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Phytoplankton ecology in the waters between Shatt Al-Arab and Straits of Hormuz, Arabian Gulf: A review

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Abstract: In the Arabian Gulf, a north to south gradient in the distribution properties of phytoplankton seems to exist. Low species diversity (<116 species), high biomass (~94 μg Chl *a* l^{-1}) and high production (~3181 μg C l^{-1} h^{-1}) characterize the Shatt Al-Arab estuarine waters in the north. To its south off Kuwait a higher species diversity (148 species), low biomass (~14 μg Chl *a* l^{-1}) and low production (~867 μg C l^{-1} h^{-1}) exist. Waters in the Gulf of Oman and Straits of Hormuz further south have the highest species diversity (~527 species), and lower biomass (~1.18 μg Chl *a* l^{-1}). Due to the impact of oceanic waters, production in these southern waters is probably lower than in the northern waters. The number of taxa phytohydrographically associated with Equatorial sub-surface and common to the Gulf decreased from south to north; they were 79 in the Arabian Gulf and 37 in the waters off Kuwait. Further north off Bushehr, Iran, probably due to lesser exchange with the open ocean, only 10 species were common. Dinoflagellates steadily increased from 34 species in 1931 to 211 in 1990. In the Gulf 18 species known to be harmful elsewhere were present. While some of these taxa are implicated in toxigenic episodes, a few attained bloom proportions in the Gulf but flag a warning for the potential occurrence of toxigenic redtides. Based on these limited data, it is hypothesized that the Gulf ecosystem has a gradient of maturity in the order Shatt Al-Arab≫Kuwait waters≫Gulf of Oman and Straits of Hormuz. The need to obtain synoptic field data on the spatial-temporal variations of phytoplankton is pointed. Experiments utilizing representative Gulf algal cultures will be crucial and are recommended to our understanding of the functioning of the food-web dynamics in the Arabian Gulf.

Key words: Arabian Gulf, phytoplankton biomass, production

Introduction

The Arabian Gulf is a unique environment. It is a semi-enclosed marginal sea about 1000 km long, about 200–300 km wide, with a mean depth of 35 m and has a total of 6000 km^3 volume. North of Shatt Al-Arab estuary it is bound by land and to the south connected to the Gulf of Oman through the narrow Straits of Hormuz that lead to the Arabian Sea (Fig. 1). Estimates of freshwater inflow into the Gulf range between 5×10^6 to $100\times10^6\,m^3$ (Grasshoff 1976). The rivers Tigris and Euphrates in the north discharge annually each $45.3\times10^6\,m^3$ water, and 57.6×10^6 and 4.8×10^6 t sediment, respectively (Reynolds 1993). Because of the

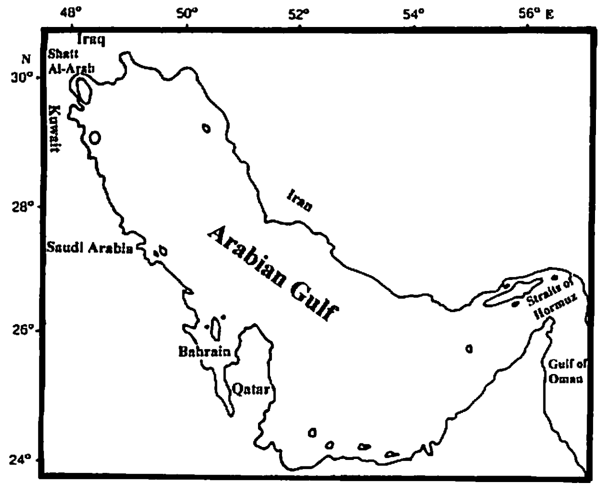

Fig. 1. The Arabian Gulf, Shat Al-Arab to Gulf of Oman region.

surrounding arid desert and enormous loss of water due to evaporation that does not exceed the precipitation and river run off, surface coastal waters attain a maximum temperature of ~32°C and salinity of 44.30‰ (Saad 1976; Jacob & Al-Muzaini 1990). A north to south gradient with high salinity and lower temperature in the northern Gulf to lower salinity and higher temperature at Hormuz Strait exists (Halim 1984). Unique to the Gulf is the *Shamal*, that signifies in Arabic northwest winds round the year. During winter it is infamous due to its association with the strongest winds and high seas (Perrone 1981). During winter under the NW winds a counter clockwise circulation sets in. The dense water formed by the winter cooling and evaporation sinks to the bottom in the central Gulf and eventually flows out through the Straits of Hormuz as a thin layer into the Gulf of Oman (Grasshoff 1976; Halim 1984). This vertical mixing results in oxygenation down to the bottom (Siebold 1973). The estimated residence time, i.e., the ratio of the volume of water to the volume exchange rate, in the Gulf is about 2–5 years (Reynolds 1993) close to the earlier estimate of 3 years (Koske 1972).

The Arabian Gulf is a distinct biotope. Although listed in the 49 Large Marine Ecosystems (Sherman 1993), synthesis relating to its primary, secondary and tertiary driving forces that control the variability in biomass yields has not been completed. It does not fit into any three from tropical and subtropical areas, i.e. areas of upwelling (Cushing 1971), monsoon areas, and wet-dry systems (Longhurst 1991). The Gulf experiences several environmental perturbations such as the annual spillage of about 160×10^6 t (Jacob & Al-Muzaini 1995), discharge of cargo vessel ballast waters, both attendant with oil explorations traditional to this region. Estimates of oil pollution in the Gulf vary between 3% of the total oil pollution in the world to 15–20%. At 3% it amounts to 47× the average estimates for a marine environment of a similar surface area (Linden et al. 1988). Besides, discharges from coastal dredging operations, effluents from power and desalination plants, petrochemical industries, slaughterhouses, dairy plants and sewage treatment plants compound the stress on this unique ecosystem.

