Vol. 34: 201–211, 1986 | MARINE ECOLOGY – PROGRESS SERIES Mar. Ecol. Prog. Ser. | Published December 19

Winter blooms of phytoplankton in the Arabian Sea as observed by the Coastal Zone Color Scanner

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ABSTRACT: Mean phytoplankton chlorophyll concentrations as estimated by the Nimbus-7 Coastal Zone Color Scanner are presented for December 1978 to April 1979 and November 1979 to March 1980 for 8 offshore areas of the Arabian Sea north of 10° N. Appreciable regional differences in levels and timing of changes of concentration were found, with large blooms being especially common in late winter north of about 20° N. Differences between the 2 autumn/winter periods in the timing of blooms were marked. Monthly means of surface water temperatures (for 2° × 2° squares) and winds (for 5° × 5° squares) did not provide explanations for the changes in pigment concentrations. Average chlorophyll concentrations north of about 20° N were significantly higher than those between about 10° and 15° N both prior to and during the months of seasonally elevated pigment levels.

INTRODUCTION

The Arabian Sea is a low-latitude sea under marked continental influence. As a consequence, winds reverse their directions seasonally, causing drastic changes in the surface currents; also, the seasonal range of the sea surface temperature (SST) is large, leading to convective overturn in the north during winter. The resulting vertical mixing should transport nutrients upward into the photic zone at seasonally varying rates, which in turn should affect the growth rates of phytoplankton as these are controlled in low latitudes by nutrient supply rather than light. Presumably, life cycles of many zooplankton species and the downward flux of particulate organic matter out of the photic zone are influenced by this seasonality.

The atlases of the hydrography of the Arabian Sea by Wooster et al. (1967), Wyrtki (1971), and Hastenrath & Lamb (1979) included brief discussions of the depicted patterns. During the northeast or winter monsoon and the subsequent transition period, from November into late spring, the pattern of predominant surface currents in the open sea is similar to that of the trade wind and equatorial zones of the other oceans, but coastal upwelling is absent. The climatological temperature regime for the open sea was treated in detail by Colborn (1975), and the region of our concern corresponds to his Primary Areas 2 to 5. Surface salinity is markedly higher in the northern part of the Arabian Sea and results in high surface-water density when combined with the low SST during the winter (monthly mean for February north of latitude 24° N: 22 °C). During this time, a mixed layer of 100 to 120 m depth develops here (e.g. Wyrtki 1971); apparently, the dry and cool winter monsoon causes convection which is not found at similar latitudes elsewhere (Banse 1984). Even so, surface values of nitrate during the autumn-winter period are below 0.5 μM N l^{-1} and often undetectable, except in the northwestern corner which during early autumn is affected by advection from the Arabian coastal upwelling (Wyrtki 1971). The few available ammonium observations show the customary low values of the subtropics (e.g. Dietrich et al. 1966, Lukashev 1980).

As stated, the vertical mixing during winter should add nutrients to the upper layers of the open northern Arabian Sea, leading to enhanced algal growth, as off Bermuda, 7° further north than the northern border of the Arabian Sea (Menzel & Ryther 1961, see also Platt & Harrison 1985). However, existing information on photosynthesis and chlorophyll in the Indian Ocean at large (Krey & Babenerd 1976) and the Arabian Sea

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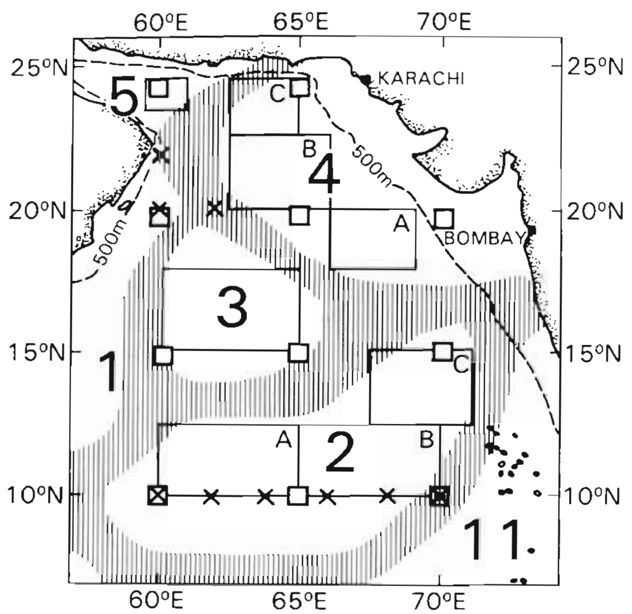


Fig. 1. Arabian Sea with major hydrographic areas as defined by Colborn (1975) separated by hatching, and areas and subareas used in present study (rectangles). ×: center locations of surface temperature observations; squares: central positions of wind and long-wave radiation measurements (note exceptions in text)

(Qasim 1982, Banse 1984) is scant in respect to material on phytoplankton seasonality. The last paper inferred the occurrence of winter blooms in the north. Subsequently, the seasonal distribution of chlorophyll in the upper 25 m was evaluated by Banse (1986) using ship observations for Colborn's (1975) hydrographic Areas 2 to 4 (Fig. 1). During October to March, a marked increase of chlorophyll appeared in the northernmost area, Area 4, and presumably also in the adjoining Area 5 (Gulf of Oman) but was not observed in the central Area 3 in spite of a deep mixed layer. As would be expected for low latitudes, pigment concentrations in the southernmost Area 2 were small; apparently, the only slight seasonal cooling had no effect. Overall, temporal coverage of the study was poor, and there was concern about the accuracy of part of the measurements in view of the pore size of filters used by some of the expeditions.

