17(2)

A two-decade record of surface chlorophyll "a" and temperature in offshore waters of the Basque country (southeastern Bay of Biscay)





Marta Revilla Ángel Borja Almudena Fontán Javier Franco Manuel González Victoriano Valencia Revilla, M., Borja, A., Fontán, A., Franco, J., González, M., and Valencia, V., 2010. A two-decade record of surface chlorophyll "a" and temperature in offshore waters of the Basque country (southeastern Bay of Biscay). *'Revista de Investigación Marina'*. 17(2): 13-20.

La serie '*Revista de Investigación Marina*', editada por la Unidad de Investigación Marina de Tecnalia, cuenta con el siguiente Comité Editorial:

- Editor: Dr. Ángel Borja
- Adjunta al Editor: Dña. Mercedes Fernández Monge e Irantzu Zubiaur (coordinación de las publicaciones)
- Comité Editorial: Dr. Lorenzo Motos Dr. Adolfo Uriarte Dr. Michael Collins Dr. Javier Franco D. Julien Mader Dña. Marina Santurtun D. Victoriano Valencia Dr. Xabier Irigoien Dra. Arantza Murillas Dr. Josu Santiago

La '*Revista de Investigación Marina*' de Tecnalia edita y publica investigaciones y datos originales resultado de la Unidad de Investigación Marina de Tecnalia. Las propuestas de publicación deben ser enviadas al siguiente correo electrónico <u>aborja@azti.es</u>. Un comité de selección revisará las propuestas y sugerirá los cambios pertinentes antes de su aceptación definitiva.



Edición: 1.ª Enero 2010 © AZTI-Tecnalia ISSN: 1988-818X Unidad de Investigación Marina Internet: www.azti.es Edita: Unidad de Investigación Marina de Tecnalia Herrera Kaia, Portualdea 20010 Pasaia Foto portada: © Iñigo Onandia (AZTI-Tecnalia)

© AZTI-Tecnalia 2009. Distribución gratuita en formato PDF a través de la web: www.azti.es/RIM

A two-decade record of surface chlorophyll "a" and temperature in offshore waters of the Basque country (southeastern Bay of Biscay)

Marta Revilla*, Ángel Borja, Almudena Fontán, Javier Franco, Manuel González, Victoriano Valencia

Abstract

The present study analyses the seasonal and interannual variability of the sea surface chlorophyll "a" and temperature, at an offshore station in the southeastern Bay of Biscay. For the period 1986-2008, physicochemical and chlorophyll "a" data were obtained annually by means of CTD profiles and bottle samples at station D2 (43° 27' N, 01° 55' W). This offshore station is considered to be non-impacted by anthropogenic influence, due to its distance (13 km) from the main pollution sources on land; as such, this makes it suitable for exploring the response of phytoplankton to oceano-meteorological forcing. The surveyed months and the total number of surveys per year have been very variable (from 2 to 12). In spite of the irregular sampling, a significant increasing trend in the sea surface temperature has been identified ($1.35.10^{-2}\pm1.07.10^{-2}$ °C.year⁻¹). The trend is very similar to that observed at a neighbouring inshore station (Aquarium, Donostia-San Sebastián), for which daily records of temperature are available. At the offshore station, chlorophyll "a" presents a slight decreasing trend (-3.8.10⁻³±4.7.10⁻³ µg.l⁻¹.year⁻¹) over the past two decades, which is also significant statistically. Although these results support the hypothesis that phytoplankton biomass is responding to changes in the water temperature within the southern Bay of Biscay, the response could be very slight (at least in surface waters). Further research is required to determine multi-decadal trends of chlorophyll "a" at other depths through the water column.