Phytoplankton, the primary producers in the marine environment, constitute an ideal window for studies aimed at understanding the food-web dynamics in an ecosystem. Their short generation time and their close coupling with the environment would enable us to discern patterns of their response and recovery to environmental perturbations more readily than the higher organisms distanced towards the harvestable end of food chain.

The scope of this review is two-fold: first to present an account on the constituents of the phytoplankton, and second to assess the magnitude of its biomass and primary production. This is followed by identification of gaps in our knowledge with a view to project future scientific needs that would enhance our understanding of the functioning of this ecosystem.

Taxonomic Composition

The first account of phytoplankton from the Gulf lists the occurrence of 34 peridineans (Bohm 1931). Since then, more than 50 publications appeared (see References). Unfortunately taxonomic identity of the species with citation of the original author is not given in a good number of these publications. As a result some of the species may be synonyms of a species now established. Because of its easy accessibility and a thriving commercial shrimp fishery, Shatt Al-Arab estuary and its canals were studied more frequently, evident from the larger proportion of publications, than from other waters in the Gulf.

A north to south gradient in the phytoplankton species diversity is indicated. In the upper reaches of the estuarine waters in general phytoplankton are less diverse, mostly diatoms compared to the open waters. From Shatt Al-Arab a maximum of 116 taxa were reported (Hadi et al. 1984), the bulk of these were members of epiphytic, tychopelagic bacillariophyceae. Other reports list 95 species (Saad & Kell 1975), 22 taxa dominated by 3 tychoplanktonic diatoms (Maulood & Hinton 1979), 77 taxa mostly diatoms (Hinton & Maulood 1980), 90 taxa with diatoms as the dominants (Hulburt et al. 1981). It is possible non-diatom taxa seem to augment the diversity as suggested by the occurrence of 101 taxa (Hinton 1982) and 53 taxa (Al-Saboonchi et al. 1990). Virtually monospecific algal blooms occurred in the Gulf, details of which are presented later.

Composition of phytoplankton from the central region off Kuwait is limited to 135 diatoms and 13 flagellates (Al-Kaisi 1976). Jamal & Pavalov (1976) reported about the same number of diatom species. Examination of fouling panels revealed 205 species of littoral diatoms (Hendy 1970). On the eastern coast of Kuwait Enomoto (1971) reported 39 diatoms including bloom proportions of *Rhizosolenia* species. and 4 dinoflagellates. Later observations of Jacob et al. (1979, 1980), unfortunately though limited to genera level, confirmed occurrence of dense patches of *Rhizosolenia* species. They also reported similar patches of *Chaetoceros* spp., *Asterionella* spp., and the macroalga *Ruttnera* species. In the coastal waters off Kuwait, blooms of *Phaeocystis* sp. occurred during November 1987 and in March and May 1988; total lipids of these contributed about 11% of the dry biomass (Al-Hasan et al. 1990). Blooms of *Phaeocystis* sp. were again reported off Kuwait during May 1996 (Al-Yamani et al. 1997). These authors also observed blooms of the non-toxic, photosynthetic ciliate *Mesodinium rubrum* Lohmann, during October 1995. The blooms yielded 1.08×10^6 cells l^{-1} and $160\,\mu g$ Chl a l^{-1}.

The greatest diversity of phytoplankton was in the open Arabian Gulf and in the Gulf of Oman. A total of 345 taxa, mainly composed of diatoms and dinoflagellates, occur in these waters. Phytoplankton diversity is more in the Arabian Gulf than in the Gulf of Oman. In the former, Al-Saadi & Hadi (1987) recorded 527 algae of which 416 were diatoms, 68 dinoflagellates, 16 blue greens, 12 silicoflagellates, 11 coccolithophores, 3 flagellates and 1 cryptomonad. Examination of preserved water samples off Qatar yielded 390 species including 225 diatoms, 152 dinoflagellates, 2 silicoflagellates and 11 blue green algae (Dorgham & Muftah 1986). The northwestern Gulf waters are equally rich in species diversity with 223 algae comprising of 134 diatoms, 86 dinoflagellates, 2 blue greens and 1 silicoflagellate

(Dorgham et al. 1987). The Arabian Gulf, which is more diversified than the Gulf of Oman (Dorgham & Muftah 1987), had 175 diatom and 124 dinoflagellate taxa while in the Gulf of Oman they correspond to 92 and 54. Further south, off the Arabian Peninsula, Basson et al. (1977) reported 161 diatom species, 14 dinoflagellates, 16 blue green algae, and 1 green alga. But more recently Jacob & Al-Muzaini (1990, 1995) revised the total taxa in the Gulf to 1220 species with 888 diatoms, 211 dinoflagellates, 82 planktonic chlorophyceae, 8 euglenophytes, 15 silicoflagellates, 15 coccolithophores and one cryptomonad.

Biomass

Cell abundance

Most of these estimates are based on analyses of preserved water samples sedimented in chambers and enumerated. However, details of actual counting procedures were not given (see Hulburt et al. 1981). Saad & Antoine (1983) stored preserved samples in wide mouthed bottles, siphoned off the supernatant, made up the remainder to 50 ml and counted the cells with a haemocytometer. It is likely their counts do not include nanoplankton and particularly the picoplankton that require a different protocol. Phytoplankton enumeration of Hulburt et al. (1981) and El-Guindy & Dorgham (1992) included filaments of blue green algae. However, all investigators did not include picoplankton enumeration, understandably because the necessary techniques (Li et al. 1983) were probably unavailable to them. For the same reason, the relative contribution of the picoplankton to the chlorophyll and primary production remains unknown.

