment enhancements.

The next point about the timing of the increased fluxes is that in the average year during the SWM, $CaCO_3$ arrives first at the western trap, followed by POC and several weeks later by opal (Haake et al., 1993; Rixen et al., 1996). The sequence is most obvious for the western trap, but less so for the central site (from Haake et al., 1993). The $CaCO_3$ is stated to be principally due to coccolithophorids (see, however, Sellmer (1999), Section 2.2.3 and Appendix), while opal is thought to be principally supplied by diatoms, with the large *Rhizolenia* spp. dominating (Nair et al., 1989; Haake et al., 1993). From Honjo et al. (1999, neglecting the two eddies, see above) it appears that 1995 differed: During February/March at sites MS-3 and MS-4, $CaCO_3$ and opal arrived within the same week, while in August there was short delay, with $CaCO_3$ appearing first (see also the decline of the Si/Ca ratio in Honjo et al., 1999, Fig. 9).

Haake et al. (1993) explained the lag in opal flux as a delay in diatom growth, caused by nitrate in the upper pycnocline increasing at shallower depth than silicate. Thus, during the seasonal deepening of the mixed layer nitrate would be entrained in the photic zone earlier than silicate. An additional viewpoint is offered by Rixen et al. (2000) by noting that nutrient-enriched surface water with a suitable Si/N ratio for diatom growth may be advected from the near-shore upwelling, but could appear offshore only after some time, thus again delaying the onset of substantial diatom growth in the presumed offshore source region of the trap material (cf. Young and Kindle, 1994). While we accept the argument about delayed diatom growth, it does not explain the weak response of chlorophyll, while the rate of export increases greatly.

2.2.2. Comments

The causal connection between low near-surface chlorophyll content and a drastic increase of POC flux at 3 km depth in the first half, or so, of the SWM in a region like Area 3, as well as a decline of the flux by the time CZCS pigment rises later on, is not obvious from the physical data used herein (essentially, MLD; see also the relation to other physical functions in Bartolacci and Luther (1999)). This is so even if only processes in the upper 200 m are considered, but not the bathy- and abyssopelagic issues of how to convey the material exported from the surface layers to great depths.

Evidently, understanding the processes in the upper water layers will be a central challenge in an integration of the CZCS and in situ observations of chlorophyll with the abiotic and biotic environmental data, as well as of the export to the sea bed. Some concepts will be reviewed here. A deep chlorophyll maximum (DCM) during the SWM will not be considered, as it seems to be usually absent from Area 3 during, at least, the first part of the season (cf. Gundersen et al., 1998; Lee et al., 2000). Our premise is that the CZCS period, 1978 to mid-1986, did not differ appreciably from the following years when the traps discussed by Haake et al. (1993) and Rixen et al. (2000) were deployed.

The cell size of the, as chlorophyll or biomass, dominant phytoplankton in nutrient-depleted waters of the Arabian Sea is quite small (e.g., Latasa and Bidigare, 1998; Savidge and Gilpin, 1999), so that only small grazers, mainly protozoans, can feed on these cells efficiently. Recall that in stratified water outside the regions with strong horizontal gradients, physical losses to populations consisting mainly of very small cells are apt to be only a few percent per day (cf. Banse, 1992, Fig. 2B). Therefore, the time change of phytoplankton concentrations can be visualized in first approximation as driven by the difference between the rates of cell division and mortality, principally from grazing in the absence of cell lysis; lysis is not yet well documented for the open sea. In the open Arabian Sea, the cell division rates are likely to be on the order of 1 d^{-1} (Landry et al., 1998; Caron and Dennett, 1999) and thus will be very much faster than the population change observed by the CZCS over the course of the SWM. Also, in the region, a marked, quick effect of nutrient addition (including ammonium, but not nitrate, silicate, or vitamins) on bulk division rates of phytoplankton assemblages of this kind was measured by Landry et al. (1998). Finally, as reviewed, the phytoplankton production during the SWM by and large keeps nitrate and especially silicate at low levels. In the similarly warm, oligotrophic waters off Bermuda, silicate levels during much of the year are likewise low, severely restrict uptake rates and, hence, are apt to regulate cell division of diatoms, since the half-saturation constant for silicate uptake in those waters of 0.9 μM is relatively high (Brzezinski and Nelson, 1996).

Developing the argument by Haake et al. (1993), is it feasible that nitrate alone, entrained in the euphotic zone of the central, open Arabian Sea shortly after the onset of the SWM, elevates the division rates of phytoplankton other than diatoms and the concurrent consumption, while the pigment concentration seemingly fortuitously does not change greatly, but higher POC flux ensues? The phrase "seemingly fortuitously" is used advisedly: a major issue for the comprehensive explanation is to understand why the near-equilibrium pigment levels are not, say, three times or one-third as high as observed.

Based on experiments in the upper layers on three cruises to the Sargasso Sea under oligotrophic conditions, Lessard and Murrell (1998) found that the average chlorophyll concentration is very close to the feeding threshold of the small zooplankton, below which feeding is suspended. They determined that the hyperbola describing the relation between food concentration and ingestion at low chlorophyll concentrations is very steep so that an increase of food, up to about a doubling, is easily and quickly removed by increasing the individual ingestion rate. Consider also that the small organisms, which are able to feed on the prevailing small phytoplankton cells, have doubling rates similar to those of their prey, so that rapid biomass increases of grazers will help to dampen further or prevent concentration increases of the small phytoplankton.

Now, if the Sargasso Sea mechanism of grazing applied also to the central Arabian Sea, why can *any* bloom be initiated by physically caused removal of nutrient limitation for the prevailing phytoplankton that at best can double its prevailing cell division rates, as shown by Landry et al. (1998)? Why can the small zooplankton not keep up as it does, for example, almost year-round in the eastern subarctic Pacific where the division rate of the small phytoplankton is seasonally mainly light regulated (Frost, 1993)?

2.2.3. Blooms during the Southwest Monsoon

The key reason for a biomass increase in the open Arabian Sea seems to be an augmented cell division rate of initially rare, large cells upon relief from nutrient limitation. They can be eaten mainly by larger zooplankton, the metazoans, which by their nature cannot grow as fast as their one-celled food, while the small cell-small grazer cycle may run similarly as before. (The argument, originally due to Malone (1971) is developed for the Arabian Sea in full in Banse (1994: Section 3.4) and Banse et al. (1996) (see also Landry et al. (1997)). Indeed, the bulk grazing rate during early September 1995 in Area 3, when chlorophyll had increased, was conspicuously smaller than the cell division rate (Landry et al., 1998, stas. 7 and 9); the imbalance was surpassed only at coastal/upwelling stations.

Taking the argument by Haake et al. (1993) further, the trigger for the increased growth of larger cells, thought to be diatoms in the Arabian Sea, would be the silicate supply. The more massive primary production of the later part of the SWM, indicated also by the changed delta-^{15}N values in the traps (Schäfer and Ittekkot, 1993), is associated with increased opal flux; so the enhanced phytoplankton production at that time is in fact based (partly or entirely?) on augmented diatom production. It remains to be explored why *large* diatoms seem to be favored. Off Bermuda in an environment similar to that of the northern Arabian Sea, vitamin preferences play a role in species succession, as reviewed by Banse and English (1994: p. 7342).

During the early SWM at the western trap site of Haake et al. (1993), $CaCO_3$ arrives first, quickly followed by the peak in POC sedimentation, while the opal flux is delayed. Addressing now the role of nitrate being supplied without much silicate during the early SWM, the key process during this period would be a nitrate-based enhanced division rate of coccolithophorids. They are small enough to be removed concurrently by the small zooplankton. A correspondingly enhanced vertical flux of $CaCO_3$ and POC results without delay, which implies that the egesta are relatively large particles with appreciable sinking rates. Thus, the enhanced production due to enhanced cell division rate would in part converted into export right away, rather than into increased biomass of phytoplankton (chlorophyll) or, as in the subarctic Pacific, of mesozoplankton. In contrast to several other oligotrophic seas, the microbial loop here would generate *heavy* particles on account of the $CaCO_3$. The mechanism of conversion to larger, fast-settling particles, however, is unclear. Aggregation of live cells is not likely at the prevailing low pigment concentrations.

In this scenario, the fate of that part of the new primary production, which the small grazers convert into their body mass, is unclear. Presumably, the first result is a greatly increased production by protozoans, nauplii, etc., aside from foraminiferans. Does the biomass of the small heterotrophs materially increase or are they concurrently removed by predatory protozoans and the larger zooplankton? The latter would be the obvious source of fecal pellets, since packaged egesta from the small vacuoles of protozoans or naupliar intestines, let alone single coccoliths, cannot sink fast. However, in 1995 in Area 3, metazoans may not have benefited greatly from the new secondary production, because mesozooplankton biomass in the upper 200 m was not clearly larger than in other seasons (Smith et al., 1998, Table 3).

Note in regard to foraminiferans as agents for $CaCO_3$ transport that during the first two years of observations at two open-sea locations off Arabia, the flux at depth of large specimens peaked only in early August (Curry et al., 1992). In contrast, Sellmer (1999) reported for shallow (ca. 50 m) traps in June/July 1997 on and near the

Omani shelf that foraminiferans supplied more $CaCO_3$ than did coccolithophorids. Peak fluxes of foraminiferans per day were about the same in the two papers. Also Dennett et al. (1999) touched upon the possible role of foraminiferans and actinopods for vertical flux, when they had measured an appreciable biomass, as a fraction of the entire smaller zooplankton, during the NEM and the subsequent intermonsoon.

For the late SWM with new silicate, it was implied earlier that diatom production is in order, leading to the ordinary food web strand into metazoans and fecal pellets. Perhaps, the low phytoplankton content (from chlorophyll) of the late SWM is, in part, caused by silicate limitation, since this nutrient salt even at that time may be in short supply (reviewed in Section 2.1.), as also proposed by Honjo et al. (1999).

As an alternative explanation for the steady chlorophyll concentrations during the early SWM 1995 in Box 3A, Marra et al. (1998) suggested that the underwater irradiance was insufficient because of the seasonally deepened mixed layer, so that nutrients could not be fully utilized (similarly, McCreary et al. (1996), for their "Central Basin"). Observe, though, that nutrients actually tended to be low most of this time in the region, contrary to the prediction. Further, the modeled small integrated primary production in Marra et al. (1998) would mesh with the observed increased flux at depth only if a change in the composition of the plankton community led to the export of an enlarged fraction of an actually small production. Others were also puzzled about the low chlorophyll levels during the 1995 SWM, without being able to advance an unassailable explanation (e.g., Latasa and Bidigare, 1998, p. 2161). As reviewed, the 1995 data are supported by the few in situ chlorophyll observations from three other years.

One *caveat* for the nutrient-limited aspect of the sketched mechanism is that materially nutrient (nitrate)-depressed division rates of large cells, to considerably less than half of a nutrient-saturated rate, have not yet been measured in the field with modern means; instead, the depression is inferred from photosynthetic rate normalized by chlorophyll. In iron-limited regimes, the specific growth rates of diatoms were actually not greatly reduced although the cells remained rare until a perturbation destroyed the usual grazer-prey balance (Price et al., 1994; Landry et al., 1997, p. 415). In the Arabian Sea, Sathyendranath et al. (1999) during the late SWM and the following intermonsoon found that the light saturation values of bulk phytoplankton, normalized to chlorophyll, were at all depths in the euphotic zone *lower* in the former season, when more nutrients were present (Woodward et al., 1999). Recall, though, that the light saturated rate is only a proxy for the growth rate. Finally, cells $< 2\ \mu m$ may at times reach high concentrations in the Arabian Sea (Latasa and Bidigare, 1998, Fig. 21), although they should not.

2.2.4. Blooms during the late Northeast Monsoon

The explanation for the timing and sequence of the observed fluxes at 3 km depth during the SWM, developed from the observation by Haake et al. (1993), if correct, should hold for the period during the late NEM when the mixed layer is appreciably deepened in Area 3 and when, presumably, new nutrients are entrained. In fact, on the average there is a secondary peak in POC flux at the western trap in March (Rixen et al., 2000), but apparently rarely in opal (Haake et al., 1993, Fig. 6); Honjo et al. (1999) did observe a secondary silica peak for February/ March 1995 at the nearby moorings MS-3 and MS-4. The vertical nutrient distribution in the upper ocean, however, mitigates against large entrainment into the photic zone. At least in January, March, and December 1995, the nutricline in Area 3 lay at 90–100, 60–70, and 60–70 m, respectively. Moreover, in March, several ten meters of water with only 5–7 μM nitrate occurred below it, while in the other months, > 10 to > 15 μM were present, as is also true for late January 1964 and March 1963 (*Anton Bruun* cruises A and 5; the nutricline then was observed at approximately 75 m). The change of the nitrate-to-silicate ratio with depth is essentially alike in Area 3 and Box 4C: 5, 10 and 15 μM nitrate are associated with 2–3, 4–5, and 6–8 μM silicate, respectively (from US JGOFS stas. N 2-4 and S 5-9 for January, March, and December, 1995).

Now, in February 1995 near 16°N, 62°E (close to the center of Area 3), the brief (only days) maximal mixing to 100–110 m (Rudnick et al. (1997), Fig. 3), MLD extending to the depth of a 0.1°C difference from the surface value) would have led only to a median nitrate and a small silicate entrainment, so that the absence of a genuine diatom bloom is not surprising. We must keep in mind, however, that the actual nutrient flux may be quite variable and difficult to assess accurately over a broad area: At another, close-by buoy during 1995, the again short annual MLD maximum, estimated with the same criterion, occurred somewhat earlier than observed by Rudnick et al. (1997); when a 1°C criterion was applied to the same data, a maximal MLD of almost 120 m prevailed for several weeks and was twice, but briefly, attained also later in the season (Dickey et al., 1998, Fig. 5c). Further, as in 1995, the nutrient gradients below the top of the nutricline may vary even within a season.

