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Adaptation of an algorithm for chlorophyll-a estimation by optical data in the oligotrophic Gulf of Eilat

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Abstract. Downwelling irradiance and upwelling radiance from the water surface were measured in the Gulf of Eilat (Red Sea) on 55 separate occasions in a pelagic station in the period from January 1994 to December 1996. The reflectance was calculated in seven of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) spectral channels throughout the visible spectrum. Concurrent with the optical measurement, water samples were taken to the laboratory and the concentrations of chlorophyll-a (Chl-a) were determined. The ratio of the reflectance in the blue ($R443$) to the reflectance in the green ($R550$) was regressed against the Chl-a concentration, and showed that the best-fit of the three datasets (1994, 1995 and 1996) assumed an exponential form, as found in previous work in oligotrophic waters. The coefficients determined in the current study were, however, different from those published in the literature; the reason for this probably originates in the composition of water constituents in the studied area. Small cells dominate the phytoplankton in the pelagic waters in the Gulf of Eilat, and the concentration of suspended and soluble materials of terrestrial origin is very small. The suggested algorithm enabled the prediction of Chl-a concentration within $0.08\,\mathrm{mg\,m^{-3}}$. It was shown that calibration of the coefficients, based on empirical data, is important for increasing its prediction accuracy.

1. Introduction

Chlorophyll-a (Chl-a) is present in all oxygenic photosynthesizers, and as such is used to monitor phytoplankton in aquatic environments. Characterized by well-defined and specific optical properties in the visible range, Chl-a is suitable for direct observation with optical instruments (Kirk 1994). In oligotrophic (nutrient poor) aquatic systems Chl-a is usually determined by remotely operated means

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using the following relationship (e.g. Clark 1981, Gordon and Morel 1983):

$$\text{Chl-a} = a\,(R_{443}/R_{550})^{-b} \tag{1}$$

where $R443$ and $R550$ are the reflectance values in the blue range 443 ± 10 nm and green at 550 ± 10 nm, respectively, and a and b are coefficients determined empirically from regression line fitting. Although the basic concept of using the blue and green portions of the spectrum applies over a wide range of waterbodies, the coefficients used differ conspicuously (see table 1) and should be adapted for any given location and time for the water quality monitoring. Application of the algorithm [equation (1)] without preliminary calibration may work accurately, but on the other hand it may lead to a large deviation from the real values of Chl-a (e.g. van Dijken and Arrigo 1996).

This research was conducted in the Gulf of Eilat, Israel, a relatively long, narrow and deep sea, bordered by deserts. Annual precipitation of the area is typically less than 25 mm. This leads to low run-off and hence small freshwater inputs to the saline environment. The waters of the Gulf of Eilat are ultra-oligotrophic (Iluz 1997) and the littoral fringes of the coastline harbour the world's most northern coral reefs habitats (Dubinsky 1990). Extensive development in countries surrounding the Gulf poses the threat to the fragile marine ecosystem and the need for environmental monitoring is becoming more apparent. Phytoplankton density may be used as a monitoring tool because changes in the density and hence Chl-a concentration may act as an indicator of enhanced disturbance from anthropogenic activity or natural factors (Genin *et al.* 1995). It is therefore mandatory to develop tools for rapid estimation of phytoplankton density, of which Chl-a measurement by optical means seems the most feasible.

The goal of the work was to adapt the algorithm for Chl-a estimation [equation (1)] and to derive coefficients for this ecosystem more accurately for the use of remote sensing. The work was performed onboard a research vessel with the aim of up-scaling the study to derive synoptic measurement of Chl-a concentration in the Gulf of Eilat using the following satellite sensors: Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate-resolution Imaging Spectrometer (MODIS) and Medium-Resolution Imaging Spectrometer (MERIS).

2. Materials and methods

All field measurements were performed between 11:00 and 13:00 h local time at a pelagic station in the Gulf of Eilat (29° 28′ N 34° 54′ E). Bottom depth at this station is 650 m. Simultaneous optical measurements and water sampling for laboratory Chl-a analysis were conducted once or twice per month. The number of spectral measurements was at least 10 on each occasion and, for each of the 55 field visits from January 1994 until December 1996, an average of the reflectance measurements was used to feed into the regression equation.