Although the data are limited, a north to south gradient in the cell abundance is suggested. In Bushehr, Iran, algal abundance ranged between 0.8×10^3 and 14.46×10^3 cells l^{-1} (Hulburt et al. 1981) and 4.18×10^6 cells l^{-1} in the Al-Khandak Canal, an offshoot of Shatt Al-Arab (Schiewer et al. 1982). The highest abundance (7.5×10^6 cells l^{-1}) was in the Northwest Gulf (Huq et al. 1977). Off Kuwait there were more cells (0.3×10^3–4308×10^3 cells l^{-1}) during the cool months January–March (Jacob et al. 1980) than during the warmer March–May with 0.01×10^3–414.3×10^3 cells l^{-1} (Jacob et al. 1979).

In the Arabian Gulf the cell abundance varied widely; during November it was between 1.4×10^3 and 42.0×10^3 l^{-1} (Dorgham et al. 1987), and in September from 0.07×10^3 to 449.1×10^3 cells l^{-1} (Dorgham & Moftah 1989). In the Straits of Hormuz and the Gulf of Oman during September cell densities were low, i.e. 0.2×10^3–22.7×10^3 cells l^{-1} (Dorgham and Moftah 1989). For the Arabian Gulf in the top 10 meters mean phytoplankton numbers were 18.7×10^3 cells l^{-1} and in the 10–40 m 9.5×10^3 cells l^{-1} (El-Gindy & Dorgham 1992). Cell abundance in the top 10 m and in the 10–40 m of Oman was about 3.7×10^3 l^{-1} (El-Gindy & Dorgham 1992).

Chlorophyll *a*

Chlorophyll *a*, a measure of the phytoplankton biomass showed a wide range in these three regions. In Shatt Al-Arab estuary during 28 February and 3 March, 1985 Chl *a* ranged between 0.22 and 2.89 μg Chl *a* l^{-1} (Al-Saadi et al. 1989). The annual range was between 0.52 and 3.25 μg Chl *a* l^{-1} (Huq et al. 1981) and 2 to 3 times more chlorophyll in its canals (Al Mousawi et al. 1990). Very high levels (94.3 μg Chl *a* l^{-1}) were observed in the Al-Khandak Canal (Schiewer et al. 1982). In the northwestern Gulf values during October were between 0.56 and 2.06 μg Chl *a* l^{-1} (Huq et al. 1977) with a suggestion of its accumulation in the bottom samples. During autumn biomass ranged from 2.82 to 9.07 μg Chl a l^{-1} (Huq et al. 1978).

In Kuwait waters algal biomass ranged between 0.66 and 10.52 μg Chl a l^{-1} during January to March (Jacob et al. 1980) and from 0.2 to 13.9 μg Chl a l^{-1} March–May (Jacob et al. 1979). In the colder months photosynthetic pigments were high similar to phytoplankton cell numbers and coincided with high nutrients (Jacob et al. 1982).

In the southern waters during September in the Arabian Gulf region chlorophyll levels in the top 10 m and the 10–40 m layers corresponded to 1.18 and 0.96 μg Chl a l^{-1}. For the Gulf of Oman they were 0.55 and 0.87 μg Chl a l^{-1} in the top 10 m and the 10–40 m layers, respectively (El-Gindy & Dorgham 1992).

Primary Production

Compared to reports on phytoplankton abundance, studies on primary production are rare and often are limited to short surveys utilizing oxygen exchange method. In these waters enriched with sewage, information on the sensitivity of oxygen technique and any photosynthetic quotient, critical for evaluation of the data are not given. In Shatt Al-Arab primary production values, based on oxygen exchange method, ranged between 18.5 and 52.9 μg C l^{-1} h^{-1} but in areas that received sewage it was 60× higher (Hadi et al. 1989). In Ashar Canal with 17×10^6 cells l^{-1}, and 301.9 μg C l^{-1} h^{-1}, production attained a maximum of 730.59 μg C l^{-1} h^{-1} (Al-Saadi & Antoine 1980). Near Basrah, diel periodicity of photosynthesis was absent during December when production was usually low (0.1 and 3.1 μg C l^{-1} h^{-1}, Schiewer et al. 1982). However, during a *Cyclotella meneghiniana* bloom production was high (118 μg C l^{-1} h^{-1}, Schiewer et al. 1982). In NorthWest Arabian Gulf during November when the biomass was low, production values were between 10.7 and 31.6 μg C l^{-1} h^{-1} (Haq et al. 1978).

Similar to oxygen exchange measurements, primary production estimates based on ^{14}C method in the Gulf are a few. Critical analytical details on the determination of total carbon dioxide, corrections for isotopic discrimination, respiratory losses and excretion of labeled products are missing. Only Schiewer et al. (1982) revised their values by a 6% to obtain gross production. Measurements of primary production in the Shatt Al-Arab estuary during 28 February and 3 March 1985 ranged between 5.44 and 10.3 μg C l^{-1} h^{-1} (Al-Saadi et al. 1989). Photosynthetic rates during November were low in the eastern canal of the Shatt Al-Arab and ranged from 18.5 to 52.3 μg C l^{-1} h^{-1} (Hadi et al. 1989). In the western canals that received sewage they were very high and ranged between 31.5 and 3180.9 μg C l^{-1} h^{-1} (Hadi et al. 1989).

For the Kuwait waters daily production values, calculated on the basis of several empirical relationships between total chlorophyll and day length, ranged between 70 and 660 μg C l^{-1} during January–March (Jacob et al. 1980). For March–May the average was 867 μg C l^{-1} (Jacob et al. 1979). Compared to these, results obtained using ^{14}C method for 1983–84 that ranged between 0.2 and 1.6 μg C l^{-1} h^{-1} (Literathy et al. 1988) were substantially low.

