

# Ecological Zonation of Phytoplankton and Biomass Based on Bio-Optical Parameters off Baja California during Three Summer Seasons

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## Abstract

An ecological zonation of phytoplankton was determined from its normalized spectral absorption shape ( $a_{phn}$ ) during the summers of 2001-02-03 off the west coast of Baja California. In the first two seasons, the highest abundances of the main taxonomic groups of phytoplankton were detected towards the coastal stations, but for 2003, diatoms showed higher abundances towards the oceanic region. The ecological provinces (Pv) were the footprint of the zonation in the structure of the phytoplankton community; likewise, it was observed that the spectral shape was independent of the chlorophyll-*a* ( $\text{mg}\cdot\text{m}^{-3}$ ). The effect of coastal upwelling south of Vizcaíno Bay favored the increase of phytoplankton cells. However, the composition of the community decreased in cells abundance and diversity due to the influence of the phenomenon called El Niño “débil” reported to the south of the California Current for the years 2002-03.

## Keywords

Ecological Zonation, Phytoplankton, Bio-Optics, El Niño Débil

## 1. Introduction

The structure of the phytoplankton community and its primary production are a fundamental part of the marine pelagic ecosystem since it contributes a quarter of the total carbon fixation rate with 35 - 50 Gt C Y<sup>-1</sup> with an important role in the global carbon cycle CO<sub>2</sub> via the biological carbon pump [1] [2]. Such assertions ponder the importance to know the phytoplankton taxonomic composition

and its spatial-temporal variability at a regional and mesoscale level, as well as the biogeochemical processes and physiology of phytoplankton in the oceans, including the transfer of energy to deep layers and gas exchange with the atmosphere [3] [4]. For this reason, the scientific community has increased studies and implemented methodologies on phytoplankton ecology and its short and medium term variability, in order to determine a better understanding of primary productivity and changes in the biological ecosystem in relation to anomalous events such as “El Niño-La Niña” [5]. During El Niño events, the temperature tends to increase associated with a decrease in the concentration of nutrients, chlorophyll *a* and primary productivity [6], the thermocline sinks and the presence of warm waters with few nutrients, on the contrary in La Niña events, where the surface temperature decreases, the thermocline rises and the concentration of nutrients and primary productivity levels increase [7]. The physical and biological oceanographic conditions in the CC off Baja California (BC) during 2001 period have been widely characterized by [8] [9] [10], where these authors emphasize the presence of upwelling that favoring the increased of phytoplankton. Authors such as [10] [11] [12] used climate indices such as the ENSO (El Niño-Southern Oscillation), MEI (Multivariate El Niño) [13], and PDO (Pacific Decadal Oscillation) [14] to determine oceanographic differences that occurred between the summers 2002-03 in relation to the 2001 to the south of the CC off Baja California. Currently, the high variability of photosynthetic pigments allows us to detect changes in phytoplankton biomass, as well as the physiological state of cells through bio-optical parameters such as light absorption coefficient by phytoplankton ( $a_{ph}$ ). Actually, these changes in the communities can be detected using satellite data, and thus allow to improve the bio-optical algorithms already established in relation to the color ocean [15] [16]. Recent studies have shown a high variability of the  $a_{ph}$  in relation to the concentration and composition of pigments, remarking in a certain flat shape of the spectral curve so-called packet effect, caused by large cells by decreasing the efficiency of light absorption [11] [17] [18] [19]. Likewise, the non-linear relationship between the  $a_{ph}$  vs Chl-*a* concentration, which makes it difficult to estimate the bio-optical parameters through remote sensors, since phytoplankton communities include different species and sizes; which reflect differences in the shape and magnitude of the spectral curve [20]. In this study, the ecological zonation of phytoplankton provinces was characterized based on differences on the spectral absorption shape ( $a_{ph}/440\text{nm}$ ), mainly if we observed anomalous oceanographic interannual changes off Baja California during the summers 2001-02-03.

## 2. Materials and Methods

### 2.1. Study Area

The Baja California Peninsula is located between 24°N - 32°N and 112°W - 119°W, the ocean flows along its west coast what is known as the California

Current System (SCC), which has an influence on the hydrographic conditions off Baja California (BC). The SCC, includes the California Current (CC) with a depth ~0 - 300 m and southward flow with velocity less than  $25 \text{ cm}\cdot\text{s}^{-1}$  [21] and the California Countercurrent (CCC) with a coastal circulation and a discontinuous seasonality [22]. The interannual variability of the SCC is related to climatological changes and atmospheric circulation in mid-latitudes, causing anomalies such as swirls, meanders and fronts that influence the pelagic ecosystems off Baja California [23] [24]. The wind forcing it has been considered that the main mechanism that regulates the SCC, and which acts on the CC producing instability of the system during spring-summer that favoring the process of the coastal upwelling's [25].