Resumen

En este estudio se analiza la variabilidad estacional e interanual de la concentración de clorofila "a" y la temperatura superficial del mar en una estación situada en mar abierto, sobre la plataforma, en el sudeste del Golfo de Vizcaya. Durante el periodo 1986-2008 se tomaron datos de variables físico-químicas y de clorofila "a", todos los años, mediante CTD y muestras de agua recogidas con botella, en la estación D2 (43° 27' N, 01° 55' W). Esta estación se considera libre de impacto antropogénico, dada su distancia a las principales fuentes de contaminación en la costa (13 km). Debido a esto, dicha estación es adecuada para el estudio de la respuesta del fitoplancton al forzamiento océano-meteorológico. Los meses en los que se realizaron los muestreos, así como el número de muestreos por año, fueron muy variables (de 2 a 12). A pesar de la irregularidad del muestreo, se identificó una tendencia significativa en la temperatura superficial, que aumentó a una tasa de 1,35.10⁻²±1,07.10⁻² °C.año⁻¹. Esta tendencia es muy similar a la observada en una estación cercana, situada en el litoral (Aquarium de Donostia-San Sebastián), de la cual se dispone de datos diarios de temperatura. En la estación D2, durante las últimas dos décadas la clorofila presentó una tendencia de leve descenso $(-3,8.10^{-3}\pm4,7.10^{-3}\mu g.l^{-1}.año^{-1})$, que resultó también significativa. Aunque estos resultados apoyan la hipótesis de que la biomasa fitoplanctónica está respondiendo a los cambios en la temperatura del sudeste del Golfo de Vizcaya, la respuesta podría ser muy débil (al menos, en la superficie del mar). Se recomienda continuar investigando para determinar las tendencias, a largo plazo, de la clorofila a otras profundidades de la columna de agua.

Introduction

Lying at the base of the marine food-webs, marine phytoplankton is altered greatly by the main hydrometeorological and oceanographic factors (e.g., temperature, salinity, light and mixing-stratification processes). In order to understand the biological responses to natural oscillations within the environment,

¹ AZTI-Tecnalia; Marine Research Division; Herrera Kaia, Portualdea s/n; 20110 Pasaia; Spain, mrevilla@pas.azti.es

* Corresponding author

long-term series of the most relevant variables is an important prerequisite.

At a global scale, there is a strong negative relationship between satellite-derived primary production and sea surface temperature (SST), with a closely coupled relationship between ocean productivity and climate variability (Reid *et al.*, 2009). In the North Atlantic and over multi-decadal periods, changes in phytoplankton species and communities have been associated with Northern Hemisphere SST trends and variations in the North Atlantic Oscillation (NAO) index (Beaugrand and Reid, 2003). Whilst at an interannual time-scale, correlations between SST and phytoplankton are weak, due to high variance inherent in phytoplankton populations (Reid *et al.*, 2009). Over the whole Northeast Atlantic, an increase in phytoplankton biomass in cooler regions and a decrease in warmer regions have been reported (Richardson and Schoeman, 2004).

In the Northern hemisphere, some authors have related recent phytoplankton fluctuations to the hydrometeorological processes that, in turn, are likely to control physical parameters affecting phytoplankton growth (e.g., SST and turbulence) (Leterme *et al.*, 2005). Temperature determines the rate at which phytoplankton cells divide; nutrient supply and wind-induced turbulent mixing control the onset of the spring phytoplankton bloom (Sverdrup, 1953). All of these parameters have also been shown to be influenced by the NAO index: the atmospheric variables exerting strong forcing on the ocean and leading to changes in SST, salinity, vertical mixing, circulation patterns and, in northern areas, ice formation (Visbeck *et al.*, 2003).

Previous studies undertaken in the Basque coastal waters have shown that the SST has increased over, approximately, the past 20-30 years (González *et al.*, 2008; Goikoetxea *et al.*, 2009). In the southern Bay of Biscay, Llope *et al.* (2007) have linked the recent warming of the ocean surface with increasing stratification and weaker/shallower winter mixing; these, in turn, can lead to reduced nutrient inputs and stoichiometric changes. In this scenario, it has been hypothesized that primary production will be progressively lower and phytoplankton assemblages will change, which ultimately would affect the food webs and marine resources (Llope *et al.*, 2007). The main objective of this study is to look for long-term trends in chlorophyll "a" concentration (Chl "a"), as a proxy for phytoplankton biomass, in relation to the changes observed in the SST in the Basque coastal waters.