Why, then, do major blooms, occasionally with the highest pigment means of our entire data set, develop in Box 4C to the north in most years in February–March and extend sometimes into April, although the mean mixed-layer irradiance is bound to be lower than in Area 3 on account of climatologically deeper mixing and of less incident light because of higher latitude? Nitrate should dominate during early entrainment also in Box 4C because of the same change of the nitrate-to-silicate ratio with depth as in Area 3. According to the previous arguments, a bloom should not ensue. The differences from Area 3, however, seem to be (1) that on the named US JGOFS 1995 stations in the north, with convection extending normally to $\geqslant 100$ m (from climatology), the nutricline with > 20 μM nitrate just below was observed at 60 to > 70 m depth, which at least in January 1995, was a few ten meters shallower than in Area 3. Thus, with convection in the north easily reaching into nutrient-rich water, the phase with intermediate nitrate-low silicate of Area 3 will be brief in Box 4C. Silicate-rich water might come into the mixed layer at practically the same time as water with $\geqslant 20$ μm nitrate and permit a diatom bloom to develop, as observed in 1995 (Latasa and Bidigare, 1998). This bloom was accompanied by high export from the upper layers (Buesseler et al., 1998).

Moreover (2), silicate entrainment in the north also may be more efficient than in the central region because a low-salinity, poorly ventilated intrusion of deep water is frequently present between sigma-*t* levels of 24.5 and 25 g kg^{-1} in the very top of the pycnocline, largely to the north of the US JGOFS station line. This salinity minimum of a few decameters of vertical extent may often have been missed by sampling with bottles at standard depth (30, 50, 75, 100 m), but it appears in a few older expedition reports and in CTD traces (e.g., Somayajulu et al., 1980, Fig. 6). In a yet to be published poster (Banse, 1990) the layer was interpreted as the (modified) Indian Ocean Water of Sverdrup et al. (1942) that fills the Arabian Sea at depth. It is uplifted in the north by the interleaving of the fairly well ventilated salinity maximum between about 25 and 25.5 g kg^{-1} mentioned by Banse (1968) and more fully described by Banse (1984). Any convection will first erode this nutrient-rich deep-water, which ought to have a low nitrogen-to-silicate ratio on account of its origin (no data!). Again, a diatom bloom should be favored with which the zooplankton cannot cope immediately. The only other set of offshore data from Box 4C seems to be those of Kuz'menko (1977) for 1969 and 1972, who similarly reported large and dominant biomasses of diatoms in the open sea of boxes 4C and B but not on the shelf. She enumerated cells microscopically and converted to cell volumes; the counts included coccolithophorids.

Finally, also for the NEM of 1995, the measured low ratio of bulk instantaneous rates of mortality over cell division, i.e., high population growth rate of phytoplankton, when taken at face value, does not agree with the observed temporal pattern of sedimentation (Caron and Dennett, 1999, p. 1685).

3. Conclusions

Landry et al. (1997) noted the similarities between the processes acting in the planktonic web of iron-limited High Nitrate-Low Chlorophyll (HNLC) regions and those of nitrogen- or phosphate-limited oligotrophic regions. The small phytoplankton concentrations in the eastern tropical Pacific, a prominent example of the former regime, were characterized by Price et al. (1994: 533) as "grazer-controlled phytoplankton populations living in an iron-limited ecosystem". Is the balance between phytoplankton and zooplankton in the open, central Arabian Sea similarly maintained, with nitrogen being the principal limiting resource as in other oligotrophic regions during much of the year, but being replaced by silicate for the early SWM in analogy with iron in HNLC regimes?

To answer such a question and address persuasively the geographic differences in phytoplankton seasonality in as diverse a region as the Arabian Sea, as well as the conversion of primary production into export of carbon to depth, requires joint modeling of physical and biological variables, as pioneered for the upper layers of the area by McCreary et al. (1996) (see also Young and Kindle, 1994; Keen et al., 1997). Among the issues still outstanding are the form of the model and coefficients for key processes.

1(a) If the nutrient-based mechanism for bloom generation, as sketched by Landry et al. (1997) and in Sections 2.2.2 and 2.2.3., is common for generating blooms in oligotrophic seas, two phytoplankton compartments will normally be needed for modeling. In addition, the grazers may have to be considered in more detail than has been customary. The two phytoplankter–two zooplankter model, developed by Pitchford and Brindley (1999) for iron-limited large phytoplankton surrounded by only iron-stressed small phytoplankton under strong grazing pressure, may be applicable to the offshore Arabian Sea when iron is replaced by silicate within the concepts outlined here. The underlying phytoplankton physiology, especially a higher half-saturation constant for nutrient uptake in larger phytoplankton size classes, and the slower growth in larger animals, were formalized earlier (cf. Moloney and Field, 1991). In modeling the annual cycle phytoplankton off Bermuda, in waters in many respects so similar to the northern Arabian Sea, Hurtt and Armstrong (1996) (see also Armstrong, 1999) circumvented the need for two size classes of zooplankton feeding on two sizes of phytoplankton, but even so, the zooplankton controlled the size composition of a nutrient-stressed phytoplankton assemblage implicitly.

1(b) In a size-structured model as under (1(a)), the pigment concentrations observed from the CZCS or a spectrally similarly designed instrument should not be used to validate the model prediction of phytoplankton *concentration*. The accuracy of the predicted chlorophyll values for each of the (at least) two fractions will be unknown or poorly constrained; since the satellite pigment is equivalent to the sum of the two, it cannot validate either one. The advantage of abandoning pigment concentrations for verification purposes would be that the uncertainty about the calibration of the bio-algorithms used for satellite data, e.g., absence of good ground truth from the Arabian Sea, would not remain a serious issue. Instead of using remotely sensed chlorophyll *concentrations* for model calibration, the *timing and location of concentration changes*, especially of the appearance of blooms, might be the test criterion. The statistics for Arabian Sea CZCS data by Bartolacci and Luther (1999), which suggest lags between the strongest action of presumed physical forcing functions and pigment, also point to stressing temporal aspects of blooms, rather than biomass accumulation.

2. At the central mooring site of Rixen et al. (1996), just south of the southeastern corner of Box 3B, the cumulative POC fluxes during the SWM and the NEM for each of the three years with observations were similar. Our data show that this was not so for the CZCS pigment, and particularly not so for the second part of the SWM, characterized by elevated means. Other incongruent relations between flux and pigment were mentioned earlier. Thus, pigment concentration often does not predict flux in the region. Further, the same problem would occur were the rate of primary production estimated from pigment by a purely bio-optical model.

3. As noted, the phytoplankton dynamics are mainly driven by the difference between the physiologically effected cell division rate (nutrient, light, temperature) and the rate of mortality from grazing, when the small physical-oceanographic terms like vertical mixing and the sinking of live cells can be set aside. Moreover, the concentration of the small phytoplankton fraction might be largely effected by grazing thresholds, again independent of phytoplankton physiology. None of the zooplankton parameters are amenable to satellite observations. Remote sensing will miss the action, as it were. New collections of size-structured in situ rates and modeling might be the order of the day.

Acknowledgements

This study was made possible by an unusually good temporal coverage by the CZCS, which carried only 20 min of tape time, while one mapping of the Arabian Sea required about three adjoining scenes of 2 min each. It seems that the coverage came about almost by accident: In 1975, years before the launch of the satellite, NASA formed a CZCS Nimbus Experiment Team to design algorithms. It was asked in 1977 or 1978 to select target areas for the Color Scanner and to rank their priority. Howard R. Gordon nominated the Arabian Sea on behalf of Robert H. Evans and Otis B. Brown (all of the University of Miami), who were to spend many months with satellite receivers in Mombasa during 1978–1979 in connection with the INDEX expeditions of the First Global GARP Experiment (FGGE; GARP stood for Global Atmospheric Research Program). According to Bob Evans (personal communication, 1995), inertia let the CZCS continue to pay attention to the region at least for the years immediately following. Thus, we are doubly indebted to Otis Brown and Bob Evans, since they were also instrumental in the design of the basic processing programs for the CZCS that we and many others have used. We also salute Howard Gordon for his many contributions to algorithm theory and development.

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Appendix A

A.1. Methods

A.1.1. Color Scanner observations

A.1.1.1. Data source and selection. The observations were obtained from the Global Data Set (GDS), Distributed Active Archive Center, NASA Goddard Space Flight Center (http://daac.gsfc.nasa.gov). We reprocessed the material from level I imagery (the calibrated satellite radiances), which already was subsampled for every 4th pixel of every 4th line. Thus, beneath the satellite (nadir), each pixel represents approximately 16 km^2. Scenes collected with a gain of 1, 2 or 3 were used, when they appeared to offer valid pigment estimates within one of the boxes in Fig. 1. Observations about five days apart were chosen if available, but data on some adjoining days were also reprocessed to study day-to-day variability.

A.1.1.2. Level II processing. The atmospheric correction was performed with the DSP software system developed at the University of Miami (Feldman et al., 1989; Evans and Gordon, 1994). The algorithms correct for multiple scattering (Gordon et al., 1988) and apply default cloud and sunglint masks. The calculation of ozone and atmosphere thickness was updated since that used for the GDS (personal information, R.H. Evans, University of Miami, 1993), but the resulting differences in the pigment estimates are usually slight. Like for the GDS, a default marine epsilon of 1.0 was applied, neglecting the modification suggested as necessary by Brock et al. (1991) for the early SWM of 1979 and Brock and McClain (1992) for the early SWM of 1982. We deemed the effect of this choice to be slight for the low pigment concentrations common in the data. (For large effects in upwelled water of the tropical Atlantic Ocean, however, see Monger et al. (1997)). The decay of sensor sensitivity was incorporated, which was especially noticeable since late 1982 (Evans and Gordon, 1994; also Sturm, 1993). The water-leaving irradiance thus obtained was converted with the bio-algorithm of the GDS into a pigment estimate (chlorophyll *a* plus pheopigment). It represents the irradiance-weighted average concentration for the upper one-quarter to one-third of the euphotic zone.

A.1.1.3. Multiple-scattering interaction and cloud-ringing masks. All images were checked for adverse multiple scattering interactions and systematic errors in CZCS imagery. The procedure was developed by Martin and Perry (1994) based on the radiative transfer work of Gordon and Castaño (1989). To reduce the effect of sensor hysteresis after passing over land or bright clouds ("ringing"), the cloud screening procedure of Martin (1992), which expands Mueller's (1988) electronic overshoot algorithms, was modified (English et al., 1996). The approach identifies dubious pigment pixels from the brightness and duration of reflected radiance at 750 nm and the distance of data pixels from cloud pixels. The method not only removes contaminated pixels, but may also eliminate others that are error-free.

The effect of this screening is illustrated for an Arabian Sea image in Banse and English (1993, Pl. 1, Fig. 2). Their Table 1 shows the drastic reduction in variability for the box means (lowered standard deviations), which permits profitable discussion of smaller differences between means than is advisable for the GDS. However, only 2/3 and $< 1/2$ as many images are available here for the early and late SWM of 1979 than were used by Brock and McClain (1991), who employed a less stringent selection and reprocessing procedure.

A.1.1.4. Ground truth. The accuracy of the CZCS-derived pigment values for the Arabian Sea is not known, as is true for most other seas. A direct, but exiguous comparison between the corrected satellite radiance and in situ pigment was made only for May 1986, when the calibration stability of the CZCS was greatly reduced (Evans and Gordon, 1994). For that time, Hay et al. (1993) concluded that the low pigment values from the GDS bio-algorithm are underestimates, but GDS values $> 1.5\ \mathrm{mg\ m^{-3}}$ are overestimates. Specifically, in mid-May 1986 in Box 3A, the in situ concentrations were between 0.10 and $0.15\ \mathrm{mg\ m^{-3}}$, but not near $0.05\ \mathrm{mg\ m^{-3}}$, as calculated here. For the earlier years, however, Banse and English (1993) suggested by inference from the few reliable ship data from the Arabian Sea that the CZCS-derived pigment values are reasonably accurate. The same can be said about the present material. Most important, however, is that the geographical and seasonal *patterns* within a year, presented in this paper, are not affected by doubts about the accuracy of the bio-algorithm.

A.1.1.5. Extraction of valid pixels. To compute pigment averages for an individual date, all non-cloud pixels within a box and with a pigment estimate $< 25\,\mathrm{mg\,m^{-3}}$ were extracted from each scene and box and simply averaged. The somewhat arbitrary cut-off rests on the absence of in situ, offshore observations of not even half this value. If the box contained too few valid pixels (< 50 pixels or $< 5\%$ of pixels examined), the average for that box and day was discarded. If a box was present in more than one scene on any date, the scenes were merged before averaging.

The complete set of pigment values is plotted on a logarithmic ordinate to help differentiating more clearly among the low pigment concentrations. This is in contrast to the linear ordinate for some of the same data for 1978–1980 in Banse (1994). The drawback of the logarithmic plot is the visual suppression of blooms. Therefore, the summary in the last panel for each box is a linear plot of median pigment. In the cloud-screened data, medians do not differ greatly from, but are normally slightly smaller than the means. For all boxes, the medians were 0.92 of the means, $r^2 = 0.98$, with few means reaching 1.3 times the medians. Further in the logarithmic plots, the length of the bars (one standard deviation, SD) is misleading, because the bars are also logarithmic, so that a SD at a low concentration cannot be visually compared with that for a high concentration. Finally, note that the means and medians are often near the lower limit of the satellite's sensitivity of $0.04\,\mathrm{mg\,m^{-3}}$. Table 1 tabulates the monthly pigment means for each box and year, which are not weighted with respect to the temporal or spatial distribution within the months.

A.1.2. Physical data

M. E. Luther and D.M. Bartolacci (University of Southern Florida) obtained the 1979–1986 data for wind pseudo-stress and total heat flux from D.M. Legler (Florida State University), computed the wind pseudo-stress curl, and provided us with monthly means of the three variables for the individual years of CZCS operation. The data had been taken from the research-quality products of an objective analysis of ship observations as described in Legler et al. (1989) and Jones et al. (1995). Wind pseudo-stress is the vector wind velocity multiplied by its magnitude; wind stress would be obtained from multiplying with the density of air and a drag coefficient, the value of which is subject to debate, so that it is not being used here. Wind pseudo-stress curl is the rotational component of wind pseudo-stress; positive values result in upward Ekman pumping and vice versa. For the heat flux, see Bartolacci and Luther (1999). The resulting monthly wind and heat flux data refer to 1 × 1 and 2 × 2 degree areas, respectively. Because of the odd shapes of the boxes used for the pigment data (Fig. 1), the physical parameters were spatially averaged using coordinates that closely coincided with the pigment boxes, but were not identical.