Ships are not well suited for collecting data over large areas in a study of the geographic or temporal distribution of non-conservative properties like chlorophyll: regional and temporal changes are necessarily confounded on extended cruises. In contrast, satellites permit repeated mapping of plant pigment, especially in regions with moderate cloud cover as over the Arabian Sea during autumn and winter. Although satellite observations pertain only to the upper part of the photic zone, near-surface periodicity of algae, if caused by hydrographic processes, is bound to reflect events comprising the entire mixed layer and is thus of wider interest. Therefore, we present estimates of concentrations of plant pigments (chlorophyll and break-down products) by the Nimbus-7 Coastal Zone Color Scanner (CZCS) for assessing the presence or absence of chlorophyll enhancement in the open Arabian Sea during 2 autumn/winter periods (1978/79 and 1979/80) when frequent overflights are available. The observations are analysed by hydrographic regimes following Colborn (1975), except that the shelves are excluded and his Areas 1 (off Arabia) and 11 (the Laccadive Sea) are not considered. Also, both Areas 2 and 4 have been divided into 3 subareas (Fig. 1, rectangles). Because of infrequent satellite coverage to the south, the study concentrates on areas northward of 10° N. We demonstrate regional differences in levels and temporal pattern of chlorophyll within, and marked differences between years which form an interesting contrast to other low-latitude areas.

METHODS

Processing of CZCS imagery. Orbits covering much of the Arabian Sea, without heavy cloud cover, appropriately spaced in time, and typically with 2 or 3 sequential scenes, were selected from Level 1 images (i.e. calibrated and geographically located). They were subsampled utilizing every 4th pixel on every 2nd line. Hence, one processed pixel represents an area of ca 6 to 10 km^2. Algorithms by Gordon et al. (1983b) were used to derive estimates of water radiance and chlorophyll concentration, and the algorithm of Gordon et al. (1983a) to compensate for the time-dependent sensor degradation. For most orbits, the atmospheric correction had to be determined from the southernmost scene because the required chlorophyll concentrations of <0.25 µg l^{-1} were rarely found in the north (see Fig. 2). In the 28 determinations, the Ångström exponents for Channels 1, 2 and 3 (centered at 443, 520, and 550 nm, respectively) ranged from near zero to −0.39, −0.40, and −0.39, respectively, with the medians being −0.12 for all 3 channels.

After processing the 512 × 512 pixel scenes, pigment means were calculated for 8 areas or subareas (see Fig. 1; Area 3, the largest region, measured ca 178000 km^2, whereas Area 5, with ca 17000 km^2, was the smallest). Channel 5 (700 to 800 nm) and the aerosol radiance in Channel 4 (670 nm) were used to distinguish bands of heavy atmospheric haze and clouds from regions of saturation of the pigment algorithm (see below). Omitting the coherent patches of algorithm saturation, pigment values were averaged for the valid pixels not close to clouds. The percentages of the areas sampled (top of panels, Fig. 2) were found from the number of valid pixels; since the scenes were not remapped on an equal-area projection, the total number of pixels within an area varied depending on the location within the scene because of foreshortening at larger scan angles by the satellite. Although on some dates some areas or subareas were not seen at all by the satellite, 74 % of those that were appeared in full view albeit usually occluded partly by clouds.

For illustrating the geographic and interannual differences, the images were remapped to a transverse Mercator projection and composited into seasonal chlorophyll fields (see Fig. 4). Pixels with clouds or algorithm saturation were omitted if valid pigment values were available; otherwise, they remained depicted as clouds. In fact, Fig. 4 contains few areas with clouds. Further, some straight edges in the southwestern part of Fig. 4 (left) show that only one scene could be used for the figure; elsewhere, up to 8 images provided the averages.

Statistics. Means and standard deviations (SD) were calculated regardless of the frequency distribution (see Fig. 2). Generally, the distributions were unimodal but greatly skewed toward high values, or bimodal. Because of the skewness many SDs were large even for the unimodal distributions. Further, even the means were unreliable when the pigment algorithm saturated over appreciable areas (filled symbols in Fig. 2 & 3) so that SDs were not computed.

Often, scattered pixels with nominal chlorophyll concentrations of 10 to 30 $\mu g\ l^{-1}$ occurred while the means for the area were well below 0.5 $\mu g\ l^{-1}$. Not knowing whether these values were real or erroneous and wishing to illustrate the trend of the bulk of the data, we also calculated SDs after omitting high values such that the means were lowered by 5 % (for 1978/79 only, heavy bars in Fig. 2). To find out whether it would have been better to omit 5 % of the pixels with high pigment values, the 2 procedures were compared in 9 areas or subareas with means ranging from 0.24 to 1.48 $\mu g\ l^{-1}$ chlorophyll. Omitting 5 % of the pixels reduced the SDs from an average of 31.6 % (SD $\pm$ 6.4 %) of the pigment means to 24.2 % ($\pm$ 6.2 %) while the procedure employed for Fig. 2 yielded an average SD of 23.6 % ($\pm$ 6.4 %). Hence, our method was adequate.

Ground truth. The only offshore chlorophyll measurements for the period seem to be those of Lopukhin & Kirillov (1984) during March/April 1980. With the station dates but not the times of the casts known, comparisons were made for 3 orbits using 1 station each on 7 dates (same day or adjoining day as satellite overflight) using 3 × 3 pixel averages (corresponding to roughly 50 km^2) centered on the ship's positions. Whereas the *in situ* values ranged from 0.02 to 0.07 $\mu g\ l^{-1}$ chlorophyll (average of upper 25 m with no systematic vertical gradients if any; see Banse 1986 for data source and justification of depth interval), the satellite means ranged from 0.25 to 0.88 $\mu g\ l^{-1}$ for 2 orbits and to 1.58 $\mu g\ l^{-1}$ for the third which was located near the limb of the scene; hence, the concentrations calculated for it may be too high. The SDs ranged from 15 to 48 % of the means of the 9 pixels so that there is no doubt that the satellite values are higher than those from the ship.

The discrepancy is unlikely to have been caused by positioning errors because large areas of water with as low chlorophyll as reported by the ship were not present in the images. However, the pore size used by Lopukhin & Kirillov (1984) for collecting plankton was 1.5 µm which may have allowed a large and variable portion of the pigment to escape. On numerous stations in the tropical Atlantic Ocean, in comparable nitrate-depleted regimes, Herbland et al. (1985) found 50 % or more chlorophyll to pass a 1.0 µm Nuclepore filter. In consequence, we take the chlorophyll estimates obtained from the CZCS algorithms at face value.