Based on a set of 5 oxygen exchange measurements carbon assimilation ratios (μg C h^{-1} μg Chl a^{-1}) ranged between 1.52 and 8.25 in the North West-Arabian Gulf (Huq et al. 1978). These compare favorably with 1.2 to 14.6 ratios reported from Sharm, a heavily polluted inshore station in the Red Sea off Jiddah (Shaik et al. 1986). In Ashar Canal, and Al-Khandak Canal, offshoots of Shatt Al-Arab with high primary production, the few carbon assimilation numbers available based on oxygen exchange method were 2.4 and 1.3, respectively. These low ratios were attributed to light limitation (Schiewer et al. 1982). Assimilation numbers based on ^{14}C uptake (Fig. 4, Hadi et al. 1989) even at 2400 lux were abnormally high. For example at station 8 located in the heavily polluted waters of Al-Khandak canal, the maximum production of $3180.9\,\mu g\,C\,l^{-1}\,h^{-1}$ was in waters with $\sim 7\,\mu g\,Chl\,a\,l^{-1}$. The resulting assimilation number would be suspect. Nearly 80% of the assimilation numbers calculated from Shatt Al-Arab estuary during 28 February and 3 March 1985 (Al-Saadi et al. 1989) ranged between 2.87 and 16.8 and are acceptable.

Discussion

Floral elements and phytohydrographic associations

Tropical species constitute the bulk of the Gulf phytoplankton. Of these the oceanic component is represented by *Bacteriastrum delicatulum* Ostenfeld, *Chaetoceros peruvianum* Brightwell, *Chaetoceros coarctatum* Lauder, *Climacodium frauenfeldianum* Grunow, *Coscinodiscus centralis* Ehrenberg *Planktoniella sol* (Wallich) Schütt, *Proboscia alata* (Brightwell) Sundstörm f. *indica* (=*Rhizosolenia alata* f. *indica* [Perag.] Gran), *Proboscia alata* (Brightwell) Sundstörm f. *gracillima* (Cl.) Gran (=*Rhizosolenia alata* f. *gracillima* (Cl.) Gran), *Rhizosolenia castracanei* Peragallo, *Rhizosolenia styliformis* Brightwell, *Thalassiosira leptopus* (=*Coscinodiscus lineatus* Ehrenberg), *Thalassiosira subtilis* (Ostenf.) Gran, and *Thalassiothrix frauenfeldii* Grunow. Examples of coastal phytoplankton include *Bellorochea malleus* (Bright.) Van Heurck, *Chaetoceros diversum* Cleve, *Chaetoceros messanensis* Castracane, *Ditylum sol* (Van Heurck) De-Toni, *Hemiaulus cuneiformis* Wallich, *Leptocylindrus danicus* Cleve, *Skeletonema costatum* (Grev.) Cleve, *Stephanopyxis palmeriana* (Grev.) Grunow, *Thalassionema nitzschioides* Grunow, and *Triceratium favus* Ehrenberg.

Temperate species are relatively few in the Gulf and include *Chaetoceros affine* Lauder, *Chaetoceros compressum* Lauder, *Chaetoceros didymum* Ehrenberg, *Chaetoceros lasciniosum* Schütt, *Chaetoceros lorenzianum* Grunow, *Hemiaulus sinensis* Greville, *Odontella sinensis* (Lyngbye) Agardh (=*Biddulphia sinensis* Greville), and *Tropidoneis lepidoptera* (Greg.) Cleve.

Presence of tychopelagic diatom genera *Achnanthes*, *Amphiprora*, *Amphora*, *Caloneis*, *Campylodiscus*, *Diploneis*, *Fragilaria*, *Grammatophora* and *Licmophora* can be due to availability of solar energy necessary for their growth and photosynthesis in this shallow Gulf. The tidal exchange that is accelerated by the currents, eddies and bottom topography (Siebold et al. 1969, 1970) facilitates their redistribution.

Comparison of the distribution of phytoplankton in the Arabian Gulf with results of the numerical investigations of Thorrington-Smith (1971) in the West Indian Ocean (Appendix) reveals several interesting features. Based on the hydrographic distributions and associations between 237 species, Thorrington-Smith recognized several groups of phytoplankton. Geographical distribution of certain phytoplankton species in the Gulf seems to be governed by the local hydrographic conditions. Components of the Western Indian Ocean decreased from south to north in the Arabian Gulf. The number of diatom and dinoflagellates taxa corresponded to 62 and 17 in the Arabian Gulf in general, 54 and 12 off Qatar and 30 and 7 in Kuwait waters (Table 1). Further north of Bushehr, Iran, probably due to lesser exchange with the open ocean, the number of species common to their southern waters is reduced to about 10 (Hulburt et al. 1981).

Dorgham & Mofta (1989) based on data from 44 stations identified 6 groups in the ecological distribution of phytoplankton. The number of diatom and dinoflagellate constituents corre-

Table 1. Comparison of the distribution of diatom and dinoflagellate taxa between the Western Indian Ocean and the Arabian Gulf and between the various regions in the Gulf and the Gulf of Oman region. Data for the Western Indian Ocean are based on Thorrington-Smith (1971). Sources of data for other regions are referenced.

Common between		Diatoms	Dinoflagellates	References
West Indian Ocean	Arabian Gulf	62	17	Dorgham & Mofta 1989
Western Indian Ocean	Qatar waters	54	12	Dorgham & Mofta 1986
Western Indian Ocean	Arabian Gulf	52	12	Al-Saadi & Hadi, 1987
Western Indian Ocean	N.W.Arabian Gulf	34	8	Dorgham et al. 1987
Western Indian Ocean	Kuwait waters	30	7	Al-Yamani et al. 1997
Western Indian Ocean	Busher, Iran	10		Hulburt et al. 1981
Str. Hormuz	Arabian Gulf	10	11	Dorgham & Mofta 1989
Gulf of Oman	Arabian Gulf	47	61	Dorgham & Mofta 1989
Gulf of Oman	Str. Hormuz	3	11	Dorgham & Mofta 1989
Limited to Gulf of Oman		4	20	Dorgham & Mofta 1989
Limited to Str.Hormuz		0	5	Dorgham & Mofta 1989
Limited to Arabian Gulf		56	16	Dorgham & Mofta 1989

spond to 47 and 61 in the Arabian Gulf and Gulf of Oman; 10 and 11 mainly in the Arabian Gulf; 56 and 16 species restricted to the Arabian Gulf; 0 and 5 species recorded only in the Straits of Hormuz; 3 and 11 observed in the Gulf of Oman and the Straits of Hormuz and 4 and 20 for species restricted to the Gulf of Oman (Table 1).

