

Optical variability associated with phytoplankton dynamics in the Cretan Sea during 2000 and 2001

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Abstract

Time series of *in situ* optical data and concurrent SeaWiFS observations in the Cretan Sea are used to assess the phytoplankton dynamics in an area with Case I waters. The *in situ* data were collected during the pilot operation of the multi-parametric M3A buoy system in the Cretan Sea during 2000 and 2001. The synergy and limitations of the two different data sets are discussed. The optical properties in the area of interest are found to be highly correlated with local circulation dynamics. Finally, the value of these observations for the calibration and validation of ecosystem models is demonstrated.

1. Introduction

In the framework of EuroGOOS, the EU funded Mediterranean Forecasting System (MFS) has been developed as a multinational effort for integrated operational forecasting in the Mediterranean (Pinaridi and Flemming 1998). Among other components, the system embraces the Mediterranean Moored Multi-sensor Array M3A (Nittis *et al.*, 2003) with the prime purpose being the validation of ecosystem models. The system is able to monitor meteorological and wave parameters at the sea surface, physical parameters (temperature, salinity, currents) in the upper 500 metres and optical-biochemical parameters (dissolved oxygen, chlorophyll-a, nutrients, light attenuation) in the euphotic zone. This mooring is situated in the Cretan Sea, 20 miles north of the port of Heraklion, and its design was based on similar experiences for multi-parametric measurements (e.g. the Bermuda Test-Bed Mooring, Dickey *et al.*, 1998).

The hydrological structure in the Cretan Sea is dominated by multiple scale circulation patterns and is characterised by intense mesoscale activity (Georgopoulos *et al.*, 2000), with multiple scales of temporal variability (from synoptic to interannual). The circulation in the Cretan Sea is dictated by the combined effect of two gyre features, an anticyclonic eddy in the west and a cyclonic eddy in the east (Georgopoulos *et al.*, 2000; Theocharis *et al.*, 1999). The position of the dipole is not fixed but highly variable and the system becomes more energetic during winter. During spring, summer and autumn the Cretan Sea is stratified and exhibits an oligotrophic ecosystem characterised by a food chain composed of very small phytoplankton cells and a microbial loop, both of which have a negative effect on energy transfer (carbon and nutrients) to the deeper water layers and the benthos. This is magnified by the high water temperatures ($>14^{\circ}\text{C}$) and high oxygen concentrations ($>4\text{ml}^{-1}$) enhancing decomposition rates of organic

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matter leaching out from the euphotic zone. During this period the picoplankton is the dominant fraction followed by nano+microplankton and ultraplankton (Ignatiades *et al.*, 2002). In early spring intense mixing occurs and the euphotic zone is re-supplied with nutrients from deep waters. Even so phytoplankton biomass remains at relatively low levels due to phosphate limitation (Krom *et al.*, 1991; Thingstad and Rassoulzadegan, 1995).

In this work we assess and quality-check the optical data collected during 2000 and 2001. The array was moored at the rim of the anticyclone (Figure 1), which resulted in rather complicated dynamics. Frequent failure of the instrumentation and the significant problems with bio-fouling do not allow for a full seasonal interpretation of the time series data. Therefore only a few events will be examined and the focus will be placed on the inter-comparison between mooring optical data time series, remotely sensed ocean colour and ecological modelling outputs.

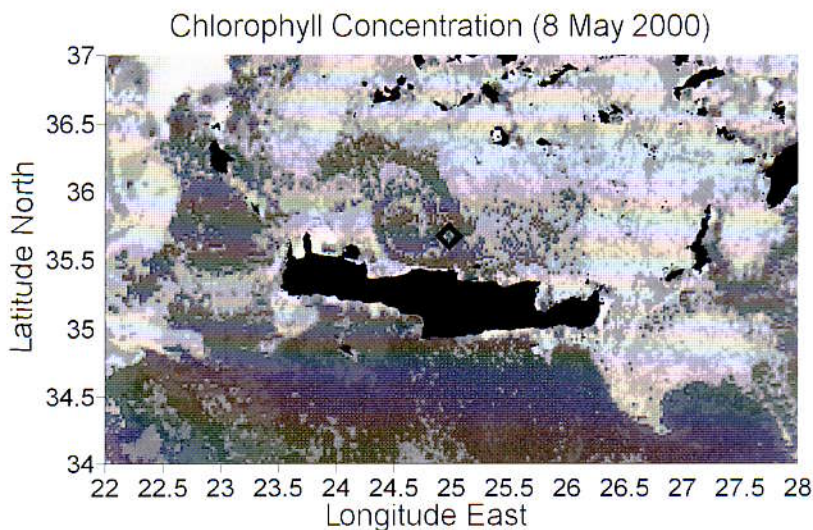


Figure 1 Surface layer concentration as observed by SeaWiFS sensor in the Cretan Sea. The anticyclone wake in the chlorophyll distribution is evident.