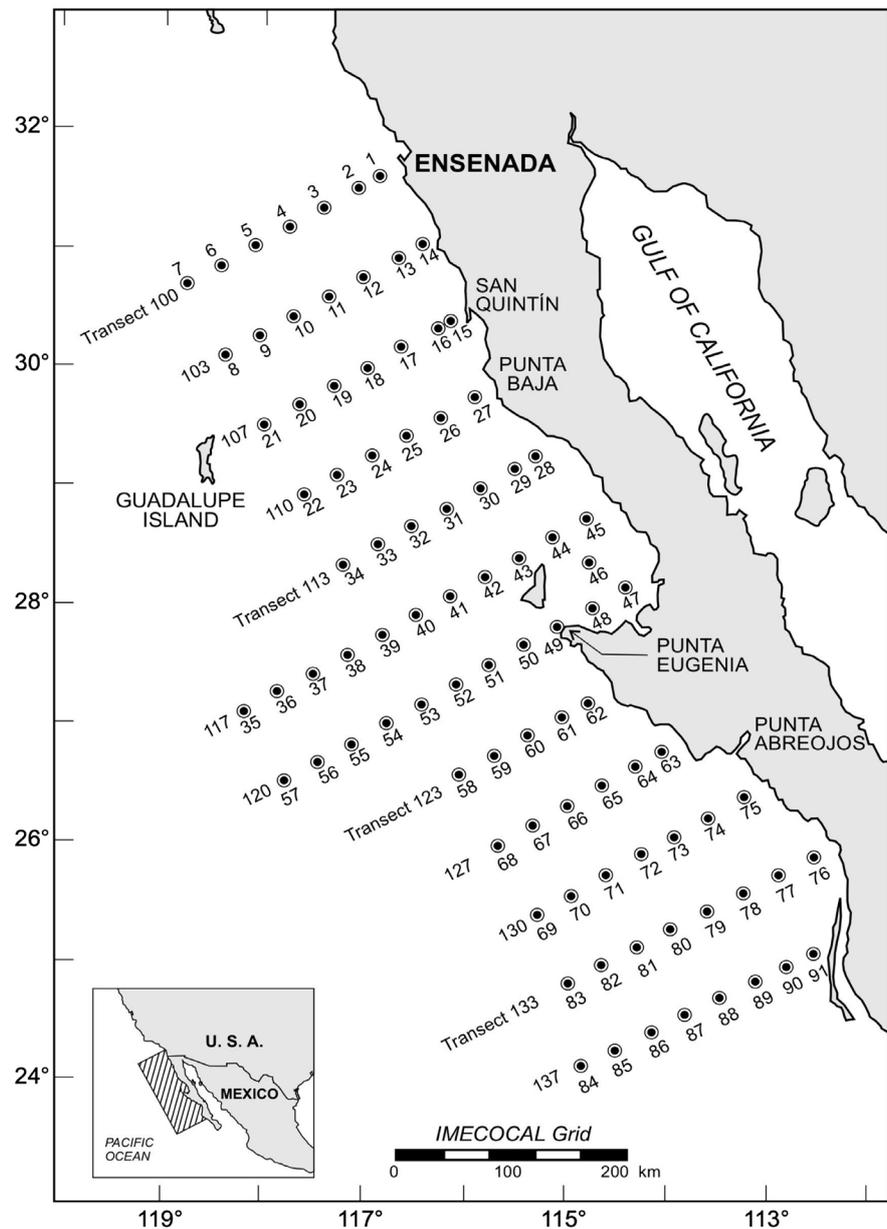
## 2.2. Sampling Strategy

Three oceanographic cruises were carried out onboard the B/O Francisco de Ulloa: 1) June 26 to July 17, 2001, 2) July 12 to August 2, 2002, and 3) July 7 to 29, 2003, within the framework of the Mexican Research California Current (IMECOCAL) Program. We analyzed samples from a total of 91 stations distributed between Ensenada, BC and south of Asunción Bay (**Figure 1**). Temperature and salinity profiles were constructed using a CTD (SeaBird SBE-911) equipped with a rosette of 5 L Niskin bottles. Biological and chlorophyll-*a* (Chl-*a*) samples were collected at 10 m depth. The absorption coefficients of the particulate material ( $a_p$ ) were obtained by filtering 1 L of sea water in filters GF/F (25 nm), stored in HistoPrep® capsules and deposited in liquid nitrogen. The concentration of Chl-*a* was obtained using the fluorometry technique according to [26]. The phytoplankton samples were stored in 250 mL dark bottles, preserved in formaldehyde (4% final concentration) and neutralized with sodium borate (pH 7.5 - 8.0) according to [27].

## 2.3. Phytoplankton Light Absorption Coefficients

To estimate the absorption coefficients, the GF/F filters were analyzed one week after each oceanographic cruise using a Shimadzu UV-2401 PC spectrophotometer with an integrating light sphere. Subsequently, a spectral sweep was carried out between 400 - 750 nm with a resolution of 1 nm and a spectral bandwidth of 2 nm, at a mean scanning speed of  $300 \text{ nm}\cdot\text{min}^{-1}$ . In the first instance, we obtained the spectral curve of the particulate material ( $a_p$ ), then the filters were rinsed with methanol for 15 min following the technique of [28] with a second spectral sweep obtaining the detritus curve ( $a_d$ ). The difference between both curves allowed obtaining the light absorption coefficient by phytoplankton ( $a_{ph}$ ). The normalized spectral shape by phytoplankton ( $a_{ph}n$ ) was obtained dividing the  $a_{ph}$  between the under area of the curve from 400 to 750 nm using Equation (1):

$$a_{ph}n = \frac{a_{ph}(\lambda)(\text{m}^{-1})}{\int_{400}^{750} a_{ph}(\lambda)(\text{m}^{-1})\delta\lambda(\text{nm})} \quad (1)$$



**Figure 1.** Map of the study area showing a subset of the original CalCOFI grid. Location of the stations sampled during the summer seasons in 2001-02-03 off Baja California. Samples were taken at 10 m depth.

