# Relationships between water temperature, nutrients and dissolved oxygen in the northern Gulf of Aqaba, Red Sea

OCEANOLOGIA, 48 (2), 2006.
pp. 237–253.



**KEYWORDS**
Nutrients
Temperature
Oxygen
Stratification
Gulf of Aqaba

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Received 20 February 2006, revised 31 March 2006, accepted 7 April 2006.

**Abstract**

Five years (1998, 2000–2003) of summer records of temperature, nutrients and dissolved oxygen concentrations in the upper 400 m of the water column of the northern Gulf of Aqaba were employed to produce a simple statistical model of the relationship between temperature versus nitrate, phosphate, silicate and dissolved oxygen concentrations. Temperature profiles in the upper 400 m during summer revealed a clear thermocline in the upper 200 m. This was reflected in nutrient and oxygen concentrations as nitrate, phosphate, and silicate increased from the surface to deep water while dissolved oxygen decreased. The best fit relationship between temperature versus nitrate and phosphate was inverse linear and the best fit correlation between temperature versus silicate and dissolved oxygen was fractional. The observed nutrient concentrations were shaped by a combination of the hydrodynamics and biological factors. Deep winter mixing and high nutrient concentrations dominate during winter. Shortly after the water stratifies in spring, the nutrients are drawn down by phytoplankton during the spring bloom and remain low throughout the rest of the year. The regression equations presented here will be useful in estimating nutrient concentrations from temperature records as long as the annual natural cycle is the main driver of nutrient concentrations and external inputs are insignificant. Deviations from these relationships in the future could provide insight into modifications in the nutrient concentrations probably resulting from new nutrient sources, such as anthropogenic inputs.

## 1. Introduction

Seawater characteristics are either conservative or non-conservative. Conservative characteristics such as temperature and salinity are not affected by the primary productivity of the system, but non-conservative characteristics such as dissolved oxygen, nutrient and chlorophyll $a$ concentrations are influenced directly or indirectly. The most important nutrients are nitrogen and phosphorus. Silicon can also be important for some organisms that have siliceous frustules. Nutrient input to the sea may occur anthropogenically or naturally through physical, chemical and biological processes. Anthropogenic sources include groundwater and river input, sewage discharge and industrial runoff, both terrestrial and sea-based (Marsh 1977, D'Elia et al. 1981, Lewis 1985, Badran & Forster 1998). Natural sources include nitrogen fixation (e.g. Wilkinson et al. 1984) and organic matter decomposition. Nitrogen fixation can occur only where and when nitrogen fixing organisms are present, whereas decomposition occurs in the sediment (Charpy-Roubaud et al. 1996, Ciceri et al. 1999, Wild et al. 2004a,b, Rasheed et al. 2004), in some complex systems such as the coral reef framework (Richter et al. 2001), and in the water column itself (Garside 1985, Jenkins & Goldman 1985, Rasheed et al. 2003). Physical processes also play an important role in nutrient redistribution by current action (Rasheed et al. 2002, Niemann et al. 2004). Vertical water mixing in the Gulf of Aqaba is well known for transferring nutrients from deep water to the upper layers (Badran 2001, Rasheed et al. 2003).

Heat flux variations in arid areas that neither receive considerable rain nor have any source of fresh water runoff are the main factors controlling the water column density structure. This directly affects the water movement both vertically and horizontally (Straneo & Kawase 1999) and subsequently determines the redistribution of all soluble and free drifting material. Such movement of soluble and particulate nutrients plays a milestone role in shaping the trophic characteristics of the water column.

The Gulf of Aqaba is a unique semi-enclosed water body located at the northern end of the Red Sea (Fig. 1a). The mean depth of the Gulf is about 800 m, with a maximum of about 1800 m, which is close to that of the Red Sea. The Gulf of Aqaba lies in the very warm section of the Saharan bioclimatic zone. The climate is arid with high evaporation and negligible precipitation, and there is no runoff. The annual variation in current is attributed to variations in generation and propagation associated

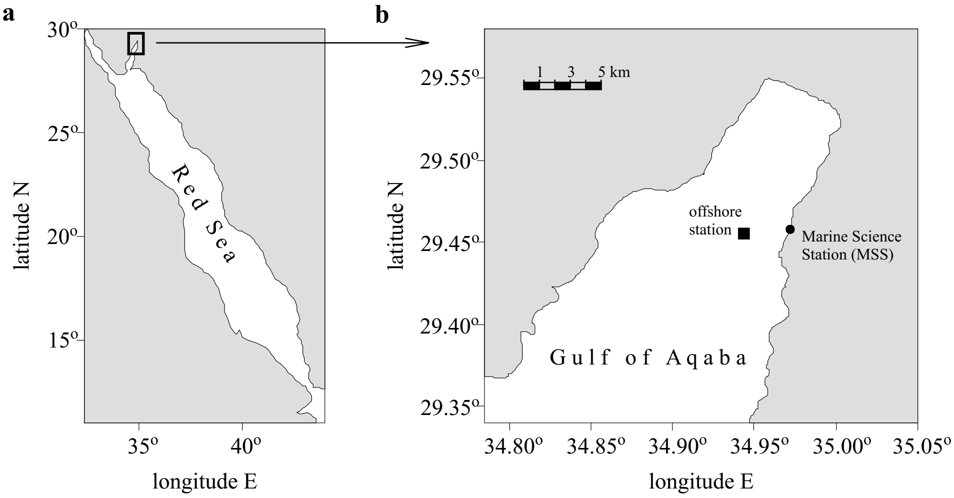


**Fig. 1.** Study site (a), offshore site for temperature [°C], nutrients [$\mu$M] and oxygen [mg dm$^{-3}$] sampling (b)

with changes in thermocline strength and structure throughout the year (Monismith & Genin 2004).