Study Area

Along the Basque coast (southeastern Bay of Biscay), the longest time-series on Chl "a", together with other oceanographical variables (including SST), has been obtained at station D2 (43° 27' N, 01° 55' W), which is located 13.1 km offshore and at a water depth of 110 m (Figure 1). At station D2, Chl "a" and SST have been measured since 1986. On the other hand, the longest time-series on SST within this area corresponds to an inshore station (Aquarium), located adjacent to the city of Donostia-San Sebastián (43° 19' N, 02° 00' W) (Figure 1). At the Aquarium station, SST has been measured since 1946.

Sea surface salinity (SSS), at D2, for the period 1986-2008, was 34.79 ± 0.67 psu (average \pm standard deviation, n=174). This value indicates the presence of 2.3% of continental and rainfall waters in the surface waters of the study area. Continental waters coming from the river basins around the southeastern Bay of Biscay (mainly from the Oria basin to the Adour basin) are, as expected, a factor of fertilisation of the surface waters of the study area (Valencia and Franco, 2004; Díaz *et al.*, 2007; Ferrer *et al.*, 2009). Some peak values of Chl "a" concentration are coincident with low SSS values in the dataset. Nevertheless, within the context of the present study, the pulses of fertilization produced by the continental runoff can be considered as a factor of the hydroclimatic variability in the area; therefore, can be included into the variations of the seasonal and annual cycles.



Figura 1. Map showing location of the sampling station (D2), within the context of the Bay of Biscay. The neighbouring station (Aquarium) is also shown.

Data Material and Methods

Time-series on sea surface Chl "a" and SST from D2 (the offshore station) represent the period between April 1986 and December 2008, with a total of 174 data points over 23 years. The sampling frequency has been very irregular, with 2-12 data points per year. From 1986 to 1990, Chl "a" was estimated in water samples taken at discrete depths (0, 5, 10, 20, 30, 50, 75, 100 m), by Niskin bottles. Water was filtered through Whatman GF/C filters and pigments were extracted in 90% acetone. The absorbance of the extracts was read on a UV/VIS spectrophotometer (Shimadzu). Chl "a" was estimated according to the equations of Jeffrey and Humphrey (1975). SST was measured in the field, at the same depths, by specific sensors. Since 1991, fluorescence and SST have been recorded by CTD at continuous vertical profiles. CTD fluorescence units have been calibrated regularly against spectrophotometer measurements of Chl "a", in natural water samples.

At the Aquarium (inshore station), SST has been measured in bucket samples by means of a thermometer, on a nearly daily basis, always at 10 a.m.

Statistical analysis

In order to study the seasonal variability and the long-term trends in sea surface Chl "a", the data collected in surface waters (0-1 m) at D2 station have been analysed (Figure 2). The annual variability of Chl "a" was studied by means of a non-linear fitting procedure. Thus, the averaged monthly values were calculated from Chl "a" data available since 1986. Subsequently, the monthly data were fitted statistically to a linear combination of basis functions:

$$y^{aprox.}(t) = \sum_{i=1}^{N} C^{i} P_{i}(t)$$

Where:

- y^{aprox.}: estimator of the objective variable y
- $P_i(t)$: basis functions
- *N*: number of basis functions
- Cⁱ: constant coefficients of the linear combination



Figure 2. Data of sea surface chlorophyll "a", at station D2

The coefficients of the linear combination were calculated by means of the Levenberg-Marquardt algorithm (Pres *et al.*, 1989). This methodology was applied also to SST data available from the same sampling station (Figure 3).

The basis functions used to illustrate the annual variability of Chl "a" and SST are shown in Figures 4 and 5, respectively. The *a* parameter (phase lag) was calculated by minimising the function of the absolute deviation of the difference between the statistical fitting and the data as follows:

$$Error(a) = \frac{1}{Ndata} \sum_{j=1}^{Ndata} \left| y^{aprox.}(a, t_j) - y(t_j) \right|$$

Finally, the difference between the measured and the estimated values, for chlorophyll and temperature, was calculated by means of the annual variability obtained from the abovementioned methodology. The linear trend was determined by a method of linear fitting, based upon minimising χ^2 (Pres *et al.*, 1989).

