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Chloropbyll estimation in the Southeastern Mediterranean using CZCS images: adaptation of an algorithm and its validation

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Abstract

Region-specific algorithm to derive chlorophyll concentration from Coastal Zone Color Scanner (CZCS) images was adopted following field measurements in the Southeastern Mediterranean Sea, in June 1992. Reflectance in the range 400 to 700 nm, chlorophyll concentration and seston dry weight were measured simultaneously at 21 stations. The optical model used based on algorithm for Case I waters, using shipboard simulation of CZCS channels for adaptation of parameters. The resulting model was validated with an independent data sets from series of cruises in the Southeastern Mediterranean (1981-1984). Concurrent CZCS images were used for retrieval of the radiance ratio Channel 1/Channel 3, for each station. The resulting ratios were then used to calculate chlorophyll concentrations. A comparison between those calculated concentrations and the actual chlorophyll measurements showed that an estimation error of chlorophyll as low as 0.013 mg m^{-3} was achieved.

1. Introduction

Coastal Zone Color Scanner (CZCS) images provide information about the distribution of optically active constituents in the ocean. Such images are an important tool to examine phytoplankton and turbidity over large areas. The application of CZCS data for the Southeastern Mediterranean has been limited in the absence of optical models that relate chlorophyll (Chl) concentrations to reflectance for this region.

The most widely applicable remote sensing method for measuring chlorophyll (Chl) concentration has been the use of the reflectance in the blue region of the spectrum relative to green (e.g., Gordon and Morel, 1983). The technique was successfully used for monitoring Case I waters (Morel and Prieur, 1977), where concentrations of all optically active components co-varied. These bio-optical algorithms were derived from in situ measurements and the difference between various models is expressed mainly in the coefficients used.

The goal of this study was to implement a quantitative remote sensing method for estimation of chlorophyll in the Southeastern Mediterranean, using CZCS images and having in mind tools available in the near future, e.g., SeaWiFS. CZCS was active from 1978 to 1984, therefore the data available from

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that time period may be used as base line for monitoring of long term changes occurring in this part of the world.

The goal of this work was achieved following steps: (1) field data collection; (2) adaptation of algorithm for Chl estimation; (3) application of the algorithm for interpretation of CZCS processed images and (4) validation of the image analysis data with Chl measurements done at the time of image acquisition. Although the present data set is probably not comprehensive enough to be representative of the entire Southeastern Mediterranean, the locations of the measurements were sufficiently dispersed to cover a wide range of chlorophyll and suspended matter concentrations.

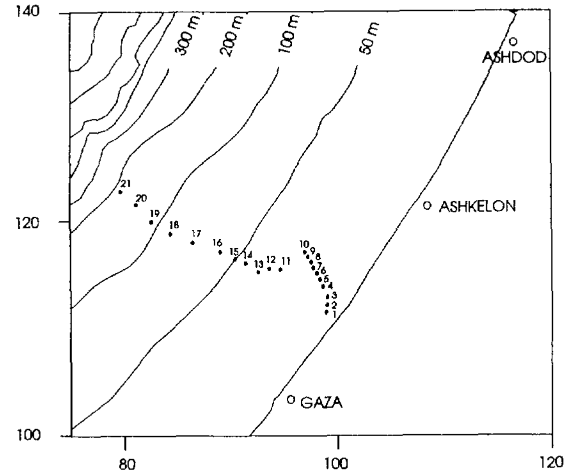

Fig. 1. Location of the stations occupied R/V *Shikmona* on July 22, 1992.

2. Methods

We tried to sample as wide a range of Chl and SM concentrations as possible. The most appropriate areas for measurements were determined from a preliminary analysis of more than 100 CZCS images of the Southeastern Mediterranean. The analysis suggested that the area with the highest optical variability is offshore Gaza. Twenty one locations were sampled on 22nd July 1992, in the Southeastern Mediterranean. Water depth ranged from 8 m to 200 m (Mayo et al., 1993). The position of the stations in the test area near Gaza is shown in Fig. 1.

