Revista de Biología Marina y Oceanografía
Vol. 54, N°1: 70-81 , 2019
DOI: https://doi.org/10.22370/rbmo.2019.54.1.1495

ARTICLE

Inter-annual variability of oceanographic conditions and phytoplankton in Valparaíso Bay (~33°S), central Chile

Variabilidad inter-anual de las condiciones oceanográficas y del fitoplancton en la bahía Valparaíso (~33°S), Chile central

Pilar Aparicio-Rizzo[1] and Italo Masotti[1,2*]

[1]Facultad de Ciencias del Mar y de Recursos Naturales, Universidad de Valparaíso, Av. Borgoño 16344, Viña del Mar, Chile
[2]Centro de Observación Marino para Estudios de Riesgos del Ambiente Costero (COSTA-R), Universidad de Valparaíso, Viña del Mar, Chile
*Corresponding author: italo.masotti@uv.cl

Resumen.- Se estudió la variabilidad inter-anual de las condiciones oceanográficas y de la abundancia y biomasa del fitoplancton en una estación fija ubicada en la bahía de Valparaíso (~33°S) usando 10 años (1986-1996) de observaciones *in situ*. La serie temporal mostró vientos S-SO intensos y una cuasi-permanente actividad de surgencia que enriquecen de nutrientes la columna de agua y sustentan al fitoplancton en la bahía. El cambio más importante en las condiciones bio-oceanográficas fue observado durante el evento de El Niño 1987, con aumento de la temperatura, caída en la salinidad y en la concentración de nitrato y fosfato, así como en la biomasa del fitoplancton en comparación con La Niña 1988 cuando se detectó agua mas fría, salada y rica en nutrientes. Bajo condiciones El Niño (1987-1988 y 1993) se registraron altas descargas del río Aconcagua que precedieron la caída en la salinidad y el aumento en la abundancia de dinoflagelados. Se observaron dos periodos con diferencias en las condiciones oceanográficas; 1988-1992 presentó baja temperatura e incremento en los nutrientes (nitrato), la biomasa del fitoplancton y en la abundancia de diatomeas en comparación al periodo 1993-1996. A lo largo del periodo de estudio se registró una tendencia positiva en la surgencia, acompañada con una caída en la biomasa del fitoplancton y la abundancia de dinoflagelados. Este estudio proporciona nuevas evidencias sobre la influencia de El Niño Oscilación del Sur (ENOS) en el fitoplancton y las condiciones oceanográficas en la zona costera frente a Chile central.

Palabras clave: Fitoplancton, surgencia, Río Aconcagua, bahía Valparaíso, ENOS

Abstract.- The inter-annual variability of oceanographic conditions and phytoplankton abundance and biomass was studied using 10 years (1986-1996) of *in situ* observations at a fixed station in Valparaíso Bay (~33°S). The time series analysis revealed that strong S-SW winds drive a quasi-permanent upwelling activity that maintain the nutrients availability in the water column to fuel the phytoplankton in the bay. The most important changes in bio-oceanographic conditions were observed during 1987 El Niño event, which was characterized by higher temperatures but lower values for salinity, nitrate, and phosphate concentrations, together with a decrease of phytoplankton biomass compared to 1988 La Niña event when colder, saltier, and nutrient-rich upwelled water were observed. High Aconcagua River discharges were observed during the El Niño conditions (1987-1988 and 1993), which led to a decrease in surface salinity and a high abundance of dinoflagellates. Two periods with differences in bio-oceanographic conditions were observed; 1988-1992 showed lower temperatures but higher nutrients (nitrate), phytoplankton biomass and abundance of diatoms than 1993-1996 period. Throughout the study period, positive trends in upwelling activity was registered accompanied by a fall in phytoplankton biomass and dinoflagellate abundance. This paper provides new evidences concerning the influence of El Niño Southern Oscillation (ENSO) in phytoplankton and oceanographic conditions in the coastal upwelling off central Chile.

Key words: Phytoplankton, upwelling, Aconcagua River, Valparaíso Bay, ENSO

INTRODUCTION

Upwelling events driven by wind are characterized by a high temporal variability from quasi-weekly to inter-annual scales (Strub *et al*. 1998, Rutllant & Montecino 2002) in the coastal waters off central Chile (~30º-37ºS). These events regulate the oceanographic environment, the biomass, and the composition of planktonic organisms (Iriarte & González 2004, Anabalón *et al*. 2016). Along this coastal region, several upwelling foci—characterized by high phytoplankton biomass and primary productivity (PP)—have been described (Marín & Olivares 1999, Thiel *et al*. 2007, Anabalón *et al*. 2016, Testa *et al*. 2018). These upwelling foci have been associated with headlands like Punta Lengua de Vaca in Coquimbo (~30ºS), Punta Curaumilla in Valparaíso (~33ºS), and Punta Lavapié in Concepción (~37ºS). In these headlands areas, intense S-SW winds in the spring-summer period produce upwelling favourable conditions generating cold and nutrient rich water filaments that fuel micro-phytoplankton growth (Marín & Olivares 1999, Thiel *et al*. 2007).

Several studies have shown inter-annual upwelling variability probably related to “El Niño Southern Oscillation” (ENSO) that produces a weakening of upwelling favourable winds (Shaffer *et al*. 1999). Previous studies showed a decrease in S-SW winds during El Niño (EN) events with a drop in coastal upwelling activity (both in intensity and duration) along southern-central Chile (Montecinos & Gómez 2010). This scenario induces changes in oceanographic conditions with a deepening of the thermocline and a reduction in nutrient input to the photic layer, which triggers a decrease in phytoplankton biomass (chlorophyll-*a*) and PP (Ulloa *et al*. 2001, Pizarro *et al*. 2002).

Punta Curaumilla is located in the south of Valparaíso Bay in central Chile (~33ºS). It is one of the active upwelling foci in the region with quasi-permanent S-SW winds (Sievers & Vega 2000). Here, upwelling events cause cold, nutrient-rich, sub-equatorial water to rise fuelling the photic layer in the bay (Sievers & Vega 2000, Silva & Valdenegro 2003). The phytoplankton biomass increases and large cell-sized and colonies of diatoms appear in surface waters (0-20 m) during these upwelling events (mostly in the spring and summer) (Avaria & Orellana 1975, Avaria *et al.* 1989).

The ENSO influence have also been described at Valparaíso Bay and adjacent areas (~32º-33ºS) with positive anomalies to sea temperature, deepening of isolines (nutrient and temperature), and drops in oxygen and nitrate concentration (Avaria *et al*. 1989, Sievers & Vega 2000). During the EN 1982/83 event, the arrival of warm sub-tropical water mass was related to a reduction in the abundance and biomass of phytoplankton as well as to changes in the composition with an increase in phytoplankton species typical of sub-tropical waters (Avaria *et al*. 1988, 1989). In addition, changes in salinity and nutrients (silicate increment) in this area have been associated with an increase in the Aconcagua River flow due to rain and snow-melt increase under EN conditions (Prado & Sievers 1987, Sievers & Vega 2000, Pellicciotti *et al*. 2007).

In upwelling areas of the Chilean coast, river discharges can also modify oceanographic conditions and nutrient export (Léniz *et al*. 2012, Pérez *et al*. 2015, Masotti *et al*. 2018). Thus, previous studies have shown that an increase in river flow changes salinity and the exportation of nutrients (Pérez *et al*. 2015, Masotti *et al*. 2018). Nutrients from rivers can maintain phytoplankton biomass and productivity in the coastal area, especially during upwelling weakening periods (Sievers & Vega 2000, Masotti *et al*. 2018, Testa *et al*. 2018).

Recent studies in central Chile (~30º-37ºS) using long time-series data (5-10 years) have explained the complexity of a coastal system where diverse factors including upwelling activity, river discharge, and ENSO forcing can affect phytoplankton community and productivity (Corredor-Acosta *et al*. 2015, Anabalón *et al*. 2016, Masotti *et al*. 2018, Testa *et al*. 2018). While several studies have been carried out in Valparaíso Bay to describe the seasonal composition of phytoplankton (Avaria & Orellana 1975, Avaria *et al*. 1989), no reports detail the inter-annual scale. Thus, this work studied the inter-annual variability of oceanographic conditions and their impact on phytoplankton in Valparaíso Bay during 10 years of observations from a fixed bio-oceanographic station.

