PHYTOPLANKTON BLOOMS IN THE CHUBUT RIVER ESTUARY (ARGENTINA): INFLUENCE OF STRATIFICATION AND SALINITY

Virginia Villafañe*, E. Walter Helbling* y José Santamarina**

ABSTRACT. Phytoplankton blooms in the Chubut River Estuary (Argentina): influence of stratification and salinity.

In the period of 1986-1987 monthly sampling was done in the Chubut River Estuary, Chubut, Argentina. During 1986, chlorophyll-a values were low, less than 5 µg/l. However, in 1987 two peaks appeared, one in the low salinity region (inner regime) with chlorophyll-a concentration up to 45 µg/l, and the other in the high salinity region (outer regime) with chlorophyll-a up to 60 µg/l. The phytoplankton composition of the inner regime was dominated by the diatom Aulacoseira granulata (Ehr.) Simonsen, while in the outer regime the diatom Odontella aurita (Lyngbye) Agardh was the most abundant specie. In May 1987 low stratification (periods of low river discharge) and high nutrient concentrations (mainly nitrate) made possible the development of a bloom of **A. granulata** in the inner regime. Following this, in July 1987, an increase in river discharge caused an increase in the stratification of the water column. This condition, together with higher amounts of nutrients transported by the river to the outer regime, was favorable for **O. aurita**, which developed a significant bloom.

Key words: Phytoplankton, stratification, salinity, estuary.

RESUMEN. Floraciones fitoplanctónicas en el estuario del río Chubut, Argentina: influencia de la estratificación y la salinidad.

Durante 1986 y 1987 se realizaron muestreos mensuales en el estuario del río Chubut, Chubut, Argentina. En 1986 los valores de clorofila-a fueron bajos, menores que 5 µg clor-a/l. Sin embargo, durante 1987, aparecieron dos máximos: uno en la masa

* Universidad Nacional de la Patagonia, Chubut, Argentina. (Present address: A-002-Polar Research Program. Scripps Institution of Oceanography, La Jolla, CA, 92093-0202, USA).

** Centro de Ingeniería Oceánica, Buenos Aires, Argentina.

de agua de baja salinidad (régimen interno), con valores de clorofila-a de hasta 45 µg clor-a/l, y el otro en la masa de agua de alta salinidad (régimen externo), con valores de clorofila-a de hasta 60 µg clor-a/l. La especie fitoplanctónica dominante en el régimen interno fue la diatomea **Aulacoseira granulata** (Ehr.) Simonsen, mientras que en el régimen externo la diatomea **Odontella aurita** (Lyngbye) Agardh fue la especie más abundante. En el mes de mayo de 1987 la baja estratificación (período de baja descarga del río) y una alta concentración de nutrientes (en especial nitrato) posibilitaron el desarrollo de A. granulata alcanzando altos valores en la concentración de clorofila-a. Seguidamente, en el mes de julio un incremento en el caudal del río produjo una mayor estratificación en la columna de agua. Esta última condición, juntamente con altas cantidades de nutrientes transportados por el río, y aportados al régimen externo, favorecieron a **O. aurita**, la cual pudo desarrollar una floración significativa.

Palabras claves: Fitoplancton, estratificación, salinidad, estuario.

INTRODUCCION

From an ecological point of view, the estuaries are a transition zone from a "stable" freshwater regime to a "stable" marine regime. This may have strong consequences on the ecosystem and living resources. Ecologically, the transition of freshwater to seawater results in a change in the species composition. (Greve 1990).

Estuaries are complex systems governed by hydrographic factors, such as the tidal action and the mixing of freshwater and seawater, which produce complex structures that experience a continuing change in space and time (Greve 1990; Kausch 1990).

The hydrodynamics and the estuarine circulation are two processes that affect and control the distribution and biomass of phytoplankton (Malone et al. 1980; Malone et al. 1988) and specially in the low salinity waters of the estuary (Morris et al. 1978; Fillardo & Dunstan 1985; Moon & Dunstan 1990).

The hydrodynamics and circulation in the Chubut River Estuary is greatly influenced by the river discharge. During 1986 and 1987 the river discharge experienced very extreme values ranging from 8 m3/s to 76 m3/s (Helbling 1989).

Previous studies (Perillo et al. 1987; Perillo et al. 1989) have established different classifications and

characteristics of the Chubut River Estuary. These works describe the hydrography and dynamics of the estuarine circulation. Helbling 1989, has pointed out changes in the circulation and stratification and determined that the estuary changes from well mixed to salt-wedge with increasing river discharge. He also showed that factors such as: the variation in salinity, the river flux, the height of the tide and the stratification of the water column are the conditional variables of the general dynamics of the estuary.