At each sampling station, the upwelling radiance of the water, L_w, and L_o, the upwelling radiance of the standard reflectance $BaSO_4$ plate, were measured with a portable LICOR LI-1800 radiometer in the range from 400 to 700 nm with spectral resolution of 2 nm. The measurements of upwelling radiance of the water were taken at least five times using a telescope with a field of view of 15°. Measurements were made from the ship board about 6 m above the water surface. Therefore, the upwelling radiance of the water was collected from an area of 1.5 by 1.5 m. Each observed radiance spectrum of the water was divided by the appropriate spectrum of upwelling radiance of the reference plate to give a radiance reflectance, $R = L_w/L_o$.

To minimize the contribution of specular reflected light during clear sky conditions, the telescope was directed at the water surface at an angle of about 20° off the nadir into the opposite direction of the sun azimuth, where the specular reflectance has its minimum.

Surface Chl was deduced from reflectance spectra using either the R_{440}/R_{550} or R_{520}/R_{550} reflectance ratios (e.g., Gordon and Morel, 1983).

Water was sampled with a 5 l Niskin sampler 0.5 m to 10 m below the surface; the integrated sample was analyzed. Two 200 ml subsamples were immediately filtered under 10 mm Hg vacuum onto GF/C filters, in dim light, and stored on dry-ice. Upon return to the laboratory, 10 ml of 90% acetone was added and each sample was sonicated for 1 min, and left in the dark at 4°C, overnight. The extract was measured fluorometrically after centrifugation. The average difference between duplicates was about 3%.

Dry weight of suspended matter (SM) was determined gravimetrically. An appropriate volume of water was filtrated through pre-dried (1 h, 500°C) and pre-weighed GF/C filters. Deviation from average value (two replicates) never exceeded 10%.

For validation of the algorithm, chlorophyll concentrations were derived from work done in 1981–1984 in Eastern Mediterranean (Berman et al., 1984a,b). Data were collected during six cruises conducted between July 1981 and June 1984 (July and December 1981, April and July 1982, February 1983 and June 1984). Details of the cruises are published elsewhere (Berman et al., 1984a,b, 1986;

Megard and Berman, 1989; Townsend et al., 1988). At each station, eight sampling depths were chosen to correspond to approximately 100, 50, 25, 12, 6, 3 and 0.5% of surface irradiation. Determination of photosynthetically available surface and down-welling irradiances were made with LICOR Quantum meter. Transparency was measured with Secchi disk, 40 cm diameter. Chlorophyll concentrations were determined by fluorometry in discrete samples which were concentrated by filtering 250 ml through 984H glass fiber filters and extracted into 90% acetone. At pigment concentration levels which were often encountered (typically of less than 0.1 mg Chl m^{-3}) the accuracy of this technique was about 25%. The integrated value of chlorophyll down to the depth of one attenuation length divided by the depth provided an estimate of mean near-surface chlorophyll concentration (Megard and Berman, 1989). Near-surface chlorophyll concentration was monitored between stations en route by in-vivo fluorescence, using a flow from the ship's intake into a Turner Designs 10 Fluorimeter. The in-vivo chlorophyll fluorescence was calibrated by measuring pigments in discrete water samples.

The size of the plankton was determined by passing samples through a 20 m Nitex nets (by gravity) or 3 μm Nuclepore filters. The results from these measurements are the "ground truth" data needed for the validation of the optical model.

CZCS images chosen for validation of the adopted algorithm were selected using the following guidelines: (1) the image was obtained within one week of the date of ground-truth measurement; (2) the image was acquired on a cloudless day and with minimal noise. Using the mentioned above criteria seven CZCS images were selected.