Materials and methods

Study area

The study was located in the coastal area of Valparaíso Bay, central Chile (~32º55'- 33º30'S). This bay is an open embayment with N-NE orientation, a width of *ca*. 7 miles between the headlands of Punta Concón (north) and Punta Ángeles (south), and a depth of *ca.* 90 m in the centre of the bay (Fig. 1). The Aconcagua River (32º55'09"S; 71º30'28"W) is located at the north of the bay, over Punta Concón (Fig. 1).

Meteorological, hydrological data and upwelling index

A historical time-series data (10 years) of physical (temperature and salinity), chemical (nutrients concentration), and biological (phytoplankton biomass and diatoms and dinoflagellates abundance) variables was examined to explore the relationships between the oceanographic conditions and inter-annual variability of phytoplankton in the area.

The data was obtained in a weekly to fortnightly bio-oceanographic monitoring carried out from August 1986 to December 1996, in a fixed station located on the shelf two miles (~3.7 km) offshore of Caleta Montemar (32°58'02''S;71°35'00''W) at the north of Valparaíso Bay (St. M, Fig. 1). This station is exposed to both the local coastal upwelling activity and the Aconcagua River plume influence (Avaria *et al*. 1989, Sievers & Vega 2000).

Daily wind data were obtained from the historical archives of the Centro Meteorológico de la Gobernación Marítima de Valparaíso (CENMETEOVALP). Speed and direction (u and v components) data were collected from the "Faro Punta Ángeles" meteorological station (33º04'00''S; 71º38'00''W) located 60 m above sea level at the south of Valparaíso Bay (Fig. 1) and were processed for the 1987-1996 period.

The upwelling index (UI) was calculated by Bakun's equation (Bakun 1973) for coastal areas (M_x*100 m):

$$UI= (\tau_Y / f \times \rho_w) \times 10^3$$

where τ_Y is the *y* wind stress component, *f* is the Coriolis parameter (7.923 e -5 rad s^{-1}), and ρ_w is the seawater density (1,025 kg m^{-3}).

The wind stress was calculated using hourly wind speed (W, m s^{-1}) and v component (north-south) data (W_y, m s^{-1} rad), a dimensionless drag coefficient (Cd= 1.4×10^{-3}), and the air density (ρ_a= 1.22 kg m^{-3}, normal conditions).

$$\tau_Y = \rho_a \times Cd \times W \times W_y$$

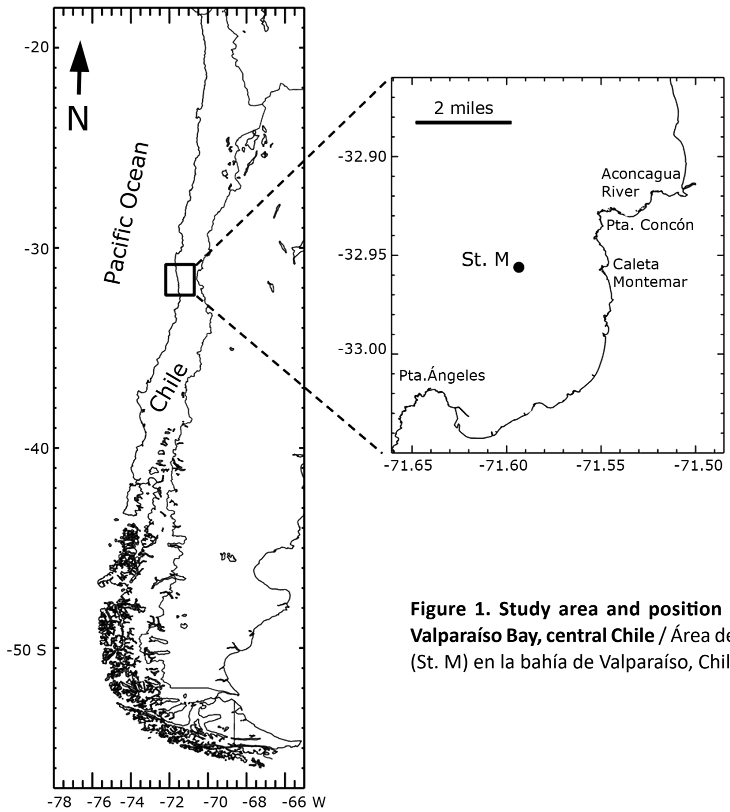

Figure 1. Study area and position of the bio-oceanographic fixed station (St. M) in Valparaíso Bay, central Chile / Área de estudio y ubicación de la estación bio-oceanográfica (St. M) en la bahía de Valparaíso, Chile central

To perform the long-term characterization of "El Niño" and "La Niña" events multivariate ENSO Index (MEI) data obtained from the NOAA website(1) were used (Wolter & Timlin 2011).

For the hydrological analysis, daily data of the Aconcagua River flow was obtained from the San Felipe station (32º55'09"S / 71º30'28"W; 630 m above sea level) at the Dirección General de Aguas (DGA)(2) for October 1986 to December 1996.

Oceanographic data

Between August 1986 and December 1996 discrete water column samples (0, 5, 15, 25, 40, 55 m) of temperature, salinity, and nutrients (Nitrate-NO_3^-, Phosphate-PO_4^{3-}, and Silicate-SiO_4^{4-}) were collected in the fixed station (St. M). Temperature (ºC) was measured *in situ* with protected reversing-calibrated thermometers arranged at the sampling bottle. A Tsurumi Seiki digital induction salinometer measured salinity at the marine chemistry laboratory. For dissolved inorganic nutrients, water samples were stored in cleaned plastic bottles and kept in the dark at -20 ºC until analysis via spectrophotometry in the marine chemistry laboratory. Phosphate (PO_4^{3-}) was analysed following Murphy & Riley (1962) methodology modified by Koroleff (1983). The Strickland & Parsons (1968) methodology as modified by Grasshoff (1983) was employed for nitrate (NO_3^-) and Parsons *et al*. (1984) for silicate (SiO_4^{4-}).

Phytoplankton data

Phytoplankton biomass - chlorophyll-*a*

Samples for analysis of phytoplankton biomass, measured as chlorophyll-*a* (Chl-*a*; mg m^{-3}), were obtained by a Niskin bottle at six depth levels (0, 5, 10, 20, 30, 50 m). Chlorophyll-*a* was determined by spectrophotometry, using a modified Lohrenz & Jeffrey (1980) method combined with Parsons *et al*. (1984). Analysis of acetonic extracts of phytoplankton collected on 0.45 µm cellulose membrane filters and stored at 4 ºC in the darkness for 24 h were realized with a UV 120-12 Shimadzu spectrophotometer.

Micro-phytoplankton abundance

Quantitative phytoplankton analyses (cells L^{-1}) were conducted using discrete water samples at 0 and 10 m (over 500 samples). Water samples (~200-250 ml) were preserved in Lugol's iodine solution in darkness until

1 <http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html>
2 <www.dga.cl>

analysis. Phytoplankton cells were counted using a Wild M-40 inverted microscope after sample sedimentation in 5, 10, or 50 cm^3 chambers following the method described by Utermöhl (1958) at the phytoplankton laboratory. The micro-phytoplankton (20-200 µm) was categorized into two main groups: diatoms (Bacillariophyceae) and dinoflagellates (Dinophyceae). The total abundance (cells L^{-1}) of both groups corresponds to total species abundance at 0 and 10 m depths, respectively.

Data processing

Meteorological (wind and UI), hydrological (river flow), oceanographic (temperature, salinity and nutrients) and micro-phytoplankton data (chlorophyll-*a*, diatoms and dinoflagellates abundance) were categorized according to inter-annual variability by calculating the annual mean and standard deviation per year. Annual mean values (n= 10) were employed to study the dissimilarity and tendency along the time series.