However, the ways in which these changing conditions (salinity, stratification, flux), affect the distribution and the dynamics of phytoplankton in the Chubut River Estuary have been unknown until now.

The objectives of the present work are: a) to study the existence of phytoplanktonic groups associated with different salinity and stratification conditions, b) to determine the relationships between the phytoplankton distribution observed in this research and the dynamics of the estuarine circulation established by other studies, and c) to explain the circumstances and conditions for the formation of phytoplankton blooms in the estuary.

STUDY AREA

The Chubut River Estuary is located in the Chubut Province, at latitude 43º20' S and longitude 65º04'W (Figure 1). The present study was done in the region that goes from the river's mouth to the Rawson Bridge (9 km upstream). The city of Rawson, capital of the Chubut Province, is settled in the upper boundary of this study area.

The Chubut river has a yearly average discharge of 56 m3/s (data from Agua y Energía Eléctrica). This value varies throughout the year due to rain and snowfall. However, the flux is mainly regulated by the Florentino Ameghino Dam, located 120 km upstream from the mouth.

Previous studies in this area (Helbling 1989) have determined that only during high tide it is possible to find the three characteristic regimes of an estuary (Hansen & Rattray, 1965): inner regime, central regime and outer regime.

MATERIALS AND METHODS

During 1986 and 1987 we did monthly cruises to take water samples at three different stations. These station were called: a) St.1 Tide Guage b) St. 2: Harbor and c) St. 3: Elsa (Figure 1). When possible, we took additional

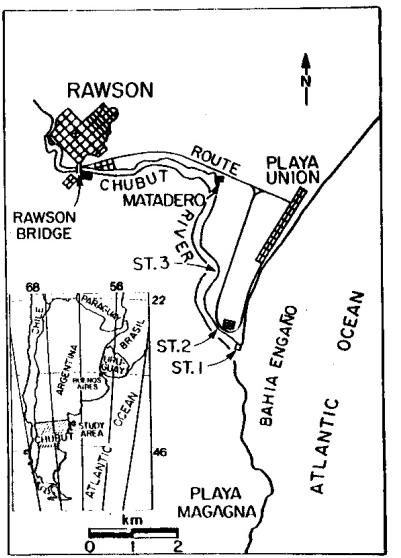

Figure 1: Chubut River Estuary. Study area and sampling stations: St.1: Tide Gauge, St.2: Harbor and St. 3: Elsa.

samples in areas adjacent to these stations.

In 1986 we did the sampling during high tide, while in 1987 it was done during high and low tide. In this latter year, when the meteorological conditions made it possible, we took samples during high and low tide in the same day.

In each cruise we took samples at surface and at depth (variable between 1m and 4m) with a Van Dorn bottle (3 liters capacity). Samples were fractioned to analyze and determine: chlorophyll-a (chl-a), phytoplankton composition, salinity and nutrients. We also measured in situ water temperature and conductivity with a protected SIAP thermometer and a WTW conductimeter, respectively.

For chl-a analysis usually 500 ml of water were filtered through a Millipore HA filter (0.45 μ), previously coated with MgCO3. The filters with the retained material were kept in darkness and in freezing conditions (-20ºC) until analysis. Chl-a was extracted with 90% acetone, and the fluorescence measured in Turner 110 fluorometer (Holm-Hansen et al. 1965). For salinity analysis 250 ml of sample were taken in glass bottles, and the determination was done with a Plessey salinometer.

Phytoplankton samples were taken in 250 ml brown glass bottles, and they were kept in darkness until fixation which was done immediately after completion of each cruise. The samples were fixed with 5 ml of 40% formaldehyde diluted to 20% with distilled water and neutralized with sodium borate, to reach a final concentration of 0.4% (Throndsen 1978).

The phytoplankton identification was done with a Leitz and a Zeiss microscope using different magnifications (up to 1000x). In some specific cases, permanent slides were made, with and without previous cleaning of cells. Samples were cleaned following the method described in Balech & Ferrando (1964) with a slight modification. Potassium permanganate were added in acid medium (hydrochloric acid), followed by the addition of hydrogen peroxide until decoloration. For permanent slides, samples were mounted between slide and coverslide with Hyrax mounting medium (refraction index = 1.65). Cells were identified to genus and/or species, and in some cases they were classified according to size.