A.1.3. Coordinates for the boxes

Where positions of corners (normally, at full degrees) cannot easily be read from Fig. 1, the coordinates are given here, starting in the left upper or northern-most corners and proceeding clockwise, with N and E for latitudes and longitudes omitted. Box 1A: 19, 58; 18.5, 58.5; 15, 55; 16, 55. Box 1B: 18.5, 58.5; 18, 59; 14, 55; 15, 55. Box 1C: 21, 60; 20, 60; 18, 59; 18.5, 58.5. Box 1D: 22, 60; 21, 60; 18.5, 58.5; 19, 58. Box 2C: 14, 67.5; 16, 71; 12.5, 71; 12.5, 67.5. Divider between boxes 3A and B: 18, 63; 15, 62. Box 4A: 21.5, 67.5; 20, 69; 18, 70; 18, 66; 19, 65. Box 4B: 22.5, 62.5; 22.5, 66; 21.5, 67.5; 19, 65; 20, 62.5. Box 4C: 24.5, 62; 24.5, 65; 22.5, 66; 22.5, 62. Box 5: 25, 58.5; 25, 61; 23, 60; 23.5 (erroneously placed on land), 58.5.

A.2. Variability of pigment data

The date-to-date variability of means was usually small, although very rarely could the same part of a box be observed on successive days. The distribution of pigment values within a box was often non-Gaussian. The standard deviations in the figures of the Appendix are to convey an idea about the variability (or uniformity!) of pigment concentrations within dates over huge areas. They cannot show, however, the kind of horizontal pigment distribution that yields a given S.D. Generally, at very low mean concentrations (ca. 0.05 mg m^{-3}) as in, e.g., Area 2 from March to May, the pigment lacked a distinct pattern. An average content of 0.2–0.4 mg m^{-3} with an SD of ca. $\pm$ 0.1 mg, however, may represent (1), a contiguous region of ca. 0.4 mg m^{-3} as in the northwest part of Box 2A while the rest of the box contained water of 0.15–0.2 mg m^{-3} (20 February 1980) or (2), long ($>$ 200 km) bands with ca. 0.5 mg m^{-3} of pigment imbedded in water of 0.15 to 0.2 mg m^{-3} (e.g., Box 3A, 17 and 19 March 1979; similarly, boxes 3A and 3B on 20 February 1980). However, a mean of 0.6–0.7 mg m^{-3} (SD, ca. $\pm$ 0.4) and, hence, conspicuous in the respective panels, may reflect a fairly uniform mottled pattern, as seen over much of Box 4B on 13 February 1980, and is a representative mean, in contrast to the earlier examples.

Very large standard deviations ($\geqslant \pm 1$ mg m^{-3}) may result from, for example, (1) two gyres of ca. 100 km diameter, one with 4 mg m^{-3} in the center apparently rotating anti-clockwise, and one with 2 mg m^{-3} probably rotating clockwise, being surrounded by water of 0.6–0.7 mg m^{-3} pigment (25 February 1980). (2) A similar statistic held for a mostly obscured Box 4C, into which water of 3–5 mg m^{-3} extended from the coast (12 May 1981; somewhat similarly, Box 4C on 7 November 1981). (3) The huge SD for Box 4C on 12 and 18 November 1981 were caused by a large field of 4–5 mg m^{-3} pigment without sharp borders in the western part of the box (increasing to 7–8 mg toward Area 5), while the remainder contained water with 0.5–0.7 mg^{-3}, with a few spots of only 0.3 mg. When the SD were high, the frequency distribution of pigment pixels was often bimodal, so that the averages depicted in the panels are misleading. Under such conditions, a ship not guided by a satellite would have difficulty in observing anything that is representative, perhaps even without realizing it.

In slightly more than one-half of 43 d (24 out of 112 two-minute scenes) between September and May, from among the dates already used in Banse and English (1993), conspicuous scattering in the 440, 520 and 550 nm channels of the CZCS, not associated with clouds or haze, was interpreted as caused by coccolithophorids; it might also have been due to *Oscillatoria* (formerly, *Trichodesmium*). The majority of these cases showed patches with sharp edges, suggesting eddies, or sometimes drawn-out filaments. As examples of size, two occurrences formed bands approximately 175 km by 375 km and 250 km by > 400 km; another band stretched $> 1,000$ km, revealing complex patterns of advection and eddies. The locations of some of the high-scattering waters coincided with those of enhanced pigment, while others did not. No geographic or temporal pattern could be perceived. Brock and McClain (1992) noted especially frequent occurrences of what they considered to be coccolithophorid blooms during the weak SWM of 1982, in contrast to the observations for the three preceding years.

A.3. Detailed treatment of pigment and physical data in the areas

The following sections present the pigment data for each area in detail and include notes about physical-oceanographic aspects. The basis is visual comparison of interannual similarities and differences between regional patterns of physical forcing acting on the sea surface, mostly for the same years as the CZCS observations. The terms “wind stress” (or “stress”) and “curl” stand for wind pseudo-stress and wind pseudo-stress curl (see Section A.1.2). Few quantitative conclusions can be reached, but similar to the content of a map that is described verbally the text is to make points that may guide later investigators. To arrive at more complete descriptions, we also refer to in situ chlorophyll, nutrient, and physical-oceanographic measurements. The chlorophyll measurements are based on bottle-collected water, unless “fluorescence” indicates the use of a submerged fluorometer measuring in vivo fluorescence. All values are rounded.

Mostly for 1995, raw data are referred to, obtained from the US JGOFS Data Archive (http://usjgofs.whoi.edu/arabianobjects.htmp) and henceforth called US JGOFS Data Archive. Note regarding the silicate data for 1995 that the analysis was set up for the entire expected range, 0–180 μM, so that a difference of < 1 μM in the surface layer may hardly be significant (L. Codispoti, message to US JGOFS principal investigators, 28 October 1996).

For each Area, physical data are reviewed first, then features in the figures from the CZCS daily observations are described (Fig. 3), followed by notes about in situ chlorophyll (or pigment) and nutrient observations. Sometimes, discussions of special points are advanced, but the arguments or conclusions in the body of the paper are not repeated.

A.3.1. Area 2

During 1979–1985, the wind stress in boxes 2A and C peaked in June or July and was somewhat lower than in Box 3A to the north, while the curl was usually most negative in July or August. The summer peaks of the stress declined from Box 2A to Box 2C and tended to occur in boxes 2B and C a month later than in Box 2A. The summer minimum of the curl was as negative in Box 2B as in Box A, but attained about half these values in Box 2C.

Table 1
Monthly pigment means (mg m^{-3}) for each box and year

Year	Month	Box 1A	Box 1B	Box 1C	Box 1D	Box 2A	Box 2B	Box 2C	Box 2D	Box 3A	Box 3B	Box 4A	Box 4B	Box 4C	Box 5
1979	Jan.	0.24	0.25	0.31	0.33	0.18	0.12	0.18	0.16	0.15	0.25	0.33	0.24	0.19	0.15
1980		0.47	0.32	0.38	0.44	0.25	0.18	0.19	0.27	0.27	0.34	0.57	0.42	0.91	0.64
1981		1.67	1.13	2.30	3.14	0.28	0.19	0.19	0.25	0.65	0.64	0.53	0.54	0.54	0.74
1982		0.35	0.30	0.47	0.54	0.22	0.16	0.14	0.20	0.28	0.33	0.35	0.60	0.42	1.96
1983							0.13	0.20				0.82			
1984		0.34		0.33		0.20	0.09	0.15	0.20	0.26	0.31	0.62	0.51	0.53	0.88
1985		0.27	0.18	0.41	0.45	0.17	0.16	0.14	0.17	0.19	0.22			1.72	1.08
1986															
1979	Feb.	0.32	0.34	0.36	0.37	0.20	0.15	0.15	0.17	0.25	0.26	0.39	0.32	0.28	0.29
1980		0.48	0.41	0.41	0.57	0.23	0.10	0.10	0.21	0.32	0.37	0.31	0.54	0.80	3.29
1981									0.44						
1982		0.54	0.50	0.76	0.72	0.18	0.11	0.10	0.27	0.72	0.35	0.67	0.69	0.63	1.07
1983		2.37	0.96	1.76	2.19	0.30	0.08	0.16		0.51	0.42	0.44	0.51	0.57	2.45
1984		0.48	0.37	0.54	0.43	0.17	0.11	0.08	0.37	0.28	0.32	0.29	0.29	0.32	0.57
1985						0.18	0.07	0.10	0.12	0.26	0.20	0.26	0.32	0.45	1.62
1986		0.64	0.76	1.04	0.58				0.33						
1979	Mar.	0.48	0.46	0.39	0.42	0.16	0.08	0.08	0.20	0.34	0.31	0.29	0.38	1.22	1.68
1980		0.32	0.22	0.32	0.35	0.13	0.09	0.09	0.12	0.16	0.22	0.18	0.34	0.62	5.26
1981			0.32						0.23						
1982		0.34	0.23	0.56	0.71	0.08	0.07	0.07	0.12	0.27	0.21	0.26	0.69	1.72	2.66
1983		0.30	0.27	0.32	0.42	0.10	0.07	0.10	0.14	0.19	0.21	0.43	0.69	1.31	1.84
1984		0.26	0.29	0.73	0.96	0.15	0.06	0.07	0.21	0.34	0.32	0.44	0.89	2.67	1.55
1985		0.23	0.26	0.30	0.38	0.13	0.09	0.12	0.15	0.21	0.17	0.13	0.29	0.85	4.41
1979	Apr.	0.23	0.17	0.19	0.49					0.26	0.20	0.22	0.35	0.85	1.80
1980		0.14	0.12	0.15	0.30	0.09	0.06	0.08	0.08	0.10	0.09	0.09	0.13	0.20	0.28
1981		0.18	0.11	0.19	0.21	0.08	0.06	0.07	0.10	0.12	0.10	0.10	0.14	0.22	0.99
1982		0.18	0.14	0.25	0.35	0.09	0.07	0.08	0.08	0.16	0.22	0.12	0.20	0.38	1.39
1983		0.23	0.18	0.20	0.27	0.07	0.07	0.07	0.08	0.14	0.15	0.19	0.28	0.76	1.98

1984		0.25	0.12	0.41	0.57	0.07	0.06	0.07	0.10	0.16	0.13	0.10	0.31	0.35	0.61
1985							0.06	0.07			0.09	0.08	0.11	0.29	
1986						0.06	0.06	0.07		0.08	0.10	0.10	0.18	0.53	0.50
1979	May	0.16	0.12	0.11	0.13	0.06	0.06	0.06		0.08	0.08	0.09	0.13		0.49
1980						0.05	0.06	0.06		0.05		0.05			
1981		0.16	0.15	0.10		0.08	0.08	0.08		0.09	0.07	0.13	0.08	1.13	
1982															0.19
1983		0.10	0.06	0.11	0.17					0.08	0.07	0.10	0.13	0.22	0.46
1984															
1985															
1986						0.05	0.05	0.05		0.05	0.05	0.06			
1979	Jun.					0.05	0.06	0.06	0.05	0.07	0.06	0.06	0.08	0.19	
1980						0.06	0.05								
1981															
1982															
1983						0.12									
1984															
1985															
1986						0.06	0.06	0.06							
1979	Jul.					0.09						0.56			
1980						0.10	0.07	0.09	0.09						
1981															
1982															
1983						0.14	0.09								
1984															
1985															
1979	Aug.					0.42	0.68				2.19	0.53	0.53		0.57
1980						0.49	0.13		0.14			0.19	0.32	1.61	0.31
1981															
1982															
1983															
1984															
1985															

Table 1 (*continued*)

Year	Month	Box 1A	Box 1B	Box 1C	Box 1D	Box 2A	Box 2B	Box 2C	Box 2D	Box 3A	Box 3B	Box 4A	Box 4B	Box 4C	Box 5
1979	Sep.	5.53	1.40	1.96	2.67	0.82	0.36	0.22		1.68	1.70	0.48	1.48	2.15	1.55
1980															
1981						0.69	0.17	0.09	0.36	2.57	0.75	0.17	1.22	1.58	2.17
1982		1.50		2.64		0.33	0.14	0.12		0.74	0.43	0.15	0.22	0.29	0.21
1983													0.35	0.51	0.34
1984		2.63	0.75	0.57	1.55	0.31	0.09	0.10		0.39	0.42	0.17	0.44	1.04	0.50
1985															
1979	Oct.	1.43	1.09	1.17	1.73	0.34	0.16	0.20	0.55	0.79	0.68	0.29	0.76	2.04	1.34
1980		2.38	1.45	2.41	3.01	0.21	0.15	0.14	0.24	0.52	0.44	0.17	0.62	0.92	1.56
1981		1.55	0.64	1.27	2.21	0.27	0.13	0.10	0.28	0.61	0.23	0.16	0.47	1.04	1.81
1982		0.51	0.39	1.38	0.97	0.23	0.12	0.14	0.33	0.35	0.29	0.17	0.24	0.33	0.35
1983		0.82	0.59	0.83	1.33	0.18	0.11	0.09	0.20	0.31	0.20	0.15	0.22	0.32	0.29
1984		0.36	0.27	0.33	0.42	0.10	0.09	0.10	0.13	0.16	0.20	0.12	0.25	0.56	0.69
1985						0.11	0.09	0.06			0.20				
1978	Nov.	0.32	0.21	0.46	0.48	0.16	0.11	0.23	0.13	0.22	0.23	0.18	0.33	0.36	0.32
1979		1.69	0.67	1.70	1.80	0.17	0.18	0.23	0.28	0.44	0.44	0.36	0.59	1.06	1.24
1980		0.57	0.38	0.76	0.55	0.21	0.19	0.15	0.20	0.31	0.30	0.31	0.49	0.68	1.45
1981		0.83	0.37	0.51	0.48	0.24	0.15	0.20	0.22	0.30	0.27	0.35	0.55	1.20	3.69
1982		0.54	0.33	0.40	0.68	0.29	0.21	0.23	0.28	0.57	0.40	0.37	0.47	0.65	1.23
1983		0.30	0.34	0.71	0.99	0.15	0.10	0.12	0.16	0.31	0.24	0.23	0.30	0.42	0.44
1984		0.30	0.28	0.40	0.45	0.16	0.10	0.15	0.16	0.19	0.23	0.19	0.36	0.79	1.24
1985		0.16	0.15	0.19	0.31	0.12	0.12	0.10	0.10	0.16	0.20	0.15	0.30	0.43	0.80
1978	Dec.	0.26	0.22	0.28	0.27	0.16	0.19	0.42	0.17	0.18	0.19	0.23	0.21	0.20	0.19
1979		0.51	0.46	0.60	0.60	0.28	0.16	0.21	0.30	0.28	0.31	0.42	0.56	0.67	0.74
1980						0.26	0.17	0.22		0.35	0.42	0.57	0.61	0.79	1.27
1981		0.48	0.37	0.59	0.91	0.24	0.15	0.14	0.17	0.27	0.36	0.35	0.36	0.49	2.00
1982				0.43	0.46	0.28	0.19	0.21		0.63	0.55	0.60	0.74	0.71	0.53
1983						0.21	0.15	0.15	0.21	0.26	0.27	0.33	0.41	0.41	0.45
1984		0.26	0.25	0.60	0.58	0.20	0.13	0.18	0.18	0.19	0.20	0.23	0.27	0.48	0.52
1985		0.44	0.25	0.31	0.59	0.15	0.13	0.13	0.17	0.29	0.30	0.34	0.62	0.74	2.26