Multivariate analyses were applied using PAST v 3.11 software (Hammer *et al.* 2001). A Cluster analysis was developed using annual mean values (0-30 m) of temperature, salinity, nutrients (NO_3^-, PO_4^{3-} and SiO_4^{4-}), and phytoplankton biomass (Chl-*a*) from 1987 to 1996, along with surface values of upwelling index (UI) and river flow. A Permutational analysis of variance (one-way PERMANOVA) was applied to assess the significant difference between groups.

During the study period years under different ENSO phases were selected to check changes between the oceanographic and hydrological conditions together with phytoplankton in the bay, by a comparative analysis of year-to-year using the non parametric U Mann-Whitney test. The years 1987/88, 1989/90 and 1995/96 were selected following historical El Niño-La Niña events since 1950s for NOAA Multivariate ENSO Index (MEI) classification. Finally a non-parametric Mann-Kendall test was used to study trends along time series period in the bay.

Results

Meteorological and hydrological conditions

The daily wind data showed the dominance of S-SW winds, which exhibited intensification along the time series. From 1988 to 1996, the UI (upwelling index) ranged between 31.4 and 59.4 $m^3 s^{-1}$ showing persistent upwelling favourable conditions (Fig. 2B; >100 $m^3 s^{-1}$), and scarce downwelling events (<2% values under -100 $m^3 s^{-1}$). There was an increase in the UI intensity during the study period with the highest annual mean values in the last years of the time series (1993-1996; >50 $m^3 s^{-1}$) when the maximum UI values (1994, ~980 $m^3 s^{-1}$; 1995-1996, ~974 $m^3 s^{-1}$); were registered. In addition, a seasonal signal both in wind and in UI was observed (Table 1, Fig. 2 A-B).

Throughout the study period, the Aconcagua River showed year-to-year variability (range ~0-263 $m^3 s^{-1}$) with annual mean values ranging between 2 and 49.4 $m^3 s^{-1}$. The highest river discharge events (>150 $m^3 s^{-1}$) were observed in 1986 and 1987; with the highest river flow mean value in 1987. There was also a progressive decrease in river flow during the study period with values below 1 $m^3 s^{-1}$ between 1993 and 1996 when the minimum river flow was registered (Table 1, Fig. 2C).

The sea surface salinity (SSS) ranged between 32.41 and 34.41 mean values. Several salinity decline events were observed in coincidence with high river flow especially between late 1986 and 1988. The lowest SSS value was registered in 1987 when the highest river flow was observed (Table 1; Figs. 2C and D). Correlation of year-to-year SSS and river flow variability showed an inverse significant value (rs= -0.74, $P < 0.05$).

Table 1. Inter-annual variability of: Upwelling Index (UI) ($m^3 s^{-1}$), River flow ($m^3 s^{-1}$), and Sea Surface Salinity (SSS, 0 m). Mean ± standard deviation values and range (minimum-maximum) / Variabilidad inter-anual del: Índice de Surgencia (UI) ($m^3 s^{-1}$), Caudal del río ($m^3 s^{-1}$), y Salinidad Superficial (SSS, 0 m). Valores del promedio ± desviación estándar y rangos (mínimo-máximo)

	UI	River flow	SSS
1987	-	49.42 ± 48.38* (2.93 - 263.00)	32.41 ± 1.81* (26.30 - 34.45)
1988	45.15 ± 84.04 (-320.04 - 551.62)	23.70 ± 31.86* (1.24 - 160.00)	33.63 ± 0.93* (30.63 - 34.50)
1989	34.80 ± 78.74* (-614.62 - 444.50)	12.55 ± 17.20* (1.82 - 95.20)	34.07 ± 0.49* (32.02 - 34.62)
1990	31.40 ± 93.16* (-568.96 - 769.90)	4.44 ± 5.16* (0.11 - 29.50)	34.41 ± 0.28* (33.72 - 34.98)
1991	33.44 ± 89.99 (-568.96 - 670.30)	18.86 ± 21.98 (0.64 - 107.00)	-
1992	43.66 ± 111.76 (-875.50 - 835.39)	26.27 ± 20.21 (8.22 - 108.00)	-
1993	58.35 ± 126.96 (-492.47 - 875.50)	22.26 ± 16.26 (0.71 - 144.00)	33.54 ± 0.80 (31.56 - 34.96)
1994	57.81 ± 140.32 (-589.46 - 980.66)	12.30 ± 12.60 (0.97 - 54.90)	34.36 ± 0.45 (33.62 - 35.30)
1995	53.28 ± 123.96* (-670.30 - 974.41)	9.25 ± 7.77* (0.06 - 34.90)	34.16 ± 0.45 (33.54 - 34.89)
1996	59.39 ± 142.96* (-621.80 - 974.41)	2.00 ± 2.58* (0 - 19.60)	34.23 ± 0.17 (33.96 - 34.47)

*$P < 0.05$ statistically significant

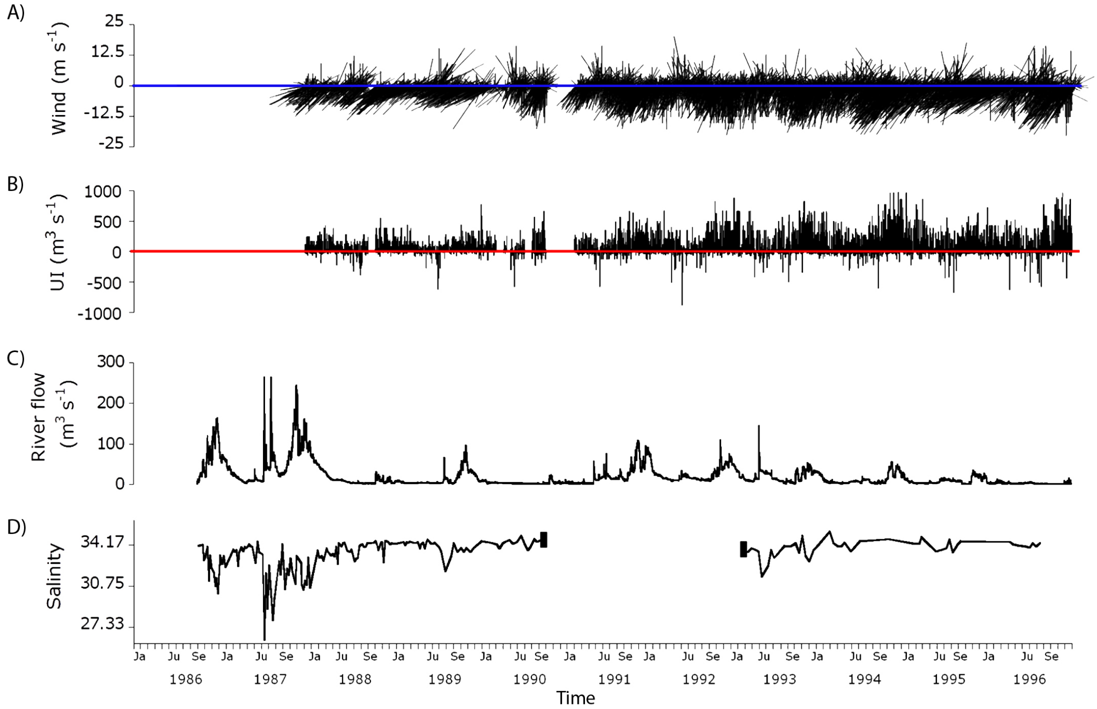

Figure 2. Time series of: A) alongshore wind, B) Upwelling Index (UI), C) Aconcagua river flow and D) Sea Surface Salinity (SSS), from August 1986 to December 1996. White areas represent no available data. Negative direction is equatorward and positive direction is poleward / Serie temporal del: A) Viento diario, B) Índice de Surgencia (UI), C) Caudal del río Aconcagua y D) Salinidad Superficial (SSS). Áreas blancas indican no datos

Table 2. Inter-annual variability of: Salinity, Temperature (°C), Nitrate-NO_3^- (µM), Phosphate-PO_4^{3-} (µM) and Silicate-SiO_4^{4-} (µM) in water column (0-30 m). Mean ± standard deviation values and range (minimum-maximum) / Variabilidad inter-anual de: Salinidad, Temperatura (°C), Nitrato-NO_3^- (µM), Fosfato-PO_4^{3-} (µM) y Silicato-SiO_4^{4-} (µM) en la columna de agua (0-30 m). Valores del promedio ± desviación estándar y rangos (mínimo-máximo)