The presence of a considerable amount of sediments have complicated the use of conventional methods of quantification of phytoplankton. This problem has been also observed by other investigators (Martha Ferrario, personal communication). To solve the problem of sediments, different techniques were tried. We chose a Sedgwick-Rafter chamber of 1 ml capacity (McAlice 1971) as the most appropriate counting method for the Chubut river samples. The magnification used to count the samples was 200x. Cells were counted in a known area until 200 were seen and this value was extrapolated to "cells per milliliter". The value of cells per milliliter, when colonies or chains were counted, was obtained multiplying the average cells per colony by the number of colonies. This method could introduce errors, but they are considered small when compared with errors derived from random sampling (Lund et al. 1958). The principal weakness of the Sedgwick-Rafter chamber is that does not allow examination with high magnification due to the depth of the chamber and the focal distance (Campbell 1973).

RESULTS

For a better interpretation of the results the distribution of phytoplankton will be presented as a function of the salinity and of the

stratification.

PHYTOPLANKTON AS A FUNCTION OF SALINITY

The distribution over time of chl-a as a function of salinity (Figure 2) shows that while in 1986 chl-a values were low (generally less than 5 µg chl-a/l), in 1987 two peaks were observed. These peaks of chl-a were associated with low and high salinity masses of water.

In the inner regime (salinity less than 3 parts per mil) the peak of chl-a (approximately 45 µg chl-a/l) was in May 1987, while in the outer regime (salinity higher than 30 parts per mil) the maximun value (up to 60 µg chl-a/l) was observed in July 1987. At intermediate salinities (central regime) values were less than 10 µg chl-a/l throughout the study period.

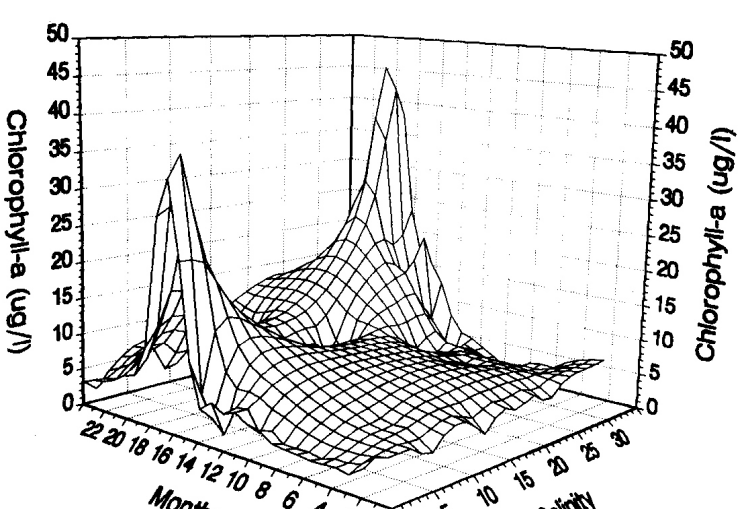

Figure 2: Chlorophyll-a (µg/l) distribution as a function of salinity (parts per mil) and time (months). Notice two peaks of chlorophyll-a, one in month 17 (May 1987) with low salinities and the other in month 19 (July 1987) with high salinities. Month 1 is January 1986, month 24 is December 1987.

The concentration of total phytoplanktonic cells (in cells per milliliter) showed values up to 19 x 10^3 cell/ml in the low salinity region and 10 x 10^3 cell/ml in the high salinity region (Figure 3a). In salinities between 5 and 10 parts per mil an appreciable concentration of cells (almost 5 x 10^3 cells/ml) was observed (Figure 3a).

Figure 3b presents the concentration (cells/ml) of the diatom Aulacoseira granulata (Ehr.) Simonsen, which reached maximum values (near 15 x 10^3 cells/ml) in the inner regime, an diminished sharply in abundance towards high salinities regions. However, a small "step" in the concentration of this diatom appeared in salinities that range between 5 and 10 parts per mil.

Figure 3c shows the concentration (cells/ml) of the diatom Odontella aurita (Lyngbye) Agardh. This diatom reached a maximum (approximately 6.5 x 10^3 cells/ml) in the outer regime, and its concentration decreased with a reduction in salinity, reaching values close to zero in the inner regime.

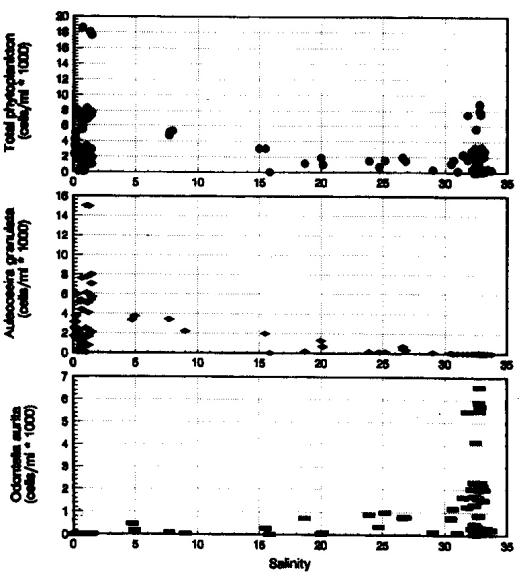

Figure 3: Phytoplankton concentration in thousands of cells per milliliter as a function of salinity (parts per mil). a) Total phytoplankton cells. b) Aulacoseira granulata, and c) Odontella aurita.

