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COMPARISON OF UNDERWATER LIGHT FIELD PARAMETERIZATIONS AND THEIR EFFECT ON A 1-DIMENSIONAL BIOGEOCHEMICAL MODEL AT STATION ESTOC, NORTH OF THE CANARY ISLANDS

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ABSTRACT

Light abundance is a major prerequisite for primary production in pelagic ecosystems. Throughout the last decades a number of analytic descriptions for the radiative transfer of light in oceanic water, in particular of the photosynthetically available radiation (PAR) were developed and validated against experimental data (see for example the comparisons by MOBLEY ET AL. (1993) and SIMPSON AND DICKEY (1981)). With the increasing number of biogeochemical models for oceanic ecosystems various descriptions of PAR(z) were also applied (e.g. FASHAM ET AL. (1990), EVANS AND PARSLOW (1985), DONEY ET AL. (1996)).

This paper compares the effect of different underwater light field parameterizations at the ESTOC station (29°10'N, 15°30'W) north of Gran Canaria, Canary Islands. It discusses the typical winter and spring situation, derived from experimental data. These PAR(z) descriptions are incorporated in a 1-dimensional biogeochemical model of the upper ocean driven by daily forcing fields that are taken from the ECMWF reanalyzes over a five-year period. The turbulence closure scheme of GASPAR ET AL. (1990) was used to compute the evolution of the upper ocean physical environment on a fine vertical grid ($\Delta z=2$ m). The comparison of diagnostic parameters such as the annual primary production (aPP) gives comparable results independed of the parameterizations chosen (aPP=6.5 g $C/(m^2a) \pm 15\%$). Differences in the phytoplankton distribution in the water column are taken into account by an exponentially weighted detection function for an imaginary satellite, thus simulating the penetration depth of ocean color remote sensors. The large variation (±45%) of this parameter underlines the important role of a realistic though computationally effective parameterization of the underwater light field in biogeochemical models.

1. INTRODUCTION

The *European Station for Time-Series in the Ocean Canary Islands* (ESTOC) is located 60 nautical miles north of Gran Canaria and Tenerife (29°10'N, 15°30'W, water depth 3600 m). Its surface waters are part of the Canary current, the eastern branch of the subtropical gyre [TOMCZAK AND GODFREY (1994)] and hence is characterized by partially oligotrophic conditions. The station is equipped with moored traps and current meters, with additional monthly ship-based measurements taken since 1994 as a part of JGOFS [LLINAS ET AL. (1997)]. Since 1997 these time-series measurements are done as a part of the European CANIGO project (Canary Islands Azores Gibraltar Observation). The experimental data presented in this paper were obtained in these two projects.

CRUISES AND METHODS

Recently, the investigation of the carbon and particle fluxes in case 1 waters by optical means has met increasing interest [Dickey (1991)]. Especially *in situ* instruments provide a fast and sensitive method for determination of optically active substances like chlorophyll *a*, Gelbstoff (colored dissolved organic matter) or apparent optical parameters like the underwater light field. During two cruises north of the Canary Islands a new bio-optical *in situ* probing system [Barth et al. (1997a)] was applied. The system includes a fluorometer [Heuermann et al. (1995)], a transmissometer [Barth et al. (1997b)] and a radiometer with multi-wavelength detection capability. Instruments and methods are described in the cruise reports [Wefer and Müller (1998), Neuer and Reuter (1999)] and in the above-mentioned publications and are not subject of this paper. RV Meteor cruise M37/2b took place in January and RV Victor Hensen cruise VH397/2 in April 1997. Both cruises included a transect along 29°N, from the coastal region near the African Shelf (10°W), through ESTOC towards 18°W, north of La Palma (Fig. 1).