#### 2.4. Composition and Biomass of Phytoplankton

To determine the taxonomic groups of phytoplankton, 50 mL of seawater were sediment during 24 h following [29], using an inverted microscope (Carl Zeiss at 160 $\times$  and 400 $\times$ ). Nano and microphytoplankton were identified at genus level according to [30] [31] [32]. In this study, only diatoms were measured through an ocular micrometer, because the size is more homogeneity and stable than dinoflagellates and facility the calculator of the biomass. These measurements were converted to biovolume ( $\mu\text{m}^3$ ) assuming the stoichiometric forms suggested by [33]. The biomass of the population is calculated following Equation (2):

$$B_p = C_p \cdot V_p \cdot F_p \quad (2)$$

where  $B_p$  is the biomass population ( $\mu\text{g C L}^{-1}$ ),  $C_p$  cell concentration (cells  $\text{L}^{-1}$ ),  $V_p$  average cellular bio-volume ( $\mu\text{m}^3$  cells  $\text{L}^{-1}$ ), and  $F_p$  conversion factor from bio-volume to carbon according to [34]. The genera were sorted and classified hierarchically according to the Niche Amplitude Index [20] [35] following Equation (3). The  $B_i$  value indicates the importance of the distribution of any taxon along the stations grid.

$$B_i = \exp \left[ - \sum_{j=1}^K (P_{ij}/R_j) \ln(P_{ij}/R_j) \right] \quad (3)$$

where  $B_i$  is Niche Amplitude Index,  $(P_{ij}/R_j)$  is the proportion of the genus  $i$  in the sample  $j$ , and  $(P_{ij}/R_j)$  over the sum proportion in each genus.

## 2.5. Ecological Zonation of Phytoplankton

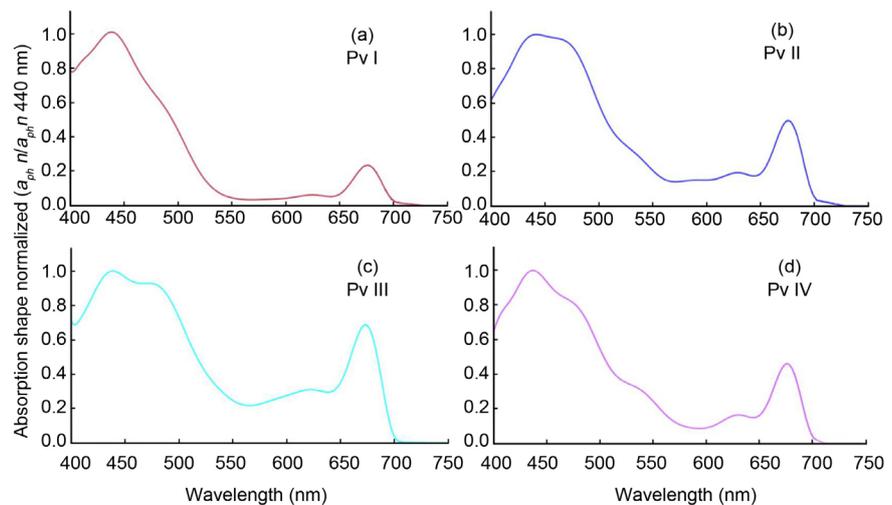
In this study, we considered that the absorption spectral shape  $\left( \frac{a_{ph}n}{a_{ph}n_{440\text{ nm}}} \right)$

is the fingerprint that reflects the photosynthetic pigments of phytoplankton and with a *posteriori* analyses us make up separated and grouped in similar spectral curves as the most representative phytoplankton composition in each station. For this reason, the spectral curves were characterized by the slope differentiation method (440 - 550 nm), as reported by [20].