The PRR-600 profiling reflectance radiometer (Biospherical Instruments) has seven of the SeaWiFS wavelength bands: 412 ± 10, 443 ± 10, 490 ± 10, 510 ± 10, 555 ± 10, 665 ± 10 and 694 ± 10 nm. It was deployed just below the water surface and downwelling irradiance and upwelling radiance were recorded. The PRR radiometer is a dual-beam instrument with two heads simultaneously measuring upwelling radiance and downwelling irradiance with a cosine-corrected diffuser. The reflectance (R) in each spectral channel was calculated as the ratio of the upwelling

radiance (L_u) to downwelling irradiance (E_d):

$$R = L_u/E_d \tag{2}$$

With the completion of the optical measurement, a water sample was collected at 1 m below the water surface by a 5 l Niskin bottle, transferred to a plastic carboy and put in the dark, prior to further processing in the laboratory, which took place approximately 1 h after the sampling. In the laboratory, Chl-a concentration was determined fluorometrically (Holm-Hansen *et al.* 1965), on duplicated 200 ml samples, filtered onto GF/F filters and extracted for 24 h in the dark at 4° C in 90% acetone. The difference between duplicate Chl-a analyses did not surpass 10% in any case.

3. Results and discussion

Chl-a concentrations ranged between 0.05–0.45 mg m^{-3}. The highest Chl-a concentrations were found in January–February, when the water column was mixed and influx of nutrients enhances primary productivity. Chl-a was particularly low in July–August, when nitrate concentration in the upper 100 m layer of the water column was <0.1 mg m^{-3} (Lindell and Post 1995). The reflectance ratio $R443/R550$ varied between 1.5 (January 1995) and 8 (August 1994), and its relation with Chl-a concentrations was described by a power function [equation (1)], suggested previously for those variables in oligotrophic waters (e.g. Gordon and Morel 1983). Reasonable correlations between the ratio and Chl-a concentration were observed for each year (minimal coefficient of determination exceeded 0.8), although best-fit

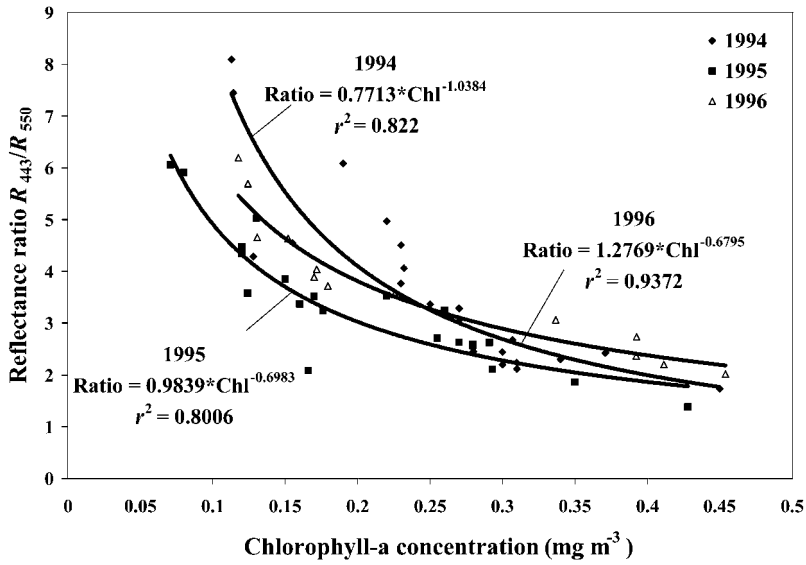

Figure 1. Plot of the reflectance ratio $R443/R550$ against Chl-a concentration. The reflectance was measured just below the water surface in a pelagic station, in the Gulf of Eilat (29° 28′ N 34° 54′ E). The measurements were taken from January 1994 until December 1996, with the reflectance determined by a PRR-600 profiling reflectance radiometer. The results were arranged in annual groups and the best-fit function for each set of results was calculated. The best-fit functions and the coefficients of determination (r^2) are specified near the curves.

functions for each year were different (figure 1). The coefficient b in equation (1) was large in 1994 and it was smaller in 1995 and 1996. The difference between best-fit functions was more pronounced for Chl-a concentrations below 0.25 mg m^{-3}. The best-fit function (with $r^2 = 0.71$, $p < 0.0001$ and standard error of 0.08 mg m^{-3}) for all three datasets, acquired in the Gulf of Eilat from 1994–1996 was as follows (figure 2):

$$\text{Chl-a} = 0.704\,(R_{443}/R_{555})^{-0.985} \tag{3}$$

Comparison of the relationships between the ratio of $R443/R550$ and Chl-a concentration, obtained in the current study with the results of other studies is presented in table 1. In all cases, the best fit was achieved using a power function. The closest correlation to our dataset is the coefficients suggested by Gordon *et al.* (1983). Their model describes the Gulf of Eilat's datasets reasonably well. For 1995, the relationship between the ratio $R443/R555$ and Chl-a concentration with coefficients provided by the Gordon *et al.* (1983) model had a coefficient of determination, r^2, larger than 0.82 (figure 2). However, for 1994 and 1996 datasets, reflectance ratios were slightly larger than in studies on other waterbodies (table 1). The reason for this probably originates in the composition of water constituents in the studied area. Small cells dominate the phytoplankton in the pelagic waters in the Gulf of Eilat, and the concentration of suspended and soluble materials of terrestrial origin is very small (Lindell and Post 1995, Iluz 1997).