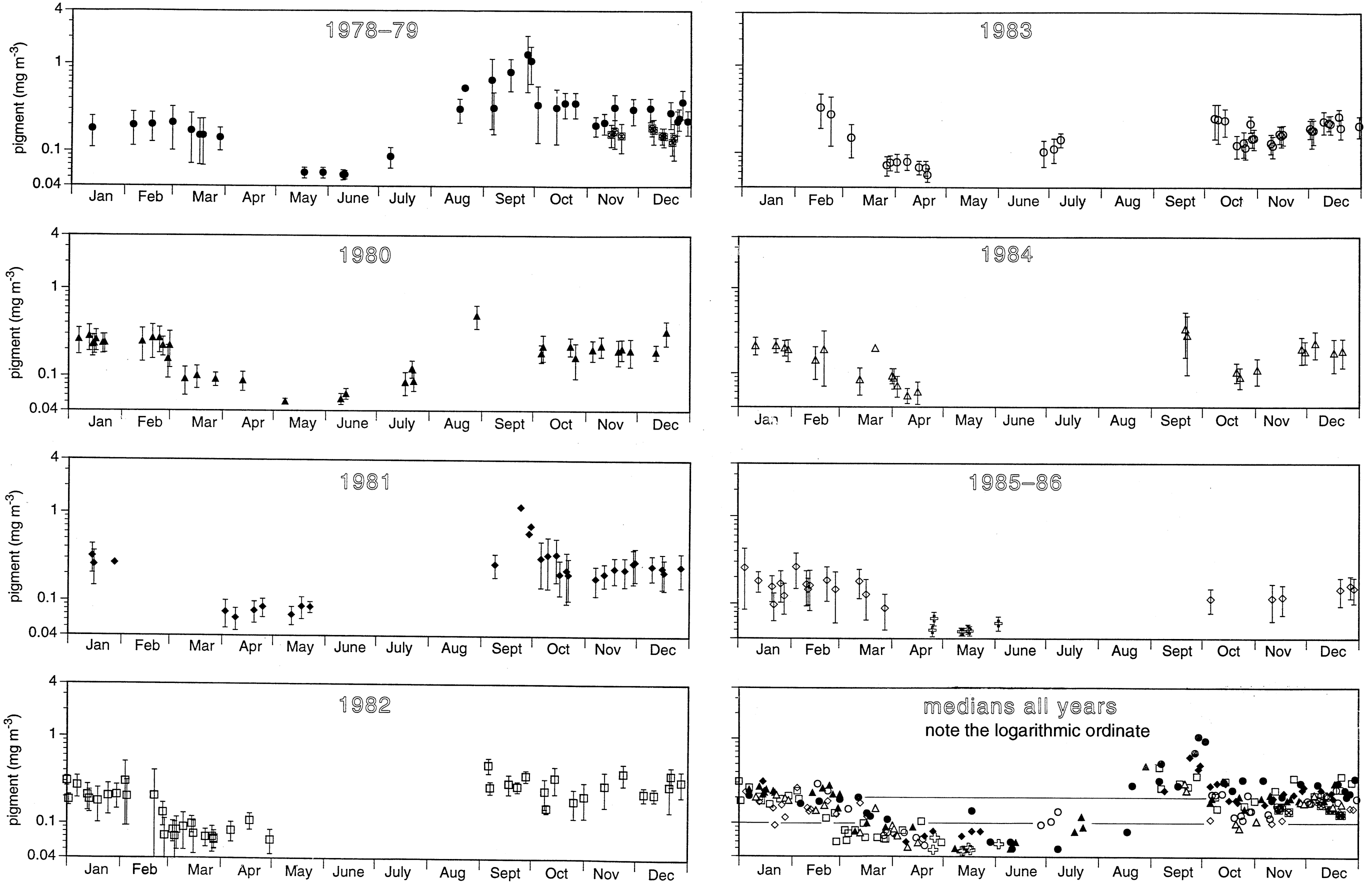

Fig. 3. Pigment values for all dates with reprocessed data for the years of operation of the Coastal Zone Color Scanner for Box 2A (Fig. 1). For all boxes *means* with logarithmic ordinates in all panels, except the last. Panels for 1978–1979: Squares, 1978; circles, 1979. Panels for 1985–1986: diamonds, 1985; crosses, 1986. Bars, one standard deviation (SD); SD usually omitted when larger than the mean, but note that for some very low means, the SD is smaller than the height of the symbols. Last panels, *medians* with linear ordinates for all years combined, using same symbols as in individual panels; note the changed scale of the ordinate for Area 5.

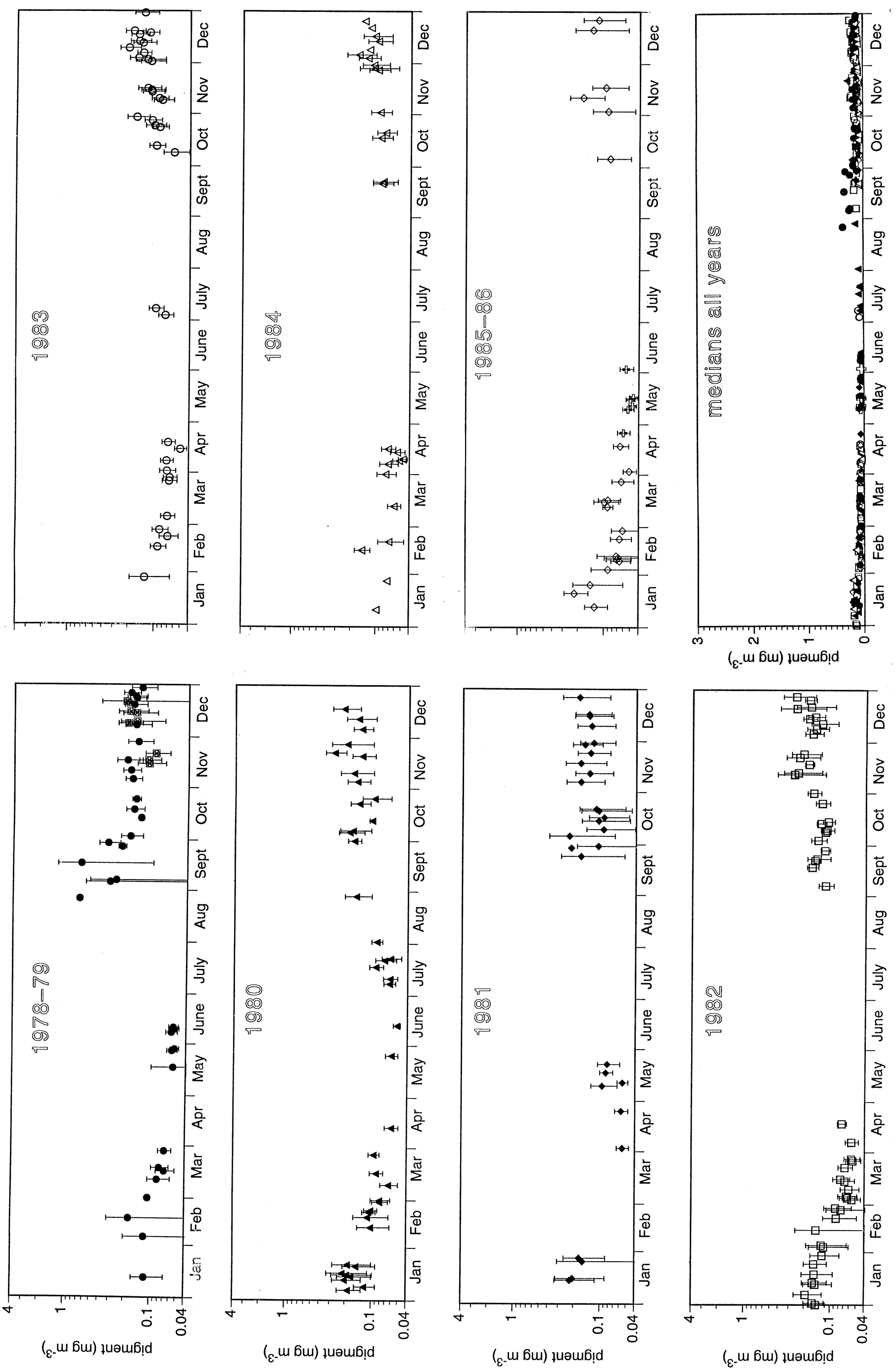

Fig. 3 (*continued*). Box 2B (see also attached caption for Box 2A, p. 1655).

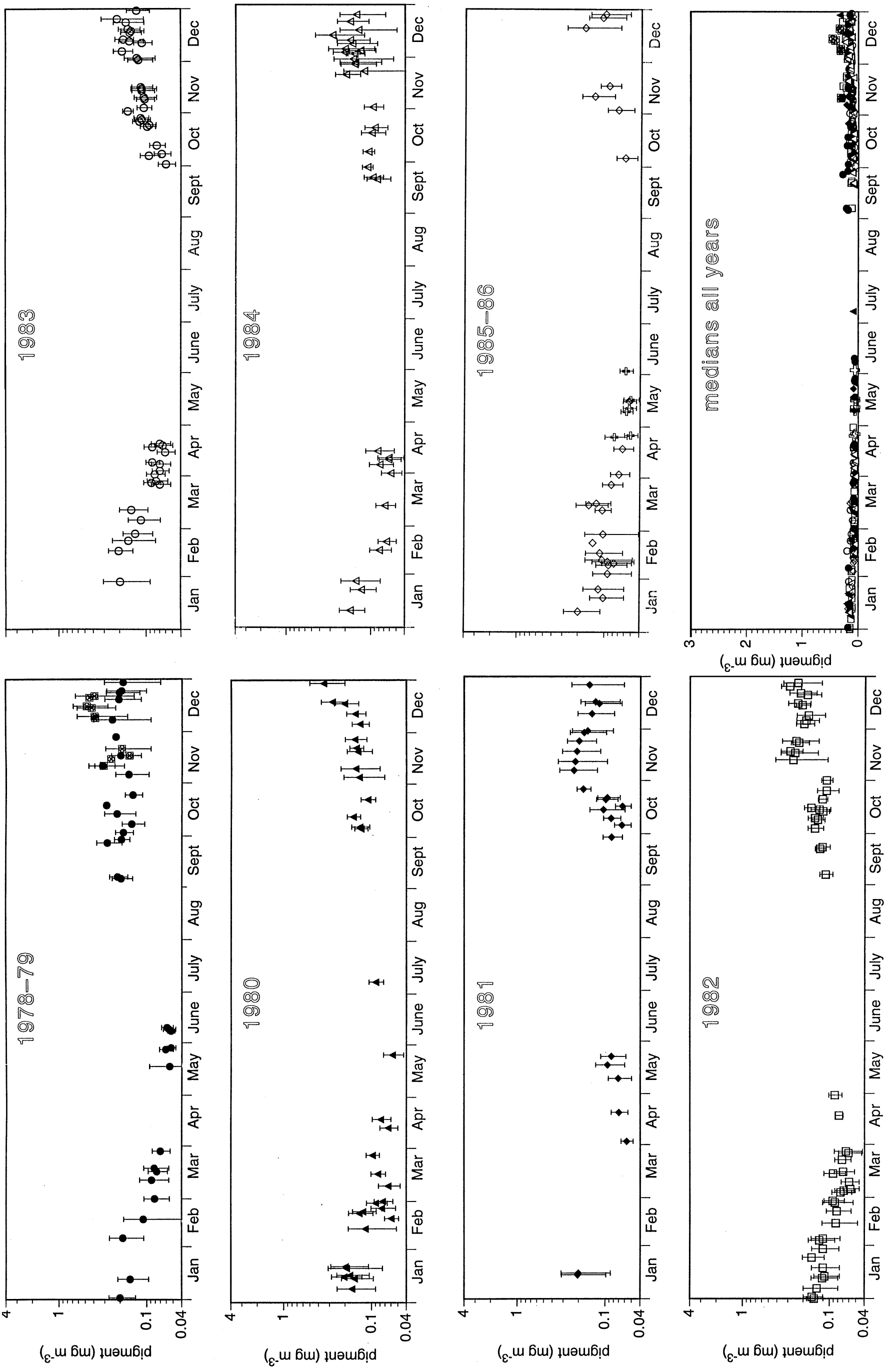

Fig. 3 (*continued*). Box 2C (see also caption for Box 2A, p. 1655)