The most dominant phytoplankters in the Gulf belong to the Equatorial sub-surface group identified by Thorrington-Smith (1971). Of the 527 species reported in the Gulf (Al-Saadi & Hadi 1987), 81 were common with the western Indian Ocean of which 22 belonged to Equatorial sub-surface group. They are *Amphidinium* sp., *Asteromphalus heptactis* (de Breb) Ralfs, *Bacteriastrum delicatulum* Cleve, *Bactriastrum elongatum* Cleve, *Chaetoceros atlanticum* Cleve, *Chaetoceros danicum* Cleve, *Chaetoceros pendulum* Karsten, *Chaetoceros affine* Lauder, *Chaetoceros peruvianum* Brightwell, *Coscinodiscus marginatus* Ehrenberg, *Guinardia flaccida* (Castracane) Peragallo, *Guinardia cylindrus* (=*Rhizosolenia cylindrus* Cleve), *Nitzschia bicapitata* Cleve, *Nitzschia braarudi* Hasle, *Nitzschia closterium* (Her.) W. Smith, *Nitzschia seriata* Cleve, *Nitzschia sicula* Castracane, *Planktoniella sol* (Wallich) Schütt, *Proboscia alata* (Brightwell) Sundstrom (=*Rhizosolenia alata Brightwell*), *Rhizosolenia hebetata* Bailey, *Rhizosolenia hebetata semispina* (Hensen) Gran, *Thalassiosira excentrica* Schmidt (=*Coscinodiscus excentricus* Ehrenberg), *Thalassiosira oestrupii* (Ostenfeld) Proschkina-Laverenko. It is of interest that Thorrington-Smith grouped station 5390 off the Arabian Coast with 5331 in the shear zone region. Further, stations 5423 and 5425 grouped together from the southern boundary of the equatorial under current are characterized as a region of fluctuating conditions. Phytoplankton was rich at these stations and consisted of *Chaetoceros affine* f. *circinalis* (Meunier) Hustedt, *Bacteriatrum teneue* Steemann Nielsen, *Chaetoceros decipiens* Cleve, and *Dactyliosolen mediterraneus* Peragallo, of which the last was reported from the Arabian Gulf (Al-Saadi & Hadi 1987).

Occurrence of the diatom *Nitzschia seriata* Cleve in the Equatorial sub-surface group of phytoplankton deserves a comment. In the Indian coastal seas (Subrahmanyan 1946; Nair 1959), in the Arabian Gulf (Dorgham & Mufta 1986) and in the West Indian Ocean (Thorrington-Smith 1971) it is recorded. This species is now revised as *Pseudonitzschia seriata* (Hasle 1972) and is considered to occur only in subarctic and polar waters north of 45°. There are 9 *Nitzschia* species forming stepped chains with a tendency to be placed girdle view up in water mounts, although a distinction can be made only in valve view or under an electron microscope. Its occurrence in various oceanic areas is regarded with skepticism (Hasle 1972). Because of (a) close morphological similarities among 3 forms of *Nitzschia pungens*: *seriata*, *multiseries* and *pungens*, (b) occurrence of morphological variations (Subba Rao & Wohlgeschaffen 1990), and (c) their implication of in the production of the neurotoxin domoic acid (Subba Rao et al. 1988) correct identification of *Nitzschia seriata* is essential.

This classification is based on observations limited to September and its utility would be much more if based on an extensive year round sampling. For example, of the 56 diatoms and 16 dinoflagellates from group 3 identified as restricted to the Arabian Gulf there are several species that are widely distributed outside the Arabian Gulf. A few examples are *Bacillaria paxillifer* (Mull.) Hendy, *Chaetoceros atlanticum*, *Chaetoceros boreale* Bailey, *Chaetoceros convolutum* Castracane, *Chaetoceros danicum* Cleve, *Chaetoceros diversum* Cleve, *Chaetoceros lasciniosum* Schütt, *Chaetoceros lauderi* Ralfs, *Chaetoceros psedocurvisetum* Mangin, *Chaetoceros lauderi* (reported as *weissflogii*, a synonym) *Chaetoceros affine* Lauder, *Chaetoceros breve* Schütt, *Chaetoceros teres* Cleve, *Climacosphenia moniligera* Ehrenberg, *Corethron criophilum* Castracane *Coscinodicus excentricus* Ehrenberg, *Grammatophora marina* (Lyngbye) Kütz, *Gyrosigma balticum* (Ehrenb.) Cleve, *Odontella aurita* (Lyngbye) Agardh (=*Biddulphia aurita* (Lyngbye) de Brébisson), *Odontella mobiliensis* (Lyngbye) Agardh (=*Biddulphia mobiliensis* (Bail.) Grunow ex Van Heurck, *Pleurosigma angulatum* (Queckett) W. Smith *Rhizosolenia styliformis* Brightwell, *Thalassiosira gravida* Cleve, and *Triceratium favus* Ehrenberg. Similarly examples from dinoflagetaes include *Ceratium minutum* Jorgensen, *Gonyaulax spinifera* (Clap. and Lach.) Diesing, *Gonyaulax catenata* Levander, *Prorocentrum gracile* Schütt, *Protoperidinium pyriforme* (Pauls.) Balech, and *Pyrodinium bahamense* (Bohm) Steidinger, Test et Taylor.