Table 1
Optical properties of the water content and concentrations of constituents as measured along the transect from Gaza to the open sea on July 22, 1992

Station	Time hr:min	Distance (km)	Turbidity NTU	SM (mg/l)	Chl (mg m^{-3})
1	08:38	0.5	4.7	3	0.364
2	09:08	1.0	3.7	2.19	0.224
3	09:37	1.5	9.5	1.62	0.300
4	10:05	2.0	7.8	2.25	0.320
5	10:30	2.5	2.9	1.75	0.200
6	11:00	3.0	3.0	1.86	0.230
7	11:20	3.5	7.0	1.97	0.250
8	11:45	4.0	4.2	1.35	0.264
9	12:05	4.5	3.5	1.81	0.310
10	12:30	5.0	4.5	2.09	0.270
11	13:30	6.0	4.0	2.54	0.150
12	13:51	7.0	3.4	1.57	0.164
13	14:12	8.0	2.0	1.40	0.102
14	14:35	9.0	2.3	1.40	0.092
15	15:00	10	2.9	1.85	0.152
16	15:34	12	1.3	1.59	0.140
17	16:09	14	2.1	1.74	0.046
18	16:37	16	3.0	1.25	0.082
19	17:37	18	3.2	1.53	0.074
20	17:43	20	7.0	1.17	0.028
21	18:07	22	7.5	0.89	0.062

3. Results and discussion

3.1. Field measurement

Chl concentration decreased from 0.36 mg m^{-3} near the shore to less than 0.1 mg m^{-3} at the distance of 5–7 km from the coast. Chl concentrations declined slightly further offshore and reaching less than 0.05 mg m^{-3} 20 km from the shore (Table 1 and Fig. 2). The majority of the chlorophyll was attributed to the picoplankton fraction with of less than 3 μm in diameter. HPLC analysis of phytoplankton pigments of samples showed that the dominant algal groups were prymnesiophytes, cyanophytes and prochlorophytes.

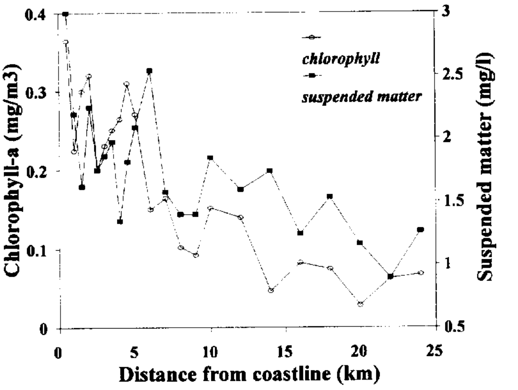

Fig. 2. Suspended matter and chlorophyll distributions along the transect on July 22, 1992.

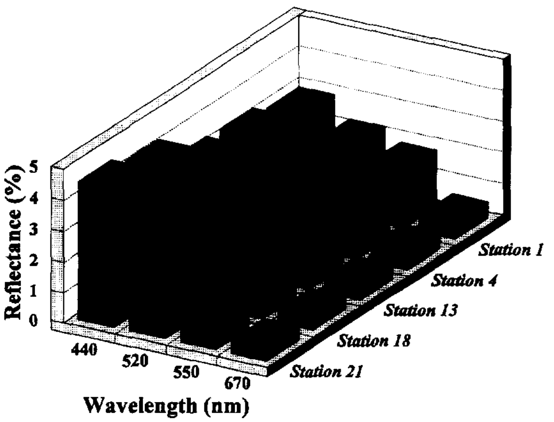

Fig. 3. Reflectance spectra taken at stations 1, 4, 13, 18 and 21 on July 22, 1992. The measured reflectances were integrated over the wave bands of CZCS.

The distribution of SM concentrations along the transect showed a somewhat similar trend (Fig. 2), decreasing from 3 g m^{-3} near the shore to about 1 g m^{-3} 20–25 km off coast, but it apparently did not co-vary close with the Chl concentrations. The determination coefficient between Chl and SM, r^2, was 0.44. Several patches of high SM were observed (6 km offshore, between 10 and 14 km, and at 17 km). High SM concentrations were also found far from the coast (Mayo et al., 1993).