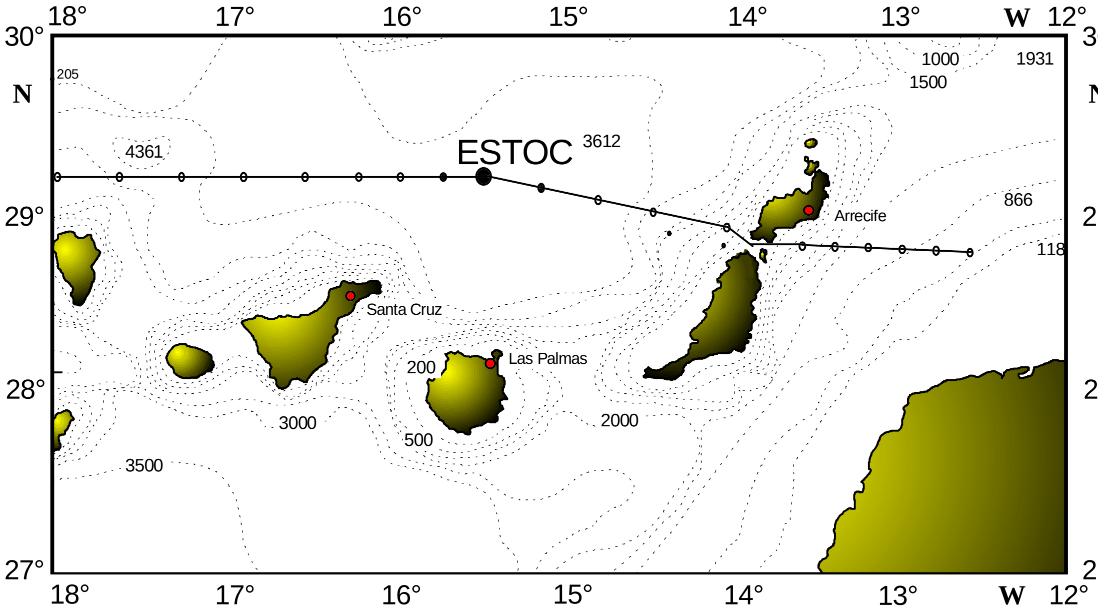

Fig. 1: Shared cruise tracks of M37/2b (01/97) and VH397/2 (04/97) along 29°N. Both cruises were incorporated in the monthly ESTOC (29°10’N, 15°30’W) sampling scheme.

SEASONAL VARIATIONS ALONG 29°N

The typical winter situation at ESTOC (Llinas et al. (1997)) is well represented during M37/2b (01/97) by a deep mixed layer down to 116 m depth. A homogeneous chlorophyll *a* concentration is observed in the upper 90 m of ~0.25 mg chl *a* m^{-3} and a small maximum of 0.30 mg chl *a* m^{-3} at 108 m depth.[1] Water masses are identically stratified along the whole transect at 29° N. That means, no upwelling occurred at the African shelf. The mean 10% and 1% depth of the photosynthetically available radiation (PAR, defined from 400 to 700 nm) are 63 and 124 m (Tab. 1).

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[1] Extracted chlorophyll *a* data by kind permission of Dr. O. Llinas, ICCM, Gran Canaria.

During the spring cruise (VH397/2 - 04/97) we encountered upwelling conditions close to the shelf with chlorophyll concentrations reaching 1.1 mg chl *a* m^{-3}. At the ESTOC site, however, a shallow mixed layer of 45 m could be observed. Chlorophyll *a* profiles showed very low surface concentrations above a pronounced deep chlorophyll maximum at about 94 m with 0.63 mg chl *a* m^{-3} (Fig. 2 and 3). Gelbstoff and particulate material other than phytoplankton are at too low concentrations, to significantly influence the underwater light field. Therefore we classify ESTOC as a case 1 water region [MOREL AND PRIEUR (1977)], with Jerlov oceanic water type IA (K_d(475nm)=0.0285 m^{-1} ±8% in the upper 50 m) [JERLOV (1976)].