The seasonal range of the sea surface temperature in the northern Gulf of Aqaba is about 6–7°C (Al-Rousan et al. 2002, Manasrah et al. 2004). The upper 200 m segment of the water column in the northern Gulf has different characteristics during summer and winter. During summer, there is a strong thermocline with a temperature range in the upper 200 m of 21 to 27°C. During winter the water column is well mixed with a temperature range in the upper 200 m of ~20.5–21.0°C. The water column below 200 m is more or less comparable during summer and winter with a temperature range similar to that in the upper 200 m during winter.

Nutrient concentrations, particularly nitrate, phosphate and silicate, in the offshore water of the Gulf of Aqaba exhibit similar profiles to those of the temperature, but with an inverse relationship (Klinker et al. 1978, Badran 2001, Badran et al. 2005). Strong nutriclines of nitrate, silicate and phosphate exist during summer and complete mixing in the entire water column is normal in winter. Badran (2001) investigated only the upper 200 m, whereas Klinker et al. (1978) investigated the entire water column down to the bottom (1600 m) but reported no clear difference between the water at 200 m and the deeper water.

These obvious associations between temperature and nutrient concentrations in the water column of the Gulf of Aqaba have not yet received any quantitative statistical assessment. This aim of the present work was to produce a simple statistical model for the relationship between temperature as the independent driving factor on the one hand, and nitrate, phosphate, silicate and dissolved oxygen concentrations as dependent factors on the other. The model computations are based on five years of summer records of temperature, nutrients, and oxygen in the upper 400 m of the water column. Useful though the regression equations will be for predicting nutrient concentrations from the water temperature, they can also serve as a baseline for the Gulf, which receives no significant anthropogenic nutrient input. Deviations in the derived empirical relationships in the future may be indicative of new forcing conditions, such as anthropogenic input of nutrients.

## 2. Material and methods

The data set used for the statistical analysis consists of five years (1998, 2000–2003) of monthly measurements of temperature, nitrate, phosphate, silicate and oxygen in the upper 400 m water column of the northern Gulf of Aqaba (Fig. 1b). The sampling station was about 3 km offshore of the Marine Science Station (MSS) and 650 m deep. All the oceanographic equipment necessary for the investigation was installed on a small vessel, a Boston Whaler (6 m $\times$ 2 m). The boat was equipped with a winch, an electric generator (GP 5203 SB), a Global Positioning System (GPS) (GP–80) and a depth finder (Echo scan series). Samples for nutrient analysis were collected using Nisken Bottles at every 25 m down to 200 m and every 50 m thereafter down to 400 m. Nutrient analysis was carried out spectrophotometrically using methods developed from Strickland & Parsons (1972). Oxygen was measured using a YSI water quality monitor (600XL). Temperature was measured using a self-contained Conductivity, Temperature and Depth meter (CTD) (Ocean Sensors OS200 & OS453) at 1 m intervals. The statistical analysis was carried out using Statview 5.0 software, SAS Institute Inc.

## 3. Results

### 3.1. Thermohaline structure

Seawater temperature profiles for the period May 1997 to April 2003 are shown in Fig. 2a. The seasonal variation exhibits thermal stratification during summer (May–November) and water mixing during winter (January –April). The strongest stratification occurred during August–September of every year and reached a maximum depth of about 250 m. On the other hand, the maximum mixing depth occurred during March–April of every year and exceeded the deepest sampling point (450 m). The difference in salinity in the upper 450 m (Fig. 2b) was less than 0.63 over the entire study

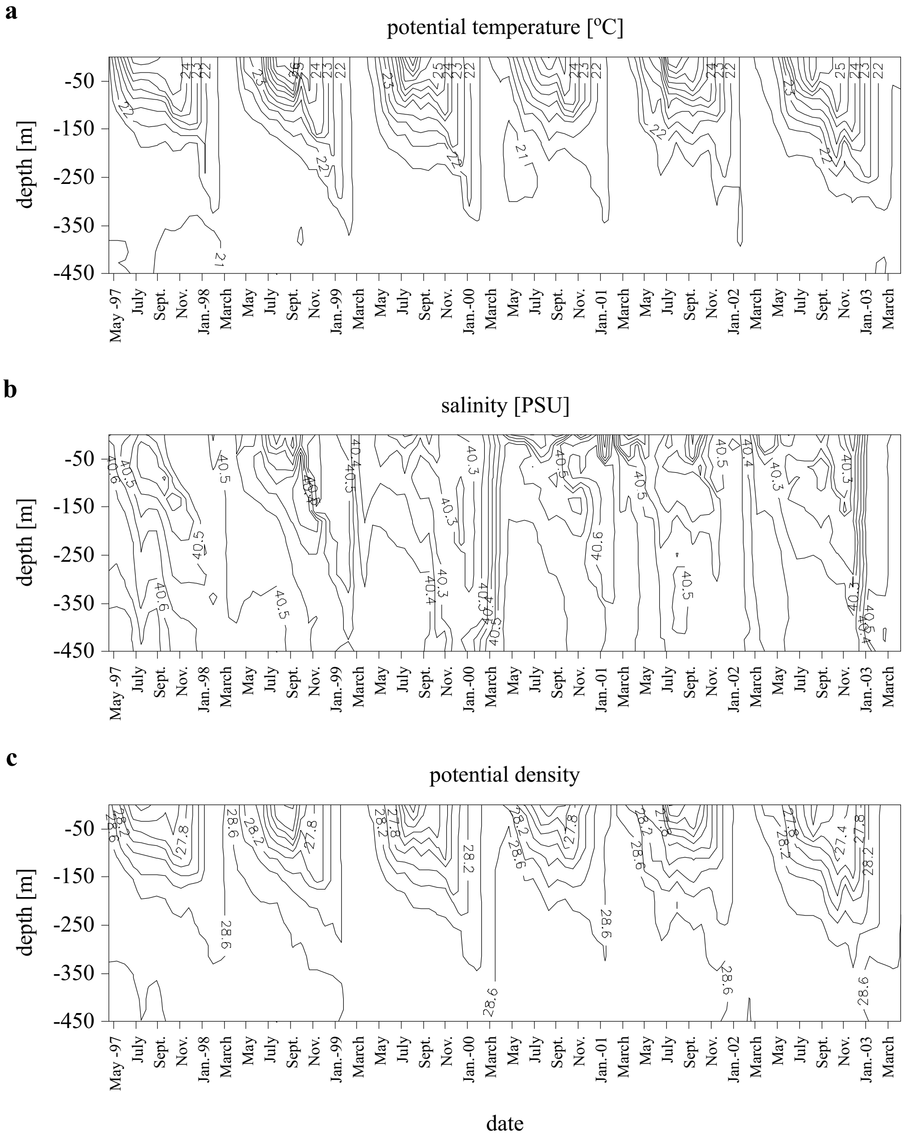


**Fig. 2.** Annual cycles of temperature [°C], salinity and density $\sigma_t$ in the northern offshore water of the Gulf of Aqaba during the period May 1997–May 2003