Saturation of pigment algorithm. The pigment algorithm saturated in an appreciable number of scenes, especially in the middle and northern areas, and more so in the 1979/80 period than the preceding autumn and winter. Without doubt, local phenomena are the cause since the same algorithms and programs have been used successfully off the U.S. east coast without encountering saturation even around pigment means of 10 $\mu g\ l^{-1}$ (McClain et al. 1984, 1985, McClain & Atkinson 1985). The cause was neither sun glint, nor the aerosol correction, nor (judging from the normal, low radiance in Channel 3) coccolithophorids or desert dust suspended in the water. Further, while an enrichment of the mixed layer by upwelling off Arabia would be feasible at this time for Subarea 2A and Area 3 (e.g. Ryther & Menzel 1965), it is out of the question for Subarea 4A (Banse 1968). However, surface blooms of Cyanophyceae (*Oscillatoria* sp., formerly *Trichodesmium*) are common in the Arabian Sea during winter and spring (Carpenter 1984) and can lead to visible accumulations near or at the surface. From the satellite, pigment concentrations then would appear high since the vertical distribution would be strongly weighted at the surface. As soon as enhanced turbulence, e.g. wind, had redistributed the material throughout the mixed layer, the signal of *Oscillatoria* chlorophyll 'diluted' by perhaps 50 times would vanish into the background of the other plankton chlorophyll. In fact, saturation occurred in mid-November 1979 in Subarea 2A, Area 3, and Subareas 4A & B (off-scale in the latter, Fig. 2) and the pigment distributions were bimodal. Eleven d later, the saturation had disappeared and the new means were similar to the lower modes (lower concentration peaks in the distributions,

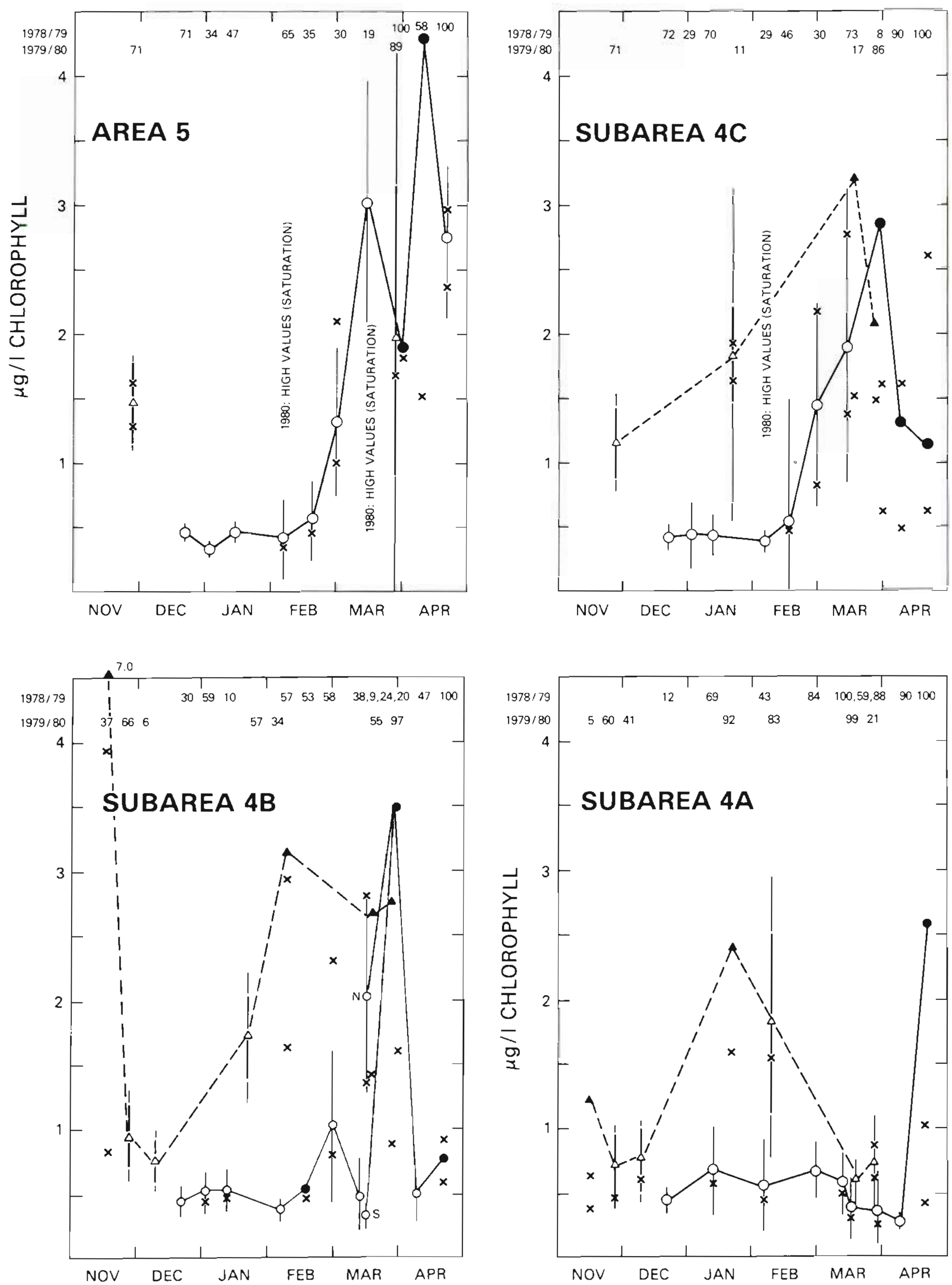
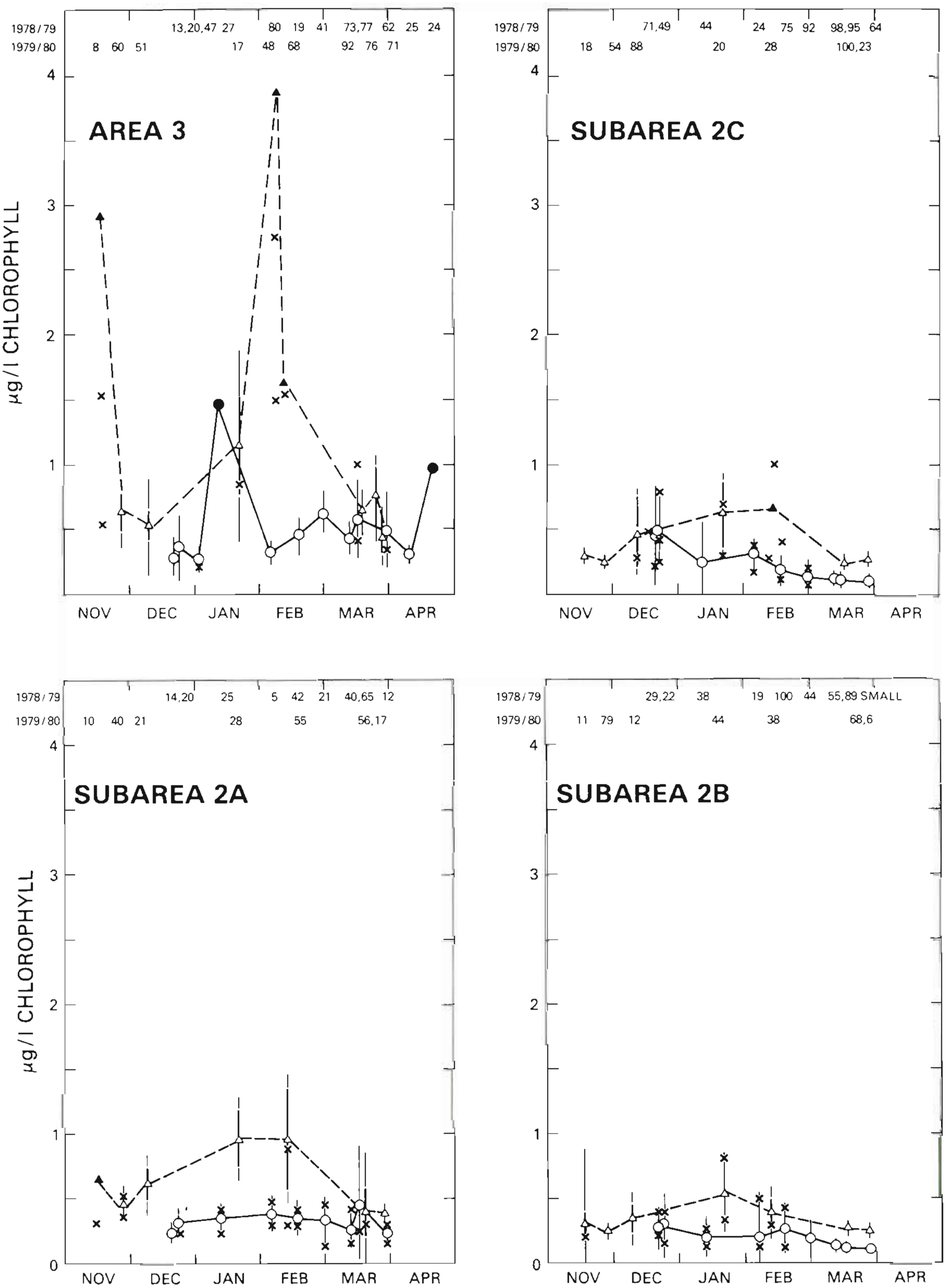