Observations of Dorgham & Moftah (1989) are significant and suggest existence of marked variations in the phytoplankton composition probably due to hydrographic differences and possible incursion of algae from the Gulf of Oman or from outside the Gulf into the Arabian Gulf. Phytoplankton species can be used as indicators of water movements (Subba Rao 1976). To do so, systematic and synoptic data are to be obtained, correct identity of the species is to be established, biogeographical distribution of the species studied, its sterile distribution known and its abundance related to water masses based on temperature, salinity and density (Smayda 1958; Semina et al. 1977).

Phytoplankton blooms and harmful algae

Occurrence of blooms of *Cyclotella meneghiniana* Kütz, *Chlamydomonas* sp., *Euglena acus*, *Chaetoceros* spp., *Rhizosolenia* spp., *Asterionella* spp., *Ruttnera* sp., *Phaeocystis* sp. and members of cyanophyceae, some of which are implicated elsewhere in toxic episodes flag a warning for potential shifts in phytoplankton abundance. Al-Hansan et al. (1990) associated occurrence of such blooms to inorganic nutrient enrichment caused by an increased disposal of untreated sewage. Results of Dorgham & Moftah (1989) indicate dominance of several species in the net plankton samples. Examples are *Pseudosolenia calcar-avis* (Schulze) Sundström (=*Rhizosolenia calcar-avis* Shultz) (<90%), *Trichodesmium* sp. (<90%), *Ceratium furca* Claparde et Lachman (<80%), *Chaetoceros curvisetum* Cleve (<80%), *Rhizosolenia shrubsolei* Cleve (<75%), *Coscinodiscus perforatus* v. *pavillardii* Ehrenberg (<60%), *Proboscia alata* (Brightwell) Sundström, (=*Rhizosolenia alata*) f. *indica* Gran (<50%), *Thalass-*

siothrix frauenfeldii Grunnow (<50%) and *Pyrodinium bahamense* (Bohm) Steidinger, Test et Taylor (<38%).

Results of Dorgham et al. (1987) do suggest abundant growth of the dinoflagellates in the Gulf associated with pollution. Three harmful dinoflagellates *Pyrodinium bahamense* (Bohm) Steidinger, Test et Taylor, *Lingulodinium polyedra* (Stein) Dodge (=*Gonyaulax polyedra* Stein) and *Prorocentrum micans* Ehrenberg co-occur in the Gulf (Dorgham & Moftah 1989). These taxa are listed potentially harmful (see Lassus 1985; reports of the International Council for the Exploration of the Seas, Subba Rao, unpublished data). The high frequency (38%) of occurrence of *Pyrodinium bahamense* (Bohm) Steidinger, Test et Taylor in the waters off Qatar, and United Arab Emirates is associated with maximum concentrations of phosphorus (1.23 μg at l^{-1}) and nitrate (0.90 μg at l^{-1}). This suggests existence of a potential for development of harmful algal blooms in the Arabian Gulf (Dorgham & Moftah 1989). There is ample evidence to show that monospecific blooms of algae, particularly the dinoflagellates, could result in toxigenic episodes (Smayda 1990; Subba Rao 1994).

Several harmful algae occur in the Arabian Gulf waters. This is evident from a comparison of the taxa of primary producers in the Arabian Gulf (Jacob & Al-Muzaini 1990) with the list of harmful algae compiled from reports of the International Council for the Exploration of the Seas (Subba Rao, unpublished data). Presence of 38 taxa is to be noted which includes the following 18 identified to the species level: the blue green alga *Nodularia spumigera* Jurgens, the diatoms *Amphora coffeaformis* Kützing, *Chaetoceros atlanticum* Cleve, *Chaetoceros convolutum* Castracane, *Chaetoceros danicum* Cleve, *Chaetoceros decipiens* Cleve, *Nitzschia pungens* Grunow and the dinoflagellates *Ceratium furca* (Ehrenb.) Claparde et Lachman, *Ceratium fusus* Dujardin, *Ceratium trichoceros* Kofoid, *Dinophysis acuminata* Claparde et Lachman, *Dinophysis caudata* Saville-Kent, *Lingulodinium polyedra* (Stein) Dodge (=*Gonyaulax polyedra* Stein), *Gonyaulax polygramma* Stein, *Gonyaulax spinifera* Diesing, *Prorocentrum sigmoides* Bohm, *Prorocentrum micans* Ehrenberg, and the silicoflagellate *Dictyocha speculum* Ehrenberg (=*Distephanus speculum* [Ehrenberg] Haeckel). Occurrence of blooms of *Phaeocystis pouchetii* during November, March and May (Al-Hasan et al. 1990) and *Mesodinium rubrum* Lohmann, during August in Kuwait Bay was noted earlier.

The other 18 taxa identified up to the genus level include the blue green algae *Anabaena* sp., *Amphanizomenon* sp., *Microcystis* sp., *Trichodesmium* sp., and the diatoms *Asterionella* sp. *Bacteriastrum* sp., *Coscinodiscus* sp., *Cyclotella* sp., *Eucampia* sp., *Fragilaria* sp., *Leptocylindus* sp. *Rhizosolenia* sp. and *Thalassiosira* sp. and the dinoflagellates *Gyrodinium* sp., *Katodinium* sp., and *Triadinium* sp. Additionally the euglenoid flagellates *Euglena* sp., *Trachelomonas* sp., and the green alga *Dunaliella* sp. also occurred. It will be necessary to establish their identity to the species level to decide their harmful or toxigenic nature.