2. Data

The M3A array hosts four CTD instruments at depths of 40, 65, 90 and 115 metres, fitted with additional sensors of beam transmittance at 660nm, fluorescence, spectrally integrated irradiance (PAR) and dissolved oxygen. The sampling period is set to 3 hours, however for the purposes of this work daily averages are used. In order to calibrate the optical sensors, during the bi-monthly maintenance cruises, water samples were collected and water column profiles with a similar pre-calibrated CTD were taken. Serious technical complications involving PAR sensors and bio-fouling problems with the optical sensors were encountered during the period under consideration, thus the available dataset is severely limited.

Concurrent daily SeaWiFS data for the period January 2000–December 2001 were provided by NASA's Goddard Space Flying Center (GSFC). The Institute of Marine

Biology of Crete (IMBC), as an Authorised SeaWiFS Data User, received level-3 data as standard mapped image (SMI) product with a resolution of 9 km (at the equator). Images were received in Hierarchical Data Format (HDF) files and were processed using Windows Image Manager (Kahru and Brown, 1997), which allowed for automated image scaling conversion, georeference and data extraction for the location of M3A array. The conversion formula that was applied to the images is NASA's level-3 logarithmic scaling equation:

$$\text{Chl}a(\text{mg} \cdot \text{m}^{-3}) = 10^{0.015 \cdot /3\text{m_data} - 2} \quad (1)$$

3. Results and discussion

From scalar irradiance profiles in the visible (PAR) the average diffusion attenuation coefficient K_{PAR} was estimated and the attenuation depth was found to be around 20 m during the deployment period. This defines the layer from which 86% of remotely sensed water-leaving radiance emanates. A straightforward comparison of SeaWiFS data to the upper layer chlorophyll bottle data taken during different cruises indicates that both datasets follow a similar seasonal cycle, however, SeaWiFS derived chlorophyll concentrations are higher by 37% (Figure 2).

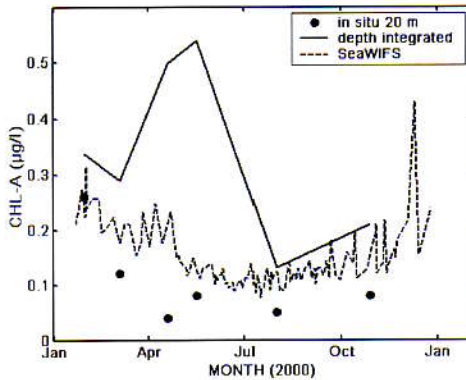


Figure 2 Comparison of surface layer chlorophyll concentration as remote sensed (SeaWiFS) and *in situ* measured from water samples. Also depicted the depth integrated concentration (arbitrary units) calculated from CTD profiles.

Moreover, the total depth-integrated chlorophyll concentration which exhibits a strong peak during May (Figure 2), does not produce a similar signature in the layer sensed by SeaWiFS. Given the strong component of the interannual variability in the local ecosystem, the use of statistically derived vertical modes might be in doubt. Thus the surface concentration as sensed by satellites cannot be easily extrapolated in depth.

In general, the $c(660)$ beam attenuation coefficient was found to have low correlation with fluorescence as was expected (Kichen, 1982). The coefficient has a tendency to decrease with depth, indicating its association with microorganism and detrital particle concentration.

From the entire 2-year record, three distinctive events will be presented in this work. The first depicts the spring bloom as was observed during late April and early May 2000 (Figure 3). This was a period when the mixed layer was shallower than 40m and the stratification process was underway. Records from the ADCP suggest that relatively calm water conditions prevailed with current speeds below 20cm s^{-1} . The pressure recorded by the 115m pressure sensor also indicates that the mooring line was held vertical during this period and confirms that the monitored parameters are representative of the respective instrument's nominal depth. Recorded chlorophyll concentration at 65m increased and reached a maximum during early May. The system is largely driven by the hydrodynamics and especially by the occurrence of deep mixing events. Thus in late winter to early spring the increase in light and temperature in conjunction with the transportation of nutrients in the euphotic zone results in an increase in chlorophyll. It is interesting to note, that the SeaWiFS sensor misses this bloom, which is a column process with a strong component below the first optical depth. Another remark is that during this event the correlation between beam attenuation coefficient and fluorescence is high. This association can be attributed to the high phytoplankton concentration during the bloom period consisting of cells having such size distribution that act as effective scatterers and probably to the increased chlorophyll pigment absorption at this wavelength.