period. The behavior of seawater density $\sigma_t$ (Fig. 2c) followed basically that of the seawater temperature both in time and depth.

### 3.2. Temperature, nutrient and oxygen profiles

The present study focuses on the temperature and nutrient and dissolved oxygen concentrations in the open water of the northern Gulf of Aqaba during the summer stratification period. Fig. 3 shows temperature, nitrate, phosphate, silicate and oxygen records during the summer months (June –October) of all the years observed. The records of the year 2001 are highlighted as an example of a one-year record. All variables (temperature, nitrate, phosphate, silicate and oxygen) were tested for normality using the Statview software: they proved to have normal distributions. Thus, the one-way analysis of variance (ANOVA) test was used for inter- and

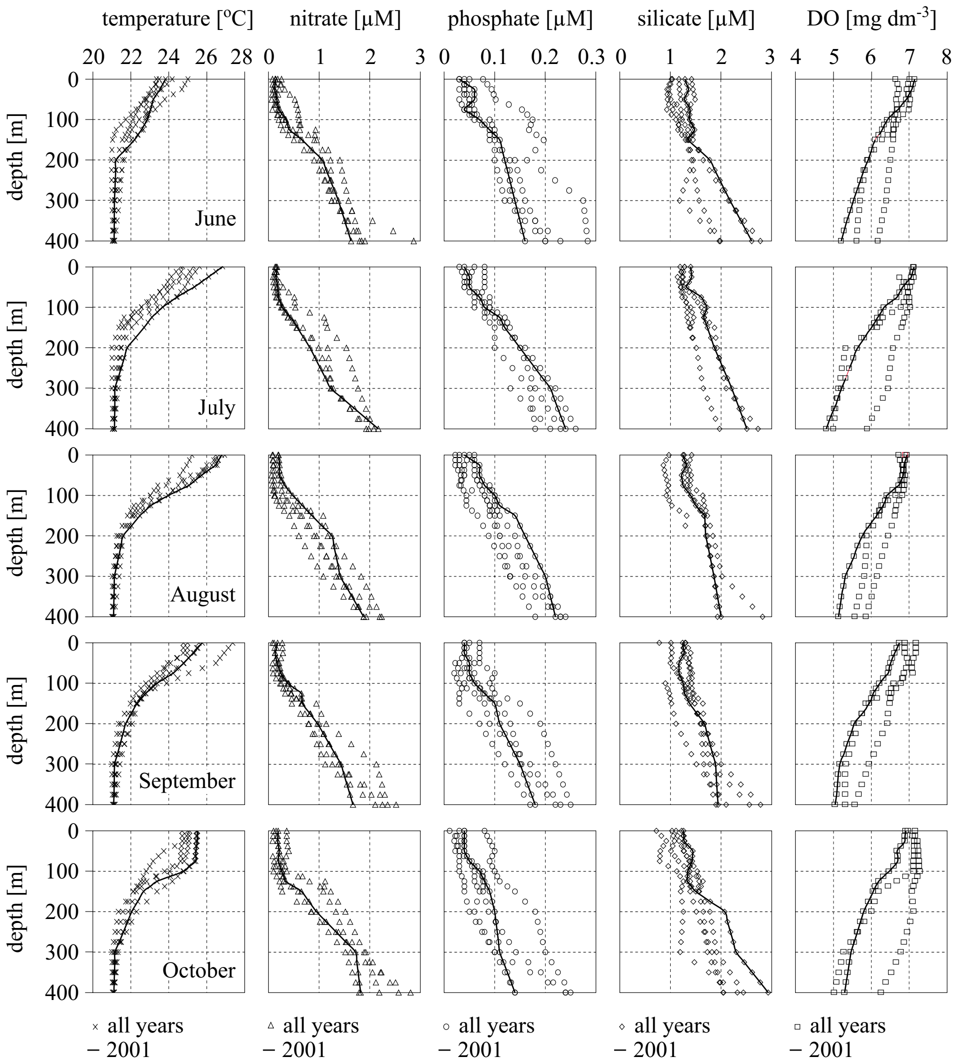


**Fig. 3.** Nitrate [$\mu$M], phosphate [$\mu$m], silicate [$\mu$m] and oxygen [mg dm$^{-3}$] profiles in the offshore water of the northern Gulf of Aqaba during the summer months (June–October) of every year observed (1998, 2000–2003)

intra-year statistical comparisons of all variables during the summer months (Table 1). The test revealed significant differences for temperature records among the summer months of all the study years, but no significant differences were found in nitrate, phosphate, silicate or oxygen. Therefore, the regression analysis of temperature versus the other variables was carried out on a monthly basis, i.e. the data was pooled for the same month in the different years. The seawater temperature profiles in the upper 400 m during summer (Fig. 3) revealed a distinct thermocline in the upper 200 m that became significantly weaker in the deeper water. During June, when the stratification started to build up, the difference between the surface and 200 m waters was about $2.64 \pm 0.49$°C (sea surface temperature $\sim 23.97 \pm 0.66$°C), whereas the temperature between 200 and 400 m in the water column was almost homogenous, with values from 20.98 to 21.54°C. The thermocline during August and September displayed a maximum temperature difference of about $4.47 \pm 1.00$°C between 0 and 200 m depth. The average sea surface temperature during August and September was $26.06 \pm 0.90$°C, while the average temperature in the 200–400 m water