cruise	**M37/2b (01/97)**	**VH397/2 (04/97)**
time period	06/01/ - 22/01/97	25/04/ - 03/05/97
mixed layer depth [m]	116	45
depth of chl *a* abundance [m]	nearly homogeneous 0-90 small maximum at 108	maximum at 94
maximum chl *a* concentration [mg chl *a* m^{-3}]	0.30	0.63
mean 10% depth [m]	63	47
mean 1% depth [m]	124	90

Table 1: Parameter values for ESTOC derived from the two cruises. Mixed layer depth is defined by a ΔT=0.2°C criterion. Chlorophyll *a* concentrations are derived from *in situ* chl *a* prompt fluorescence measurements, calibrated by extracted chl *a* concentrations. All values are calculated from stations ±30 nautical miles from ESTOC (total of 3 stations).

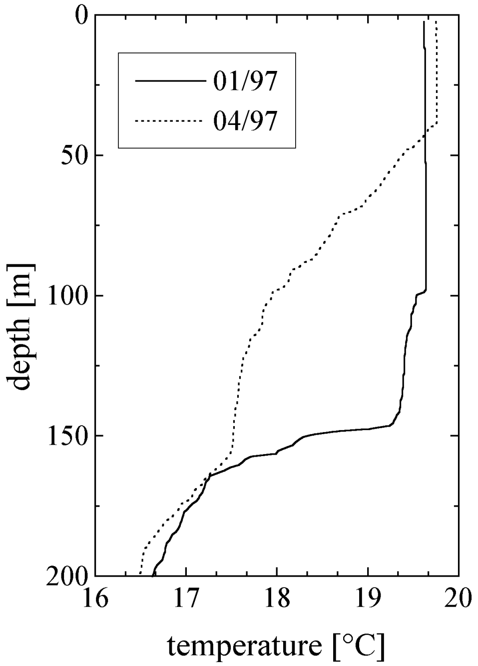

Fig. 2: Temperature profiles at ESTOC in the upper 200 m for both cruises.

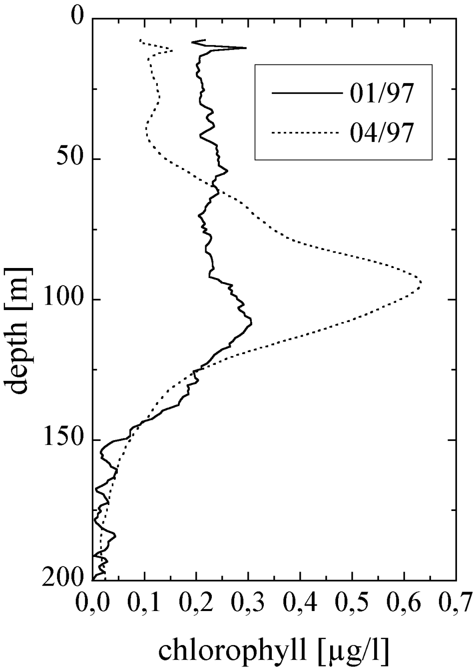

Fig. 3: Chlorophyll *a* profiles at ESTOC in the upper 200 m for both cruises.

2. DIFFERENT PARAMETERIZATIONS OF PAR(Z)

Light is a crucial parameter since it limits growth in pelagic ecosystems. Therefore, different biogeochemical models use a variety of parameterizations of the underwater light field. Most of these parameterizations concentrate their efforts on the spectrally integrated photosynthetically available radiation (PAR), using broad band photosynthesis-to-irradiance (P*vs.*E) relations as growth functions. Others separate the light field into direct and diffuse light and/or make use of wavelength-dependent P*vs.*E-curves (Kyewalyanga et al.(1992)). Simpson and Dickey (1981) make a comparison of the first group of PAR(z) parameterizations, identifying a) simple exponential, b) bimodal and c) multiband approaches. This paper compares different PAR(z) parameterizations following this classification. To evaluate their influence on primary production and other seasonal processes they are incorporated into an 1-d biogechemical model at station ESTOC. PAR(0) is the radiation just below the surface and is taken as 45% of the total solar irradiance above sea level, though Baker and Frouin (1987) show a dependence of this ratio on solar elevation, aerosols, water vapor and ozone.