	Salinity	Temperature	NO_3^-	PO_4^{3-}	SiO_4^{4-}
1987	33.77 ± 1.20* (26.30 - 34.62)	13.17 ± 1.30* (11.69 - 18.06)	9.60 ± 6.49* (0.72 - 25.28)	1.34 ± 0.71* (0.10 - 2.96)	10.13 ± 5.88 (1.83 - 33.66)
1988	34.14 ± 0.60* (30.63 - 34.68)	12.58 ± 1.16* (10.71 - 16.07)	14.37 ± 6.66* (0.70 - 28.70)	1.57 ± 0.54* (0.54 - 2.94)	9.68 ± 7.25 (0.10 - 42.70)
1989	34.28 ± 0.34* (32.02 - 34.69)	13.31 ± 1.31* (11.13 - 17.73)	12.17 ± 6.21 (0.80 - 28.10)	1.44 ± 0.65* (0.33 - 3.20)	7.54 ± 5.32* (0.10 - 25.30)
1990	34.50 ± 0.17* (33.72 - 34.98)	12.40 ± 0.97* (11.00 - 15.42)	12.65 ± 6.24 (0.70 - 24.30)	1.85 ± 0.59* (0.50 - 2.76)	12.87 ± 7.29* (0.10 - 26.70)
1991	-	13.27 ± 1.19 (11.40 - 16.66)	11.99 ± 5.89 (0.60 - 23.90)	1.37 ± 0.55 (0.34 - 2.41)	7.95 ± 4.91 (0.15 - 22.70)
1992	-	12.80 ± 1.47 (10.71 - 17.80)	15.23 ± 7.02 (1.50 - 27.90)	1.56 ± 0.55 (0.43 - 2.64)	17.30 ± 11.33 (3.00 - 64.10)
1993	34.15 ± 0.64 (31.56 - 35.26)	13.09 ± 1.35 (11.40 - 16.95)	8.03 ± 7.12 (0.50 - 26.20)	1.43 ± 0.56 (0.34 - 2.59)	12.74 ± 7.09 (2.00 - 34.20)
1994	34.66 ± 0.53 (33.62 - 36.03)	14.31 ± 2.00 (11.55 - 18.09)	11.05 ± 7.39 (0.60 - 26.30)	2.08 ± 0.92 (0.50 - 4.80)	12.41 ± 6.20 (0.80 - 28.10)
1995	34.31 ± 0.34 (33.54 - 34.89)	13.33 ± 1.73 (11.17 - 16.85)	8.46 ± 5.93* (0.50 - 23.20)	1.86 ± 0.75* (0.43 - 3.41)	18.39 ± 9.65* (2.70 - 44.90)
1996	34.28 ± 0.15 (33.96 - 34.65)	12.77 ± 1.08 (10.88 - 16.82)	6.22 ± 4.25* (0.80 - 18.10)	1.54 ± 0.63* (0.50 - 4.46)	13.64 ± 11.74* (1.90 - 43.80)

*$P < 0.05$ statistically significant

Oceanographic and phytoplankton conditions in the water column

The annual mean values of water column temperature (0-60 m) ranged between 12.40 and 14.31 ºC along the time series (1986-1996). The lowest values were registered from 1988 to 1992 and in 1996. Minimum value was registered in 1988 and 1992, in coincidence with the ascent of 12 ºC isotherm, which also was observed in 1989, 1990, and 1991 (Fig. 3A). In 1994 the highest temperature was recorded (17.8 °C) with a sharp warming of the water column (>16 ºC) (Table 2, Fig. 3A).

Salinity in the water column (0-60 m) was homogenous with mean values ranging between 33.77 and 34.66. The lowest salinity (26.30) was observed in surface water (0-5 m) in 1987 and values greater than 35.00 were detected in 1994 along the water column (Table 2, Fig. 3B).

Nutrients showed a vertical gradient, and the lowest values were observed in the surface waters (0-15 m) (Fig. 4). Annual mean values of nitrate (NO_3^-) ranged between 6.22 µM (1996) and 15.23 µM (1992). From 1988 to 1992, high NO_3^- concentrations (>15 µM) were observed at 15-60 m, with mean values ranging between 12.17 and 15.23 µM. From 1993 to 1996, a decrease was detected with mean values between 6.22 and 11.05 µM (Table 2, Fig. 4A). Phosphate (PO_4^{3-}) mean values ranged from 1.34 to 2.08 µM. A sharp vertical gradient with a low PO_4^{3-} surface layer (<1.50 µM; 0-10 m) was observed between 1987 and 1993 (Table 2, Fig. 4B). Both nitrate and phosphate showed a deepening of minimum surface values in the water column in 1987 (Figs. 4A and B).

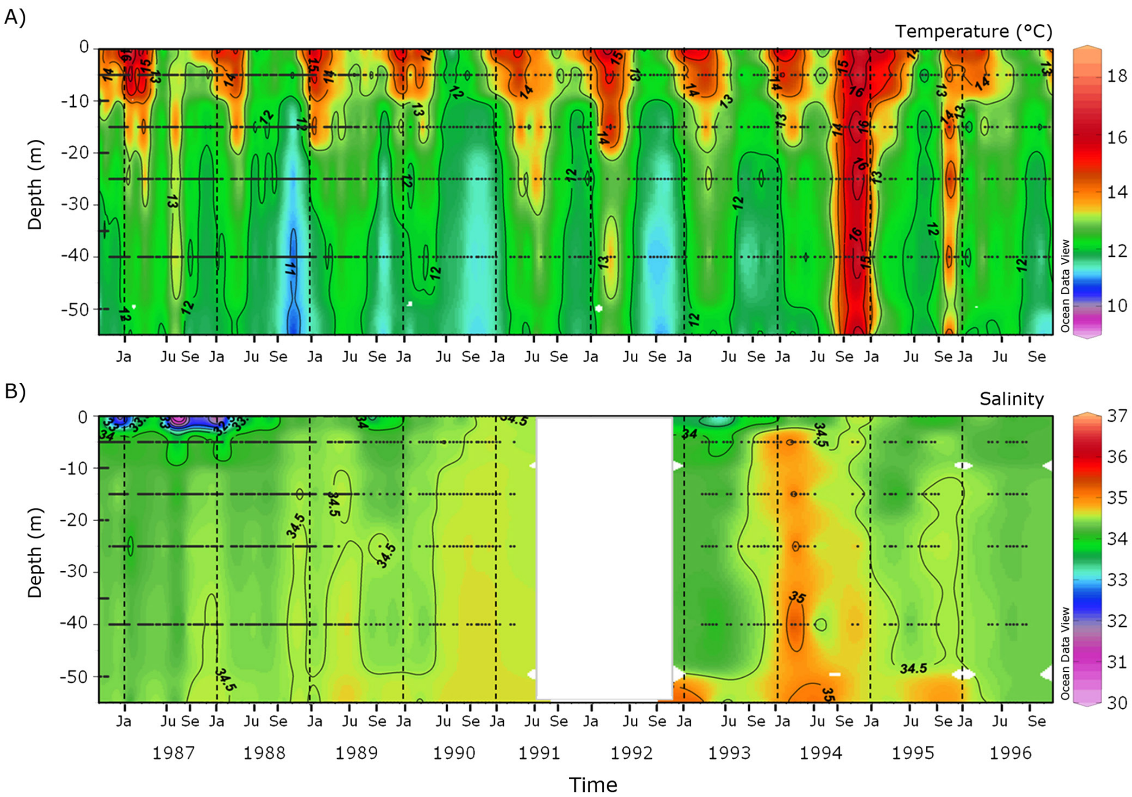

Figure 3. Time series of: A) Temperature and B) Salinity in water column (0-60 m), from August 1986 to December 1996. Black points indicate sampling depths. White area represents no registered data / Serie temporal de: A) Temperatura y B) Salinidad en la columna de agua (0-60 m), desde agosto de 1986 hasta diciembre de 1996. Puntos negros indican las profundidades de muestreo. Áreas blancas indican no datos