$$\chi^{2} = (1 - r^{2}) \sum_{i=1}^{Ndata} (y_{i} - \overline{y})^{2}$$
$$r = \frac{\sum_{i=1}^{Ndata} (x_{i} - \overline{x}) \cdot (y_{i} - y)}{\sqrt{\sum_{i=1}^{Ndata} (x_{i} - \overline{x})^{2} \cdot \sum_{i=1}^{Ndata} (y_{i} - \overline{y})^{2}}}$$

Results

Sea surface chlorophyll ranged between 0.0 and 3.3 μ gl⁻¹ (Figure 2). SST ranged between 10.98 and 25.05 °C (Figure 3). The error functions, on the basis of the phase lag, corresponding to the Chl "a" and SST data are shown in Figure 6. The optimal value of the phase lag is 32 and 43 days for the chlorophyll and temperature, respectively. These values correspond to the winter maximum in Chl "a" (in early February) and to the winter minimum in SST (in mid February).

The monthly averaged Chl "a" time-series and the corresponding statistical adjustment of the annual variation are shown in Figure 7. The same results for the SST are shown in Figure 8. Within the proposed model, the C¹ and C² coefficients represent the annual



Figure 3. Data of sea surface temperature (SST), at station D2



Figure 4. Basis functions for the statistical adjustment of sea surface chlorophyll "a".



Figure 6. The absolute deviation between the data (sea surface chlorophyll and temperature) and the statistical approximations, for different values of the *a* parameter (phase lag).



Figure 8. Monthly average and standard deviation of sea surface temperature (SST) at station D2. The line indicates the statistical adjustment of the annual variation.



Figure 5. Basis functions for the statistical adjustment of sea surface temperature (SST).



Figure 7. Monthly average and standard deviation of sea surface chlorophyll "a" at station D2. The line indicates the statistical adjustment of the annual variation.



Figure 9. The temporal trend of sea surface chlorophyll "a", at station D2, from 1986 to 2008. Values presented are the difference between the measured data and the data estimated for an average year.

average and the semi-amplitude of the oscillations (chlorophyll or temperature), with respect to the averaged values, respectively. The coefficients are C¹=0.593 µg.l⁻¹, C²=0.232 µg.l⁻¹, C³=-0.029 µg.l⁻¹ and C⁴=-0.057 µg.l⁻¹, for the chlorophyll. For the temperature, the coefficients are C¹=16.638 °C, C²=-5.109 °C and C³=0.936 °C.

The differences between the measured values of Chl "a" and those estimated by statistical fitting are shown in Figure 9. The trend has been calculated from those data, by linear fitting based on minimising χ^2 . A slight decreasing trend (-3.8·10⁻³±4.7·10⁻³ µg·l⁻¹.year⁻¹) is obtained from 1986 to 2008, with the trend being highly significant (*q*=0.65, with *q*>0.1 being highly significant).

The trend analysis obtained, by linear fitting based on minimising χ^2 , for the SST data is shown in Figure 10. In this case, a warming trend of $1.35 \cdot 10^{-2} \pm 1.07 \cdot 10^{-2}$ °C.year⁻¹ is detected for the period 1986-2008. Once again, the trend is highly significant (*q*=0.41).



Figure 10. The temporal trend of sea surface temperature (SST) at station D2, from 1986 to 2008. Values are the difference between the measured data and the data estimated for an average year.

Discussion

The marked seasonality in SST observed at D2 has been reported previously for other areas studied along the Basque coast, both in offshore and inshore waters (Valencia *et al.*, 2004; Revilla *et al.*, 2009). Surface chlorophyll concentrations at the offshore station were within the range typically found by other authors in the shelf waters of the Cantabrian Sea, southern Bay of Biscay (e. g., Serret *et al.*, 1999; Calvo-Díaz *et al.*, 2008; Bode *et al.*, 2009). The seasonal pattern of Chl "a" was coherent with the annual cycle of mixing and stratification that determines the nutrient concentrations and the retention of the phytoplankton biomass in the surface layers of the water column (Valencia and Franco, 2004). Thus, the annual variability in Chl "a" coincided with the typical pattern described for the temperate seas and observed in the Cantabrian Sea by Varela (1996), which is dominated by the spring bloom, followed by a minimum in summer and a secondary bloom in autumn.