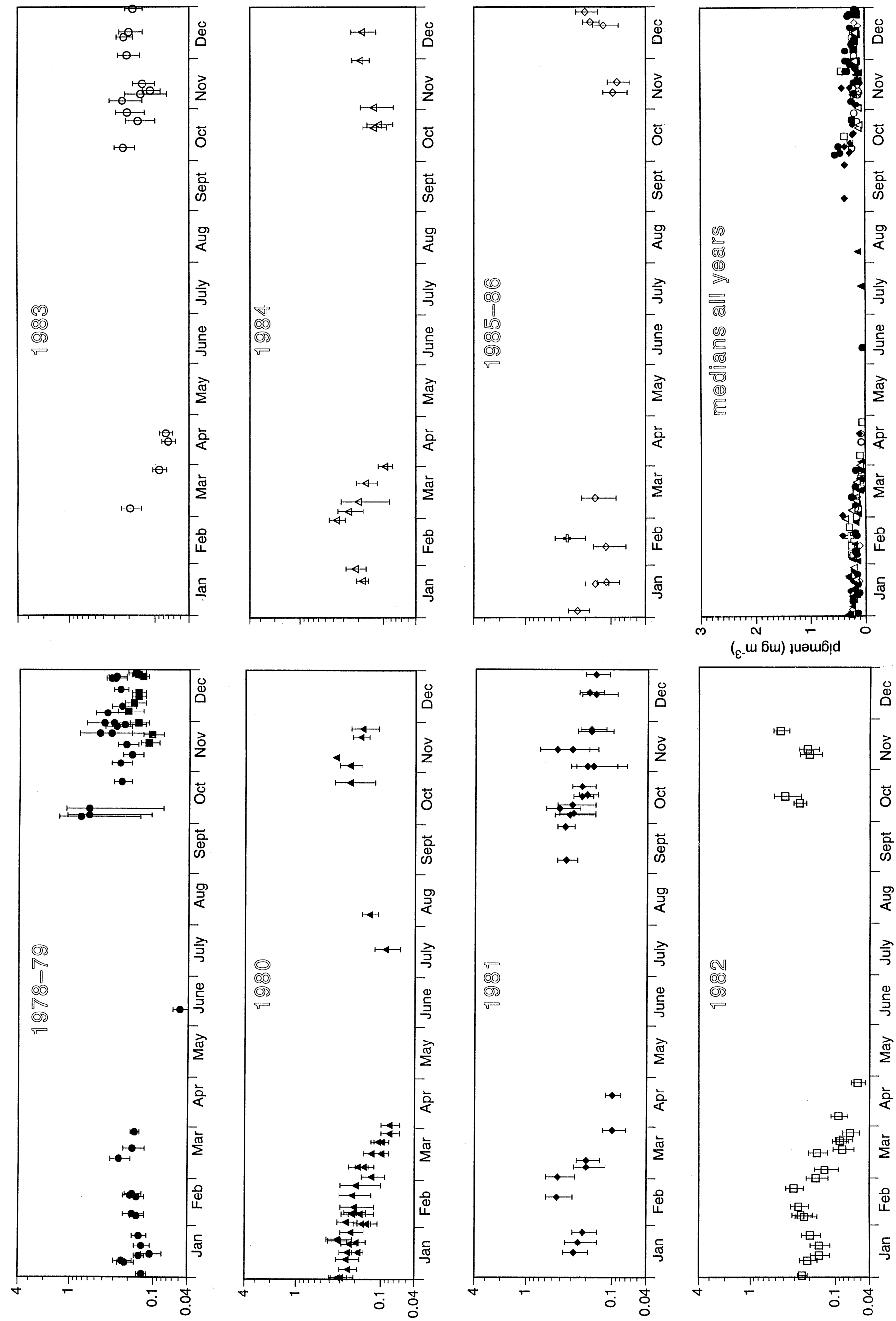

Fig. 3 (*continued*). Box 2D (see also caption for Box 2A, p. 1655).

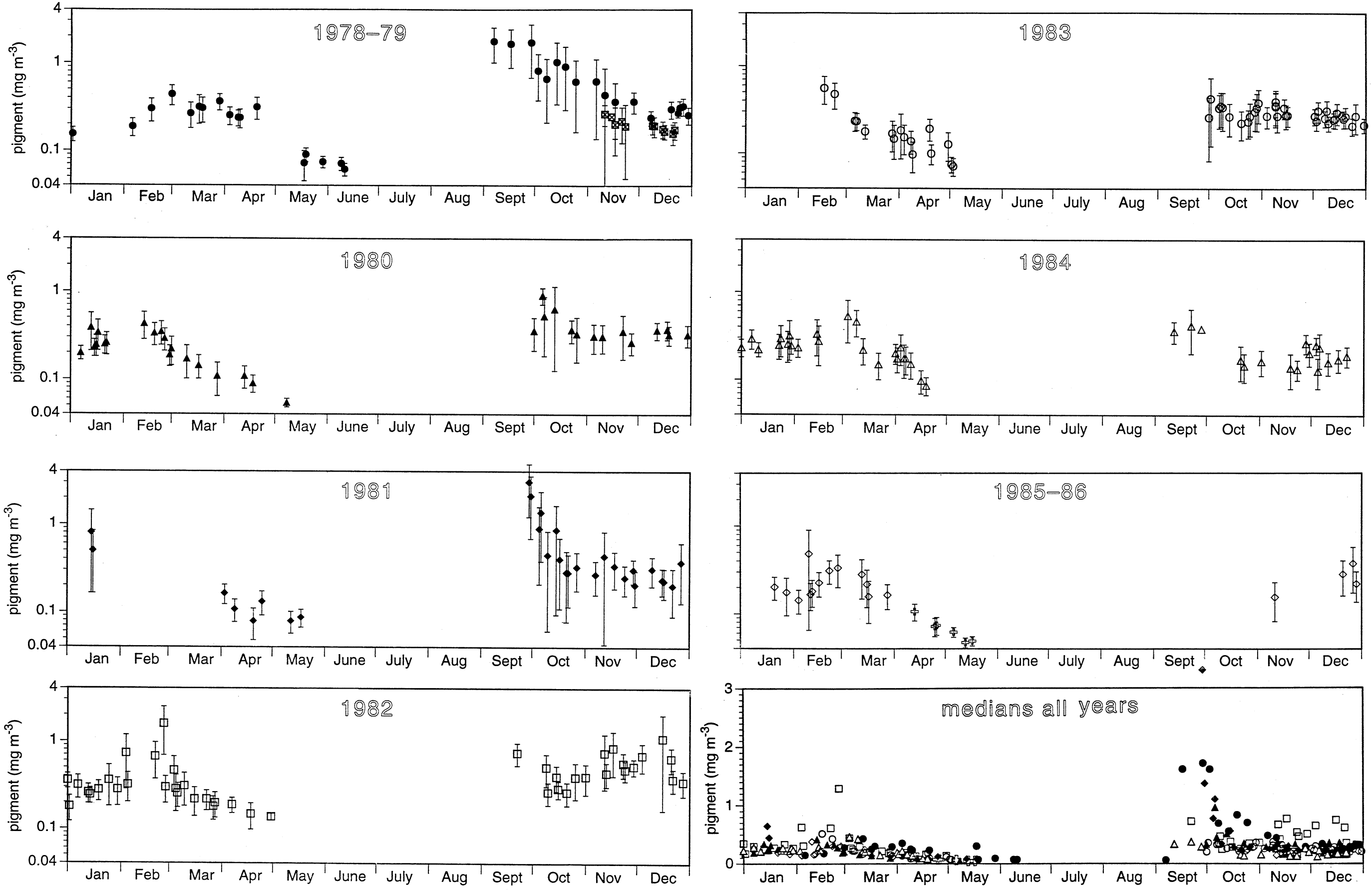

Fig. 3 (*continued*). Box 3A (see also caption for Box 2A, p. 1655).

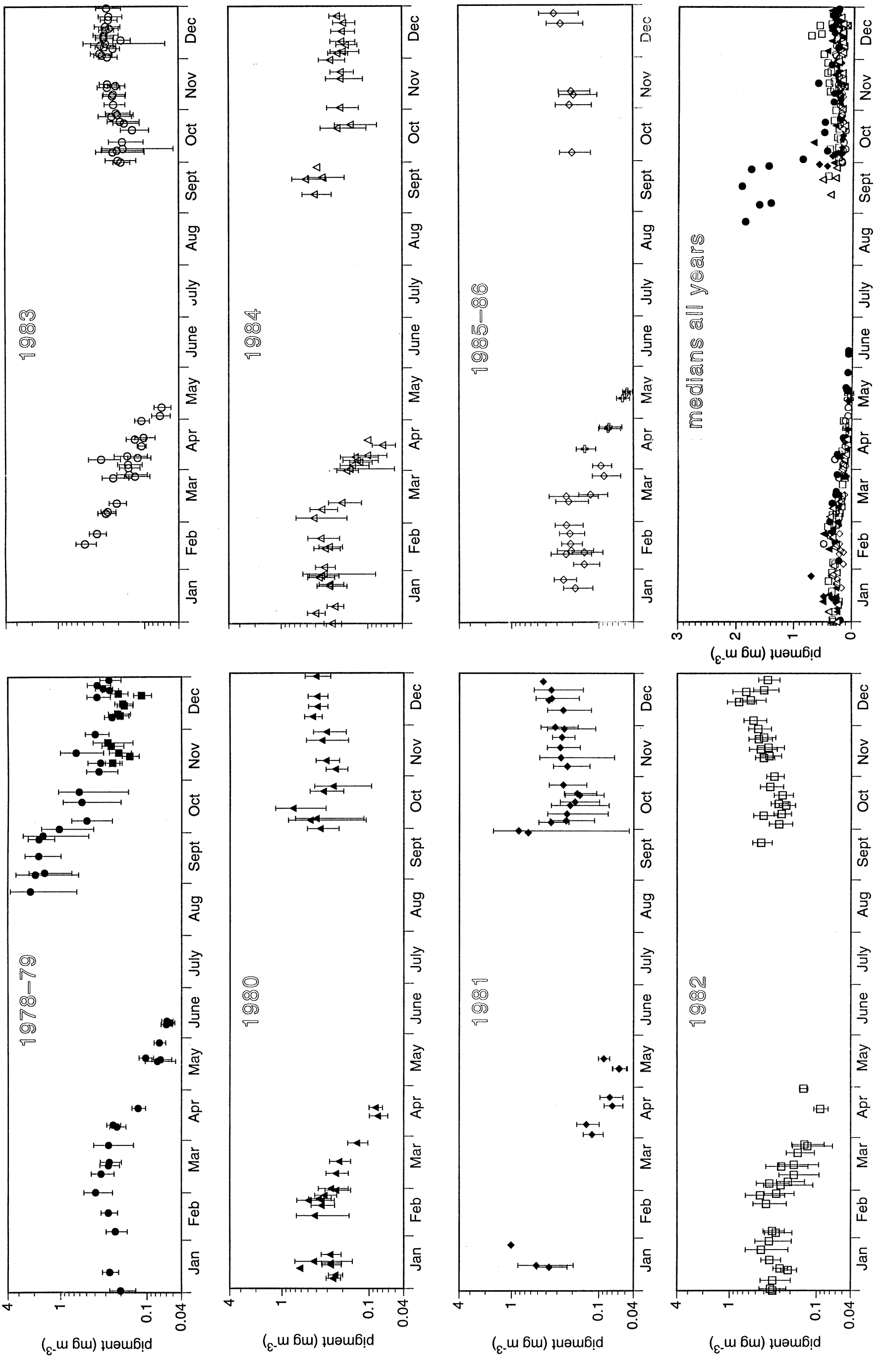

Fig. 3 (*continued*). Box 3B (see also caption for Box 2A, p. 1655).

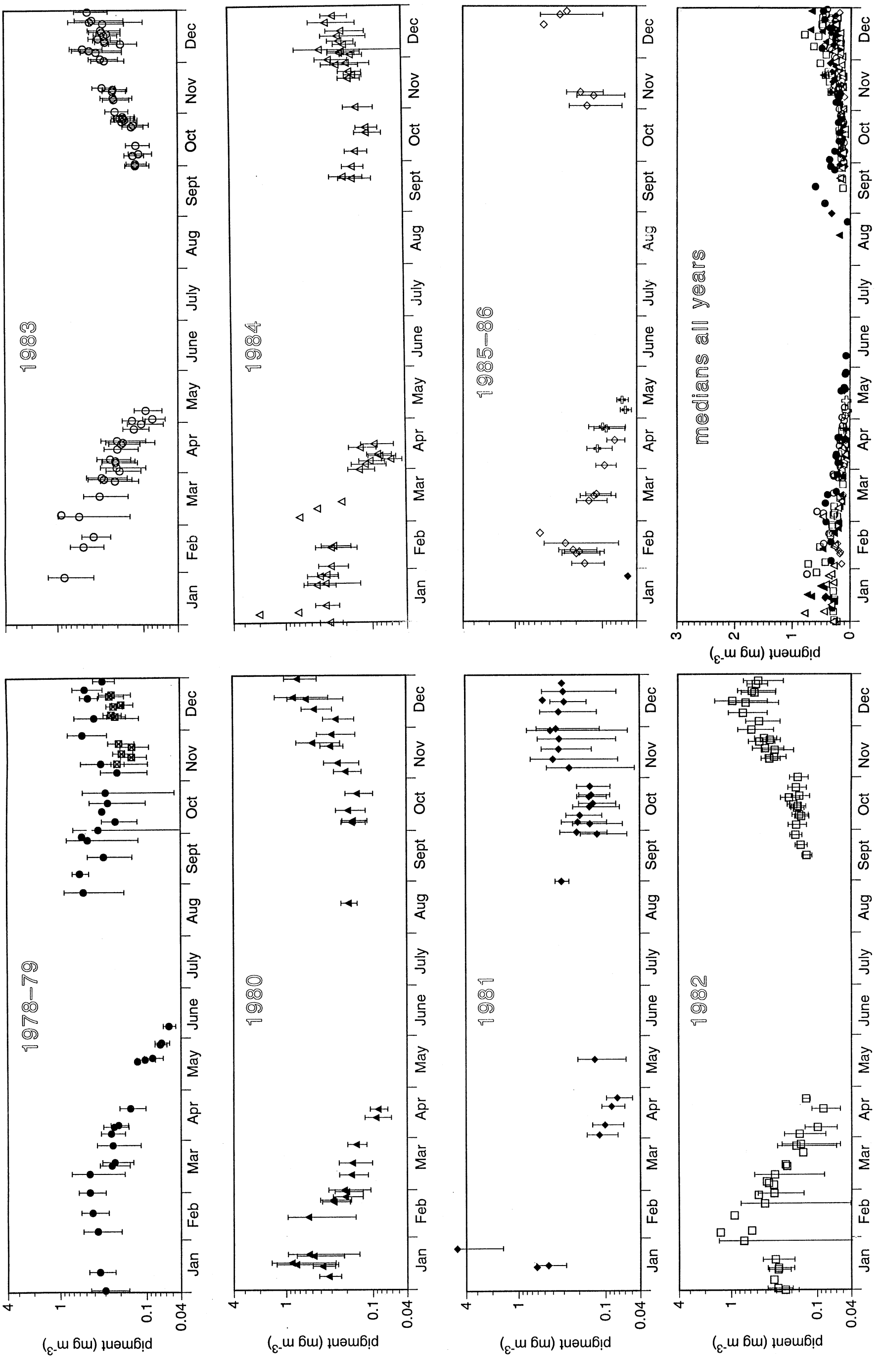

Fig. 3 (*continued*). Box 4A (see also caption for Box 2A, p. 1655).