The reflectance in the channels of the CZCS were simulated by extraction of relevant bands of the measured reflectance spectra. The effect of variation in constituent concentration on reflectance was clearly seen in Fig. 3. As Chl and SM concentration decreased (along the transect from the shore to open sea), the reflectance R_{440} increased, while R_{550} and R_{520} decreased. Such pattern of reflectance spectra resulted in the appearance of a spectral band with minimal sensitivity to variation in constituent concentrations near 500 nm. The standard deviation of reflectance for all spectra measured reached minimal value at 500 nm (Fig. 4). This is in agreement with results described by Gordon et al. (1983).

The recorded spectra converged to a common value of reflectance at 670 nm, a result indicating that we effectively blocked a high percentage of surface reflected light. At 670 nm the reflectance, as measured above the water surface, was less than 0.3%.

3.2. Adaptation of the algorithm

The waters of the Southeastern Mediterranean are among the most oligotrophic described. These waters are characterized by high reflectance in the blue range of the spectrum and, as rule, have an anomalously low blue to green reflectance ratio R_{440}/R_{550} when compared to Case I waters having the same pigment concentrations (Berman et al., 1984a,b; Megard and Berman, 1989).

The accuracy of known algorithms (e.g., Morel, 1980; Gordon and Morel, 1983; Gordon et al., 1983) for the Southeastern Mediterranean was assessed. Of the published algorithms, the model of Gordon et al. (1983) developed for Case I waters, fitted the measured data set best:

$$C_{chl} = 1.12 * (R_{440}/R_{550})^{-1.71}, \text{mg m}^{-3} \quad (1)$$

But even this algorithm overestimated Chl concentration; an error of Chl assessment was more than 40% for Chl > 0.1 mg m^{-3} and of more than 80% for low Chl (< 0.06 mg m^{-3}). Consequently, a modified algorithm, adapted for the area, was devised. The algorithm used here is of the general form (e.g. Gordon and Morel, 1983). Regression of Chl against R_{440}/R_{550} resulted in the following function:

$$C_{chl} = 0.914 * (R_{440}/R_{550})^{-1.86}, \text{mg m}^{-3} \quad (2)$$

with $r^2 = 0.83$ (Fig. 5).

3.3. Application and validation of the optical model

Adapted algorithm (Eq. 2) was applied to measurements from an independent data sets. This data

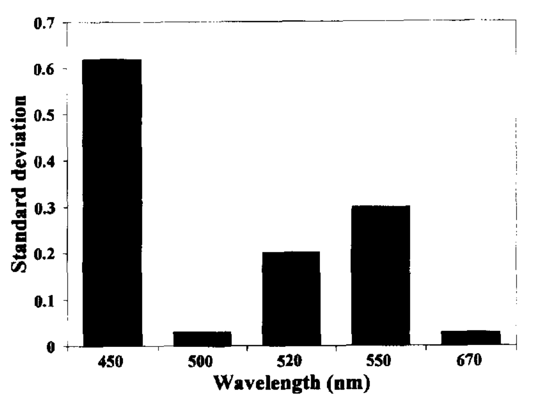

Fig. 4. The standard deviation of reflectance, simulated in the bands of CZCS, for 21 spectra measured.

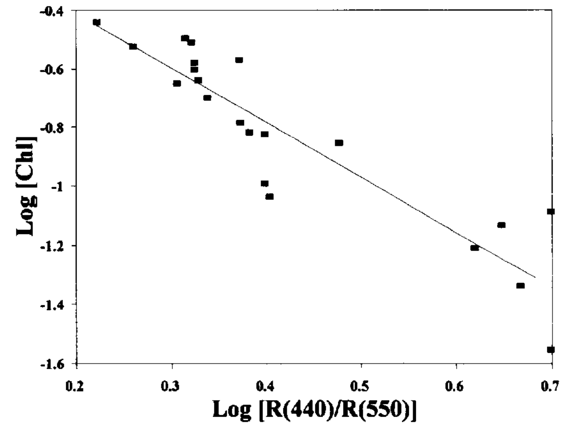

Fig. 5. Log-transformed quantities Chl-*a*, as measured analytically, plotted versus reflectance ratio R_{440}/R_{550}, measured by LI-1800 radiometer. Line presents Eq. (2).