In the long-term, the increasing trend observed in SST is in

agreement with that observed in the daily SST series of the Aquarium of Donostia-San Sebastián (inshore station), from the mid 1980s. Such an increase was relatively higher at the Aquarium, at around 2.410⁻² °C.year⁻¹ (González et al., 2008). Similarly, Goikoetxea et al. (2009) found a warming trend in the SST series of the Aquarium, over the past three decades (1977-2007); this was preceded by an opposite cooling trend, over the period 1947-1977. Other authors have reported a warming pattern over the northwestern shelf of the Iberian Peninsula for the recent decades. For example, Bode et al. (2009) showed a rate of increase of 1.810⁻² °C.year⁻¹ over the western area (Galicia) and 1.210⁻² °C.year⁻¹ within the Cantabrian Sea. Variability in the atmosphere can be linked to the warming trend observed in the southeastern Bay of Biscay, as a positive phase of the East Atlantic (EA) pattern has characterized much of the 1977-2004 period (Borja et al., 2008; Goikoetxea et al., 2009). The direct influence of the air temperature appears to be the most influential factor over the SST in this area. However, other parameters, such as irradiance, turbulence and the balance between upwelling and downwelling, contribute in some extent to the SST fluctuations (Borja et al., 2000; Fontán et al., 2008; Goikoetxea et al., 2009).

Regarding long-term trends in chlorophyll "a", Bode et al. (2009) did not identify evidence for a significant change at two sites, in Galicia and the central Cantabrian Sea, respectively, for the past 10-20 years. However, these investigators reported a significant increase in the primary production measured in Galicia, together with significant changes in the relative abundance of phytoplankton species and groups, at both of the sites. Metabolic effects and changes in the phytoplankton composition, driven by SST, have been reported also by other authors. For example, Lassen et al. (2009) undertook mesocosm experiments in Norway, with natural phytoplankton communities prior to the spring bloom. These investigators found that increments of approximately 3-6 degrees, above the *in situ* temperature, caused earlier blooms; they yielded also lower carbon biomass. The increase in temperature affected phytoplankton composition, as the warm treatments presented higher abundance of peridinin-containing dinoflagellates and Thalassionema nitzschioides (a diatom species). Richardson and Schoeman (2004) studied the time-series of the Continuous Plankton Recorder survey, covering the Northeast Atlantic between 1958 and 2002. The regions occupied in their study could be classified into two different turbulence-nutrient regimes, associated with temperature. These investigators concluded that in cooler waters, with relatively strong turbulence and plentiful nutrients, it is likely that warming will boost metabolic rates as well as increase stratification; both processes would lead to increased phytoplankton abundance. In contrast, in warmer and more stratified waters, with limited nutrients, it is likely that warming may reduce total phytoplankton abundance (at least of large cells). The slight decrease in the surface chlorophyll identified in the present study in the southeastern Bay of Biscay is consistent with the conceptual model of Richardson and Schoeman (2004) that describes the effect of increasing temperature in marine systems with seasonal stratification and limited nutrient concentrations. Nevertheless, the response of the phytoplankton biomass to the warming in other areas of the Northwest Iberian Peninsula could differ, in relation to the relative influence of several hydrographic factors at a local scale (e. g., upwelling-downwelling activity and runoff), as explained by Bode *et al.* (2009). Moreover, the main factors likely to affect phytoplankton dynamics (besides light, temperature and salinity) are turbulence and the related nutrient supply (Leterme *et al.*, 2005), which have not been studied in this contribution.

Conclusions and Recommendations for Future Studies

In offshore waters within the southeastern Bay of Biscay, a slight but significant decreasing trend in the sea surface chlorophyll "a" is detected for the past 23 years. Simultaneously, a significant warming trend in the SST data is observed.

Due to the natural high intra- and inter-annual variability of the phytoplankton biomass in the marine systems, it is recommended for future studies to acquire data at a higher frequency and on a more regular basis. For example, by using fluorometers connected to oceano-meteorological stations or buoys. Improvements in data acquisition would permit the application of different statistical packages, which could add more information on the patterns of the physico-chemical and biological variables.