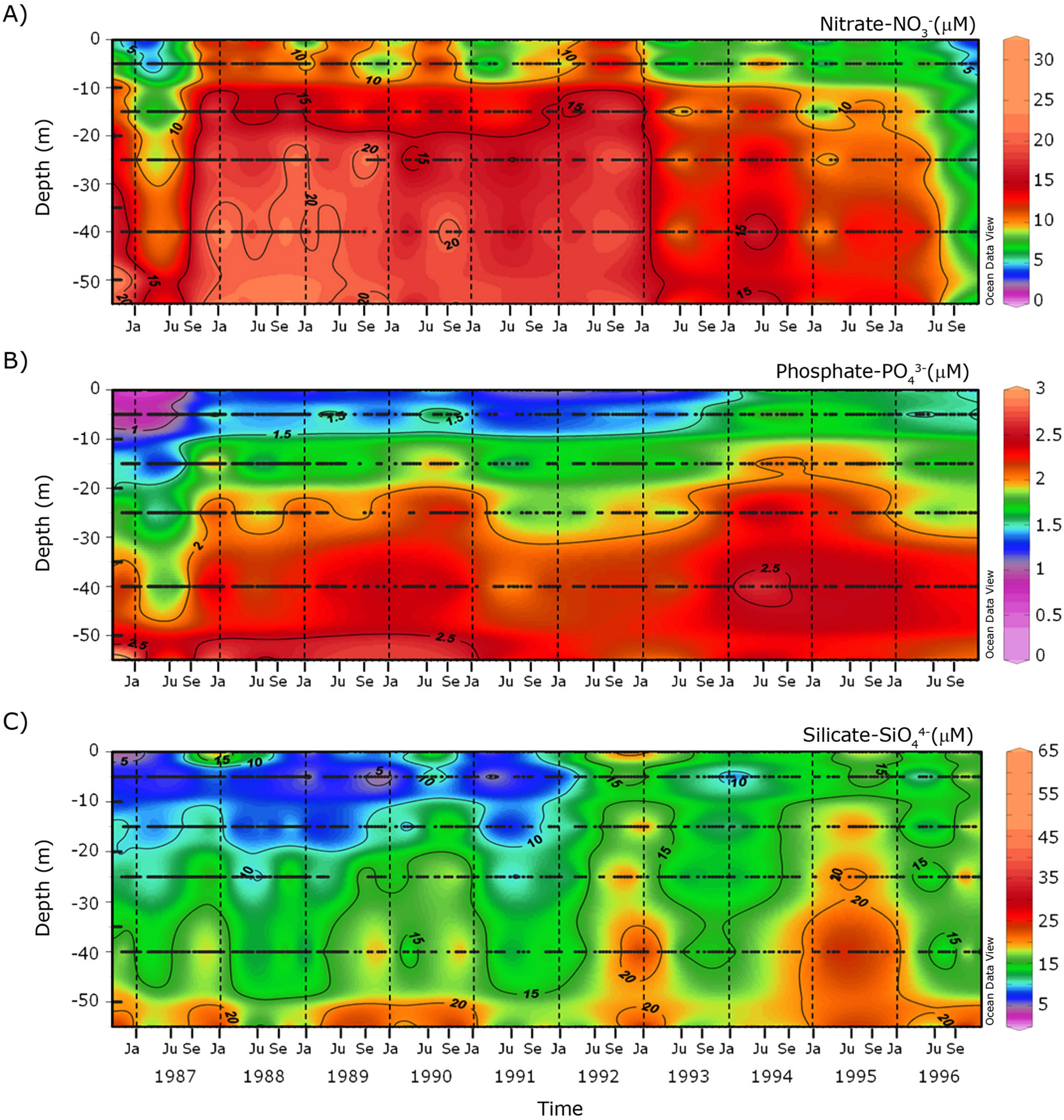

Figure 4. Time series of nutrients concentration: A) Nitrate-NO_3^-, B) Phosphate-PO_4^{3-} and C) Silicate-SiO_4^{4-} in water column (0-60 m), from August 1986 to December 1996. Black points indicate sampling depths / Serie temporal de la concentración de nutrientes: A) Nitrato-NO_3^-, B) Fosfato-PO_4^{3-} y C) Silicato- SiO_4^{4-} en la columna de agua (0-60 m). Puntos negros indican las profundidades de muestreo

Silicate concentrations (SiO_4^{4-}) ranged between 7.54 and 18.39 μM. Similar to phosphate, silicate displayed low surface concentrations (<10 μM; 0-10 m) during the first years of the study (1987-1991). However, enrichment occurred between 1992 and 1996, which had the highest annual mean values (18.39 μM) and the maximum concentrations (64.10 μM) of the entire study period (Table 2, Fig. 4C).

Phytoplankton biomass (Chl-*a*) had mean values that ranged from 1.23 to 3.45 mg m^{-3}. A sub-surface (5-10 m) maximum can be observed, but this one decreased from 1988 to 1994-95 when Chl-*a* dropped below 1.5 mg m^{-3}. During 1988 and 1996 high Chl-*a* concentrations, over 3,0 mg m^{-3} to 20-25 m, were registered (Table 3); contrasting to 1994 and 1995 years that had the lowest mean values of phytoplankton biomass (Table 3; Fig. 5A).

Table 3. Inter-annual variability of: phytoplankton biomass (Chl-*a*; mg m⁻³), and total abundance (Total Abu.) of diatoms and dinoflagellates (cells L⁻¹). Mean ± standard deviation values / Variabilidad inter-anual de: la biomasa del fitoplancton (Chl-*a*; mg m⁻³), y la abundancia total (Total Abu.) de diatomeas y dinoflagelados (céls. L⁻¹). Valores del promedio ± desviación estándar

	Chl-*a* (0-30 m)	Diatoms (Total Abu.) x10³	Dinoflagellates (Total Abu.) x10³
1987	3.07 ± 3.69*	455.56 ± 687.62	66.37 ± 283.55
1988	3.45 ± 3.43*	790.68 ± 1606.52	14.30 ± 41.63
1989	2.76 ± 3.28*	898.98 ± 1466.93	16.06 ± 45.57*
1990	2.43 ± 3.41*	826.74 ± 1388.47	1.91 ± 2.98*
1991	2.07 ± 2.95	622.84 ± 889.25	2.60 ± 4.45
1992	2.69 ± 4.18	1064.58 ± 1572.46	1.24 ± 2.39
1993	2.57 ± 3.80	988.22 ± 1788.92	21.89 ± 70.34
1994	1.23 ± 1.44	418.31 ± 776.39	0.88 ± 1.58
1995	1.50 ± 2.14*	463.39 ± 812.53	0.57 ± 0.78
1996	3.44 ± 4.19*	613.04 ± 816.79	7.55 ± 14.51

*$P < 0.05$ statistically significant

The diatom inter-annual mean abundances ranged between 418.31x10³ and 1,064.58x10³ cells L⁻¹. The highest mean value was registered in 1992. Otherwise 1994 showed the lowest abundance in coincidence with lowest Chl-*a* values. In 1988, 1989, 1990, 1992, and 1993 high annual mean values were found (Table 3). In 1988 (November, 0 m) diatoms abundance registered highest value overpassing 10,000x10³ cells L⁻¹ (Fig. 5B).

Overall, dinoflagellates were in low abundance versus diatoms (10-220 fold lower), which clearly dominated the area. The dinoflagellate abundance means values (0 and 10 m) ranged between 0.57 and 66.37x10³ cells L⁻¹. High abundance events were observed especially in the autumn of 1987 when the highest value was recorded (>840 x 10³ cells L⁻¹, Fig. 5C). Similar events occurred in 1988, 1989, and 1993 when high mean annual values (~14-22x10³ cells L⁻¹) were registered (Fig. 5C, Table 3).