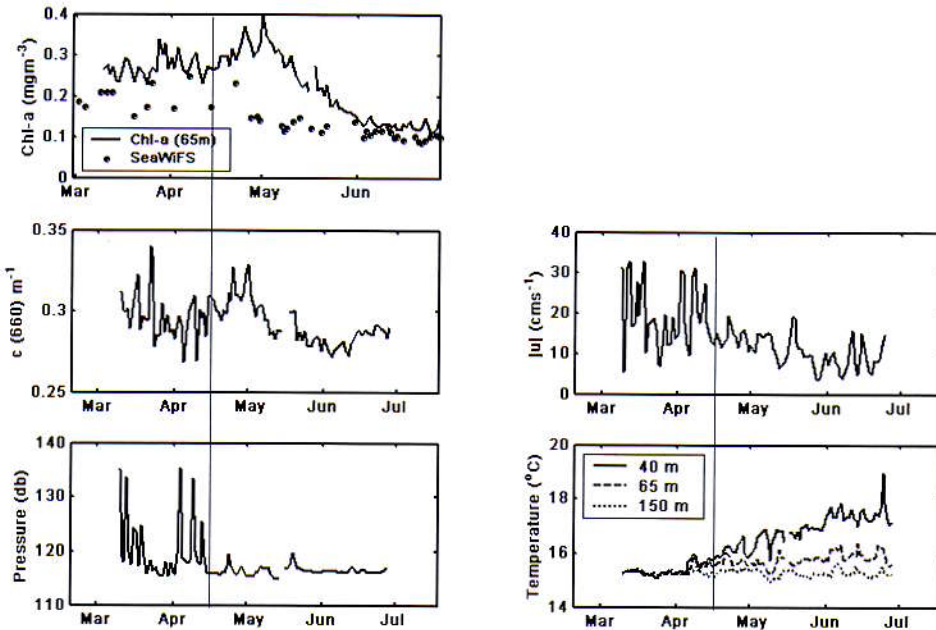


Figure 3 Spring bloom sequence and environmental conditions monitored during May 2000 by M3A array.

The second event occurred during September 2000 (Figure 4). Strong southern currents (40cm s^{-1}) forced the mooring line to bend 70m and thus the M3A CTDs sampled deeper and cooler layers than anticipated. This is depicted in the chlorophyll concen-

tration and beam attenuation coefficient. Both decrease since the sensors are placed below the chlorophyll maximum of the season, which is expected to be around 90 m.

The third event occurred during the period from July to September of 2001 (Figure 5). The beam attenuation coefficient exhibits a smooth increase at all depths, starting in early July 2001. This condition corresponds to an intrusion of relatively cold water masses that halt the process of seasonal temperature build up. Moreover there is indication in the SeaWiFS record of a short-lived chlorophyll peak. All these suggest a slow intrusion of the cyclonic gyre in the M3A location. This situation ends abruptly in early September. Nutrient depleted and warm water is re-established in the area when the anti-cyclone is re-positioned much closer to the mooring site.

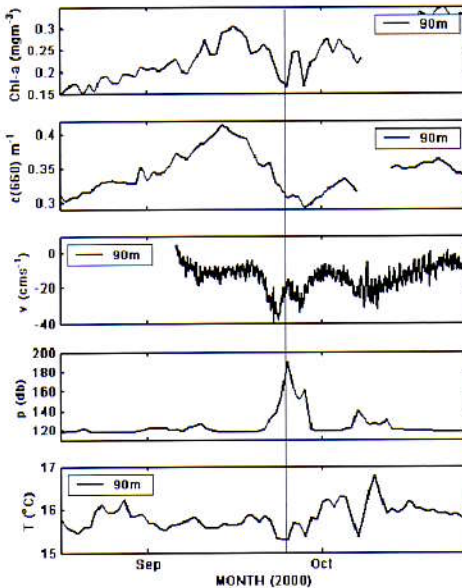


Figure 4 Bending of mooring line due to strong southern currents resulted in fictitious chlorophyll concentration decrease