Relationships between reflectance ratio $R443/R550$ and Chl-a concentration varied notably for each year (figure 1). The ratio $R443/R550$ in 1994 was larger for low Chl-a concentrations than in the following years and larger in 1996 than in 1995. The changing relationship between the reflectance ratio and Chl-a concentration is a sign of temporal variation in the absorption characteristics of Chl-a.

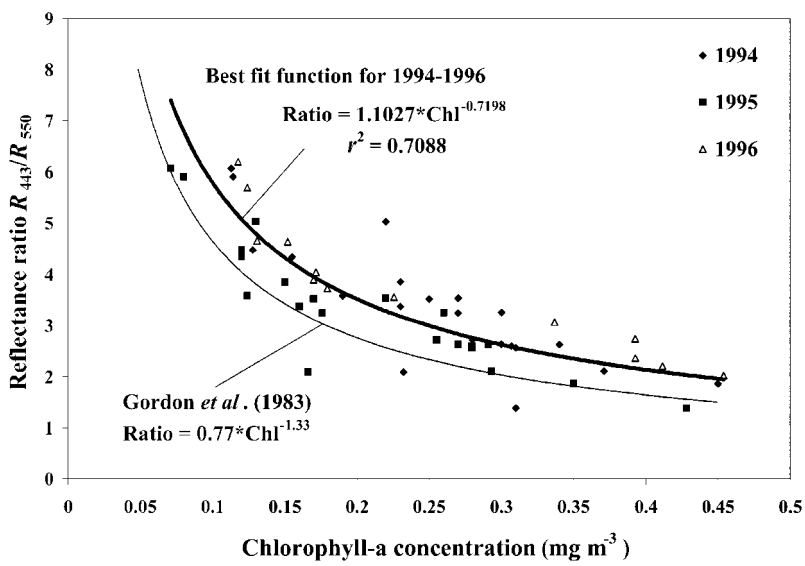

Figure 2. The reflectance ratio $R443/R550$ plotted vs chlorophyll concentrations. Solid line represents best-fit function for all data (1994–1996). Thin line represents $R443/R550$ vs Chl-a relationship by Gordon *et al.* (1983).

Table 1. Comparison of the parameters of the best-fit function of the reflectance ratio R_{443}/R_{550} against Chl-a concentration. In all cases the best-fit function is a power function of the type: Chl-a $= a \times (R_{blue}/R_{green})^{-b}$, where R is the reflectance value in the respective wavelength and a and b are coefficients. The determination coefficient (r^2) in each case is specified.

Source	R_{blue}	R_{green}	a	b	r^2
Gordon and Clark 1980	443	550	0.50	−1.27	0.98
Morel 1980	440	560	1.62	−1.40	0.76
Morel 1980 (case 1)	440	560	1.92	−1.80	0.97
Smith and Wilson 1981	443	550	0.78	−2.12	0.94
Gordon *et al.* 1983	443	550	0.77	−1.33	0.91
Gordon *et al.* 1983 (case 1)	443	550	1.13	−1.71	0.96
Gitelson *et al.* 1996	443	550	0.91	−1.86	0.87
This study, 1994	443	550	0.63	−0.79	0.82
This study, 1995	443	550	0.70	−1.14	0.80
This study, 1996	443	550	1.27	−1.38	0.94
This study, 1994–1996	443	550	0.70	−0.98	0.71

A parallel change in the phytoplankton composition was not detected; other water constituents were not measured in this series of experiments. Therefore, it is not possible to comment at this time on whether these were the causes of the changing relationship.

The relationship between the ratio $R443/R550$ and Chl-a concentration, obtained for the 1994 dataset, was used to predict the Chl-a concentration in 1995 and 1996. Using the reflectances $R443$ and $R550$ acquired in 1995 and 1996, Chl-a concentrations were estimated from the equation

$$\text{Chl-a} = 0.63\,(R_{443}/R_{550})^{-0.79} \tag{4}$$

Predicted Chl-a concentrations were compared to those actually measured. The coefficient of determination between the predicted and the measured Chl-a concentrations was $r^2 = 0.69$, and the standard error of Chl-a prediction was less than $0.08\,\text{mg}\,\text{m}^{-3}$ (figure 3). This prediction provides greater accuracy for the Gulf of Eilat than when algorithms established for other environments (table 2) were used.