**Table 1.** One-way ANOVA comparison test for temperature, nitrate, phosphate, silicate and oxygen records among the summer months (June–October) for all the years observed (1998, 2000–2003) in the offshore water of the northern Gulf of Aqaba

| | | Summer months (all years observed) | | | | | Probability (ANOVA test) |
|---|---|---|---|---|---|---|---|
| Variable | Means | June | July | Aug. | Sept. | Oct. | $p$ (among months) |
| T | mean | 23.013 | 22.633 | 22.118 | 23.011 | 22.882 | $< 0.0001$ (significant) |
| | SD | 1.928 | 1.572 | 1.021 | 1.645 | 1.68 | |
| | SE | 0.180 | 0.147 | 0.095 | 0.153 | 0.157 | |
| $NO_3^-$ | mean | 0.805 | 0.812 | 0.806 | 0.859 | 0.952 | 0.4396 (non-significant) |
| | SD | 0.624 | 0.641 | 0.649 | 0.676 | 0.747 | |
| | SE | 0.058 | 0.067 | 0.062 | 0.066 | 0.073 | |
| $PO_4^{3-}$ | mean | 0.117 | 0.125 | 0.107 | 0.104 | 0.092 | 0.1023 (non-significant) |
| | SD | 0.064 | 0.062 | 0.059 | 0.062 | 0.057 | |
| | SE | 0.006 | 0.006 | 0.005 | 0.006 | 0.005 | |
| $SiO_2$ | mean | 1.464 | 1.622 | 1.540 | 1.512 | 1.527 | 0.1117 (non-significant) |
| | SD | 0.409 | 0.383 | 0.390 | 0.378 | 0.434 | |
| | SE | 0.040 | 0.042 | 0.043 | 0.036 | 0.040 | |
| $O_2$ | mean | 6.362 | 6.249 | 6.305 | 6.190 | 6.483 | 0.1734 (non-significant) |
| | SD | 0.509 | 0.738 | 0.531 | 0.650 | 0.708 | |
| | SE | 0.061 | 0.090 | 0.064 | 0.078 | 0.085 | |

SD – standard deviation, SE – standard error.

was $21.23 \pm 0.19$°C. Subsequently, deterioration of the stratification began during October in the upper 75 m with an average temperature of about $24.96 \pm 0.57$°C, while the stratification was displaced downward to between 75 and 300 m in the water column with temperatures between 25.42 and 21.01°C. Below 300 m down to 400 m, the water was mixed with an average temperature of $21.13 \pm 0.08$°C.

The temperature stratification was mirrored by the nutrient and dissolved oxygen distributions in the entire water column. Nitrate, phosphate and silicate increased from the surface to deep water, but dissolved oxygen decreased. Nitrate concentrations remained persistently low (av. $0.21 \pm 0.11$ $\mu$M) in the upper water column (surface to 100 m), but reached $1.79 \pm 0.35$ $\mu$M in the lower water column (300–400 m). Phosphate and silicate exhibited a similar trend: low concentrations of both were low ($0.06 \pm 0.03$ and $1.23 \pm 0.19$ $\mu$M, respectively) in the upper water column, with higher values ($0.19 \pm 0.04$ $\mu$M and $2.07 \pm 0.36$ $\mu$M, respectively) being recorded in the lower water column. Oxygen concentrations decreased gradually with increasing depth in the water column, from $6.96 \pm 0.17$ mg dm$^{-3}$ in the surface water to $5.45 \pm 0.45$ mg dm$^{-3}$ at 400 m.

## 4. Discussion

In the northern Gulf of Aqaba the seawater temperature varies significantly between winter and summer (Fig. 2a), whereas the salinity shows no significant seasonal variation and does not represent a major factor affecting the changes in the seawater density (Fig. 2b, c). Seawater temperature is therefore the major factor in controlling density, playing a major role in winter convection (mixing) and summer stability (stratification), which in turn drive the biogeochemical cycle in the northern Gulf of Aqaba (Labiosa et al. 2003).

The factors controlling the seawater temperature in the Gulf of Aqaba are numerous, amongst them the warm water inflow from the Red Sea and the air-sea heat flux (Genin et al. 1995, Manasrah et al. 2004). The Red Sea waters entering the Gulf of Aqaba are about 2°C warmer than the waters already in there. The warming caused by the direct air-sea heat flux can have a much greater effect than the warm water inflow from the Red Sea (Manasrah et al. 2004). Thermal stratification builds up gradually during summer (May–September) because of the increasing air temperature, which exceeds the water temperature by about 15°C during the daytime in August (Manasrah 2002). Deterioration of the summer stratification begins during October, initially in the upper waters. This is explained by the drop in the nighttime air temperature to below 18°C, which is c. 8°C below the temperature of the surface water. The progressive decrease in air temperature leads to a permanent loss of buoyancy and causes the density of the surface water to pass a critical threshold, after which vertical convection occurs, so that the continuous deepening of the convection becomes dominant during winter (Manasrah 2002).

Stratification conditions are reflected in the concentrations of nutrients, including nitrate, phosphate and silicate (Klinker et al. 1978, Badran 2001, Castro et al. 2002, Al-Qutob et al. 2002). As thermal stratification starts to develop in June and intensifies with time until September, nutriclines also begin developing (Fig. 3). In October, when mixing conditions start to appear in the surface water, the nutricline also starts to break down and the concentrations become approximately uniform in the upper 100 m of the water column. Temperature may also influence nutrient concentrations in summer by affecting the photosynthesis rate (Tait 1981, Pliński & Jóźwiak 1999) in addition to affecting the mixing of the water column. Light intensity can also indirectly affect nutrient concentrations during summer. In spring it is high enough to allow a bloom, but in summer that light is photo-inhibitory: this, in combination with low nutrients, lowers productivity in surface waters. Since the light irradiance is high in the upper water column, primary producers increase nutrient consumption (e.g. Badran 2001, Corwith & Wheeler 2002). This may lead to a significant decrease in nutrient concentrations in the euphotic zone (0–100 m, Fig. 3) adding to the stratification conditions that limit nutrient intrusion from the deep-water reservoir (Badran 2001, Castro et al. 2002). The low nutrient concentrations in the upper 100 m in summer may therefore be attributed to high primary productivity at the start of the summer stratification and to the depletion of the main source of these nutrients in the upper offshore water.