Fig. 2. Temporal changes of pigment means for areas and subareas approximately arranged as in Fig. 1. Circles refer to 1978/79, triangles to 1979/80; filled symbols indicate saturation of pigment algorithm (some scenes of Areas 4C and 5 exhibited a general algorithm saturation as noted). For clarity, the means for 1978/79 and 1979/80 are connected by full and dashed lines, respectively (except for Area 5). Bars indicate standard deviations; heavy bars represent SDs after omitting approximately 5 % of the observations with high pigment content (1979/80 only); crosses identify the modes of the frequency distributions (1 cross for a



mode of a unimodal distribution that differs appreciably from the mean and 2 crosses for bimodal distributions; high modes where pigment saturation resulted in dubious accuracy were omitted). Percentages of subareas sampled on each date are located on the top of the panels. 'N' and 'S' signify northern and southern parts of an area for an interrupted satellite scene. Dashed lines in Subarea 4B indicate a bifurcated portion of the solid line

Fig. 2) for the former date. Also, 3 out of the 4 areas had considerably less cloud cover suggesting a weather change between the 2 overflights. Similar reasoning, including the very high apparent rate of pigment increase that may come about by the surfacing of *Oscillatoria* cells, might pertain to other dates, e.g. Area 3 in mid-February 1980 or Subarea 4B in March 1979.

Ancillary data. Monthly means of sea surface temperature for 2° × 2° squares were available from the National Meteorological Center (NMC) of the National Oceanic and Atmospheric Administration, Rockville, Maryland, USA. They were based on surface *(in situ)* observations only and had been processed according to Reynolds & Gemmil (1984). Essentially, values are medians of the raw data and interpolated where observations are missing. The data distribution in space and time was not supplied. Anomalies of the monthly values from the average monthly means for 1970 to 1984 were also provided.

Mean zonal and meridional wind vectors from approximately 5° × 5° squares, also obtained from NMC, were used by us to calculate resultant winds. The means are based on NMC's Final Analysis (see Arkin 1982, Kistler & Parrish 1982). Finally, on the same approximate 5° × 5° grid, monthly means (from daily data) of outgoing long-wave radiation (Gruber & Winston 1978) were likewise obtained from NMC.