It should be noted that the algorithms presented in table 1 were derived from data measured within a limited area and within a short period of time. In our case, the database consisted of measurements taken all year round. In this case, changes in phytoplankton composition as well as in composition of non-organic suspended matter are most probable. In work done in waters with greater primary productivity, it was found that the prediction accuracy declined if used for data measured over a whole season; that reduction in predictive ability was caused by change in pigment composition and phytoplankton cell size (Gitelson *et al.* 2000).

The interannual variability, found in this work, underlines the necessity to calibrate the algorithm for each season and location, as the inherent optical properties of water constituents and the composition of the suspended and dissolved components may change.

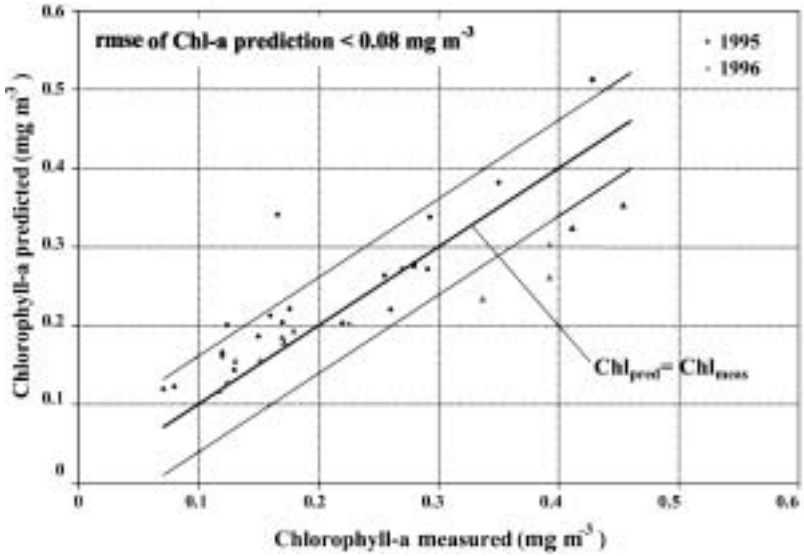

Figure 3. The predicted Chl-a concentration plotted against the concentration measured by a regular wet laboratory procedure. The best-fit function found for Chl-a vs $R443/R550$ relationship in 1994 [equation (4)] was used to predict Chl-a concentration in 1995 and 1996. Solid line is $Chl_{pred} = Chl_{meas}$; thin lines are one rmse ($0.08\,mg\,m^{-3}$) of Chl-a prediction.

4. Conclusions

The chosen wavelengths of reflectance for the construction of algorithms for the prediction of Chl-a concentration in oligotrophic waters in the Atlantic Ocean (and subsequently elsewhere) — namely in the blue and green portions of the electromagnetic spectrum — are suitable for the Gulf of Eilat. The reflectance ratio $R443/R550$ and Chl-a concentration measured in the laboratory, by standard analytical methods, related closely ($r^2 > 0.8$) in three consecutive years of field study. The suggested algorithm enabled Chl-a prediction within $0.08\,mg\,m^{-3}$. The algorithm has increased accuracy in predictive power over other methods, because it is tuned to the specific oligotrophic properties of the Gulf of Eilat. This work, performed at the water surface from a research vessel, is a prerequisite for the employment of remotely operated sensors such as SeaWiFS, MODIS and MERIS,

Table 2. Parameters of linear regression between the measured and predicted values of Chl-a in the Gulf of Eilat, in 1995–1996, using different algorithms.

Source	r^2	X variable	Intercept	rmse
This work	0.689	0.676	0.080	0.080
Morel 1980	0.651	1.439	0.023	0.186
Gordon *et al.* 1983	0.658	0.698	0.020	0.089
Gordon *et al.* 1983 (case 1)	0.616	0.893	−0.024	0.125
Gordon and Clark 1980	0.664	0.460	0.019	0.085
Smith and Wilson 1981	0.563	0.521	−0.033	0.081
Morel 1980 (case 1)	0.605	1.476	−0.054	0.211
Gitelson *et al.* 1996	0.597	0.685	−0.029	0.099

and demonstrated the feasibility of such an approach in the Gulf of Eilat — a unique and endangered ecosystem.

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