set was acquired in cruises, conducted in 1981–1984, which covered both neritic and pelagic waters of the Eastern Mediterranean (Berman et al., 1984a,b). The timing of these cruises is listed in Table 2, along with the timing of CZCS images acquisition. In these cruises for the first time quantitative data on optical characteristics, chlorophyll and primary production were studied for pelagic waters in Eastern Mediterranean. Secchi depth ranged from 33 to 46 m, diffuse downwelling attenuation coefficients was from 0.031 to 0.046 m^{-1}, near surface chlorophyll from 0.026 to 0.069 mg m^{-3}. In the quantitative microscopic examination of samples the fraction of smallest cells, then assumed to be cyanophytes, was disregarded although acknowledged as an important component of the phytoplankton (Kimor et al., 1987).

The partial attenuation coefficient per unit chlorophyll concentration was larger than in other oceanic regions (at about twice as larger as the value in other oceanic regions with low (< 0.8 mg m^{-3}) chlorophyll concentrations and more than an order of magnitude larger than the mean value in more productive sea-water (Megard and Berman, 1989). The large value of attenuation coefficient was explained by the presence of very small phytoplankton with unusually dispersive cell surfaces, as *Coccolithus huxlei*, which is covered by calcareous scales (coccoliths). For this alga with cell diameter between 3 and 4 μm, beam attenuation coefficient is very large (Megard and

Table 2
Comparison of data from the cruises with data retrieved from CZCS images

Berman et al. (1984a, Berman et al. (1984b)			CZCS Data			
Stations	Date	Chl_{meas} mg m^{-3}	Image number	Date of image	R_{440}/R_{550}	$Chl_{predict}$ mg m^{-3}
Pelagic						
1-I	24/07/81	0.026	81204	23/07/81	6.931	0.0248
1-V	28/07/81	0.032	81209	28/07/81	6.467	0.0283
1-IX	30/07/81	0.024	81209	28/07/81	7.760	0.0200
2-III	11/12/81	0.076	81351	17/12/81	3.765	0.0775
2-VI	13/12/81	0.050	81351	17/12/81	3.870	0.0702
3-II	09/04/82	0.041	82109	19/04/82	4.370	0.0537
3-IV	10/04/82	0.048	82092	02/04/82	4.346	0.0593
3-VI	11/04/82	0.031	82092	02/04/82	4.481	0.0558
3-VII	12/04/82	0.039	82109	19/04/82	5.409	0.0394
3-VIII	12/04/82	0.032	82109	19/04/82	4.840	0.0467
4-IV	20/07/82	0.029	82216	04/08/82	6.207	0.0305
4-VI	21/07/82	0.039	82216	04/08/82	6.379	0.0290
Neritic						
1-III	27/07/81	0.093	81209	28/07/81	3.804	0.076
1-X	31/07/81	0.133	81209	28/07/81	2.692	0.131
2-II	11/12/81	0.088	81351	17/12/81	3.304	0.098
4-V	21/07/82	0.107	82216	04/08/82	2.646	0.148
4-VII	22/07/82	0.032	82216	04/08/82	5.590	0.037

Berman, 1989). During 1981–1984 cruises and the 1992 cruise as well coccolithophorids of less than 10 μm in diameter were always an important component of the phytoplankton. They were the most abundant phytoplankton in the surface layer during spring, although less abundant than coccoid monads (cell diameter 1–3 μm) other times of year. These data confirm suggestions by Smith and Bakker (1978) that the specific attenuance of phytoplankton chlorophyll is much larger in oligotrophic sea water than elsewhere.