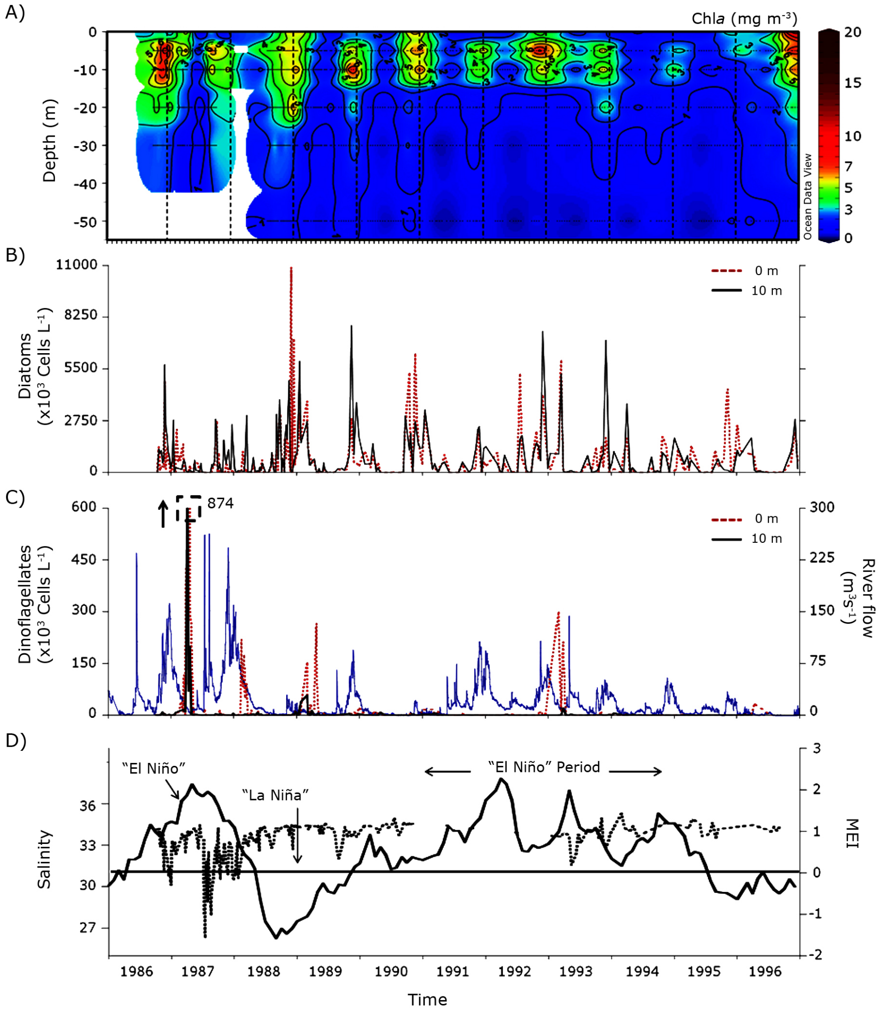

Figure 5. Time series of: A) Phytoplankton biomass (Chl-*a*, 0-50 m), B) Diatoms and C) Dinoflagellates abundance (red and black lines, 0 and 10 m), Aconcagua river flow (blue line), D) Sea surface salinity (discontinuous line) and MEI index (continuous line), from August 1986 to December 1996 / Serie temporal de: A) la biomasa del fitoplancton (Chl-*a*, 0-50 m), B) Abundancia de diatomeas y C) dinoflagelados (líneas roja y negra, 0 y 10 m), caudal del río Aconcagua (línea azul), D) Salinidad superficial (línea discontinua) e índice MEI (línea continua)

According to cluster analysis results, although 1987 was an outlier, high degrees of similarity were reached (>75%) among inter-annual variability of oceanographic conditions and phytoplankton along with surface values of upwelling index (UI) and river flow (Fig. 6). Furthermore, two statistically significant different periods can be observed: 1988-1992 and 1993-1996 (F= 7.5, $P < 0.01$; Fig. 6).

ENSO influence and time-series trend

Different events related to "El Niño"-EN (1987, 1990 to 1995) and "La Niña"-LN (1988, 1989, and 1996) were observed. The highest MEI value occurred in 1987 (~2.1, May), and the lowest was in 1988 (~ -1.6, September). The 1988 to 1992 period showed the MEI index increase. It moved from the negative values of LN-1988 to positive EN values with a maximum in 1992. The MEI index decreased from 1993 to 1996 (Fig. 5D).

In general, EN conditions (1986-1987 and 1990-1993) led to high Aconcagua River flow events. During these events, the surface salinity drop coincided with a high abundance of dinoflagellates (Fig. 5C-D).

Results showed a significant difference in both oceanographic conditions and in phytoplankton abundance and biomass, during EN/LN events (Tables 1, 2 and 3). Strongest ENSO events occurred between EN-1987 and LN-1988: salinity, temperature, and NO_3^-, PO_4^{3-} and SiO_4^{4-} concentrations together with phytoplankton biomass, UI, and river flow showed significant differences (Tables 1, 2 and 3).

During EN-1987 lower values of salinity, nitrate and phosphate concentrations, and phytoplankton biomass were observed versus LN-1988 when colder, saltier, and nutrient rich upwelled water were observed (Tables 1, 2 and 3). Similar results were obtained from LN-1989 to EN-1990 (Tables 1, 2 and 3). However, non-significant differences were observed for the temperature and salinity during the EN-1995 to LN-1996 transition (Table 2). The phytoplankton biomass (Chl-*a*) showed significant differences in all cases with an increment under LN conditions (1988, 1989, 1996; Table 3).

The results showed no trend in temperature, salinity, phosphate, silicate and diatoms abundance along the time series, but the UI showed a significant positive trend ($P < 0.05$). Aconcagua River flow, nitrate concentration, phytoplankton biomass (Chl-*a*), and dinoflagellates abundance had a significant negative trend ($P < 0.01$).

Discussion

Alongshore upwelling favourable winds (S-SW) with maximum during the spring and summer have been described in central Chile (~30º-37ºS) (Strub *et al*. 1998, Shaffer *et al*. 1999, Sobarzo *et al*. 2007, Schneider *et al*. 2017). This study revealed persistent upwelling favourable conditions in Valparaíso Bay from 1986 to 1996. These quasi-permanent upwelling favourable conditions have been observed year-to-year through the S-SW winds domain in the bay, especially in the spring/summer period when UI values range between ~100 and 500 $m^3 s^{-1}$. A Similar pattern of UI (spring-summer ~100-400 $m^3 s^{-1}$) have been recently registered in Concepcion Bay (~36.5ºS) (Anabalón *et al*. 2016).

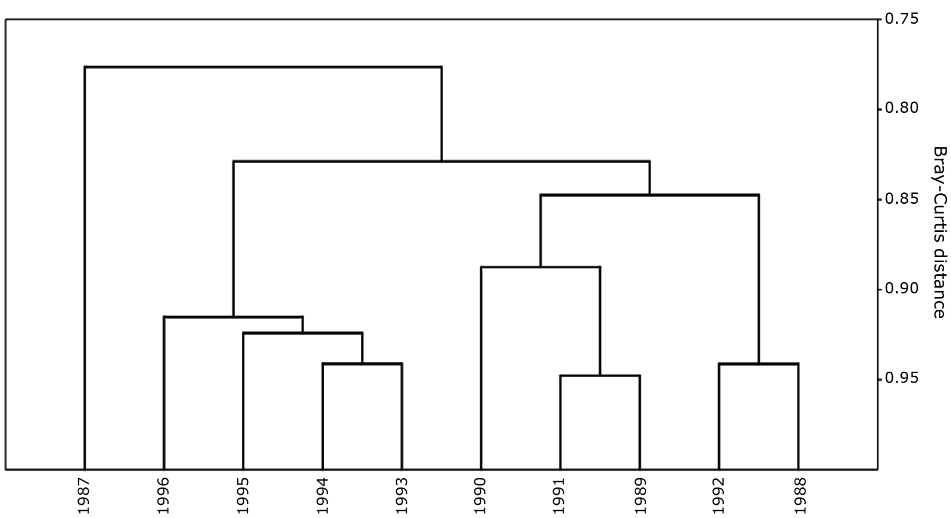

Figure 6. Cluster analysis, by Bray-Curtis Index, of the degree of similarity among bio-oceanographic characteristics, upwelling index (UI) and river flow / Análisis Cluster, por Bray-Curtis, del grado de similaridad entre las características bio-oceanográficas, el índice de surgencia (UI) y el caudal del río

During this time series, upwelling activity observed in Valparaíso Bay seems to sustain the phytoplankton biomass sub-surface maximum every year, especially during the spring and summer periods when high chlorophyll-*a* values (>3 mg m^{-3}) are observed (Fig. 5A). Although nutrients concentration (NO_3^-, PO_4^{3-} and SiO_4^{4-}) in the bay showed wide ranges along time series, values were similar to those described along coastal Chilean system with high nutrients concentrations under intense favourable upwelling activity (Anabalón *et al*. 2016, Testa *et al*. 2017). In central Chile (~30º-37ºS), a seasonal signal of phytoplankton with increases under upwelling favourable winds during spring-summer after arrival of nutrient-rich water have been well documented (Avaria *et al*. 1989, Thiel *et al*. 2007, Anabalón *et al*. 2016). Anabalón *et al*. (2016) confirmed this relationship in the coastal area off Concepcion (~36.5ºS) with a strong correlation between seasonal phytoplankton and UI signals.