Here, we compare the following PAR(z) parameterizations:

a) Exponential functions:

a1) Doney et al. (1996) used in their 1-d biogeochemical model for BATS[2] a simple empirical description introduced by Morel (1988):

$$PAR(z) = PAR(0) \cdot \exp(-0.121 \cdot \overline{chl}^{0.428} \cdot z)\,,$$

with $\overline{chl}$ [mg chl *a* m^{-3}] as the mean chlorophyll concentration over the euphotic layer and z [m] the depth. This parameterization results in a constant attenuation coefficient $k_{PAR}(z) = -\frac{\mathrm{d}PAR(z)}{\mathrm{d}z} \cdot \frac{1}{PAR(z)}$ over the whole water column.

a2) In their analytical computation of daily mean growth rates, Evans and Parslow (1985) assumed an exponential decay of irradiance by the water attenuation coefficient k_w=0.04 m^{-1} and the specific chl *a* attenuation k_{chl}=0.019 m^2/(mg chl):

$$PAR(z) = PAR(0) \cdot \exp\left(-k_w z - k_{chl} \int_0^z chl(z')\mathrm{d}z' \right).$$

b) The bimodal parameterization proposed by Paulson and Simpson (1977) incorporates the high attenuation of larger wavelengths within the first 10 m (Dera and Gordon (1968)). This results in increased $k_{PAR}(z)$ values, by using a double-exponential function:

$$PAR(z) = PAR(0) \cdot \left[R \exp\left({}^{-z}\!/_{\zeta_1} \right) + (1-R) \exp\left({}^{-z}\!/_{\zeta_2} - k_{chl} \int_0^z chl(z')\mathrm{d}z' \right) \right].$$

For Jerlov type IA waters they found R=0.62, ζ_1=0.60 m and ζ_2=20 m. The influence of chl *a* is, analog to a2), included in the shorter wavelength function.

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[2] Bermuda Atlantic Time series Study

c) The multiband description of MOREL (1988) subdivided the 400-700 nm region in N=61 bands, as an accurate though computationally expensive approach:

$$PAR(z) = PAR(0) \cdot \sum_{i=1}^{N} a_i \exp\left[-k_i^w z - \chi_i^{chl} \int_0^z chl(z')^{\eta_i^{chl}} \, \mathrm{d}z' \right]$$

with k_i^w, χ_i^{chl} and η_i^{chl} empirically resolved and given in tabular form. The weighting coefficients a_i were taken from SMITH AND BAKER (1981).

To compare these four descriptions we introduce two simulated chlorophyll *a* distributions that are assumed typical for the ESTOC station in winter and spring. A homogenously distributed phytoplankton population of 70 m depth with a chl *a* concentration of 0.25 mg chl *a* m^{-3} (Fig. 4a), and secondly a Gaussian deep chl *a* maximum at 100 m depth with a 0.6 mg chl *a* m^{-3} peak concentration (Fig. 5a). The parameterizations a) - c) are compared as logarithmic profiles of E$_d$ in Fig. 4b) and 5b) respectively. Table 2 summarizes the results from the comparison for both situations.

simulated chl *a* distribution	winter situation				spring situation			
deep chl *a* maximum [m]	homogenous from 0-70				100			
max. chl *a* concentration [mg chl *a* m^{-3}]	0.25				0.6			
PAR(z) parameterization	a1	a2	b	c	a1	a2	b	c
mean 10% depth [m]	47	53	25	49	49	59	27	58
mean 1% depth [m]	93	105	67	104	97	109	73	126
total PAR(0-150m) [µE/(m^{2}s)]	1966	2285	690	1616	2052	2525	753	1799

Table 2: Results from the comparison of light field parameterizations a) - c). PAR(0)=1000 µE/(m^{2}s), representing approx. 535 W/m^2 solar radiation above sealevel.