The oxygen saturation concentration depends on temperature and salinity (Weiss 1970). In addition to these conservative parameters, the dissolved oxygen concentration depends on the photosynthetic rate and subsequently on nutrient concentrations. High temperature and salinity cause the oxygen to be relatively low (Badran 2001): the higher the temperature, the lower the solubility of oxygen in seawater. However, in our results, low oxygen concentrations were recorded, despite the low temperature in the deep waters (Fig. 3). This may be attributed to the influence on the dissolved oxygen concentration of the photosynthetic rate, which increases the oxygen concentration (Wheeler et al. 2003). Photosynthesis occurs mainly in the euphotic zone, where light is a sufficient energy source for primary producers. Another important factor contributing to the lower consumption of dissolved oxygen in the deeper water is the degradation of particulate matter (Rasheed et al. 2003). During the summer stratification, higher concentrations of particulate matter are to be expected below the euphotic zone.

In order to visualize the relationship between the different variables and the water depth, nutrients and dissolved oxygen are plotted against temperature and depth (Fig. 4). The inverse linear relationship between temperature and both nitrate and phosphate (Figs 4 and 5) indicates that the behavior of these variables with respect to temperature can be divided into two categories. The first category is when the temperature is $< 22°C$; then there are higher nitrate and phosphate concentrations in the deep waters below the summer thermocline throughout the year ($< 200$ m). The second category occurs when the temperature is above 22°C; then concentrations are low in the upper euphotic zone (Badran 2001, Corwith & Wheeler 2002) during summer.

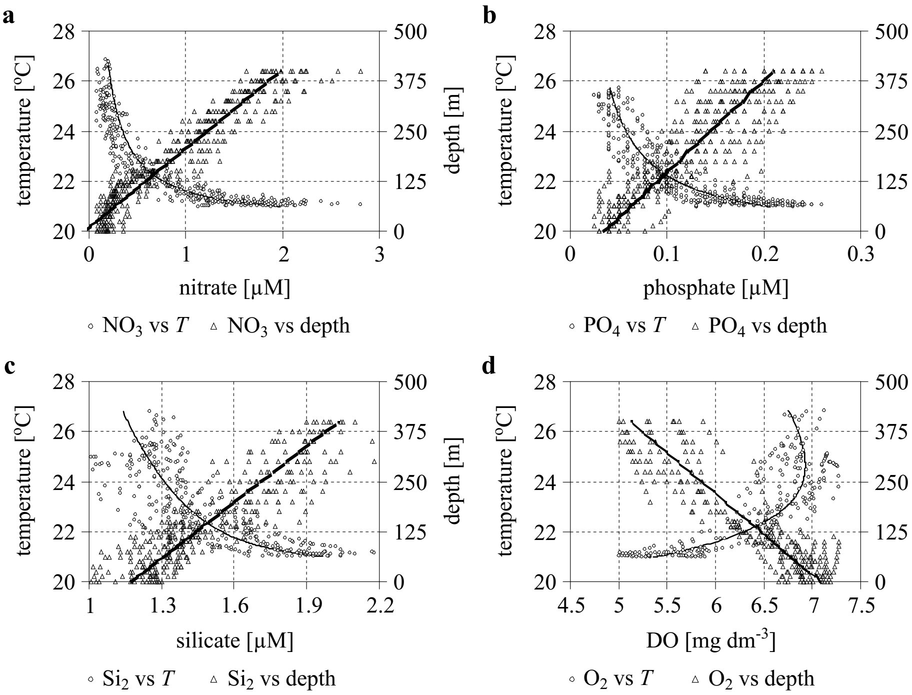


**Fig. 4.** Nutrients [$\mu$M] and dissolved oxygen [mg dm$^{-3}$] relationships with temperature [°C] and depth [m] in the offshore water of the northern Gulf of Aqaba during the summer months (June–October) of every year observed (1998, 2000–2003)

Silicate concentrations follow a similar trend to that of dissolved oxygen, but with a different relationship (Figs 4 and 5). The relative difference between the silicate concentrations in the upper and lower water columns