Inter-annual changes in both phytoplankton biomass and oceanographic conditions have been observed in the bay. Thus, changes in oceanographic conditions under a strong EN event (1987) were observed, which were marked by a drop in salinity, an increase in temperature, and a decrease in nitrate and phosphate concentrations. Cluster analysis shows 1987 as a different year in oceanographic conditions, river flow and phytoplankton biomass.

Although the intensity of the EN-1987 was lower than the EN-1982/83 and EN-1997/98 events, changes in the bay were similar to those described during previous events (Prado & Sievers 1987, Iriarte *et al*. 2000, Ulloa *et al*. 2001, Contreras *et al*. 2007). During EN-1982/83 and 1997/98, studies in Quintero (~32ºS) and Concepcion Bay (~36ºS) in Chile showed a deepening of the thermocline with warming in the water column and a lack of nutrients (Prado & Sievers 1987, Contreras *et al*. 2007). Similar conditions were described at the north of Chile in the Antofagasta coastal area (~23º-24ºS) during EN-1997/98 (Iriarte *et al*. 2000, Ulloa *et al*. 2001).

Cluster analysis also showed two different extended periods (~5 years) along time series that coincided with ENSO variability (MEI increase/decrease signal). The 1988-1992 period had lower temperature but higher levels of nitrates, phytoplankton biomass, and diatoms abundance (increase) compared to 1993-1996 period (decrease). These results have showed an inter-annual variability in the bio-oceanographic conditions of bay with ENSO forcing as a modulating factor of this variation. Although no previous studies have displayed a similar relationship, a study in the coastal area of central Chile (35º-38ºS) has shown a connection between phytoplankton biomass and ENSO forcing (Correa-Ramirez *et al*. 2012).

While several studies have showed changes in oceanographic conditions associated with ENSO, there are scarce *in situ* evidences about the effects on phytoplankton along the coast of Chile. Here, the lowest phytoplankton biomass values were registered during the extended EN period (1990-1995) (Table 3). Likewise, significant differences were detected between EN and LN year-to-year with lower biomass values in 1987, 1990, and 1995 under EN conditions (Table 3). Similar decreases in phytoplankton biomass under EN conditions were registered in the north of Chile (18º-27ºS) during EN-1982/83 and 1997/98 (Avaria & Muñoz 1987, Ulloa *et al*. 2001, Iriarte & González 2004). Moreover, there was a significant decrease in primary production (PP) observed close to coastal Antofagasta (~23º-24ºS) during El Niño 1997/98 (Pizarro *et al*. 2002, Iriarte & González 2004).

In central Chile (~28º-38ºS), ENSO events impact on oceanographic conditions and river flow. In the Valparaíso region, the increase in Aconcagua River flow has been previously reported under EN events (Pellicciotti *et al*. 2007). In addition, a decrease in sea surface salinity (~30) associated with high river discharge was observed in the area under EN events, both in 1982/83 and 1997/98 (Prado & Sievers 1987, Sievers & Vega 2000). In this study, remarkably high river flow events preceded an increase in dinoflagellate abundance (Fig. 5C) with the maximum mean value over the study period (874 x 10^3 cells L^{-1}, Fig. 5C) at the early stage of El Niño 1986/87 (Fig. 5C-D). Similar situations were observed afterwards in 1988 and 1993 (Fig. 5C). Dinoflagellate abundance in Valparaíso Bay are highest at the end of summer and autumn (Avaria & Orellana 1975), but not at this abundance level (>40 times higher) suggesting that increments in the river flow would favour high dinoflagellates abundance. Although no similar connections has been observed in the Chilean coast, studies in the coastal bays of California and China have suggested a relationship between rivers' discharges and dinoflagellates abundance due to favourable conditions for nutrients and stratification (Stoecker *et al*. 2008, Zhou *et al*. 2008, Lan *et al*. 2009, Pitcher *et al*. 2010).

Positive trends of upwelling in the area were seen during the study period (1986-1996) (Fig. 2B), but this was accompanied by a fall in the phytoplankton biomass (chlorophyll *a*, Chl-*a*) and dinoflagellates abundance. Similar trends for UI and phytoplankton biomass were observed by Corredor-Acosta *et al*. (2015) at central-south Chile (35º-38ºS) during 2002-2012. They link the reduction of chlorophyll to the development of unfavourable conditions of turbulence for phytoplankton growth due to the coastal upwelling intensification registered in the area.

Here, new efforts have been done to understand the influence of inter-annual oceanographic and hydrographical conditions on the phytoplankton in Valparaíso Bay. The time series analysis revealed that strong S-SW winds drive a quasi-permanent upwelling activity that seems to maintain the nutrient availability to fuel the phytoplankton in the bay. The most important year-to-year changes in the oceanographic conditions were observed in 1987 when an increase in temperature and a lack of nutrients and phytoplankton biomass were associated with EN conditions.

Acknowledgments

We would like to acknowledge the Facultad de Ciencias del Mar y de Recursos Naturales, Universidad de Valparaíso to facilitate the oceanographic data set from the Montemar fixed station, specially to Dr. Mario Cáceres. Thanks to Dr. Manuel Castillo for his support and advice in wind data processing. We thank to phytoplankton and marine chemistry laboratories staff involved in Montemar fixed station monitoring. This work was supported by the projects CONICYT Center of Excellence FONDAP/15110009 and PAI/ACADEMIA 7912010002.

Literature cited

Anabalón V, CE Morales, HE González, E Menschel, W Schneider, S Hormazabal, L Valencia & R Escribano. 2016. Micro-phytoplankton community structure in the coastal upwelling zone off Concepción (central Chile): Annual and inter-annual fluctuations in a highly dynamic environment. Progress in Oceanography 149: 174-188.

Avaria S & E Orellana. 1975. Estudios de ecología fitoplanctónica en la Bahía de Valparaíso. III. Fitoplancton 1972-73. Revista de Biología Marina 15(3): 207-226.

Avaria S & P Muñoz. 1987. Effects of the 1982-1983 El Niño on the marine phytoplankton off Northern Chile. Journal of Geophysical Research 92(C13): 14369-14382.

Avaria S, P Muñoz & M Braun. 1988. El fitoplancton frente a Península Los Molles, Valparaíso, Chile (32º45'S) y su relación con "El Niño" 1982-83. Revista de Biología Marina 24(1): 1-35.

Avaria S, S Palma, H Sievers & N Silva. 1989. Review of the oceanographic, chemical and planktological aspects of the Valparaíso Bay and adjacents areas. Biología Pesquera 18: 67-96.

Bakun A. 1973. Coastal upwelling indexes, west coast of North America, 1946-71. NOAA Technical Report NMFS SSRF 671: 1-103.

Contreras S, S Pantoja, C Neira & CB Lange. 2007. Biogeochemistry of surface sediments off Concepcion (~36ºS), Chile: El Niño *vs*. non-El Niño conditions. Progress in Oceanography 75: 576-585.

Correa-Ramirez MA, SE Hormazabal & CE Morales. 2012. Spatial patterns of annual and interannual surface chlorophyll-a variability in the Peru-Chile Current System. Progress in Oceanography 92/95: 8-17.