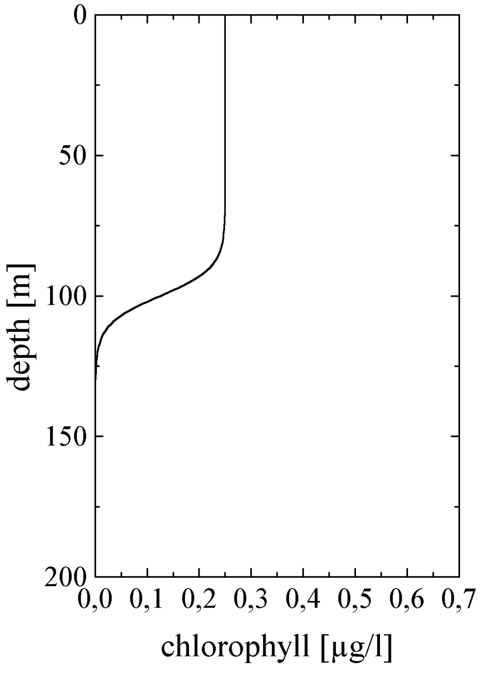

Fig. 4a: Simulated chlorophyll *a* distribution for the winter situation at ESTOC.

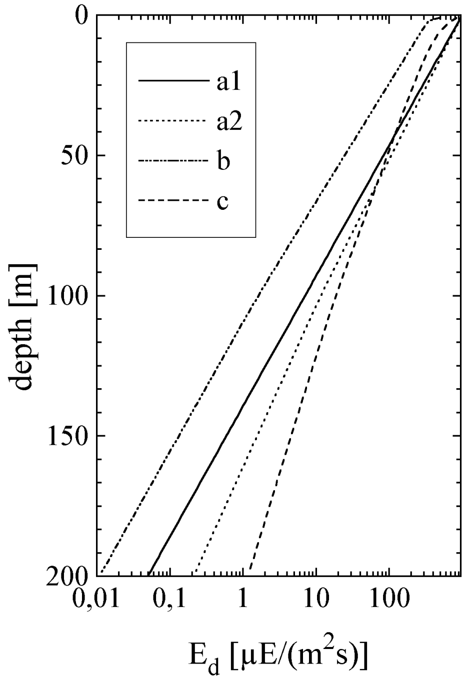

Fig. 4b: Comparison of PAR(z) from parameterizations a) - c).

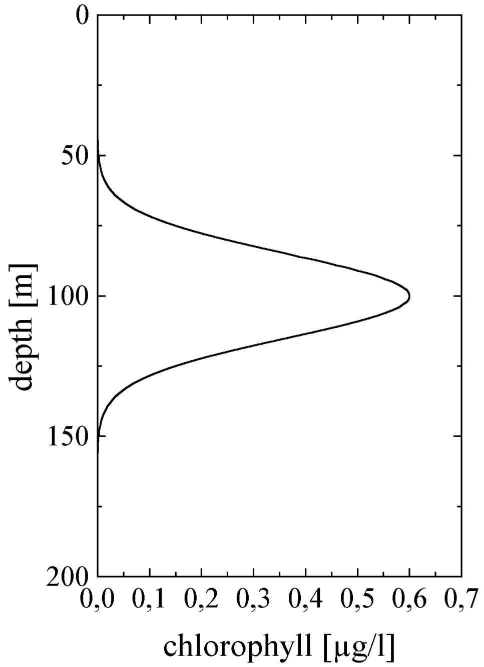

Fig. 5a: Simulated chlorophyll *a* distribution for the spring situation at ESTOC.