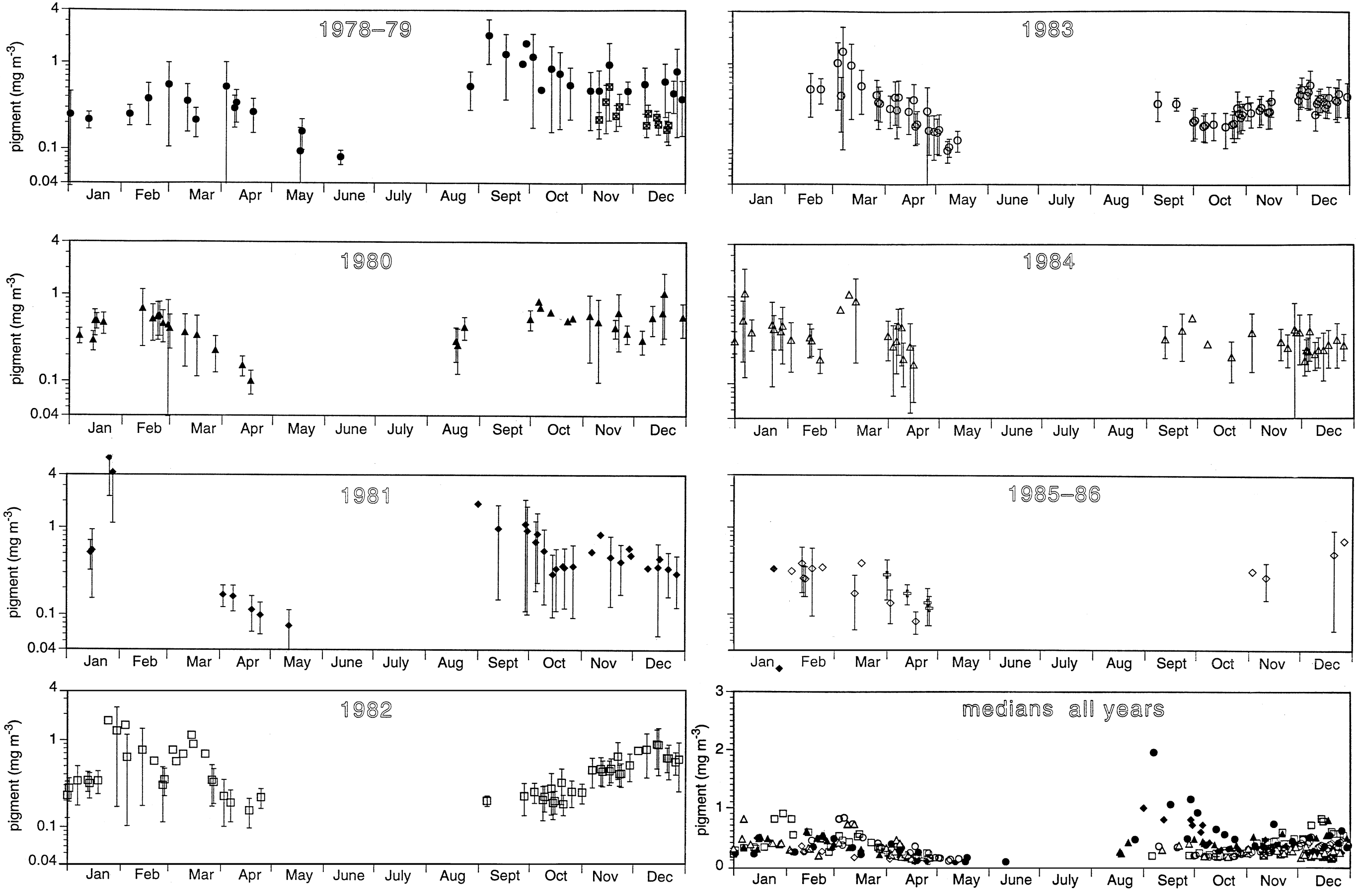

Fig. 3 (*continued*). Box 4B (see also caption for Box 2A, p. 1655).

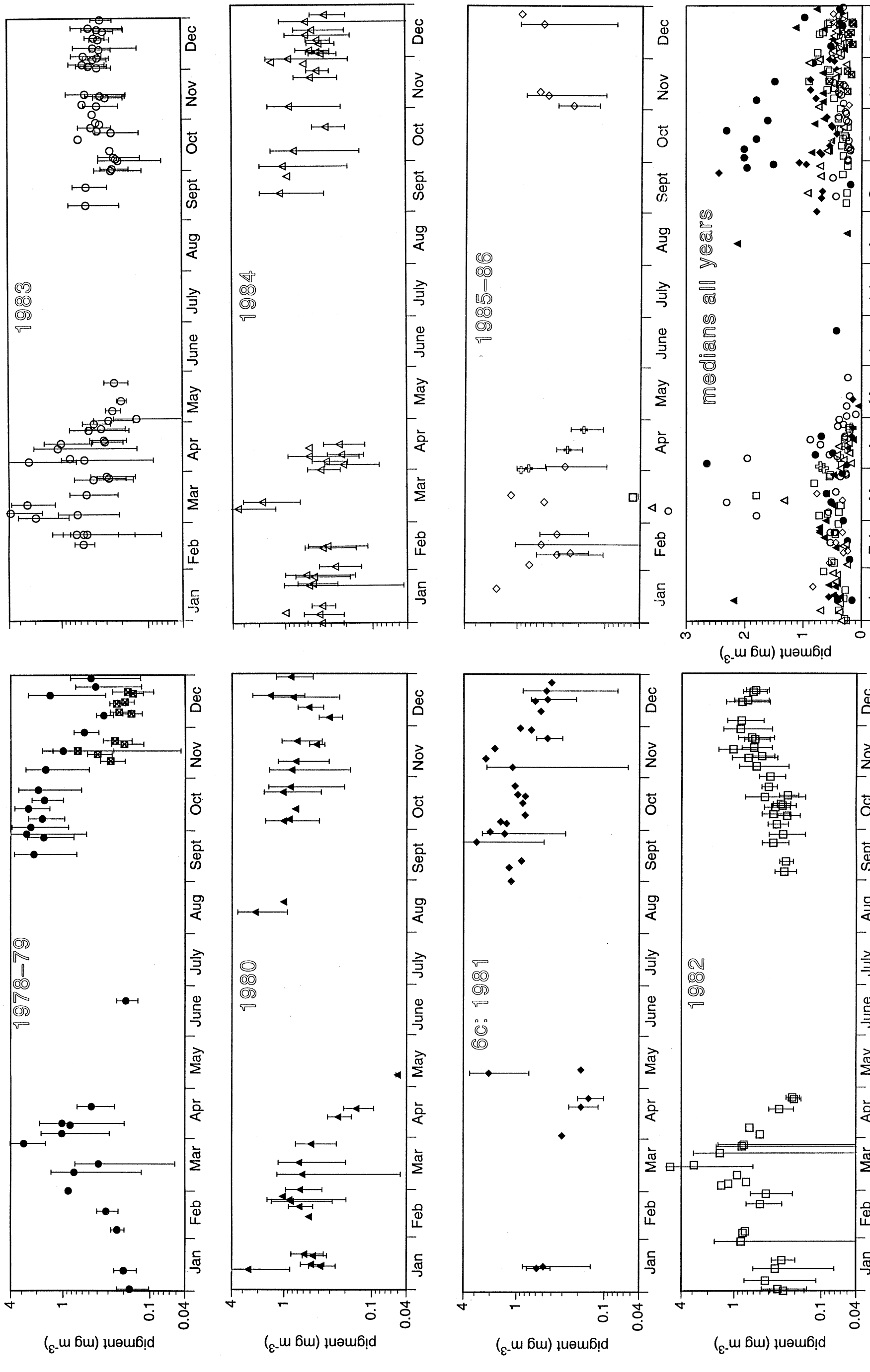

Fig. 3 (*continued*). Box 4C (see also caption for Box 2A, p. 1655).

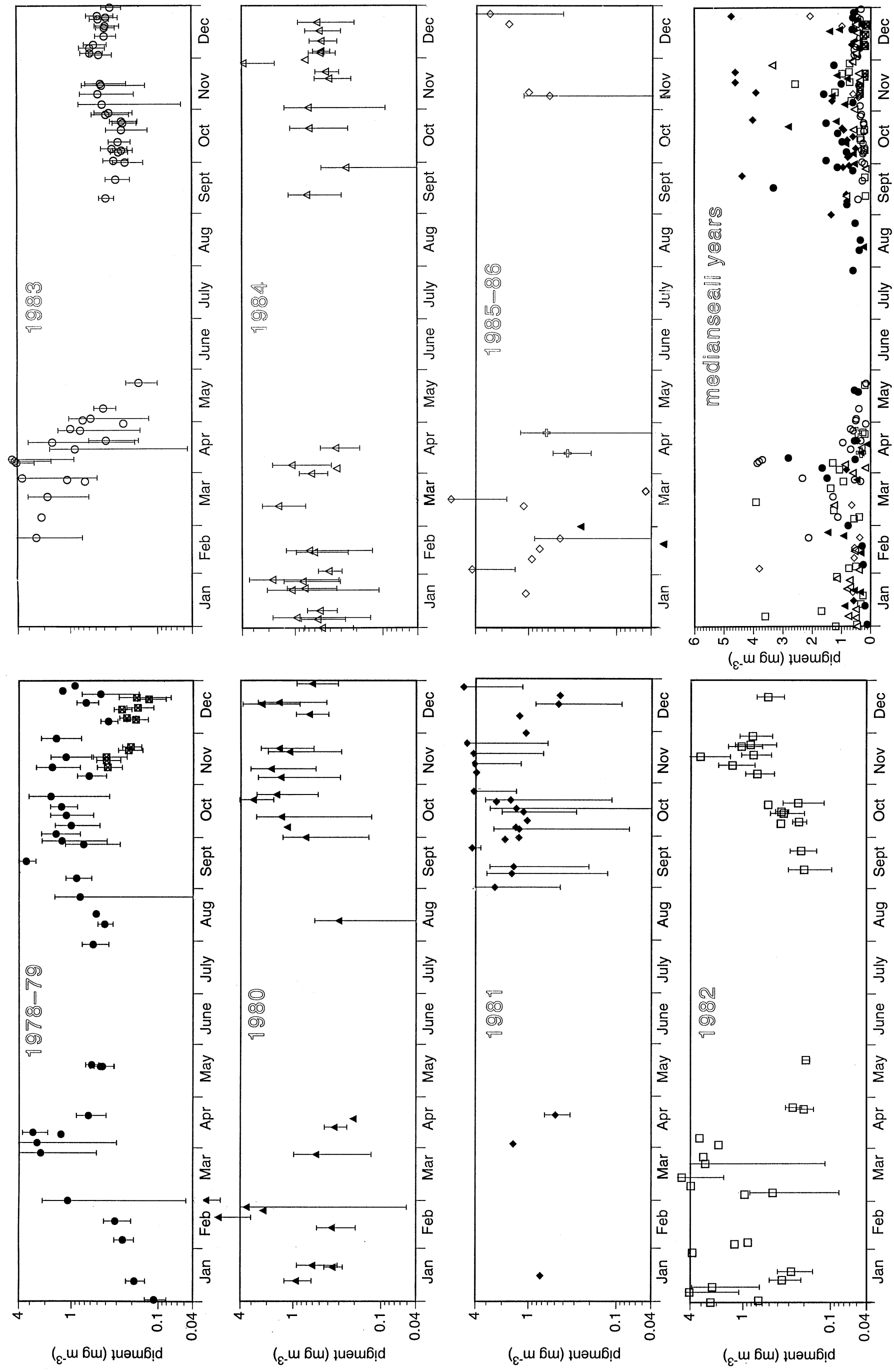

Fig. 3 (*continued*). Box 5 (see also caption for Box 2A, p. 1655).