## 3. Results

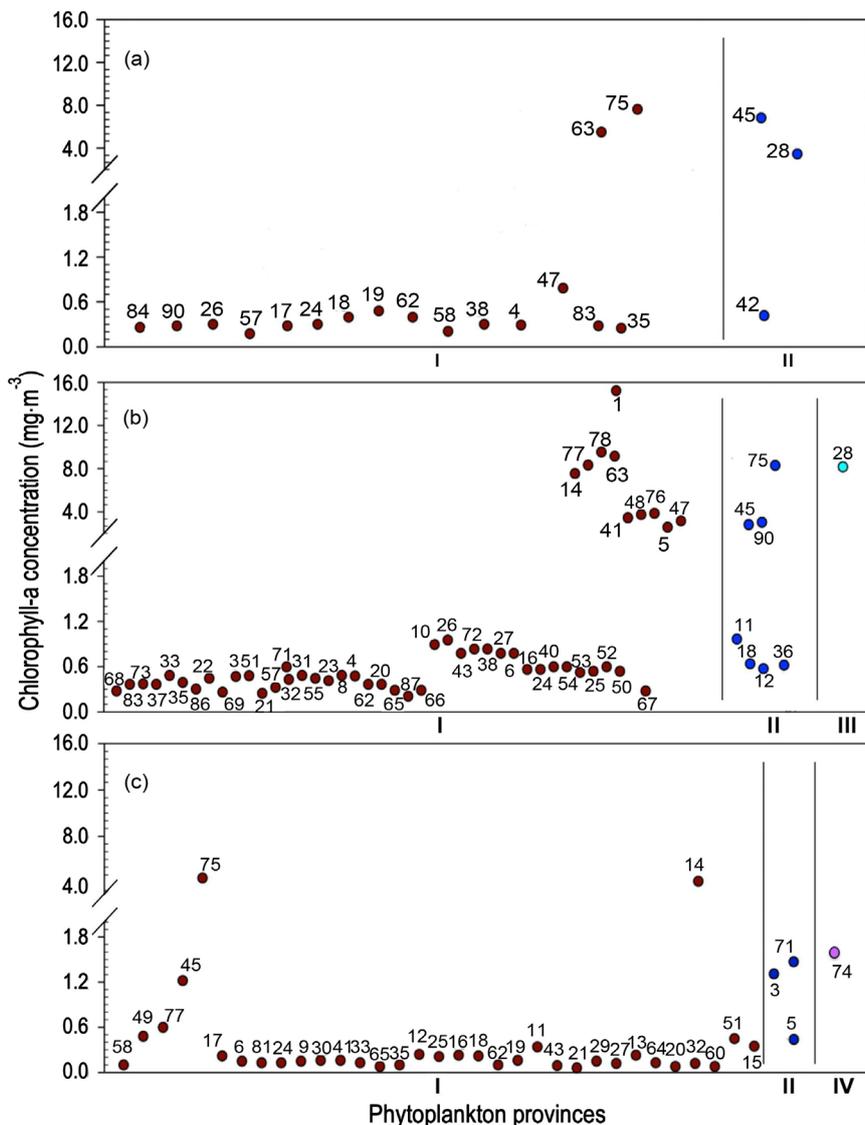
### 3.1. Coefficient of Light Absorption by Phytoplankton

A total of 117 absorption spectral curves were generated, which were grouped into four average spectral shapes (Figure 2) that represent the ecological zonation