Likewise, temporal trends in the subsurface chlorophyll maxima, or in the vertically integrated concentrations, as well as time-series of other climatic and hydrographical variables (e. g., insolation, rainfall in the catchment areas, stratification and upwelling indexes, nutrient concentration, etc.) should be studied. In order to obtain a better understanding of the response of the phytoplankton biomass to climate change, within the Bay of Biscay, this approach should be undertaken also together with the relationships between the biological and the environmental variables.

Acknowledgements

The Department of Agriculture, Fisheries and Food of the Basque Government has funded this study, by the project "Variaciones", which includes acquisition of the *in situ* data. Part of this study has been funded by the project "K-Egokitzen" from the Department of Industry, Trade and Tourism of the Basque Government. We are grateful to Luis Cuesta from the Marine Research Division of AZTI-Tecnalia, for his help on CTD data acquisition. We thank also Professor Michael Collins for advising us on this contribution. This paper is contribution number 481 from AZTI-Tecnalia (Marine Research Division).

References

- Beaugrand, G., P.C. Reid, 2003. Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Global Change Biology*, 9: 801–817.
- Bode, A., R. Anadón, J.M. Cabanas, R. Carballo, G. Casas, A. Lavín, M. Llope, J. Lorenzo, L. Mene, X.A.G. Morán, E. Nogueira, C. Rodríguez, F. Rozada, M. Ruiz-Villarreal, J. Sostres, E. Teira, L. Valdés, M. Varela, 2009. Year-to-year variability in inorganic nutrients, primary production and phytoplankton biomass off NW Spain from 1990 to 2007. ICES Annual Science Conference, Berlin, Germany. ICES CM 2009/ D13.

- Borja, A., J. Egaña, V. Valencia, J. Franco, R. Castro, 2000. 1947–1997. Estudio y validación de una serie de datos diarios de temperatura del agua del mar en San Sebastián, procedente de su Aquarium. *Ozeanografika*, 3: 139–152.
- Borja, A., A. Fontán, J. Sáenz, V. Valencia, 2008. Climate, oceanography, and recruitment: the case of the Bay of Biscay anchovy. *Fisheries Oceanography*, 17: 477-493.
- Calvo-Díaz, A., X.A.G. Morán, L.A. Suárez, 2008. Seasonality of picophytoplankton chlorophyll *a* and biomass in the central Cantabrian Sea, southern Bay of Biscay. *Journal of Marine Systems*, 72: 271–281.
- Díaz, E., V. Valencia, F. Villate, 2007. Size fractionated seston abundance and biochemical composition, over the anchovy spawning period in the Basque shelf (Bay of Biscay), during years 2000 and 2001. Journal of Experimental Marine Biology and Ecology, 341: 45-59.
- Ferrer, L., A. Fontán, J. Mader, G. Chust, M. González, V. Valencia, A. Uriarte, M.B. Collins, 2009. Low-salinity plumes in the oceanic region of the Basque Country. *Continental Shelf Research*, 29: 970-984.
- Fontán, A., V. Valencia, A. Borja., N. Goikoetxea, 2008. Oceanometeorological conditions in the SE Bay of Biscay for the period 2001-2005. A comparison with the last two decades. *Journal of Marine Systems*, 72: 167–177.
- Goikoetxea, N., A. Borja, A. Fontán, M. González, V. Valencia, 2009. Trends and anomalies in sea-surface temperature, observed over the last 60 years, within the southeastern Bay of Biscay. *Continental Shelf Research*, 29: 1060–1069.
- González, M., J. Mader, A. Fontán, A. Uriarte., L. Ferrer, 2008. Análisis de la tendencia de la temperatura superficial del agua del mar en Donostia-San Sebastián a partir del estudio de la serie del Aquarium (1946-2007). *Revista de Investigación Marina*, 4: 7 pp. www.azti.es/rim
- Jeffrey, S.W., G.F. Humphrey, 1975. New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. *Biochem Physiol Pflanz* 167: 191–4.
- Lassen, M.K., K.D. Nielsen, K. Richardson, K. Garde, L. Schlüter, 2009. The effects of temperature increases on a temperate phytoplankton community – A mesocosm climate change scenario. *Journal* of *Experimental Marine Biology and Ecology*, doi:10.1016/j. jembe.2009.10.014.
- Leterme, S.C., M. Edwards, L. Seuront, M.J. Attrill, P.C. Reid, A.W.G. John, 2005. Decadal basin-scale changes in diatoms, dinoflagellates, and phytoplankton color across the North Atlantic. *Limnology and Oceanography*, 50: 1244-1253.
- Llope, M., R. Anadón, J.A. Sostres, L. Viesca, 2007. Nutrients dynamics in the southern Bay of Biscay (1993–2003): Winter supply, stoichiometry, long-term trends, and their effects on the phytoplankton community. *Journal of Geophysical Research* 112, C07029, doi:10.1029/2006JC003573.
- Press, H.W., B.P. Flannery, S.A. Teulosky, W.T. Vettelrling, 1989. Numerical Recipes. *Cambridge University Press*. Chapter 14. Modelling of Data, 498–546.
- Reid, P.C., A.C. Fischer, E. Lewis-Brown., M.P. Meredith, M.Sparrow, A.J. Andersson, A. Antia, N.R. Bates, U. Bathmann, G. Beaugrand, H. Brix, S. Dye, M. Edwards, T. Furevik, R. Gangstø, H. Hátún, R.R. Hopcroft, M. Kendall, S. Kasten, R. Keeling, C. Le Quéré, F.T. Mackenzie, G. Malin, C. Mauritzen, J. Ólafsson, C. Paull, E. Rignot, K. Shimada, M. Vogt, C. Wallace, Z. Wang, R. Washington, 2009. Chapter 1 Impacts of the Oceans on Climate Change. Advances in Marine Biology. Pages 1-150 in D. W. Sims, editor. Academic Press.
- Revilla, M., J. Franco, J. Bald., A. Borja, A. Laza, S. Seoane, V. Valencia, 2009. Assessment of the phytoplankton ecological status in the Basque coast (northern Spain) according to the European Water Framework Directive. *Journal of Sea Research*, 61: 60–67.
- Richardson, A.J., D.S. Schoeman, 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science*, 305: 1609–1612.
- Serret, P., E. Fernádez, J.A. Sostres, R. Anadón, 1999. Seasonal compensation of microbial production and respiration in a temperate sea. *Marine Ecology Progress Series*, 187: 43–57.