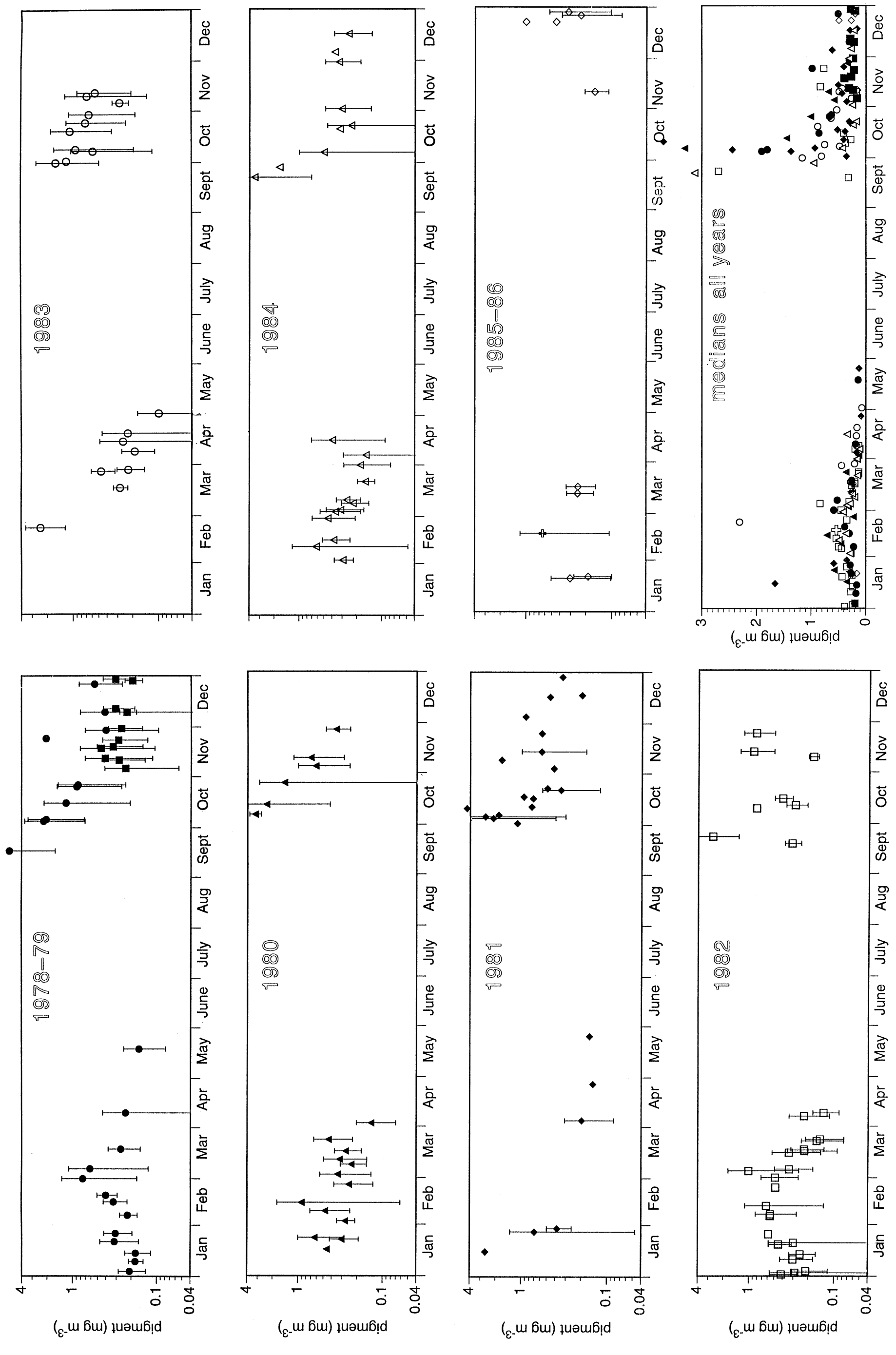

Fig. 3 (*continued*). Box 1A (see also caption for Box 2A, p. 1655).

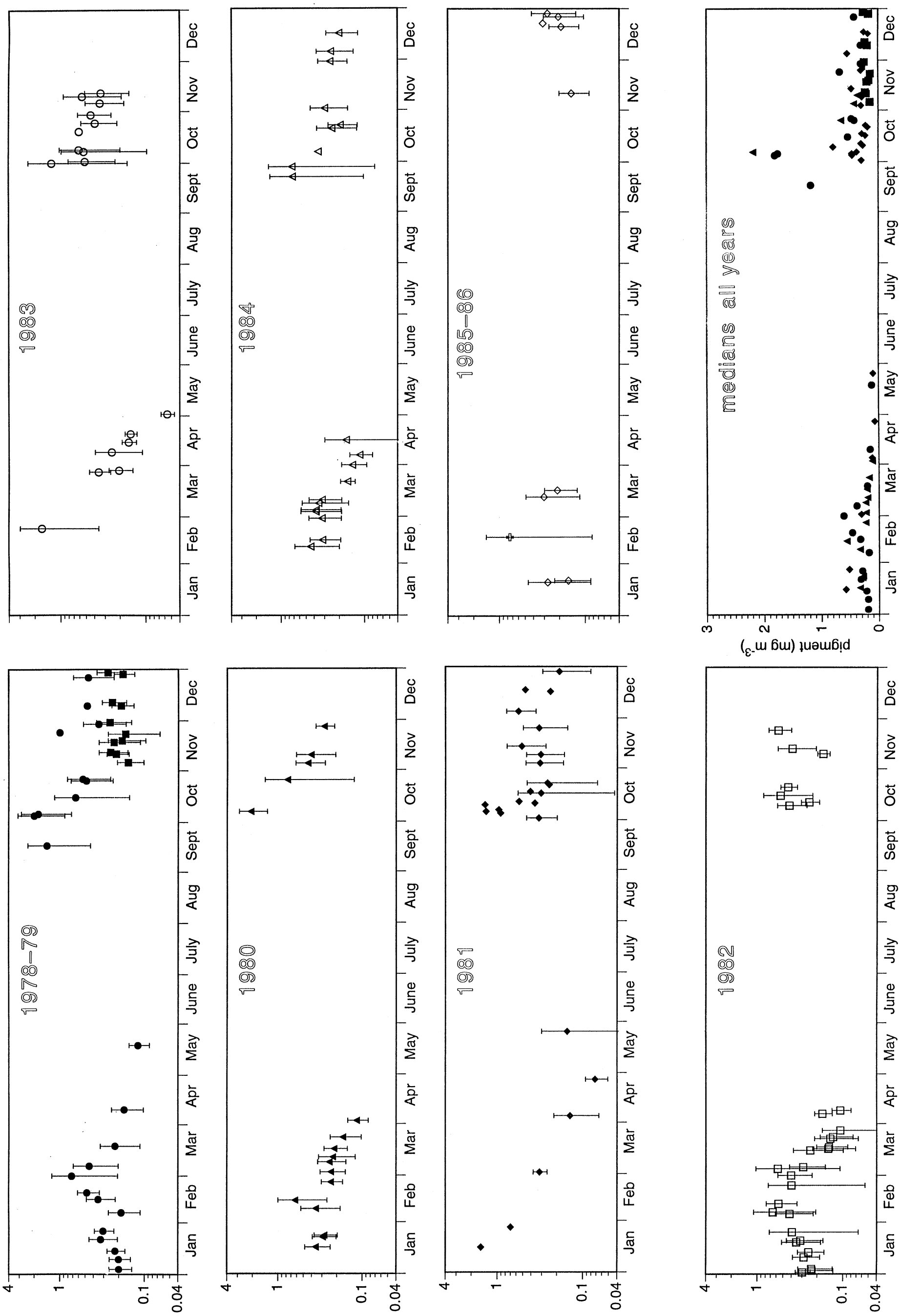

Fig. 3 (*continued*). Box 1B (see also caption for Box 2A, p. 1655).

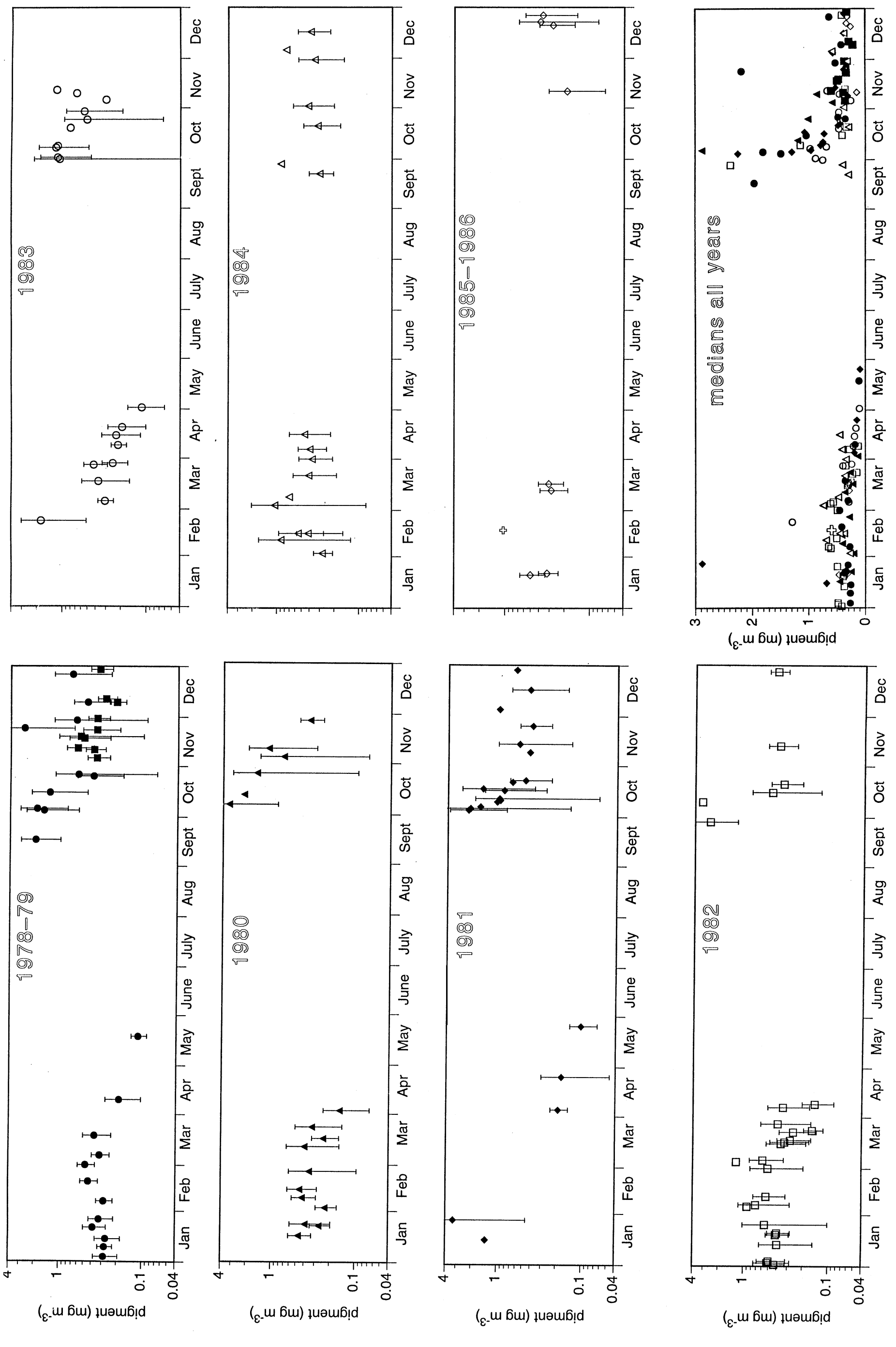

Fig. 3 (*continued*). Box 1C (see also caption for Box 2A, p. 1655).

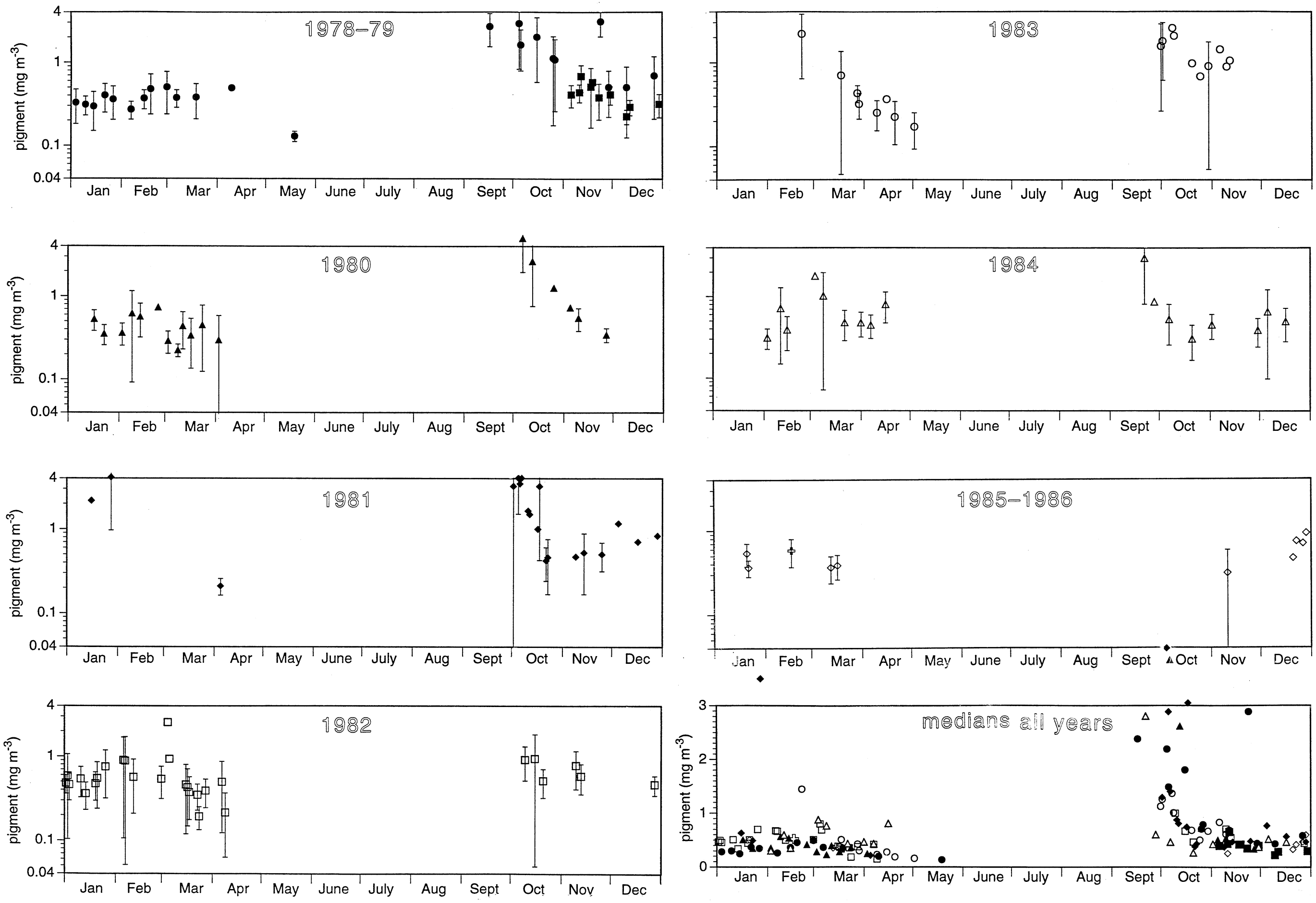

Fig. 3 (*continued*). Box 1D (see also caption for Box 2A, p. 1655).