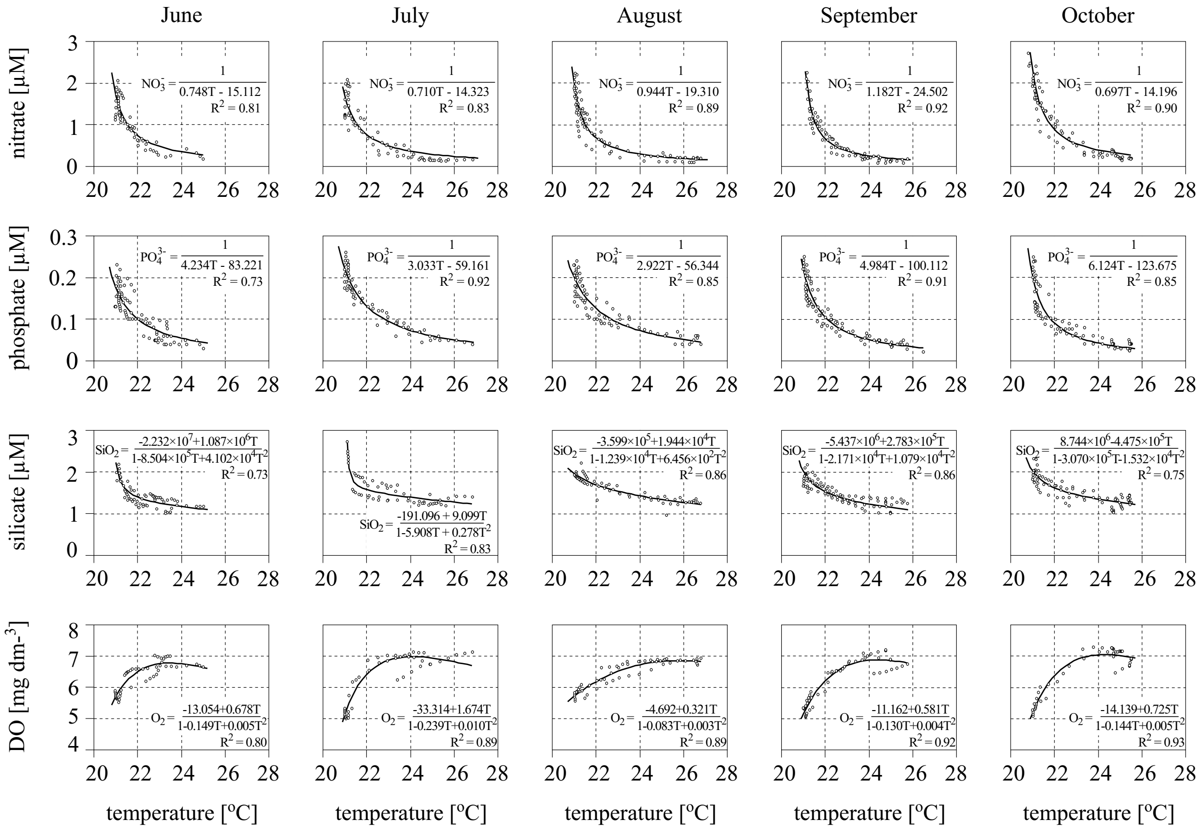


**Fig. 5.** Relationships between seawater temperature [°C] versus nitrate [$\mu$M], phosphate [$\mu$m], silicate [$\mu$m] and oxygen [mg dm$^{-3}$] in the offshore water of the northern Gulf of Aqaba during summer months (June–October). Every month represents the average of the five years: 1998, 2000–2003

was less than that of nitrate or phosphate (Fig. 5). This is the more likely because primary productivity is not limited by silicate, which enters the Gulf of Aqaba ecosystem from both the surrounding desert and the deep-water basin (Al-Fukaha 1994, Badran 2001).

Dissolved oxygen exhibited a positive relationship with temperature but an inverse relationship with depth (Fig. 4). This can be explained by the higher photosynthetic rate accompanied by a higher light intensity in the upper waters (Wheeler et al. 2003) and a lower photosynthetic rate accompanied by organic matter decomposition in the deeper waters. In the uppermost waters, however, where the temperature rises above 25°C, oxygen concentrations may decrease as a result of the lower solubility of oxygen in warmer seawater (Weiss 1970).

It has been shown and very well documented that the seawater temperature in the Gulf of Aqaba has a significant driving effect on the biogeochemical cycles (Klinker et al. 1976, Levanon-Spanier et al. 1979, Genin & Paldor 1998, Badran & Foster 1998, Badran 2001, Labiosa et al. 2003, Rasheed et al. 2003, Badran et al. 2005, Badran & Zibdah 2005). In venturing to find empirical relationships between temperature, different nutrients and dissolved oxygen concentrations, the present work has gone a step further. Fig. 5 shows a graphic representation of the relationship between seawater temperature and the different variables in the different summer months. The best fit relationship between temperature on the one hand, and nitrate and phosphate on the other, was found to be an inverse linear one, and the best fitting curve in the case of silicate and dissolved oxygen was found to be fractional.

The best fit relationships between seawater temperature and all other variables were highly significant (Table 2), but no significant differences were found using the *t*-test comparison between real observations and the values predicted by the model. The average residuals (difference between

**Table 2.** Statistical comparison (*t*-test, paired) for temperature, nitrate, phosphate, silicate and oxygen records between the real and model values in the offshore water of the northern Gulf of Aqaba during the summer months of all the years observed (1998, 2000–2003)

| *t*-test values (*p*: probability) between real observations and model | | | | | | |
|---|---|---|---|---|---|---|
| Variable | June | July | August | Sept. | Oct. | All months |
| nitrate [$\mu$M] | 0.697 | 0.382 | 0.860 | 0.624 | 0.522 | 0.242 |
| phosphate [$\mu$M] | 0.759 | 0.971 | 0.852 | 0.853 | 0.605 | 0.226 |
| silicate [$\mu$M] | 0.985 | 0.977 | 0.993 | 0.494 | 0.991 | 0.728 |
| dissolved oxygen [mg dm$^{-3}$] | 0.998 | 0.946 | 0.923 | 0.829 | 0.988 | 0.920 |

the real observations and best fitted functions) of each variable during the summer months of all years of the study are shown in Fig. 6. The residual values are relatively low compared to the average real observations in the water column and the best fitted functions. When different segments of the water column are considered, however, these values are high relative to the upper waters (euphotic zone) and low relative to the deep water (the permanently mixed deep water). Although this does detract from the predictive capability of our statistical approach in the upper water, it does not substantially affect its applicability. Top water column waters are relatively easy to sample, which makes routine analysis relatively cost effective. Besides, upper water column waters are the most susceptible to anthropogenic effects, which can easily lead to deviations from model predictions. Deep waters on the other hand are much less susceptible to anthropogenic influence but more costly to sample. This is where a statistical prediction model gains greatly in value. To overcome the difficulties and the high cost of analyzing deep oceanic waters, nutrient sensors are becoming widely used, particularly in temperate waters