RESULTS

Overview

The satellite data suggest marked differences among areas and even among subareas, marked seasonal changes within several areas, and appreciable differences between years (Fig. 2). Most of these differences seem to reflect reality as suggested by an unintentional test for replicability within 4 areas on 21 and 22 December 1978. In spite of appreciable spatial structure in pigment distributions, considerable cloud cover, as well as rather different atmospheric corrections, the pigment means are similar. The temporal consistency within several areas over longer periods, especially during 1978/79 (Fig. 2), supports the conclusion that the algorithms are working well except for the saturation problem discussed above.

Frequency diagrams of pigment values within areas and subareas were either unimodal or bimodal in spite of the often huge regions encompassed. A clearly trimodal distribution was found only once. For unimodal distributions, the coefficient of variation could be amazingly small (SDs being 20 to 40 % of the means) as in Subareas 2B & C during March 1979. For other unimodal but skewed distributions, the omission of about 5 % of the higher pigment values often resulted in a considerable reduction in the SD, indicating that 95 % of the particular area was rather monotonous (Fig. 2, heavy bars, for 1979/80). On the other hand, sparse coverage of a bloom surrounded by low 'background' (bimodal pigment distribution) may be an important cause for some of the changes in means within areas on successive dates.

For a more specific presentation of the results, we consider the southernmost region (Subareas 2A, B) to portray the 'typical' tropical open-sea situation where a small lowering of surface temperature during the northern winter produces only a slight deepening of the mixed layer. We contrast with it the more continentally influenced regions (Areas 3 to 5). The relevant aspects of the hydrography of Areas 2 to 4 were sketched in Banse (1986). Briefly, after destruction of the shallow seasonal thermocline during late autumn, a deep mixed layer occurs during winter in Areas 3 and 4 but not in Area 2. The seasonal warming creates a new seasonal thermocline beginning in March which must reduce upward eddy diffusion of nutrients. In addition, the eastern part of Area 2 is influenced during spring by low-salinity water advected from the east that further stratifies the upper layers. Area 5 in the Gulf of Oman is similar to the adjoining Area 4 during winter, both having a deep mixed layer in January/February which in Area 5 may reach at least to 100 m (Wooster et al. 1967, pl. TV3). In contrast to the central and southern regions of Area 4, nutrient-rich water has been found in Area 5 during November still at shallow depths (30 to 40 m, Gilson 1937), presumably being part of the general movement of cool, nutrient-rich water onto the shelf off Pakistan (Banse 1968, 1984) and the upwelling off Arabia, both occurring during the summer and early autumn. However, the November surface concentrations of nitrate in the outer Gulf of Oman are very low (*Anton Bruun* 1963 stations as cited in Banse 1986), implying that the effect of the Arabian upwelling is no longer felt in the surface layer of Area 5, as also concluded by Colborn (1975) from surface temperature data.

Area 2

During 1978/79, the period with the most frequent observations, pigment means tended to vary little from date to date and were generally the lowest means of the entire data set. They declined to close to 0.10 $\mu g\ l^{-1}$ with unimodal distributions and very small (relative to the means) SDs at about the time when the low-salinity water of the eastern tropical Indian Ocean had spread into the Laccadive Sea and Subareas 2B & C (cf. Wyrtki