Thus it is essential that the remote sensing algorithms for chlorophyll determination in such type of extremely oligotrophic water differ from that in more productive waters. Overestimation of chlorophyll concentration in Eastern Mediterranean by using Gordon et al. (1983) and Gordon and Morel (1983) coefficients (i.e. Eq. 1) probably is due to above mentioned very high attenuation coefficient by units of chlorophyll for very small phytoplankton.

Twelve pelagic stations and five neritic stations were chosen using the restrictions described in the "Methods" section. Their location is presented in Fig. 6. The radiance of two CZCS spectral channels - Channel 1 (440 nm) and Channel 3 (550 nm) were retrieved from the images (Table 2). The radiances R_{440} and R_{550} were used as input data for calculating of Chl concentration using Eq. (2). The next step in

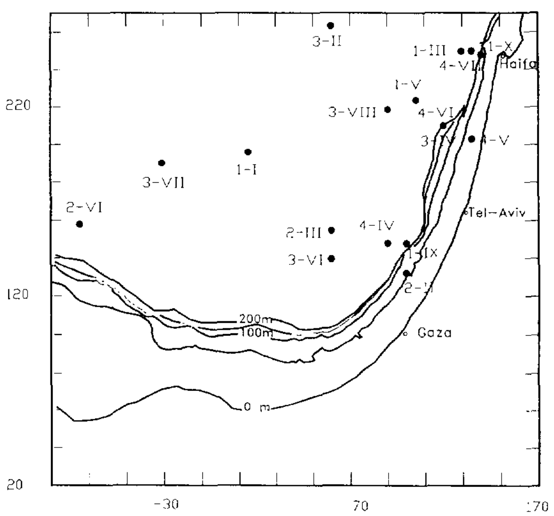

Fig. 6. Study area of the cruises, carried out in 1981–1984, showing sampling locations.

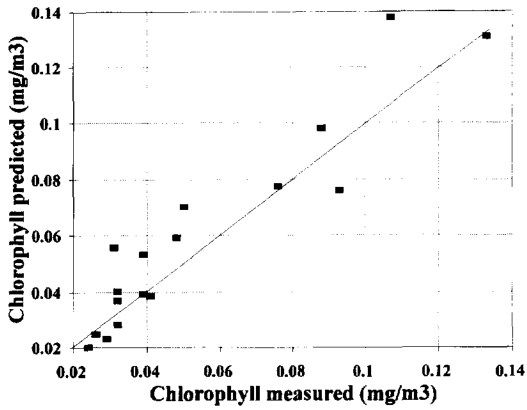

Fig. 7. Predicted Chl-*a* concentration plotted versus measured ones. The measured concentration were obtained in AID cruises in 1981–1984. The predicted concentrations were calculated using Eq. (2) with radiances retrieved from CZCS images.

validation of the algorithm was the comparison of the retrieved Chl concentrations (using Eq. 2) with the actual measurements of near-surface chlorophyll, from the cruises 1981–1984 (Fig. 7). The linear regression between measured and predicted by Eq. (2) chlorophyll concentrations was calculated:

$$\mathrm{Chl}_{\mathrm{meas}} = 0.0042 + 1.02 * \mathrm{Chl}_{\mathrm{pred}}$$

with the correlation coefficient, $r^2 > 0.88$, allowing an estimation error of chlorophyll as low as 0.013 mg m^{-3}.