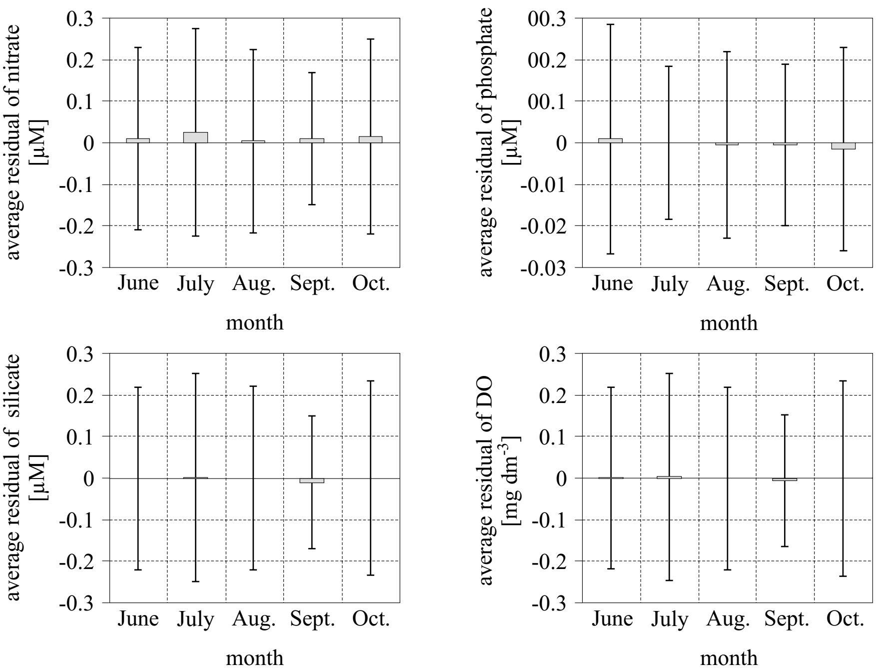


**Fig. 6.** The average of anomalies values between the real observations and the best fit relationship of nitrate [$\mu$M], phosphate [$\mu$m], silicate [$\mu$m] and oxygen [mg dm$^{-3}$] during the summer months (June–October) of every year observed (1998, 2000 –2003)

(Varney (ed.) 2000, Johnson & Coletti 2002), where nutrient concentrations are relatively high. But there are serious limitations to the use of nutrient sensors in oligotrophic waters because of the low nutrient concentrations that may go below the detection limits of the best-known nutrient sensors. Here, once a reliable statistical relationship has been established between temperature and the different nutrients, a simple CTD device recording temperature only and the application of suitable conversion algorithms can do the same job as a sophisticated nutrient sensor. Another significant aspect of our approach is that it defines empirical relationships between seawater temperature and nutrient and dissolved oxygen concentrations under natural, annual-cycle driven baseline conditions. Once these empirical relationships have been modified, one can justifiably suspect the intrusion of significant amounts of nutrients from anthropogenic sources. Our approach, together with the sporadic analysis of seawater samples, can therefore serve as an early warning monitoring technique.

## Acknowledgements

The authors would like to thank the technical staff of the Marine Science Station for their help in collecting the samples. Special thanks are due to Mr. Khalid Altrabeen and Ms. Ala Altahan for their help in the analysis.

## References

Al-Fukaha F., 1994, *A textural and geochemical study on reefal sediments of the Gulf of Aqaba, and the input of airborne dust to the area*, M. Sc. thesis, Yarmouk Univ., Irbid (Jordan).

Al-Qutob M., Haese C., Tilzer M. M., Lazar B., 2002, *Phytoplankton drives nitrite dynamics in the Gulf of Aqaba, Red Sea*, Mar. Ecol. Prog. Ser., 239, 233–239.

Al-Rousan S., Al-Moghrabi S., Patzold J., Wefer G., 2002, *Environmental and biological effects of on the stable oxygen isotope records of corals in the Gulf of Aqaba, Red Sea*, Mar. Ecol. Prog. Ser., 239, 301–310.

Badran M. I., 2001, *Dissolved oxygen, chlorophyll a and nutrients: seasonal cycles in waters of the Gulf Aqaba, Red Sea*, Aquat. Ecosys. Health Manage., 4 (2), 139–150.

Badran M. I., Foster P., 1998, *Environmental quality of the Jordanian coastal waters of the Gulf of Aqaba, Red Sea*, Aquat. Ecosys. Health Manage., 1 (1), 75–90.

Badran M. I., Rasheed M., Manasrah M., Al-Najjar T., 2005, *Nutrient flux fuels summer primary productivity in the oligotrophic waters of the Gulf of Aqaba, Red Sea*, Oceanologia, 47 (1), 47–60.

Badran M. I., Zibdah M. K, 2005, *Quality standard codes of reference of Jordanian coastal waters of the Gulf of Aqaba, Red Sea*, Chem. Ecol., 21 (5), 337–350.

Castro C. G., Rios A. F., Doval M. D., Perez F. F., 2002, *Nutrient utilization and chlorophyll distribution in the Atlantic sector of the Southern Ocean during Austral summer 1995–96*, Deep-Sea Res. Pt. II, 49 (4–5), 623–641.

Charpy-Roubaud C., Charpy L., Sarazin G., 1996, *Diffusional nutrient fluxes at the sediment-water interface and organic matter mineralization in an atoll lagoon (Tikehau, Tuamotu Archipelago, French Polynesia)*, Mar. Ecol. Prog. Ser., 132, 181–190.

Ciceri G., Ceradini S., Zitelli A., 1999, *Nutrient benthic fluxes and pore water profiles in a shallow brackish marsh of the lagoon of Venice*, Ann. Chim., 89, 359–375.

Corwith H. L., Wheeler P. A., 2002, *El Nino related variation in nutrient and chlorophyll distributions off Oregon*, Prog. Oceanogr., 54 (1–4), 361–380.

D'Elia C. F., Webb K. L., Porter J. W., 1981, *Nitrate-rich groundwater input to Discovery Bay, Jamaica: A significant source of N to local coral reefs*, Bull. Mar. Sci., 31 (4), 903–910.

Garside C., 1985, *The vertical distribution of nitrate in open ocean surface water*, Deep-Sea Res., 32 (6), 723–732.