Increase in species diversity: species introduction

A steady increase in the number of dinoflagellates during the past 60 years is of interest (Dorgham et al. 1987) which coincides with general organic enrichment in the Arabian Gulf (Fig. 2). Dorgham et al. suggested that it might be the case with the diatoms also. While partly this increase is attributable to better sampling, identification and enumeration, it may be allochthonous due to transfer of species into the Gulf from the Arabian Sea and the Gulf of Oman. Further we emphasize the role of introductions and transfer of exotic algae into the Gulf region through billions of tones of ballast water brought to the Gulf region by thousands of cargo ships and oil tankers. In the Suez Canal, Egypt at least 13 species of Red Sea origin

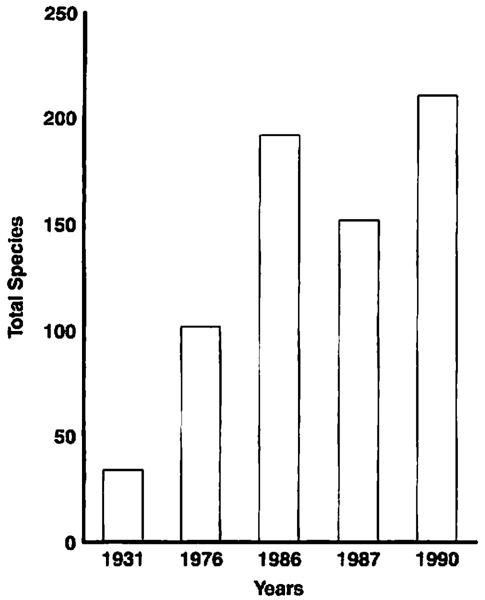

Fig. 2. Increase in the total phytoplankton species in the Arabian Gulf between 1931 and 1990.

have spread northward towards Port Said while a good number to El-Suez in the south (El-Sherif & Ibrahim 1993). Such introduced species could trigger extensive ecological changes in the phytoplankton community structure, leading to potential economic loss to commercial fisheries (Subba Rao et al. 1994).

Nutrients

Nitrates, phosphates and silicates, the nutrients essential for phytoplankton growth, are more abundant in the Northwest region (Shatt Al-Arab) than those to the south (Al-Saadi & Hadi 1987; Hulburt et al. 1981). Results of Halim (1984, Table 4) support this. During September, only phosphate, nitrite and nitrate levels but not ammonia and silica in Qatari waters were higher than in the waters off the United Arab Emirates (Dorgham & Moftah 1989). The relatively phosphate rich inflowing surface water from the Straits of Hormuz enrich this nutrient in the Arabian Gulf (Brewer & Dryssen 1985). Although local eutrophication processes seem important, widespread systematic interdisciplinary oceanographic studies will be necessary to asses the extent to which the deflected upwelled water (Halim 1984) contributes to nutrient enrichment in the Arabian Gulf.

Growth of phytoplankton from Shatt Al-Arab estuary increased significantly (6 to 7 times) due to combined enrichment of 50.5 μmol nitrate and phosphate (Al-Saadi et al. 1989). Enrichment of nitrogen or phosphorus alone did not enhance phytoplankton growth. In these turbid waters light may be a limiting factor for phytoplankton growth in the estuarine waters of Shatt-Al-Arab (Schiewer et al. 1982). It is of interest to note that growth of Bushehr phytoplankton cultures could be stimulated to an optimal level over a wide range of temperature (12–34°C) even in media with low nitrate and high phosphate (Hulburt et al. 1981). According to these authors these perpetually bright sunlight turbid waters receive 27–148 cal cm^{-2} d^{-1} exceeding the 20 cal cm^{-2} d^{-1} required for phytoplankton growth in Narragansett Bay, a nutrient rich temperate coastal bay. Precise physiological ecology studies utilizing algal cultures would be required to understand the photosynthetic functioning of this biota.

Besides the run off, decay of organic matter from sinking blooms and discharge of sewage account for the very high local phosphorus levels that result in an imbalance in the N : P ratios (Saad 1984, 1985). Under such conditions, shifts in the dominant constituents of algae are to be expected. In fact, following peaks of N : P ratios, phytoplankton blooms appeared in the Gulf of Elat, a desert enclosed sea (Levanon-Spanier et al. 1979). As discussed earlier precise enrichment experiments are needed to predict shifts in the dominance of either the picoplankton (<3 μm), nanoplankton (<20 μm) or the larger microplankton or different taxonomic groups dominated by diatoms and dinoflagellates. The consequential impact on the food-web dynamics and the commercially important mariculture operations would be far reaching.

North–south gradients: energy flow

The Arabian Gulf will be an interesting area for studies on energy flow. From the limited data presented earlier, a north to south gradient in the species diversity, abundance and biomass is indicated. Existence of a similar gradient in primary production is probable. Although not applicable in detail, the gradients are analogous to that between the Bothnian Bay and the Norwegian Coast of the Baltic Sea (Wallentinus 1991).

The Shatt Al-Arab region with its various environmental stresses, river run off, tidal exchange and mud flats represent a high physical energy system. The lower species diversity, higher biomass, higher production and lower carbon assimilation rates discussed earlier suggest that from an ecological perspective it could be a mature system (Margalef 1968). These are usually characterized by benthos dominated by filter feeders, high rates of metabolism supported by current transport of food and are heterotrophic (see Day et al. 1989). In such systems detritus resulting from sinking of algal blooms or decay of macrophytes plays a significant role in sustaining filter feeders. It is of interest that in the Gulf of Elat (Red Sea), a similar biotope from this geographical region, several hundred times more chlorophyll exists in the sand than in the plankton (Sournia 1977) which can play a significant role in the food-web dynamics.