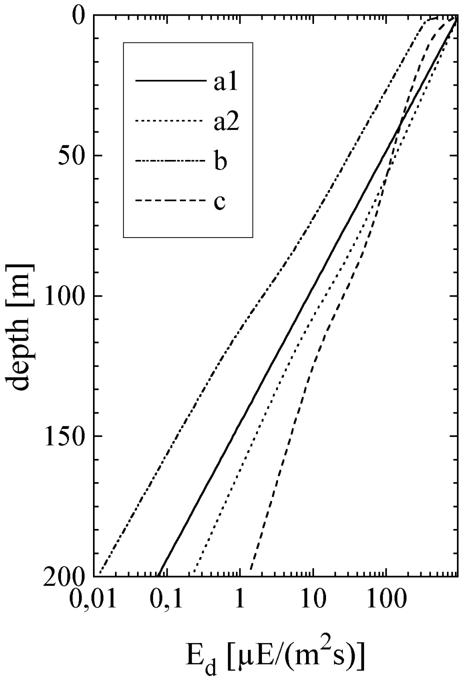

Fig. 5b: Comparison of PAR(z) from parameterizations a) - c).

3. IMPLEMENTATION OF A 1-D BIOGECHEMICAL MODEL AT ESTOC

The turbulent kinetic energy (TKE) model of GASPAR ET AL. (1990) was implemented on a vertical grid with Δz=2 m spacing. The model solves a prognostic equation of TKE as a function of static stability, vertical shear and turbulent transport of TKE. Vertical turbulent diffusivities and viscosities are then computed diagnostically using a physical argument for the mixing length scale. The model is forced at the surface by daily averaged fluxes of heat and momentum, taken from the ECMWF reanalysis, over the five-year period 1989 to 1993. The surface heat flux condition includes a flux correction term (see OSCHLIES AND GARÇON (1998)) that partially corrects for model imperfections, here in particular neglecting three-dimensional effects.

The physical model is run only once, and the biological model is run off-line on the same Δz=2 m grid. The same five-year time series of temperature (Fig. 6) and mixing coefficients is used for all experiments discussed here. This obviously neglects any bio-optical feedback on the evolution of physical variables. The biological model is a nitrogen-based NPZD (nitrate, phytoplankton, zooplankton, detritus) model presented in detail by OSCHLIES AND GARÇON (1998). Following HURTT AND ARMSTRONG (1996) the phytoplankton growth rate is given by the minimum of light- and nutrient-limited growth. The diurnal cycle of solar insolation is calculated by standard astronomical parameters (KIRK (1994)). Chlorophyll is computed from phytoplankton using a constant ratio of 1.59 mg chl *a*/mmol N. Figure 7 shows the model-derived chorophyll *a* when the light field parameterization a2) is used.