A spatial and temporal analysis of chlorophyll contents in the Southeastern Mediterranean was carried out using 73 CZCS images for different months and years. Chlorophyll for neritic stations varied between 0.07 and 0.26 mg m^{-3}, and for pelagic stations it was from 0.03 to 0.12 mg m $^{-3}$. It is fit well with the range determined in cruises carried out in 1981–1984 (Berman et al., 1986), where average chlorophyll concentrations for pelagic stations (based on integration down to app. 37% of surface irradiance, i.e. at depth of less than one attenuation length) was found to be in the range from 0.021 to 0.083 mg m^{-3}. The chlorophyll contents are higher in the winter months (November–February) with values varied between 0.075 and 0.227 mg m^{-3} and are lower between March to October (from 0.025 to 0.12 mg m^{-3}). It confirms that the low algal pigment values, measured on shipboard in cruises 1981–1984

Fig. 8. Chlorophyll distribution in the Southeastern Mediterranean derived from CZCS images using the modified optical model. (a) CZCS image number 79026, January 26, 1979; (b) CZCS image number 79195, July 14, 1979.

and in 1992 as well, are characteristic in summer for most of the Eastern Mediterranean (Fig. 8b).

The highest values of chlorophyll occurred between November 1981 and February 1982; in November 1981 at a distance of 10–15 km from shore it was 0.227 mg m^{-3} and 0.172 mg m^{-3} at 20–25 km from shore. In February 1982 it was 0.2 mg m^{-3} near the shore and 0.127 mg m^{-3} at the distance 30–35 km from shore.

In each image a neritic water mass, roughly overlying the narrow continental shelf (approx. 10–15 km off Israel), with relatively high chlorophyll concentration was observed (Fig. 8). Berman et al. (1984a,b) reported that this zone can be characterized also by low light penetrance and high primary productivity rates. Neritic water mass was differentiated from the more oligotrophic water offshore by a sharp surface front of chlorophyll. Berman et al. (1984a,b) have found that this water mass was differentiated also by temperature. Offshore water with depth of more than 100 m exhibits extreme oligotrophic characteristics. Images for summer time (Fig. 8b) indicated a more diffuse front and much more complex interaction between neritic and offshore waters. The distinction between biological and inorganic materials are problematic in shallow areas (the Egyptian shelf and near-shore Israeli cost) and more data are required to extend the above interpretation.

4. Conclusions

The optical model proposed in this study for the Southeastern Mediterranean is likely to remain useful for a long period. It was successfully used to deduce Chl concentration from CZCS images, taken in 1981–1984, though developed on the basis of data from the 1992 cruise. We assume that not only the overall chlorophyll concentrations remained within the same range in the 10–11 year span between the two research periods, but also the taxonomic composition of the phytoplankton have not changed dramatically. We lack detailed comparison but size class distribution of phytoplankton suggests stability throughout that time in the investigated area (Berman et al., 1986; Yacobi et al., 1995). HPLC analysis of phytoplankton pigments of samples taken in 1993–1994 showed that the dominant algal groups offcoast Israel (with the exception of the heavy polluted Haifa Bay) were prymnesiophytes, cyanophytes, and prochlorophytes (Yacobi, unpubl.). In samples from 1981–1984 cruises the fraction of smallest cells was an important component of the phytoplankton (Kimor et al., 1987).

This work demonstrated the need for local modifications of a general model. The unusual combination of extremely low Chl, even in neritic waters of the Southeastern Mediterranean, very small phytoplankton with unusually dispersive cell surfaces, and a relatively high load of non-organic suspended matter near the shore, makes algorithms developed for other areas barely applicable.

As a result of our research, an archive of more than 70 maps of chlorophyll distribution in the Southeastern Mediterranean was established. The information retrieved from those images will be used for the estimating of spatial and temporal Chl variation in the region.

Further investigation is required in order to broaden this model and present a comprehensive algorithm for application in remote sensing monitoring of Chl distribution in the Southeastern Mediterranean. We hope that images obtained from SeaWiFS scanner would be useful for detecting of Chl concentration in this region and for testing our findings. For optimal use of the model, a few surface samples should be taken periodically in different areas to account for the effects of variation in phytoplankton species and/or particle size distribution of suspended matter. Compiling a geographical archive for these parameters would be an important step in developing optimal algorithm for remote Chl detection in the Southeastern Mediterranean.

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