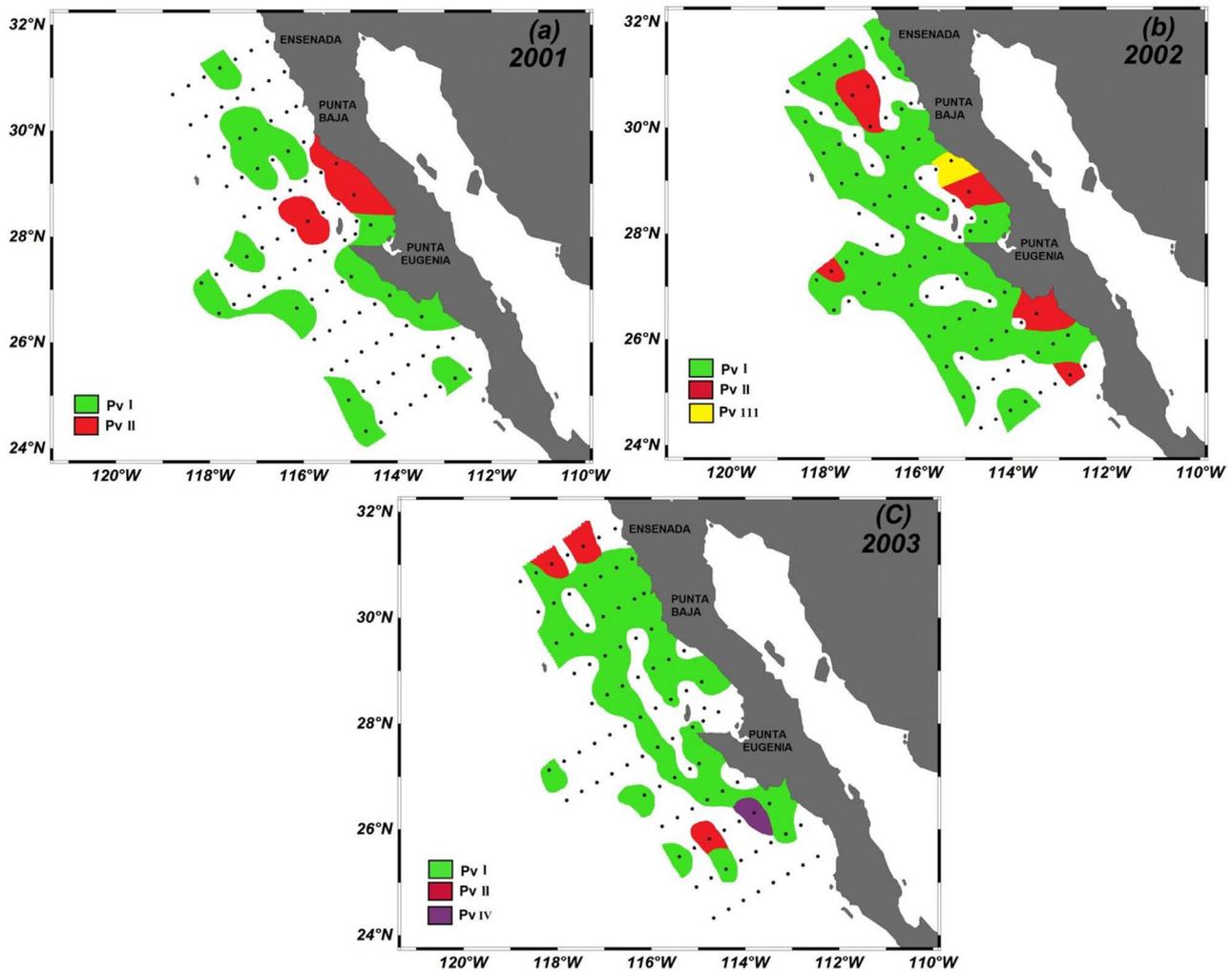


**Figure 2.** Averages of the normalized absorption shapes ( $a_{ph}n/a_{ph}n_{440\text{ nm}}$ ) during the summer season for each ecological zonation of phytoplankton provinces (Pv). (a) Pv I (102 spectral curves); (b) Pv II (13 spectral curves); (c) Pv III (1 spectral curve); and (d) Pv IV (1 spectral curve). The samples were taken at 10 m depth.

of phytoplankton denominated provinces (Pv I, Pv II, Pv III, Pv IV). For 2001 20 stations were analyzed and grouped into two different spectral shapes: Pv I with 17 stations and Pv II with 3. In contrast the 2002 grouped 59 stations in 3 provinces: Pv I with 51, Pv II with 7, and Pv III with 1 station. While in 2003 3 provinces were defined: Pv I with 34 stations, Pv II with 3, and Pv IV with 1 station (Figure 3). In general, the Pv I was reflected in 102 spectral curves, the Pv II in 13, the Pv III and Pv IV in 1 spectral curve. The spatial distribution of the Pv I during 2001 covered from Ensenada to south of Asunción Bay, while the Pv II was located in Vizcaíno Bay (Figure 4(a)). Unlike 2002 and 2003, where Pv I comprised a large part of the study area, while Pv II, Pv III and Pv IV were located in small areas (Figure 4(b) and Figure 4(c)).



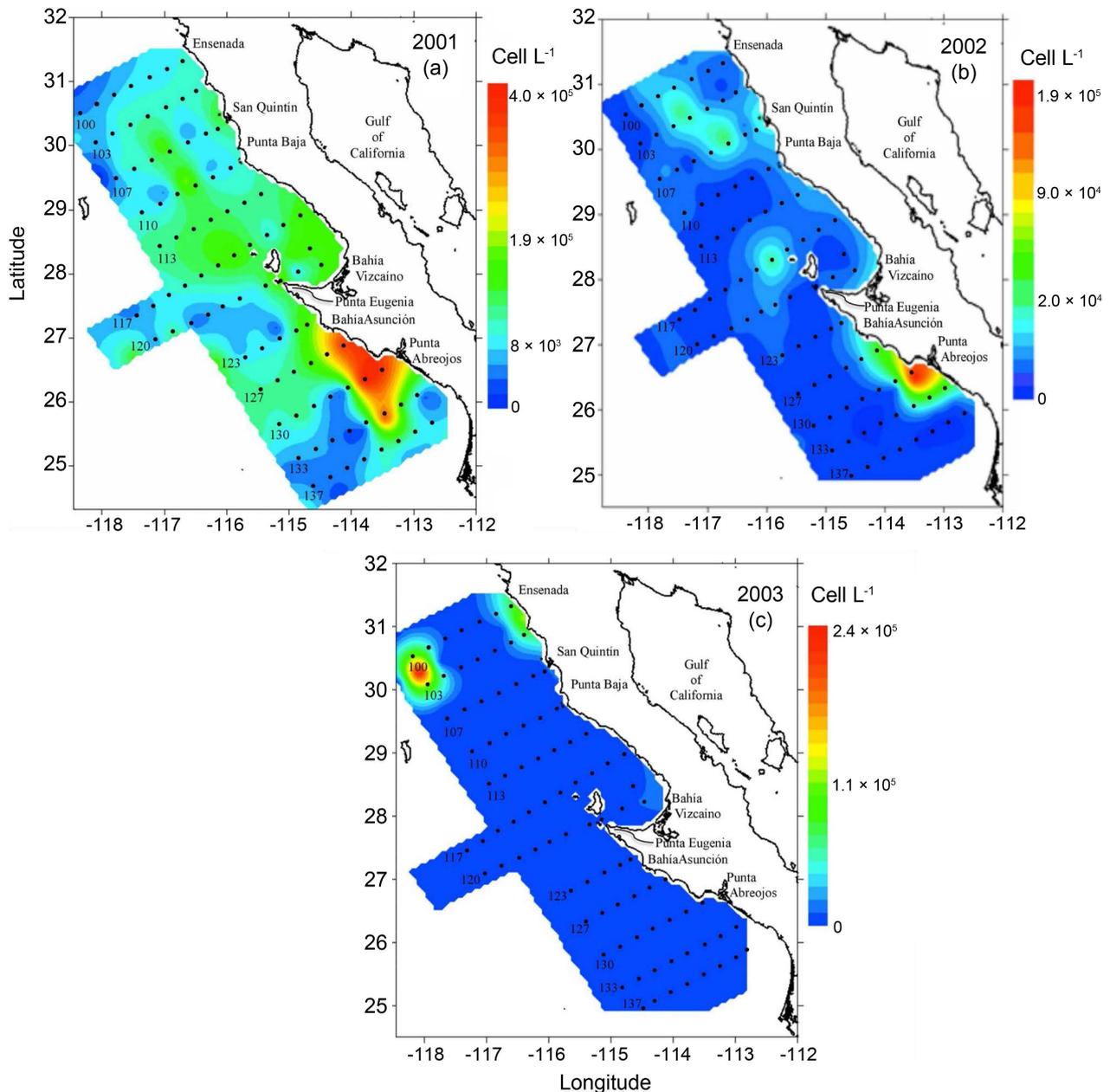
**Figure 3.** Ecological zonation of phytoplankton provinces (Pv) for each summer season (2001-02-03). The ordinate axis is chlorophyll-a concentration ( $\text{mg}\cdot\text{m}^{-3}$ ), and abscissa axes correspond to each phytoplankton provinces off Baja California. The samples were taken at 10 m depth.