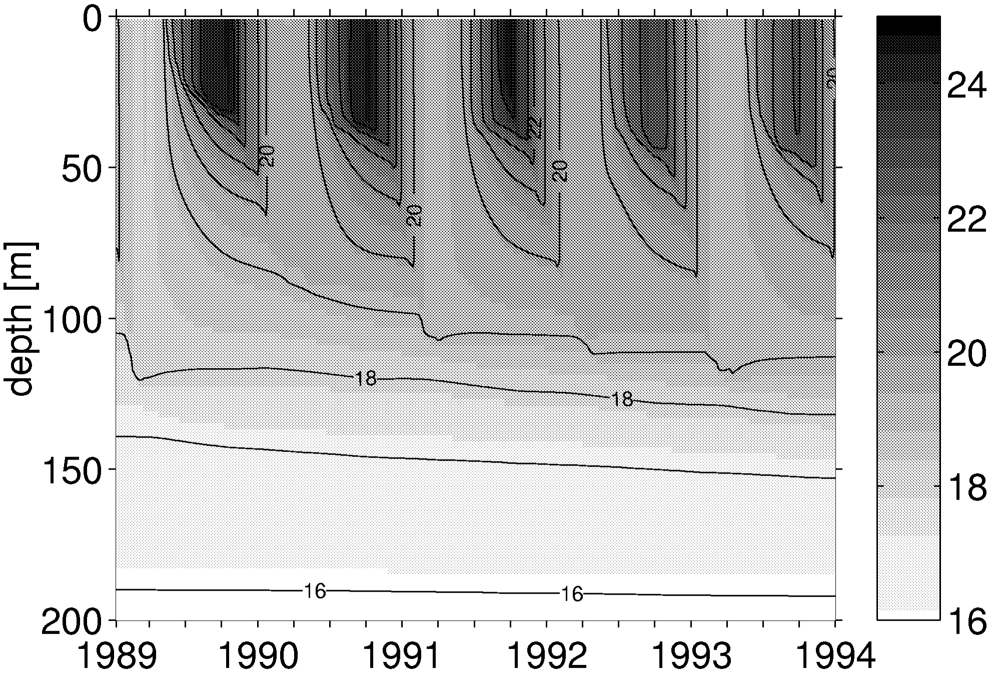

Fig. 6: Temperature distribution simulated by the 1d physical model at ESTOC for the five-year period 1989-1993.

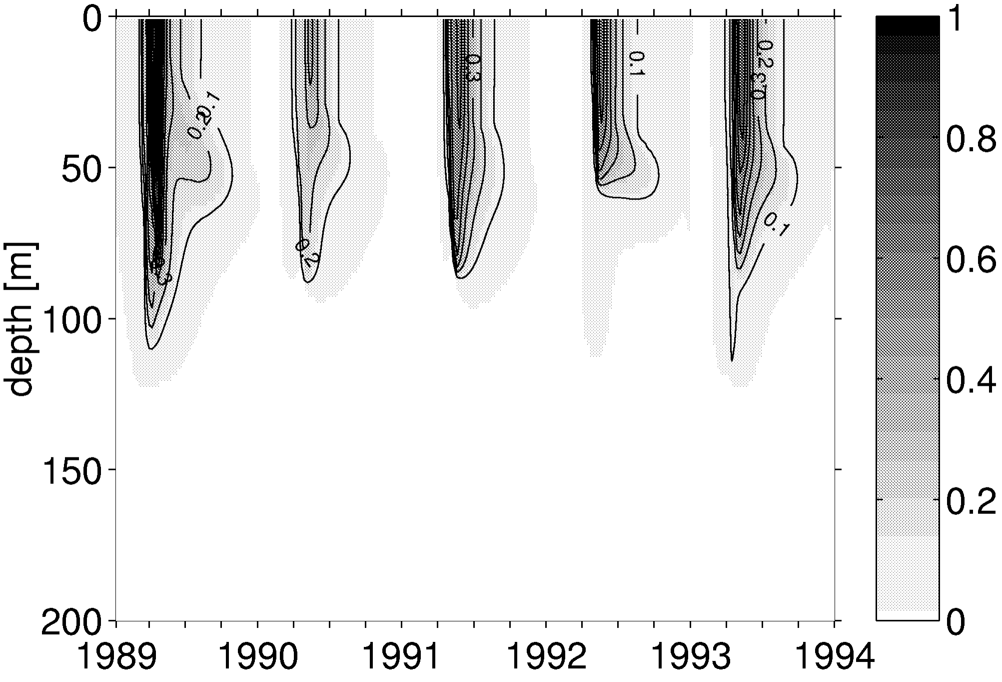

Fig. 7: Phytoplankton abundance given in chlorophyll *a* concentration [µg/l] from 1989-1993 at ESTOC from 1-d NPZD model with light field parameterization a2).