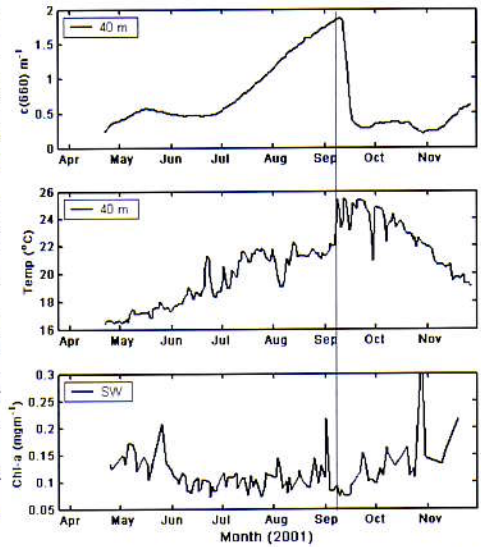


Figure 5 Dipole movement as was recorded by beam attenuation and water temperature.

4. Ecosystem model validation

Time series of the diagnostic variable of chlorophyll concentration as obtained from two ecosystem models that exist in the area are compared here against observed data. The first, the 1D Cretan sea ecosystem model (Triantafyllou *et al.*, 2003) is based on the European Regional Seas Ecosystem Model (ERSEM) (Baretta *et al.*, 1995) describing the biogeochemical cycles. The other, the 3D ecosystem model (Petihakis *et al.*, 2002) consists of two on-line, coupled sub-models: the three-dimensional Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), which describes the hydrodynamics of the area providing the background physical information to the 1D ecological model. The 3D model is interannually forced whereas the 1D is perpetually forced (same external forcing every year).

The phytoplankton pool is described by four functional groups based on size and ecological properties. These are diatoms P1 (silicate consumers, 20–200 μ), nanophytoplankton P2 (2–20 μ), picophytoplankton P3 (<2 μ) and dinoflagellates P4 (>20 μ). All phytoplankton groups contain internal nutrient pools and have dynamically varying C:N:P ratios. The nutrient uptake is controlled by the difference between the internal nutrient pool and external nutrient concentration. The microbial loop contains bacteria, heterotrophic flagellates and microzooplankton, each with dynamically varying C:N:P ratios. Bacteria act to decompose detritus and can compete for nutrients with phytoplankton. Heterotrophic flagellates feed on bacteria and picophytoplankton, and are grazed by microzooplankton. Microzooplankton also consume diatoms and nanophytoplankton and are grazed by mesozooplankton.

In Figure 6 the outputs of the two models at 15m and 65m are compared against SeaWiFS and mooring data respectively. It is apparent that at the near surface layer the evolution of chlorophyll concentration is underestimated by the 1D model in contrast with the 3D where simulated concentrations are very close to field values, with the exception the period mid winter–mid spring when the 3D model is overestimating. At a depth of 65m the chlorophyll from the 1D model follows the mooring data seasonal cycle reasonably well, while the 3D produces a maximum during summer. Oligotrophic systems like the Cretan sea exhibit two productivity maxima (end of winter and autumn), which depend on the hydrological properties. During summer a considerable production is sustained in the deeper layers close to the thermocline through a nutrient regeneration mode. Although both models depict the above pattern, the 3D model is overestimating chlorophyll presumably because the thermocline is wrongly displaced at a shallower depth due to the influence of the cyclone–anticyclone dipole.

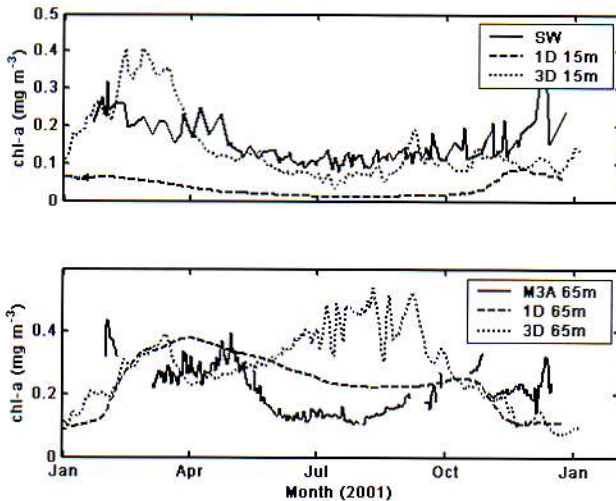


Figure 6 1D and 3D model performance at 15 and 65m depths

From the above study, it is evident that the biophysical model will benefit from the implementation of data assimilation techniques both on the circulation and ecological components. However, caution should be paid when assimilating ocean colour data. In

oligotrophic systems remotely sensed chlorophyll concentration is difficult to interpret since its maximum is close to the deep thermocline and not visible to the satellite sensor.