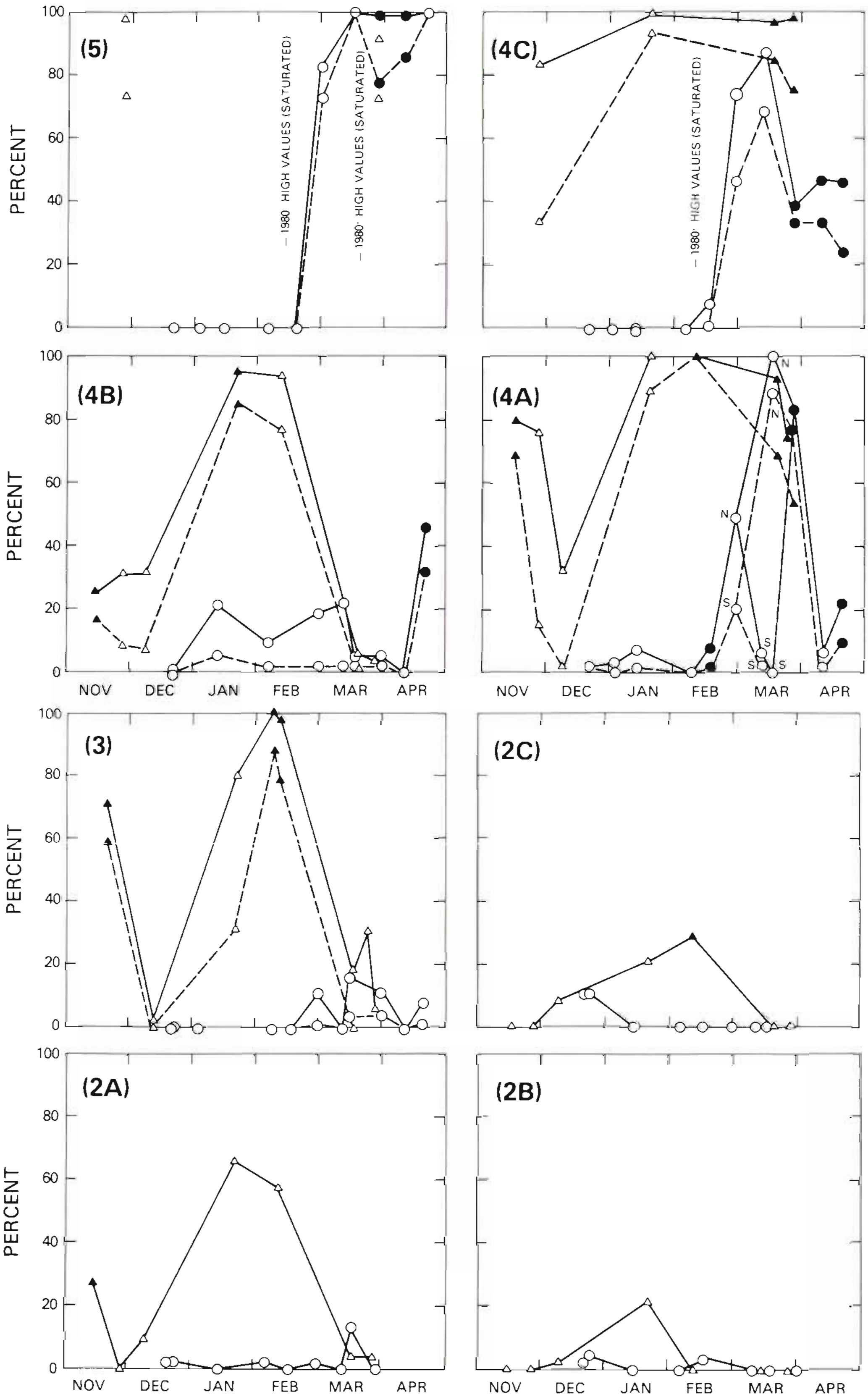


Fig. 3. Temporal changes of percentages of pigment values >0.8 µg l^{-1} (continuous, upper lines) and >1.2 µg l^{-1} (broken, lower lines) for areas and subareas as in Fig. 1. The 1.2 µg l^{-1} threshold was not used in Area 2; for Area 3 and Subarea 4A, 1.2 µg l^{-1} symbols and lines are omitted for greater clarity in Mar 1980 (all low values). In Subarea 4B, 1978/79 curves separate into N and S in late Feb (see also Fig. 2). It was not possible to connect the 1979/80 points in Area 5

1971, charts 50 and 51). Even at this low latitude, however, the variation of pigment between years was marked such that most means for 1979/80 were appreciably higher than in the preceding cool season.

Area 3

This very large region, in spite of its deep mixed layer during winter, did not greatly differ from Area 2 for 1978/79 except for more irregularity from date to date and a trend to somewhat higher means. Between November 1979 and February 1980, however, 4 out of 5 lower modes for dates with widespread pigment saturation indicated even the 'background' pigment values to be greatly elevated over the 1978/79 levels.

Areas 4 and 5

Subarea 4A largely repeated the pattern of Area 3, presumably because the isotherms in the Arabian Sea during autumn/winter tend to run from southwest to northeast, such that the thermal regimes in both regions are similar (Wooster et al. 1967), as are the surface salinities (Wyrtki 1971). In contrast, the temporal changes of pigment means in Subarea 4C and Area 5 were clearly distinguished from those of the more southern Areas 2 and 3 during 1978/79. The pattern in Subarea 4B seemed to be intermediate between the 2 pairs. The combined means for the 5 dates from December through mid-February for Areas 4C and 5 were significantly different from (higher than) those for Area 2 ($p < 0.01$, from Mann-Whitney test). More importantly, the greatly elevated concentrations in at least 3 of the northern areas during March and the first part of April did not occur in Areas 2 and 3 and perhaps not in Subarea 4A either (note low modes for April 1979 in Fig. 2). Taking the means at face value, the increase from 6 February through 17 March 1979 in Subarea 4C corresponds to an instantaneous population growth rate of 0.044 d^{-1} ($r^2 = 0.93$, $n = 4$), and that in Area 5 to 0.054 d^{-1} ($r^2 = 0.98$, $n = 4$); the population means doubled in about 16 and 13 d, respectively, in spite of grazing and sinking.

Little can be said about 1979/80 except that the pigment means were already elevated by January throughout Area 4. It is regrettable that May observations for 1978/79 and 1979/80 were not processed as data for this month are necessary for determining whether or not the shallow thermal stratification of this period leads to low pigment values (see Banse 1984).

Blooms

The often large standard deviations illustrated in Fig. 2 indicate that very few of the discussed trends are significant at the commonly used probability level of $p = 0.05$ although each mean is still based on hundreds of data points even if only 10 % of an area was visible. To demonstrate the trends more clearly, we asked where and when 'high' pigment values or blooms were present. 'High' was defined as being larger than the average of the means by 3 times the average standard deviations for all dates of 1978/79 from Subarea 2A, and those from December 1978 through mid-February 1979 from Subarea 2B. This choice excluded the period presumed to be under the influence of the eastern low-salinity water mentioned earlier, and defined an 'oceanic' threshold of about 0.8 $\mu g\ l^{-1}$ chlorophyll. The same procedure was applied to Subareas 4B & C and Area 5 for December 1978 through mid-February 1979, yielding a 'northern' threshold of about 1.2 $\mu g\ l^{-1}$. The 'oceanic' threshold was also employed in the north.

Fig. 3 illustrates the percentage of valid pixels (used for the means in Fig. 2) that exceed the 'oceanic' and 'northern' thresholds. For 1978/79, Fig. 3 again demonstrates the great seasonal change in the northern region. The northern part of Subarea 4B followed the pattern of Subarea 4C and Area 5; also Area 3 contained elevated pigment values at the time when the mixed layer should have been deepest. Further, Subareas 4B & C exhibited a marked decline in chlorophyll by April, possibly related to the establishment of the seasonal thermocline. The entire Fig. 3 shows more dramatically than Fig. 2 that 1979/80 had higher plant development during the height of winter than the preceding year. Moreover, the early appearance (January) of high values in the second winter is noteworthy for the regions where sufficient amounts of satellite data were processed.

Emphasizing the interannual differences and the north-south gradient of chlorophyll concentrations further, Fig. 4 depicts the mean pigment concentrations in the central and northern Arabian Sea for the studied 2 autumn/winter periods. These maps are to be compared for levels and patterns with the 'Winter' (November to April) charts in Krey and Babenerd (1976; e.g. pl. 21) and the map averaging all available ship observations, without regard to seasonal changes, in Qasim (1982, Fig. 15). In addition to the issue of accuracy (see 'Ground truth', above, and 'Discussion', below), the interannual differences in Fig. 4 suggest that the previously published charts need to be used with reservation. We suspect that this *caveat* holds for other open ocean areas as well.