The diagnostic variables, derived during the calculations a) - c) are:

- the annual primary production (aPP) in the upper 150 m in [g C/(m^2a)], using a fixed C:N ratio of 106:16.
- the mean annual accumulated light (maPAR), integrated over the upper 150 m in [MW/m^2=10^9 W/m^2], representing the total amount of PAR in the water column.
- the mean annual chl *a* content (maChl*a*) in the upper 150 m in [mg chl *a*/m^2]
- the mean annual exponentially weighted chl *a* content (maWChl*a*) in [mg chl *a*/m^2], taking into account the penetration depth of an imaginary satellite ocean color remote sensors. With depth z [m] we assume a weighting function $W(z)=\exp(-0.5\ m^{-1} \cdot z)$, that means at a depth of 18 m, 1% of the chl *a* concentration is taken into account.

4. RESULTS AND CONCLUSIONS

The comparison of the four parameterizations of PAR(z) (section 2) illustrates the high variability of the approaches. Penetration depth (10% and 1% depth) as well as the total visible light in the upper 150 m vary up to 40%. Hence, the description of the underwater light field is a crucial and sensitive element of pelagic ecosystem modeling. However, their influence on diagnostic variables as mean annual primary production and chl *a* content from the five year computation of the 1-d biogeochemical model is much smaller than it might be expected (Table 3). The mean aPP from parameterizations a) - c) is 6.5 g C/(m^2a) with a maximum deviation ±15%. In comparison BERGER (1989) calculated from *in situ* observations an annual primary production in the mid latitudes of the Atlantic ocean of less than 60 gC/(m^2a). For the mean maChl*a* our model gave 10.7 mg chl *a*/m^2 ± 9%, while (LLINAS ET AL. (1997)) measured ~17 mg chl *a*/m^2 in 1994. Experimental data of the other diagnostic variables were not available. In consequence for the ESTOC site, the light availability inside this comparison of four different PAR(z) parameterizations within a 1-d biogeochemical model is not a sensitive factor with respect to primary production and chlorophyll *a* content. However, it strongly affects the chlorophyll *a* distribution in the water column as can be seen from the exponentially weighted chl *a* content that shows a variation of ± 45%.

PAR (z) parameterization	a1	a2	b	c
annual PAR(0-150m) [MW/m^2]	21.25	18.50	5.48	14.36
primary production [mg C/(m^2a)]	6.84	6.00	7.67	5.47
annual chl *a* content [mg chl *a*/m^2]	11.16	10.22	11.74	9.62
annual exponentially weighted chl *a* content [mg chl *a*/m^2]	0.14	0.16	0.29	0.11

Table 3: Results from the 1-d NPZD model at station ESTOC with the different light field parameterizations a) - c). All values are mean values from the years 1989-1993.

For a realistic description of the pelagic ecosystem north of the Canary Islands, a PAR(z) description should be chosen that incorporates the two basic features of visible light in case 1 water, that is an increased k_{PAR} near the surface due to the absorption at larger wavelengths, and a specific chlorophyll *a* absorption. The multiband approach of MOREL (1998) and the modified bimodal description of PAULSON AND SIMPSON (1977) both show these features. The former approach is computationally very expensive and therefore not recommended for use in larger 3-d models and the latter one overestimates the attenuation of PAR at the ESTOC site. The parameters R=0.62, ζ_1=0.60 and ζ_2=20, given by PAULSON AND SIMPSON (1977) for Jerlov type IA waters result in very shallow 10% and 1% depths and a comparable high water attenuation coefficient k_w=0.05 m^{-1} below 20 m. We recommend ζ_2=25 m (k_w=0.04 m^{-1}), as well as R=0.3 and ζ_1=3 m, because the original formula was developed for a spectral range from 400 - 1000 nm. Using this new parameters inside our 1-d NPZD model we get aPP=6.59 mgC/(m^{2}a), maChl*a*=10.50 mg chl *a*/m^2 and maWChl*a*=0.184 mg chl *a*/m^2. This modified bimodal parameterization is computationally cheap, incorporates the basic features of visible light in case 1 waters and provides a good representation of PAR(z) inside of 1- or 3-d biogeochemical models.

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