**Figure 4.** Spatial-temporal distribution of the ecological zonation of phytoplankton provinces off Baja California during summer season according to the normalized absorption shapes (2001-02-03). The green color (Pv I), red color (Pv II), yellow color (Pv III) and purple color (Pv IV). The samples were taken at 10 m depth.

### 3.2. Spatial and Temporal Variability of Phytoplankton

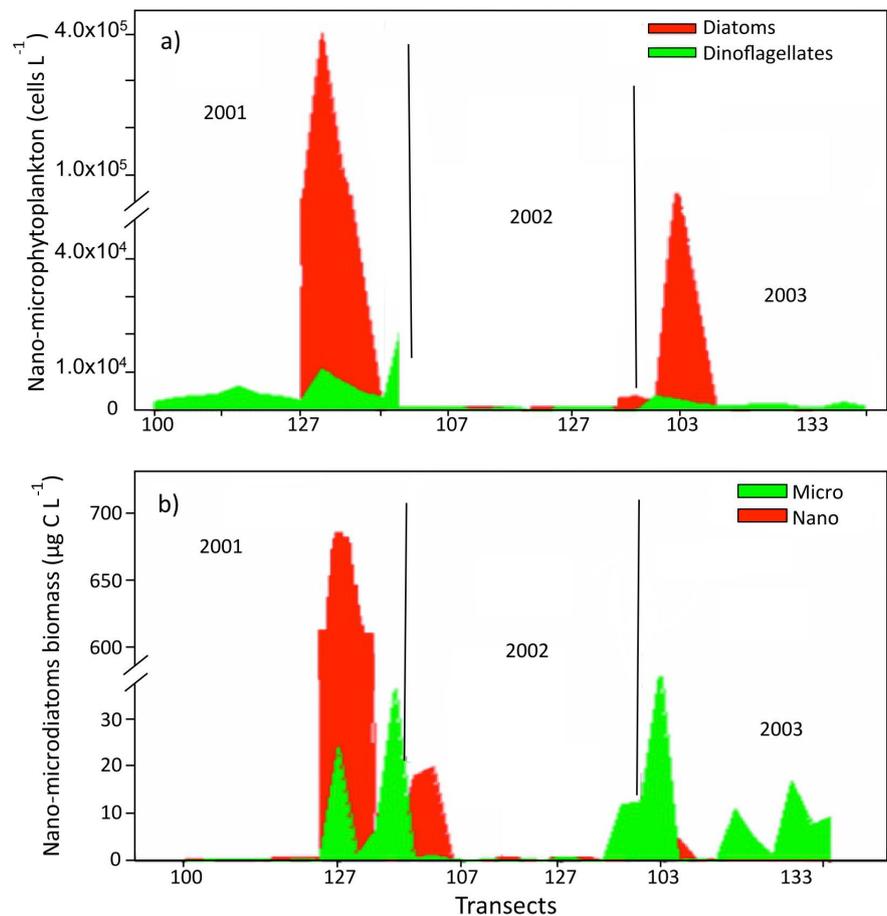
In general, during the summer of 2001 the spatial distribution of phytoplankton presented a high abundance of cells towards the coast stations, with an increase of  $3.96 \times 10^5 \text{ L}^{-1}$  cells (**Figure 5(a)**). The main taxonomic group consisted of diatoms with  $2.9 - 3.9 \times 10^5 \text{ cells L}^{-1}$  (63, 74 y 75 stations) at South of Punta Abrejos; while, dinoflagellates contributed to  $1.87 \times 10^4 \text{ L}^{-1}$  cells (**Figure 6(a)**), unlike the silicoflagellates that showed little abundance. However, during summer 2002 the abundance of phytoplankton decreased 50% compared to 2001 (**Figure 5(b)**), revealing traces of the diatom group on lines 100 and 103 near the coast ( $1.26 - 1.72 \times 10^5 \text{ cells L}^{-1}$ ) and South of Asunción Bay on lines 127 and 130 ( $1.6 - 1.9 \times 10^4 \text{ cells L}^{-1}$ ); while the dinoflagellates showed abundances of  $1.9 \times 10^4 \text{ L}^{-1}$  cells south of Punta Abrejos (**Figure 6(a)**). Finally, diatoms abundance increased during summer 2003 ( $2.39 \times 10^5 \text{ cells L}^{-1}$ ) towards the oceanic region off Ensenada and San Quintín (**Figure 5(c)** and **Figure 6(a)**).