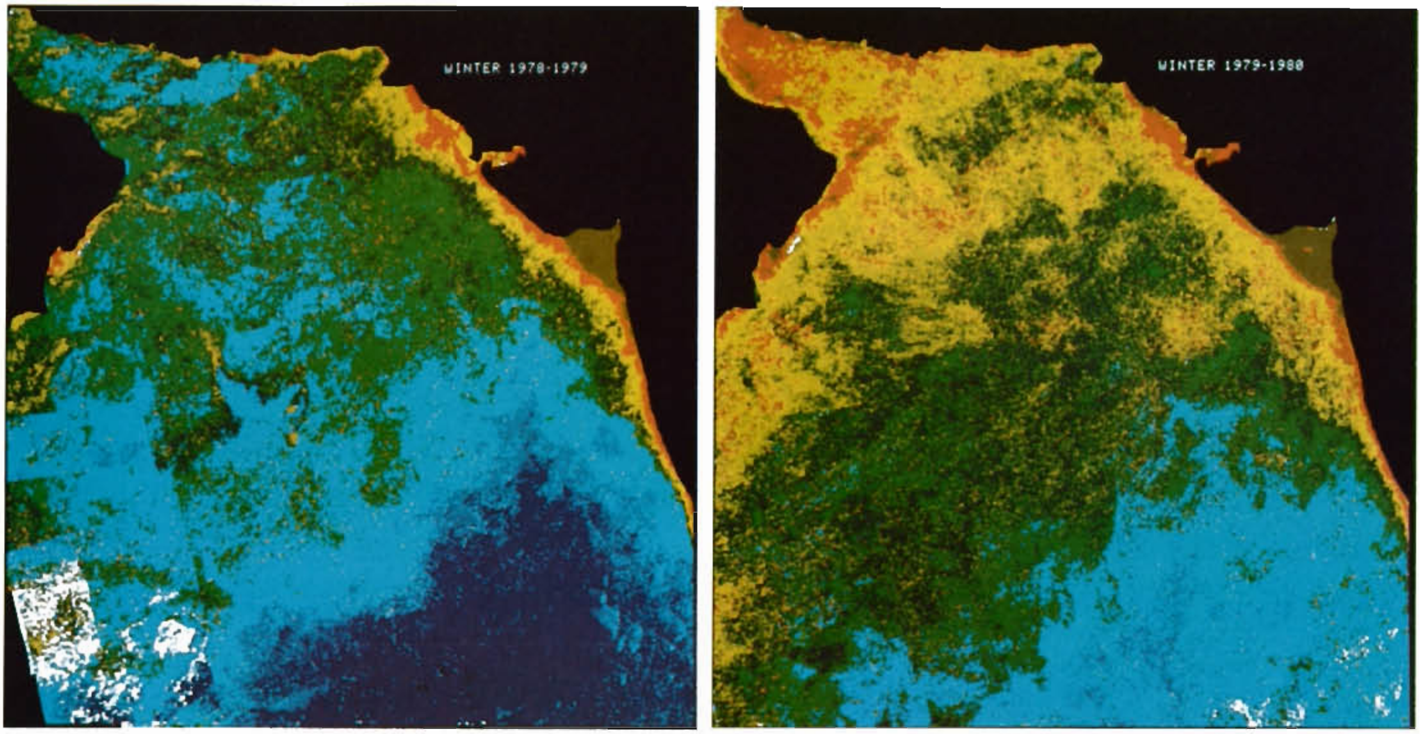


Fig. 4. Pigment averages for 1978/79 and 1979/80 between 9° and 25.5° N, and 58° and 74° E, in false colors: black, land; dark blue, 0.08 to 0.17 µg l^{-1}; blue, 0.17 to 0.25 µg l^{-1}; light blue, 0.25 to 0.45 µg l^{-1}; light green, 0.45 to 0.70 µg l^{-1}; dark green, 0.70 to 1.00 µg l^{-1}; yellow, 1.00 to 2.00 µg l^{-1}; orange, 2.00 to 4.00 µg l^{-1}; brown, 4.00 to 35.00 µg l^{-1}; white, >35.00 µg l^{-1} (saturated algorithm and clouds). See also 'Methods'

DISCUSSION

The satellite-based pigment estimates (Fig. 2) are higher, often severalfold, than those from the scattered earlier collections by ships reviewed by Banse (1986). Both data sets comprise chlorophyll *a* and phaeopigment and are, in that respect, comparable. However, only few ship observations were based on filter pore sizes of ≤0.8 µm and therefore can be expected to be accurate (see Herbland et al. 1985). Among these measurements, the *Atlantis* data from Areas 2 and 3 for March 1965 range largely between 0.05 and 0.10 µg l^{-1} while our lowest means, for March 1979 in Subareas 2B & C, range from 0.09 to 0.14 µg l^{-1}, with a lower mode in a bimodal distribution of 0.08 µg l^{-1}. The standard deviations for unimodal distributions are 0.02 or 0.03 µg l^{-1}. The concentrations calculated from the satellite being so small and near the lower limit of detection, it is impossible to say whether the differences of means between 1965 and 1979 reflect on the accuracy of our pigment algorithm or represent differences between years.

The principal point of the discussion concerns the connection between the chlorophyll in the upper part of the photic zone of a nutrient-poor region and the hydrography. We assume that vertical mixing in the interior of the Arabian Sea, increased by atmospheric processes such as lowering of sea surface temperature (SST) or wind effects other than evaporation, will enhance nutrient supply to the mixed layer and thus algal growth rates and concentrations. In fact, the previously known average hydrographic features at least qualitatively explain the differences in pigment patterns and levels between the southern and northern areas and subareas, as best demonstrated for the cool season of 1978/79 when good temporal coverage was available also in Subarea 4C and Area 5 (Fig. 2). Annual differences in weather and SST might likewise be reflected in pigment levels such that a cooler and more windy winter season leads to higher chlorophyll content in the upper layers where they would be detectable by the CZCS. However, the available climatological data do not provide a clear support or refutation of this supposition: the second year (1979/80) had higher pigment means and *higher* monthly means of SST; the SST of both years was above the average of the period 1970–84. The wind, in contrast, seems to have been stronger in the second year. Few of these trends attain anything near statistical significance.