The few higher September means ($\leqslant 1.5\,\mathrm{mg\,m^{-3}}$) in boxes 2A (1979, 1981) and 2B (1979) were not advected from the west, i.e., from regions of coastal upwelling, since they were not preceded by, or were not concurrent with, enhanced pigment in Box 2D to the west, except in late September 1979. In September of 1979 and 1981, though, large blooms prevailed in Box 3A to the north. Increases of CZCS pigment in the late SWM (September; no earlier data) were lacking in Box 2C. The November–December means in Area 2 were usually near $0.2\,\mathrm{mg\,m^{-3}}$, occasionally rising to $0.3\,\mathrm{mg\,m^{-3}}$ (boxes 2A and C, 1979), and continued at near-0.2 mg levels into January or February.

In situ chlorophyll values during March to May for the mid-1960's in Area 2 were all $< 0.1\,\mathrm{mg\,m^{-3}}$ (Banse, 1987), but slightly elevated concentrations of about $0.2\,\mathrm{mg\,m^{-3}}$ were observed in boxes 2B and C during September 1963; these were based on filters with a pore size of 4 μm and, hence, are underestimates (see Banse, 1987); cf. Owens et al., (1993) and Savidge and Gilpin, 1999) for size-fractionated carbon uptake). In Box 2A during September 1963, however, surface chlorophyll reached 0.3 to $1.5\,\mathrm{mg\,m^{-3}}$ in spite of the coarse filters employed. Nitrate levels were just above or well below 1 μM (cf. Wyrtki, 1971: Plate 62 for these data).

The in situ collections for mid-July to mid-September in 1986, 1987, 1994, and the many from 1995 in the upper layer of Area 2, largely along 65°E (no June data), ranged from approximately 0.1 to 0.6 (median, 0.2) $\mathrm{mg\,m^{-3}}$ chlorophyll (from Bauer et al., 1991; Mantoura et al., 1993; Bhattathiri et al., 1996; Latasa and Bidigare, 1998; Barlow et al., 1999; Sellmer, 1999; Goericke, unpubl.), while underway fluorescence ranged from approximately 0.1 to 0.7 (median, 0.4?) $\mathrm{mg\,m^{-3}}$ pigment (Woodward et al., 1999; the highest value was recorded in September in the NE part of Box 2A, accompanied by about 4 μM of nitrate). From mid-November through May 1 in 1994 and 1995, station data ranged from 0.05 to 0.5–0.6 (median, 0.15) $\mathrm{mg\,m^{-3}}$, with the highest values (0.15–0.6; median approximately $0.3\,\mathrm{mg\,m^{-3}}$) observed in mid-January (from Bhattathiri et al., 1996; Latasa and Bidigare, 1998; Barlow et al., 1999; Sellmer, 1999; Bidigare, Goericke, unpubl.). The nitrate concentrations in the upper mixed layer varied from 0.01 to 0.2 μM between mid-July and November (one exception of about 4 μM in September), and were usually $\leqslant 0.1$ μM from November through May (from Mantoura et al., 1993; Bhattathiri et al., 1996; Morrison et al., 1998; as well as raw data of Sellmer, 1999; and Woodward et al., 1999).

The low salinity in most surface samples accompanying pigment of the 1960's in the western parts of areas 2 and 3 for the SWM suggests advection of upwelled water from the west or north (Banse, 1987). Brock et al. (1991) doubted the advective interpretation, but Currie (1992) provided sections for those years, which clearly show low-salinity water upwelling near the coast. Similarly, low surface salinity extended in late September/early October 1995 to about 600 km from the coast (ca. 15°N, 62°, Lee et al., 2000, Fig. 13). Modeling likewise points to marked advection, in addition to nutrients supplied in place from below (e.g., Keen et al., 1997).

A.3.2. Area 3

During the NEM and the following intermonsoon, in situ data of the mid-sixties stayed largely below $0.1\,\mathrm{mg\,m^{-3}}$ (median approximatly $0.05\,\mathrm{mg\,m^{-3}}$) of chlorophyll, with the exception of two stations in late January with 0.15 mg m^{-3} (Banse, 1987). Observations for mid-November to January 1994/95 ranged from 0.2 to 0.5 (median, 0.4) mg m^{-3} (Tarran et al., 1999; Woodward et al., 1999 [fluorescence]; Bidigare, Goericke, Marra, unpubl.) and in mid-March 1995 from < 0.1 to 0.4 (median, 0.1) mg m^{-3} (Bhattathiri et al., 1996; Latasa and Bidigare, 1998).

For the SWM, a very important issue for understanding the central Arabian Sea is the chlorophyll level to be expected outside the region influenced by the coastal upwelling. There are months without CZCS data. Therefore, the SWM in situ observations will be reviewed in detail. Mid-July data for the mid-1960's ranged from 0.1 to 0.3 (median, 0.3) mg m^{-3}, and mid-August to early September values from 0.3 to 0.8 (median 0.4) mg m^{-3} (Banse, 1987). Between October 1994 and October 1995, at a one-year time-series in the southwestern corner of Box 5A, mixed-layer pigment > 0.6 mg m^{-3}, up to 1 mg m^{-3}, appeared only by mid-August 1995; a few mid-July days with concentrations approaching 1 mg m^{-3} were due to an eddy passing by (Dickey et al., 1998; Marra et al., 1998; fluorescence). Along a repeatedly run NW–SE section through Area 3, < 0.2–0.3 mg m^{-3} pigment were recorded in late June/mid-July (estimated from Lee et al., 2000, Fig. 12, fluorescence). From station data for the last days of July, mixed-layer concentrations of chlorophyll were 0.3–0.7 mg m^{-3} (Barber, unpubl.), with nitrate and silicate only at detection levels in a 60–80 m deep mixed layer; eight days later along the section, but perhaps on the shoulder of the mentioned filament/eddy crossed by the section, chlorophyll had risen to 0.5–0.6 mg m^{-3}, accompanied by 6–7 μM nitrate and 0–4 μM silicate (Sellmer, 1999). Next, 0.4–0.9 (median, 0.6) mg m^{-3} of chlorophyll were observed in early August (Barber, Goericke, unpubl.) and 0.5–2.0 (median, 0.8) mg m^{-3} during early September (US JGOFS Data Archive for fluorescence; see also Latasa and Bidigare (1998, Fig. 4) for the early August and early September cruises, cf. fluorescence in Gundersen et al. (1998). In late September/early October 1995, < 0.5 up to about 1 mg m^{-3} of pigment were recorded by fluorescence (estimated from Lee et al., 1999, Fig. 13). Finally, in early November, 0.2–0.4 mg m^{-3} were observed in Area 3 (US JGOFS Data Archive). Previous station data from mid-August 1987 were 0.3 and 0.4 mg m^{-3} of chlorophyll (Bauer et al., 1991), and surface fluorescence along a similar section during September 1994, supported by bottle data for the mixed layer (Barlow et al., 1999), ranged from 0.2 to 0.6 (median about 0.4) mg m^{-3} pigment (Woodward et al., 1999).

Also for the SWM, as stated in the main body of the paper, the wind stress curl in boxes 3A and B must be sensitive to small lateral movements of the axis of the Findlater Jet within or among years. For example, while the monthly means for the SWM during 1979–1985 in Box 3A were normally positive and usually so also in Box 5B, they were zero or negative in Box 3B in 1981. No pigment values are available to study the biological effects, if any.

During the early-August and early-September cruises in 1995, 1–11 (median, 4) and 2–7 (median, 3) μM of nitrate, as well as 1–6 (median, 3) and 1–3 (median, 1–2) μM silicate, respectively, were observed in the mixed layer (US JGOFS Data Archive; cf. Morrison et al., 1998). Outside the SWM period, nitrate in the upper mixed layer during 1994/95 ranged from < 0.1 to 0.6 μM in mid-November (2 stations; US JGOFS) and from near zero to 4 μM in late November (Woodward et al., 1999), but varied between < 1 μM in the southeast of Area 3 to 1-2 μM in the central part in mid-December. By late January, the concentrations ranged from 2 to 5 μM, but by early April had reverted to < 0.1 to 0.2 μM. During the entire period, silicate fluctuated between 1 and 3 μM, without relation to nitrate.

A.3.3. Area 4

For 1979 to 1985, the monthly wind stress peaked in July or August in all boxes, but in some years it was somewhat stronger in Box 4A, in other years in Box 4B. The stress during the SWM was weakest (by 1/3 to 1/2) in Box 4C, farthest to the north and northwest. The stress maximum of the NEM occurred in November, if it was noticeable at all as a peak. In the average for the years in boxes 4A and B (Box 4C missing), the curl was positive only during June to August. Thus, even in Box 4A under the mean path of the Findlater Jet, the curl was already slightly negative during September and favored a depression of the pycnocline, but pronounced secondary peaks were seen in November of 1979 and 1983.

During the late NEM and subsequently in boxes 4A and B, periods of 2–8 weeks with means of 0.5 to 1.5 mg m^{-3} with large SD (i.e., blooms) appeared in February/March 1982, March/April 1983, and March 1984. Subsequently, and probably related to the onset of warming and the formation of the seasonal thermocline, concentrations in the entire Area 4 declined progressively through early June to < 0.2, and often to < 0.1 mg m^{-3}. This decline occurred in 1979 in boxes 4A and B about one month later than in the other years, but no parallel was seen in the wind data.

The scarce in situ measurements for the 1960s in Area 4 (mostly, boxes 4A and B) showed elevated pigment in March versus August and late October/early November of up to 0.4 and 0.5 mg m^{-3} of chlorophyll, separated by two May observations near 0.1 mg m^{-3}. The trends in the more recent, fairly numerous data indicate no clear difference between boxes 4A and B, which will be lumped here. Unless otherwise stated, they refer to late-1994/1995. For early-to mid-January, rounded medians of near-surface chlorophyll, nitrate, and silicate were 0.6 (range, 0.4–1.0) mg m^{-3}, 3 (1.5–4) μM, and 1.5 (1–3) μM, respectively (for pigment, Barber, Bidigare, unpubl., and US JGOFS Data Archive; for nutrients, from Morrison et al., 1998, and same archive). The corresponding median concentrations of the preceding and following, physically more stratified seasonal periods, early November, early December, and March 1995 were 0.35 (0.05–0.6) mg m^{-3}, 0.2 (undetectable to 2.5) μM, and 2 (1–4) μM (same sources). A single station from April/May 1994 (Bhattathiri et al., 1996) is included here.

For the SWM, the median in-situ chlorophyll values and ranges for late July and late August 1995 were about 0.4 (0.2–0.5) and about 0.2 (0.1–1.1) mg m^{-3}, respectively. Nitrate medians were 0.1 (< 0.1–0.2) and 0.05 (undetectable to 5) μM. The silicate median for both periods lumped was 2 (1–4) μM (sources as above). In addition, there were single stations in late September 1986 with almost 0.5 and 0.65 mg m^{-3} chlorophyll (from Mantoura et al., 1993; Owens et al., 1993) and early September 1994 with an estimated 0.45 mg m^{-3} value (from Barlow et al., 1999).

A.3.4. Areas 5 and 1

No additional remarks are needed beyond those in Sections 2.1.5 and 2.1.6.

A.4. Relation of monthly pigment averages to wind forcing

Originally we hoped to find relations between CZCS pigment and forcing by wind stress and wind stress curl (actuall, pseudo-wind stress and curl, see Section A.1.2.), as well as heat flux, that were of some predictive power and would hint at reasons for interannual variability of pigment. A weakness not originally considered were missing months even in the climatological average, and more so in individual years. Simple temporal correlations of monthly pigment averages for each box for individual years (Table 1) with each of the three forcing functions yielded not one significant correlation. Better results were achieved with the overall averages for late 1978 to mid-1986, especially so, when pigment was lagged by one or two months behind the physical forcing (M.E. Luther and D.M. Bartolacci, St. Petersburg, FL, personal communication, 1997). Because a temporal correlation analysis based on climatological monthly pigment means can be found in Bartolacci (1996), details will not be presented.

We wish to make an important point, however, regarding the spatio-temporal correlations between the climatologies of monthly CZCS pigment taken directly from the Global Data Set and the three presumed atmospheric forcing functions for the period, by means of two other statistical methods (Bartolacci and Luther, 1999). Principally, only July was without any pigment data, so the authors interpolated between June and August. The main source of spatial and temporal variability turned out to be the SWM, but a lag by pigment of one or two months behind the forcing was observed. The authors were criticized by a reviewer to the effect that August would appear as the month with highest pigment simply by virtue of the interpolation, so that an artificial lag might be generated (M.E. Luther, personal communication, 1998). Our present results, however, vindicate the approach: July indeed has less pigment, and in part, noticeably so, than the following months.

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