**Figure 5.** Spatial-temporal distribution of total phytoplankton (cells  $L^{-1}$ ) at 10 m depth during IMECOCAL cruises summer season (2001-02-03).

### 3.3. Structure of the Phytoplankton Community

In hierarchical order (*Bi*), a total of 29 genera of phytoplankton were reported corresponding to the nano-microphytoplankton group ( $>5 \mu m$ ) during summer 2001-02-03, out of which 16 correspond to diatoms including: *Nitzschia*, *Coscinodiscus*, *Rhizosolenia*, *Navicula*, *Chaetoceros*, *Thalassionema*, *Cocconeis*, *Pseudoeunotia*, *Hemiaulus*, and *Eucampia*; while 13 correspond to dinoflagellates: *Gymnodinium*, *Ceratium*, *Gyrodinium*, *Oxytoxum*, *Prorocentrum*, *Gonyaulax*, *Protoperidinium*, *Dinophysis*, *Podolampas*, and *Peridinium* (**Table 1**). Its percentage contribution by taxonomic groups in relation to each province



**Figure 6.** (a) Contribution of each phytoplankton group; diatoms and dinoflagellates (cells L<sup>-1</sup>); (b) Size-fractionated biomass (µg C L<sup>-1</sup>) at 10 m depth during summer season (2001-02-03).

with spectral shape were: Pv I, showed 89% contribution of diatoms compared to the dinoflagellates that contributed 11%. Pv II, contributed with 48% of dinoflagellates and 52%; diatoms while Pv III and Pv IV presented a contribution of 72% and 88% of dinoflagellates and little presence of diatoms with 28% and 12%, respectively.

### 3.4. Biomass of Phytoplankton (Nano-Microdiatoms)

In summer 2001, the highest phytoplankton biomass occurred at south of Asunción Bay (Transects 127 and 130) where the nano-diatoms (*Nitzschia*, *Chaetoceros*, *Thalassionema*, and *Navicula*) showed values between 688 and 186 µg C L<sup>-1</sup>, respectively. Micro-diatoms (*Thalassiosira*, *Rhizosolenia*, and *Coscinodiscus*) presented values < 24 µg C L<sup>-1</sup>, in transects 127 and 137 respectively (**Figure 6(b)**). In general, during 2002 a decrease in biomass was observed, except between Ensenada and San Quintín Bay (Transects 100 and 103) where the nano-diatoms reached values of 17.8 and 19.6 µg C L<sup>-1</sup> respectively; while the micro-diatoms showed greater presence in the transect 137 with 11.8 µg C L<sup>-1</sup> (**Figure 6(b)**). Finally, during 2003 the micro-diatoms dominated in two main

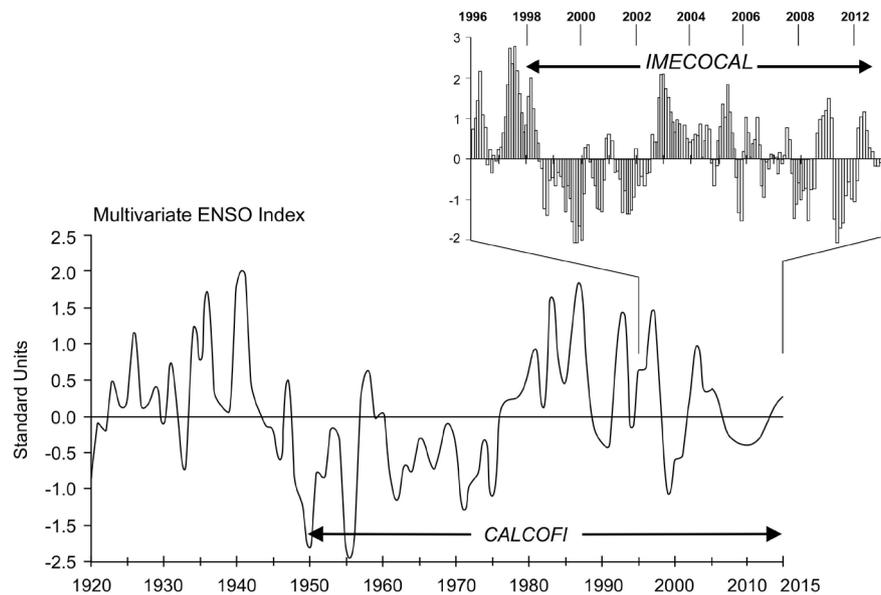


areas: 1) located between Ensenada and San Quintín with 12.3 and 40.5  $\mu\text{g C L}^{-1}$  respectively, and 2) South of Punta Eugenia with 16.6  $\mu\text{g C L}^{-1}$  (Transect 127). The rest of the study area showed intervals between 0.18 - 9  $\mu\text{g C L}^{-1}$ . (**Figure 6(b)**).