Specifically, statistics for SST and its monthly anomalies, or plots matching Fig. 2 & 3, were not attempted because we do not know which 2° × 2° squares were rich in observations and which monthly means were found by interpolation. However, it is likely that the means from grid points situated along 10° N, at the northern edge of the principal shipping lanes to the eastern Indian and Pacific Oceans, were based on numerous ship observations, as were 3 grid points just south of Area 5 (crosses in Fig. 1). Table 1 shows that the trends of the SST means were similar over the entire region, the second year being warmer than the first, especially so (by 0.5 to 1.0 °C) during October, November, February and March, and by 1 to 2 °C in April 1980.

Table 1. Averaged differences of monthly means of sea surface temperatures (1979/80 minus 1978/79, in °C) in three 2° × 2° squares, each centered on grid points as in 1st column. Standard deviations range from 0.03 to 0.15 °C, with a median of 0.10°

Grid points Lat. (°N)	Long. (E°)	Nov	Dec	Jan	Feb	Mar
22	60	0.03	0.13	0.23	1.10	0.63
20	60, 62					
10	60, 62, 64	0.17	0.13	−0.03	0.63	0.83
10	66, 68, 70	0.43	0.20	−0.13	0.27	0.17

The wind data are harder to interpret than the SST means since they were available only for 5° × 5° squares. First, we consider the 9 southernmost grid points (squares in Fig. 1) for December, January and February, the months for which pigment data were sufficient for Subareas 2A to 4B to establish a difference between the 2 years. For these 3 mo, the resultant winds were 5.3, 4.1 and 3.0 m s^{-1} in 1978/79 and 5.1, 5.0 and 4.1 m s^{-1} in 1979/80, respectively. The easterly component tended to be a little weaker in the first year (3.9, 3.3 and 1.9 m s^{-1}) than in the second (3.9, 3.6, 2.0 m s^{-1}). The same pattern also prevailed in November. During March of both years, the CZCS coverage of the 8 areas or subareas was adequate for interannual intercomparisons so that we added grid points at 24.2° N, 60° E and 24.2° N, 65° E for a further comparison. With these additions, the average of the monthly resultant winds for March tended to be higher in 1979 than in 1980 (3.9 *vs* 3.2 m s^{-1}), but this reversal of the trend was not reflected by the pigment data (Fig. 2 & 3).

The outgoing long-wave radiation, which may be taken as an indication of cloud cover, had been measured since January 1979. Using the same 5° × 5° grid as that for wind, but without the points at 19.6° N, 70° E and the 2 added points along 24.2° N, which are in part covering land (Fig. 1), the overall mean was clearly lower in January 1979 than in January 1980 (267 *vs* 281 W m^{-2}, differing at $p = 0.05$, Mann-Whitney test) but was practically indistinguishable for February and March. At this latitude, one cannot expect from reduced irradiance a direct effect on specific algal growth rate in the upper layers, and hence population growth rate. Instead, as noted by Taylor et al. (in press) on the basis of a theoretical treatment, the depth of the photic zone would be lessened such that photosynthesis, and therefore nutrient uptake, by the deep chlorophyll maximum in the pycnocline are reduced. The consequence should be an increased diffusive supply of nitrate to the upper layers. On this basis, January 1979 might have exhibited higher chlorophyll levels than January 1980 but the opposite was the case (Fig. 2 & 3). Possibly, the study of the question by means of cloud cover means on a scale of 5° × 5° squares is not useful, and no conclusions can be drawn.

Overall, the inverse relation between SST and pigment content in 1978–80, with the warmer year tending to maintain higher chlorophyll levels, was not expected while the positive relation between wind strength and pigment level is intuitively understood. Dandonneau & Gohin (1984) observed the same relation to wind strength in a 5 yr set of surface chlorophyll data from the southwestern Pacific at similar latitudes. Thus, wind mixing may also in the Arabian Sea be more important than convective overturning of the surface layer in establishing the relation between the depth of the mixed layer and pigment content. For probing further, the only wind effects that might be discussed using 5° × 5° wind fields are vertical mixing and, perhaps, the enhancement of evaporation. The wind stress curl fields over smaller areas should be considered which is not possible with the information at hand. Very likely, monthly means for 2° × 2° or 5° × 5° squares represent inappropriate temporal and spatial scales for probing these CZCS observations further. Therefore, we plan to study the SST fields from satellite data at more commensurate scales and expect to find detailed wind data at least for 1979, the year of FGGE (First GARP [Global Atmospheric Research Program] Global Experiment).

Acknowledgements. This research was conducted at NASA/Goddard Space Flight Center and supported by NASA Headquarters (Ocean Processes Branch) and the NASA Summer Faculty Fellowship Program which sponsored Karl Banse. We thank Wayne E. Esaias NASA/Goddard Space Flight Center, for help in selecting suitable orbits and for other advice. Karl Banse further gratefully acknowledges guidance during the first steps into the realm of image processing by Frank Müller-Karger, now at Horn Point Environmental Laboratories, University of Maryland, Cambridge, Maryland, USA. We would also like to thank Judy Chen of General Software Corporation in Lanham, Maryland, for her assistance in developing the computer software necessary for image processing, Phillip Arkin of the National Meteorological Center of NOAA in Rockville, Maryland, for supplying climatological data, Linda Green and William Kessler of the School of Oceanography, University of Washington in Seattle, Washington, USA, for plotting these data, and Marianne Banse for patient help in preparing the manuscript. Contribution No. 1662, School of Oceanography, University of Washington.

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This article was presented by Professor T R. Parsons; it was accepted for printing on October 1, 1986