The central region of the Gulf represented by Kuwait waters is comparable to the shallow littoral areas characterized by moderate to strong currents, bottom within euphotic zone, and oxygenated water column (see Day et al. 1989). These waters with a lesser impact of the rivers have higher species diversity dominated by diatoms. The biomass and the rate of gross production are high. Although the detritus food chain is important, direct grazing may play a significant role in the food-web dynamics. The more open environment of Hormuz Straits and the Gulf of Oman represent a low energy system with an exchange with the open ocean. This region experiences north-northwest winds during summer with a reversal to south-southeast during October–April (Halim 1984). To the north along the coast of Dhofar region, southern Oman upwelling was discontinuous (Savidge et al. 1990). During southwest monsoon upwelling is indicated by admixture of surface water with oxygen depleted, phosphate rich deeper waters. This region represents an evolving system characterized by greater species diversity, low biomass and probably less production.

Scope of future studies

To know precisely about the forcing variables that drive this unique ecosystem, we need to establish criteria for characterization of the biotopes in the Gulf. Crucial to this will be hard data along several lines: (a) the role of river run off and upwelling on the spatial and temporal distributions of various size groups of phytoplankton, (b) vertical fluxes of organic matter between the benthic and pelagic biota, (c) the effects of climatic variables on phytoplankton production, (d) importance of the river run off as a contributing factor, i.e. trace elements and humic materials that trigger algal blooms, both benign and toxigenic, and (e) response and recovery of algal populations to environmental perturbations. It will be prudent to utilize Gulf algal cultures grown under defined environmental conditions as analogues of natural blooms to test the various hypotheses.

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Appendix

Species common to the West Indian Ocean and the Arabian Gulf.

Diatoms

Asterionella glacialis Castracane
Asteromphalus heptactis Ralfs in Pritchard
Bacteriastrum delicatulum Cleve
Bacteriastrum elongatum Cleve
Bacteriastrum hyalinum Lauder
Bacteriatrum comosum Pavillard
Bacteriatrum varians Lauder
Chaetoceros affine Lauder
Chaetoceros affine Lauder f. *asymmetricum* (St Niel.) Th Smith
Chaetoceros atlanticum Cleve
Chaetoceros compressum Lauder
Chaetoceros decipiens Cleve
Chaetoceros decipiens Cleve f. *simplex* Th Smith
Chaetoceros denticulatum Lauder
Chaetoceros didymum Ehrenberg
Chaetoceros diversum Cleve
Chaetoceros laciniosum Schütt
Chaeotecros lorenzianum Grunow
Chaetoceros messanense Castracane
Chaetoceros pendulum Karsten
Chaetoceros peruvianum Brightwell
Climacodium frauenfeldianum Grunow
Cocconeis scutellum Ehrenberg
Corethron criophilum Castracane
Coscinodiscus centralis Ehrenberg
Coscinodiscus decrescens Grunow
Coscinodiscus marginatus Ehrenberg
Coscinodiscus oculis-iridis Ehrenberg
Coscinodiscus radiatus Ehrenberg
Cyclotella stylorum Brightwell
Dactylosolein mediterraneus Peragallo
Fragilaria oceanica Cleve
Grammatophora sp.
Guinardia cylindrus Peragallo (=*Rhizosolenia cylindrus* Cleve)
Guinardia flaccida Peragallo
Hemiaulus membranaceus Cleve
Leptocylindrus danicus Cleve
Melosira granulata (Ehrenb.) Ralfs in Pritchard
Navicula sp.
Nitzschia bicapitata Cleve
Nitzschia braarudii Hasle
Nitzschia closterium (Ehr.) W. Smith
Nitzschia sicula Castracane
Planktoniella sol (Wallich) Schutt
Pseudosolenia calcar-avis (Schulz) Sündstrom (=*Rhizosolenia calcar-avis* Schultz)
Proboscia alata (Brightwell) Sundström (=*Rhizosolenia alata*) f. *alata* Brightwell
Prososcia alata (Brightwell) Sundström (=*Rhizosolenia alata*) f. *indica* (Perag) Gran
Rhizosolenia bergonii Peragallo
Rhizosolenia hebetata f. *semispina* (Hen.) Gran
Rhizosolenia imbricata var. *shrubsolei* (Cleve) Schröder
Rhizosolenia styliformis var. *longispina* Brightwell
Rhizosolenia stolterforthii Peragallo
Rhizosolenia alata f. *gracillima* (Cleve) Grunow
Synedra sp.
Synedra undulata Bailey
Thalassionema nitzschioides Grunow
Thalassiothrix mediterranea var. *pacifica* Cupp
Thalassiothrix sp.
Thalassiosira leptopus (=*Coscinodiscus lineatus* Ehrenberg)
Thalassiosira excentrica Schmidt (=*Coscinodiscus eccentricus* Ehrenberg)
Thalassisira oestrupii (Ostenfeld) Proschkina-Laverenko
Thalssiothrix frauenfeldii Grunow

Dinoflagellates

Amphidinium sp.
Ceratium deflexum (Kofoid) Jorgensen
Ceratium extensum (Gourr.) Cleve
Ceratium furca (Ehrenb.) Claparde et Lachman
Ceratium fusus (Ehrenb.) Dujardin
Ceratium kofoidii Jorgensen

Ceratium macroceros (Ehrenb.) Vanhoffen
Ceratium pelagica (Ehrenb.) Vanhoffen
Ceratium pulchellum Schröder
Ceratium teres Kofoid
Ceratium trichoceros (Ehrenb.) Kofoid
Ceratium tripos (Muller) Nitzsch
Ceratium vultur Cleve
Ornithocercus sp.
Oxytoxum scolopax Stein
Prorocentrum gracile Schütt
Scripsiella trochoidea (Stein) Loeblich III

Silicoflagellate
Dictyocha fibula Ehrenberg

Cyanophyte
Oscillatoria sp.

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