#### 4. Discussion

The physical and biological oceanographic conditions in the CC off Baja California (BC) during 2001 period have been widely characterized by [8] [12], where these authors emphasize that the presence of upwelling, processes of turbulence and/or mixing cause a rise of nutrients towards the surface, favoring the increase of phytoplankton cells with a greater proportion of diatoms. Likewise, they also suggested that NW BC region was related to the presence of the event called “La Niña”. During our 2001 study, the highest abundances of phytoplankton were detected in coastal stations located between Asunción Bay and Punta Abreojos, where the nano-diatoms group (5 - 20  $\mu\text{m}$ ) dominated and presented an average biomass of 300  $\mu\text{g C L}^{-1}$ . In hierarchical order organisms most representative were: *Gymnodinium*, *Ceratium*, *Gyrodinium*, *Oxytoxum*, *Nitzschia*, *Coscinodiscus*, *Rhizosolenia*, *Navicula* and *Chaetoceros*. These results were consistent with the conceptual framework proposed in the Margalef’s Mandala [2]. In this Mandala life-forms of phytoplankton are placed in an ecological space defined by nutrients and turbulence, where the diatoms are associated with rich and turbulent waters, while in the opposite corner of the Mandala, small and swimming cells are related to calm and poor waters as well as dinoflagellates developed in calm waters and little nutrients; so we deduce in this study, a community in stage called post-emergence with an increase towards the group of dinoflagellates, as shown in **Table 1**.

Authors such as [10] [12] used climate indices such as the ENSO (El Niño-Southern Oscillation), MEI (Multivariate El Niño [13]), and PDO (Pacific Decadal Oscillation [14]) to determine oceanographic differences that occurred between the summers 2002-03 in relation to the 2001 to the south of the CC off Baja California, reaching the conclusion that the years 2002-03 showed evidence of the El Niño event “weak” in relation to those observed in 1982-83 and 1997-98 considered as a strong oceanographic anomaly. In this sense, our results about abundances and biomass phytoplankton in the El Niño years (**Figure 5(b)** and **Figure 5(c)** and **Figure 6(b)**), showed characteristics of an oligotrophic zone throughout the study area, except in the oceanic stations of the northern region (lines 100 and 103) and southern region (line 130) that showed evidence of coastal zones. This was possibly due to local oceanographic processes typical of the area, where meandering and eddies occur, as reported by [36] [37] when using satellite images. On the other hand, the group of dinoflagellates showed an increase during 2002-03 strengthening the idea of a clear decrease of the diatom group when detecting the presence El Niño event, as observed in **Figure 6(a)** and **Figure 7** in relation to the decadal interannual variability of the multivariate ENSO index of the IMECOCAL and CalCOFI (California Cooperative Oceanic



**Figure 7.** The interannual to interdecadal variability of the multivariate ENSO index of the IMECOCAL and CalCOFI Programmes in the region of the California current for the period 1920-2014 was taken from [41].

Fisheries Investigations) programs.

In order to understand that environmental and biological factors causing variability of the spectral shape in relation to phytoplankton community structure, it was necessary to determine the inherent optical properties of water [38]. Oceanographic studies related to hydrological optics have reported that light absorption coefficients have two types of variability: magnitude and shape [9] [39] [40], arguing these authors that the shape is due to pigments composition. In contrast, the magnitude is directly related to pigments concentration; as it was observed in **Figure 3**, where the phytoplankton provinces are independent of the Chl-*a* concentration.

The subjective visual and/or statistical differentiation of the spectral slope, particularly through the shoulder between 440 - 550 nm, provides a relationship between the shape and structure of the community, as observed in Pv I where the presence of diatoms it was 89% and 11% dinoflagellates. Therefore, we determined that a greater slope is characteristic of the diatom group, very similar results were reported in Baja California during spring 2008 [41]. However, Pv III in **Figure 2(c)** showed opposite characteristics to Pv I, where the percentage of dinoflagellates was greater in 72% than the diatoms group (28%). It is important to note that Pv III was only found at station 28 during summer 2002 south of Punta Baja, where it has traditionally been considered as a region of upwelling events. The Pv IV in **Figure 2(d)** was related to an increase of dinoflagellate abundances with 88% in relation to 12% of the diatoms group; similarly, a lower slope with wavy tendencies is observed, this due to the variability of pigments in the sample of particulate material in suspension. Therefore, it is concluded that the spectral curves of  $a_{ph}$  are the footprint of a taxonomic community captured

in GF/F filters with porosity  $\sim 0.7 \mu\text{m}$ , which considers the presence of picoplankton (not analyzed in this study), as well as the nano-microphytoplankton reported in this work.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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