Genin A., Lazar B., Brenner S., 1995, *Vertical mixing and coral death in the Red Sea following the eruption of Mt. Pinatubo*, Nature, 377 (6549), 507–510.

Genin A., Paldor N., 1998, *Changes in the circulation and current spectrum near the tip of the narrow, seasonally mixed Gulf of Elat (Aqaba)*, Isr. J. Earth Sci., 47, 87–92.

Jenkins W. J., Goldman J. C., 1985, *Seasonal oxygen cycling and primary production in the Sargasso Sea*, J. Mar. Res., 43, 465–491.

Johnson K. S., Coletti L. J., 2002, *In situ ultraviolet spectrophotometry for high resolution and long-term monitoring of nitrate, bromide and bisulfide in the ocean*, Deep-Sea Res. Pt. I, 49 (7), 1291–1305.

Klinker J., Reisis Z., Kropach C., Levanon I., Harpaz H., 1978, *Nutrients and biomass distribution in the Gulf of Aqaba (Elat), Red Sea*, Mar. Biol., 45, 53–64.

Klinker J., Reiss Z., Kropach C., Levanon I., Harpaz H., Halicz E., Assaf G., 1976, *Observation on the circulation pattern in the Gulf of Aqaba, Red Sea*, Isr. J. Earth Sci., 25, 85–103.

Labiosa R. G., Arrigo K. R., Genin A., Monismith S. G., Dijken G., 2003, *The interplay between upwelling and deep convective mixing in determining the seasonal phytoplankton dynamics in the Gulf of Aqaba: Evidence from SeaWiFS and MODIS*, Limnol. Oceanogr., 48 (6), 2355–2368.

Levanon-Spanier I., Padan E., Reisis Z., 1979, *Primary production in a desert-enclosed sea – the Gulf of Elat (Aqaba), Red Sea*, Deep-Sea Res., 26 (6), 673 –685.

Lewis J. B., 1985, *Groundwater discharge onto coral reefs, Barbados (West Indies)*, Proc. 5th Int. Coral Reef Symp., 6, 477–481.

Manasrah R., 2002, *The general circulation and water masses characteristics in the Gulf of Aqaba and northern Red Sea*, Meereswissenschaftliche Ber., Mar. Sci. Rep. No 50, 1–120.

Manasrah R., Badran M., Lass H. U., Fennel W., 2004, *Circulation and winter deep-water formation in the northern Red Sea*, Oceanologia, 46 (1), 5–23.

Marsh J. A., 1977, *Terrestrial inputs of nitrogen and phosphorus on fringing reefs of Guam*, Proc. 5th Int. Coral Reef Symp., 1, 331–336.

Monisnith S., Genin A., 2004, *Tides and sea level in the Gulf of Aqaba (Eilat)*, J. Geophys. Res., 109 (C04015), doi: 10.1029/2003JC002069.

Niemann H., Claudio R., Jonkers H., Badran M., 2004, *Red Sea gravity currents cascade near-reef phytoplankton to the twilight zone*, Mar. Ecol. Prog. Ser., 269, 91–99.

Pliński M., Jóźwiak T., 1999, *Temperature and N:P ratio as factors causing blooms of blue-green algae in the Gulf of Gdańsk*, Oceanologia, 41 (1), 73–80.

Rasheed M., Badran M., Huettel M., 2003, *Particulate matter filtration and seasonal nutrient dynamics in permeable carbonate and silicate sands of the Gulf of Aqaba, Red Sea*, Coral Reefs, 22 (2), 167–177.

Rasheed M., Badran M., Richter C., Huettel M., 2002, *Effect of reef framework and bottom sediment on nutrient enrichment in coral reef of the Gulf of Aqaba, Red Sea*, Mar. Ecol. Prog. Ser., 239, 277–285.

Rasheed M., Wild C., Franke U., Huettel M., 2004, *Benthic photosynthesis and oxygen consumption in permeable carbonate sediments at Heron Island, Great Barrier Reef, Australia*, Estuar. Coast. Shelf Sci., 59 (1), 139–150.

Richter C., Wunsch M., Rasheed M., Kötter I., Badran M., 2001, *Endoscopic exploration of Red Sea coral reefs reveals dense populations of cavity-dwelling (coelobite) sponges*, Nature, 413 (6857), 726–730.

Straneo F., Kawase M., 1999, *Comparisons of localized convection due to localized forcing and to preconditioning*, J. Phys. Oceanogr., 29, 55–68.

Strickland J. D., Parsons T. R., 1972, *A practical handbook of seawater analysis*, 2nd edn., Fish. Res. Bd. Can. Bull., 167, 1–310.

Tait R. V., 1981, *Elements of marine ecology: An introductory course*, 3rd edn., Heinemann, Butterworth, 448 pp.

Varney M. S., (ed.), 2000, *Chemical sensors in oceanography*, Gordon and Breach, New York, 333 pp.

Weiss R. F., 1970, *The solubility of nitrogen, oxygen and argon in water and seawater*, Deep-Sea Res., 17 (4), 721–735.

Wheeler P. A., Huyer A., Fleischbein J., 2003, *Cold halocline, increased nutrients and higher chlorophyll off Oregon in 2002*, Geophys. Res. Lett., 30 (15), 8021, doi:10.1029/2003GL017395.

Wild C., Huettel M., Kremb S., Rasheed M., Woyt H., Gonelli S., Klueter A., 2004a, *Coral mucus functions as energy shuttle and nutrient trap in the reef*, Nature, 428 (6978), 66–70.

Wild C., Rasheed M., Werner U., Franke U., Johnstone R., Huettel M., 2004b, *Degradation and mineralization of coral mucus in reef environments*, Mar. Ecol. Prog. Ser., 267, 159–171.

Wilkinson C. R., Williams D. M., Sammarco P. W., Hogg R. W., Trott L. A., 1984, *Rates of nitrogen-fixation on coral reefs across the continental-shelf of the Central Great Barrier-Reef*, Mar. Biol., 80, 255–262.