Corredor-Acosta A, CE Morales, S Hormazabal, I Andrade & MA Correa-Ramirez. 2015. Phytoplankton phenology in the coastal upwelling region off central-southern Chile (35ºS-38ºS): Time-space variability, coupling to environmental factors, and sources of uncertainty in the estimates. Journal of Geophysical Research, Oceans 120: 813-831.

Grasshoff K. 1983. Determination of nitrate. In: Grasshoff K, M Ehrhardt & K Kremling (eds). Methods of seawater analysis, pp. 143-150. Verlag Chemie, Weinheim.

Hammer Ø, DAT Harper & PD Ryan. 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica 4(1): 1-9.

Iriarte JL & H González. 2004. Phytoplankton size structure during and after the 1997/98 El Niño in a coastal upwelling area of the northern Humboldt Current System. Marine Ecology Progress Series 269: 83-90.

Iriarte JL, G Pizarro, VA Troncoso & M Sobarzo. 2000. Primary production and biomass of size-fractionated phytoplankton off Antofagasta, Chile (23-24ºS) during pre-El Niño and El Niño 1997. Journal of Marine Systems 26: 37-51.

Koroleff F. 1983. Determination of phosphorus. En: Grasshoff K, M Ehrhardt & K Kremling (eds). Methods of seawater analysis, pp. 125-139. Verlag Chemie, Weinheim.

Lan W, B Huang, M Dai, X Ning, L Huang & H Hong. 2009. Dynamics of heterotrophic dinoflagellates off the Pearl River Estuary, northern South China Sea. Estuarine, Coastal and Shelf Science 85: 422-430.

Léniz B, CA Vargas & R Ahumada. 2012. Characterization and comparison of microphytoplankton biomass in the lower reaches of the Biobío River and the adjacent coastal area off Central Chile during autumn-winter conditions. Latin American Journal of Aquatic Research 40(4): 847-857.

Lohrenz CJ & SW Jeffrey. 1980. Determination of chlorophyll in seawater. UNESCO Technical Papers Marine Science 35: 1-20.

Marín V & GR Olivares. 1999. Estacionalidad de la productividad primaria en bahía Mejillones del sur (Chile): una aproximación proceso-funcional. Revista Chilena de Historia Natural 72: 629-641.

Masotti I, P Aparicio-Rizzo, MA Yevenes, R Garreaud, L Belmar & L Farias. 2018. The influence of river discharge on nutrient export and phytoplankton biomass off the Central Chile coast (33º-37ºS). Seasonal cycle and interannual variability. Frontiers in Marine Science: Coastal Ocean Processes, <doi: 10.3389/fmars.2018.00423>

Montecinos A & F Gómez. 2010. ENSO modulation of the upwelling season off southern-central Chile. Geophysical Research Letters 37: L02708, <doi: 10.1029/2009GL041739>

Murphy J & JP Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27: 31-36.

Parsons TR, V Maita & CM Lalli. 1984. A manual of chemical and biological methods for seawater analysis, 173 pp. Pergamon Press, Oxford.

Pellicciotti F, P Burlando & K Van Vliet. 2007. Recent trends in precipitation and streamflow in the Aconcagua River Basin, central Chile. Glacier Mass Balance Changes and Meltwater Discharge. IAHS Assembly in Foz do Iguaçu, Brazil, 2005. IAHS Publications 318: 17-38. Centre for Ecology and Hydrology, Wallingford.

Pérez CA, MD DeGrandpre, NA Lagos, GS Saldías, E-K Cascales & CA Vargas. 2015. Influence of climate and land use in carbon biogeochemistry in lower reaches of rivers in central-southern Chile: Implications for the carbonate system in river-influenced rockyshore environments. Journal of Geophysical Research: Biogeosciences 120: 673-692.

Pitcher GC, FG Figueiras, BM Hickey & MT Moita. 2010. The physical oceanography of upwelling systems and the development of harmful algal blooms. Progress in Oceanography 85(1-2): 5-35.

Pizarro G, JL Iriarte & V Montecino. 2002. Mesoscale primary production and bio-optical variability off Antofagasta (23-24ºS) during the transition to El Niño 1997-1998. Revista Chilena de Historia Natural 75: 201-215.

Prado R & HA Sievers. 1987. Distribution of physical and chemical water characteristics off peninsula Los Molles, Chile (32º45'S) and its relation to the "El Niño" 1982/83 phenomenon. Revista de Biología Marina 23(1): 31-75.

Rutllant J & V Montecino. 2002. Multiscale upwelling forcing cycles and biological response off north-central Chile. Revista Chilena de Historia Natural 75: 217-231.

Schneider W, D Donoso, J Garcés-Vargas & R Escribano. 2017. Water-column cooling and sea surface salinity increase in the upwelling region off central-south Chile driven by a poleward displacement of the South Pacific High. Progress in Oceanography 151: 38-48.

Shaffer G, S Hormazabal, O Pizarro & S Salinas. 1999. Seasonal and interannual variability of currents and temperature off central Chile. Journal of Geophysical Research 104(29): 951-961.

Sievers HA & SA Vega. 2000. Physical-chemical response of Valparaíso Bay to upwelling generated at Point Curaumilla and to El Niño Phenomenon. Revista de Biología Marina y Oceanografía 35(2): 153-168.

Silva N & A Valdenegro. 2003. Evolución de un evento de surgencia frente a punta Curaumilla, Valparaíso. Investigaciones Marinas 31(2): 73-89.

Sobarzo M, L Bravo, D Donoso, J Garcés-Vargas & W Schneider. 2007. Coastal upwelling and seasonal cycles that influence the water column over the continental shelf off central Chile. Progress in Oceanography 75: 363-382.

Stoecker DK, AE Thessen & DE Gustafson. 2008. "Windows of opportunity" for dinoflagellate blooms: Reduced microzooplankton net growth coupled to eutrophication. Harmful Algae 8: 158-166.

Strickland JDH & TR Parsons. 1968. A practical handbook of seawater analysis. Bulletin, Fisheries Research Board of Canada 167: 1-311.

Strub PT, JM Mesias, V Montecino, J Rutllant & S Salinas. 1998. Coastal ocean circulation off western South America. In: Robinson AR & KH Brink (eds). The Sea 11: 273-313. John Wiley & Sons, New York.

Testa G, I Masotti & L Farias. 2018. Temporal variability in net primary production in an upwelling area off Central Chile (36ºS). Frontiers in Marine Sciences: Coastal Ocean Processes, <doi: 10.3389/fmars.2018.00179>

Thiel M, EC Macaya, E Acuña, WE Arntz, H Bastias, K Brokordt, PA Camus, JC Castilla, LR Castro, M Cortés, CP Dumont, R Escribano, M Fernández, JA Gajardo, CF Gaymer, I Gomez, AE González, HE González, PA Haye, J-E Illanes, JL Iriarte, DA Lancellotti, G Luna-Jorquera, C Luxoro, PH Manríquez, V Marín, P Muñoz, SA Navarrete, E Perez, E Poulin, J Sellanes, HH Sepúlveda, W Stotz, F Tala, A Thomas, CA Vargas, JA Vasquez & A Vega. 2007. The Humboldt Current System of Northern and Central Chile. Oceanographic processes, ecological interactions and socioeconomic feedback. Oceanography and Marine Biology: An Annual Review 45: 195-344.

Ulloa O, R Escribano, S Hormazabal, RA Quiñones, RR González & M Ramos. 2001. Evolution and biological effects of the 1997-98 El Niño in the upwelling ecosystem off northern Chile. Geophysical Research Letters 28(8): 1591-1594.

Utermöhl H. 1958. Zur Vervollkommung der quantitativen Phytoplankton-Methodik. Mitteilungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 9: 1-38.

Wolter K & MS Timlin. 2011. El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). International Journal of Climatology 31(7): 1074-1087.

Zhou M-J, Z-L Shen & R-C Yu. 2008. Response of a coastal phytoplankton community to increased nutrient input from the Changjiang (Yangtze) River. Continental Shelf Research 28: 1483-1489.

Received 11 September 2018 and accepted 22 January 2019

Associate Editor: Gabriela Muñoz C.