Acknowledgements

The work was carried out within the framework of the Mediterranean Forecasting System–Pilot Project (MFS–PP). We acknowledge the support of the European Commission MAST3 Programme that financed the project under contract no. MAS3–CT98–0171. The project was co-financed by the General Secretary of Research and Technology of the Hellenic Ministry of Development.

References

- Baretta, J.W., W. Ebenhoh and P. Ruurdij, 1995. The European Regional Seas Ecosystem Model, a complex marine ecosystem model. *Netherlands Journal of Sea Research*, 33: 233–246.
- Blumberg, A.F. and G.L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. In: N.S. Heaps (Editor), *Three-Dimensional Coastal Ocean Circulation Models*. Coastal Estuarine Science. AGU, Washington, D.C., pp. 1–16.
- Dickey T., D. Frye, H. Jannasch, E. Boyle, D. Manov, D. Sigurdson, J. McNeil, M. Stramska, A. Michaels, N. Nelson, D. Siegel, G. Chang, J. Wu and A. Knap, 1998. Initial results from the Bermuda Testbed Mooring program. *Deep-Sea Research I*, 45, 771–794
- Georgopoulos, D., G. Chronis, V. Zervakis, V. Lykousis, S. Poulos and A. Iona, 2000. Hydrology and circulation in the Southern Cretan Sea during the CINCS experiment (May 1994–September 1995). *Progress in Oceanography*, 46: 89–112.
- Ignatiades, L., S. Psarra, V. Zervakis, K. Pagou, E. Souvermezoglou, G. Assimakopoulou, and O. Gotsi-Skreta, 2002. Phytoplankton size-based dynamics in the Aegean Sea (Eastern Mediterranean). *Journal of Marine Systems*, 36: 11–28.
- Kahru, Mati and C.W. Brown, 1997. *New Techniques for Detecting Large-Scale Environmental Change*. 155pp, Landes Bioscience.
- Kichen, J.C., J.R.V. Zaneveld and H. Pak, 1982. Effect of particle size distribution and chlorophyll content on beam attenuation spectra. *Applied Optics*, 21: 3913–3925.
- Krom, M.D., N. Kress, and S. Brenner, 1991. Phosphorus limitation of primary productivity in the eastern Mediterranean Sea. *Limnology Oceanography*, 36(3): 424–432.
- Nittis, K., C. Tziavos, I. Thanos, P. Drakopoulos, V. Cardin, M. Gacic, G. Petihakis and R. Basana, 2003. The Mediterranean Moored Multi-sensor Array (M3A): System Development and Initial Results. *Annales Geophysique*, (In press).
- Petihakis, G., G. Triantafyllou, J.I. Allen, I. Hoteit, and C. Dounas, 2002. Modelling the Spatial and Temporal Variability of the Cretan Sea Ecosystem. *Journal of Marine Systems*, 36(3–4): 173–196.
- Pinardi, N. and N. Flemming (editors), 1998. *The Mediterranean Forecasting System*. Science Plan. EuroGOOS Publication No 11, SOC, Southampton, ISBN 0–904175–35–9
- Theocharis, A., E. Balopoulos, S. Kioroglou, H. Kontoyiannis and A. Iona, 1999. A synthesis of the circulation and hydrography of the South Aegean Sea and the Straits

of the Cretan Arc (March 1994–January 1995). *Progress in Oceanography*, 44: 469–509.

Thingstad, T.F. and F. Rassoulzadegan, 1995. Nutrient limitations, microbial food webs, and ‘biological C-pumps’: suggested interactions in a P-limited Mediterranean. *Marine Ecology Progress Series*, 117: 299–306.

Triantafyllou, G., G. Petihakis and J.I. Allen, 2003. Assessing the performance of the Cretan Sea ecosystem model with the use of high frequency M3A buoy data set. *Annales Geophysicae*, (In Press).