- Sverdrup, H.U., 1953. On conditions of the vernal blooming of phytoplankton. Journal du Conseil International pour l'Exploration de la Mer, 18: 287-295.
- Valencia, V., J. Franco, 2004. Main characteristics of the water masses. In: Borja, A., Collins, M. (Eds.), *Oceanography and Marine Environment* of the Basque Country. Elsevier, Amsterdam, pp. 197–232.
- Valencia, V., J. Franco, A.Borja, A. Fontán, 2004. Hydrography of the Southeastern Bay of Biscay. In: Borja, A., Collins, M. (Eds.), *Oceanography and Marine Environment of the Basque Country*. Elsevier, Amsterdam, pp. 159–194.
- Varela, M. 1996. Phytoplankton ecology in the Bay of Biscay. Scientia Marina, 60 (Supl. 2): 45–53.
- Visbeck, M., E.P. Chassignet, R. Curry, T. Delworth, B. Dickson, G. Krahmann, 2003. The ocean's response to North Atlantic Oscillation variability, p. 113–146. In J. W. Hurrell, Y. Kushnir, G. Ottersen, and M. Visbeck [eds.], The North Atlantic Oscillation: Climate significance and environmental impact. *Geophysical Monograph Series*, No. 134.



azti tecnalia

Txatxarramendi ugartea z/g 48395 Sukarrieta (Bizkaia) Tel.: +34 94 657 40 00 Fax: +34 94 657 25 55 Herrera Kaia, Portualdea z/g 20110 Pasaia (Gipuzkoa) Tel.: +34 94 657 40 00 Fax: +34 94 657 25 55 Parque Tecnológico de Bizkaia Astondo bidea. Edificio 609. 48160 Derio (Bizkaia) Tel.: +34 94 657 40 00 Fax: +34 94 657 25 55