The concentration of total phytoplanktonic cells (cells/ml) as a function of salinity and time is presented in Figure 4a. A maximum value was observed in the inner regime in May 1987 (month 17 in Figure 4). Also, a high value were observed in the outer regime in July of 1987 (month 19 in Figure 4). Although the maximum concentrations of cells were found in the inner and outer regimes, it is possible to find a moderate concentration of cells (around 5×10^3 cells/ml) in the central regime with salinities between 5 and 10 parts per mil.

Concentrations of A. granulata and O. aurita in relation to salinity and time are shown in Figure 4b and 4c. It is possible to see that a peak of concentration of A. granulata appeared in May 1987, while O. aurita showed high values in July 1987.

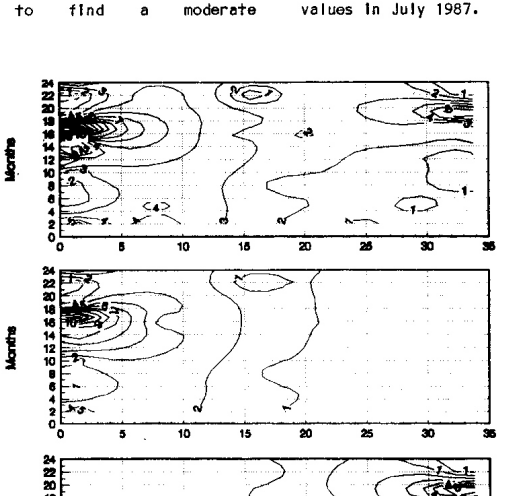

Figure 4: Phytoplankton distribution in thousands of cells per milliliter as a function of salinity (parts per mil) and time (months). a) Total phytoplankton cells, b) Aulacoseira granulata, and c) Odontella aurita. Month 1 is January 1986, month 24 is December 1987.

From Figures 3 and 4 it is possible to observe that the space and time variability in the phytoplankton concentrations, was due, mainly, to two diatom species: **A. granulata** and **O. aurita**. It is important to point out that these two diatom represented, generally, more than 80% of the total concentration of cells in the samples, **A. granulata** dominates in samples from the inner regime, while **O. aurita** was the most abundant specie in the samples from the outer regime. This situation only changed in February 1986, where the concentration of **O. aurita** was almost equal or surmounted by **Odontella mobiliensis**.

In addition to the two above mentioned diatoms, there were other differences beetwen the phytoplankton of the inner and outer regime. In the inner regime, **Nitzschia spp.**, **Gomphonema spp.**, **Surirella sp.**, were some of the species that appeared with **A. granulata**. In the outer regime **Triceratium alternans**, **Triceratium antediluvianum**, **Triceratium favus**, **Corethron criophilum**, **Licmophora sp.**, **Actinoptychus sp.**, **Rhabdonema adriaticum**, were found with **O. aurita**. Although some flagellates were present in both regimes, the diatoms were dominants in all samples.

PHYTOPLANKTON AS A FUNCTION OF THE STRATIFICATION

The stratification parameter **dS/So** (Hansen & Rattray, 1966) was used to describe stratification of the Chubut River Estuary. This parameter is a nondimensional number defined as the ratio between the salinity differences from surface to bottom (dS) and the average salinity (So). This parameter is a function of flux, tide height, and position in the estuary (Hansen and Rattray, 1965). A low number of dS/So indicate a low stratification and more homogeneous conditions, while a high number of dS/So indicate the presence of layers of different salinities with a significant stratification.

The changes in the stratification parameter dS/So over time during 1986 and 1987 are presented in Figure 5. In general, lower values of dS/So were found in 1986 with numbers smaller than 0.2. An exception to this trend was found in the month of October with a value of 0.5. In the month of July 1987 values of dS/So reached a maximum of 1.55, remaining high during almost all winter and spring.

Figure 6a presents the chl-a concentration as a function of the stratification parameter dS/So. High values of chl-a were associated with high and low values of stratification (1.55 and 0.1, respectively). With values of dS/So of approximately 0.1, chl-a reached values of 45 µg chl-a/l, while low chl-a values (less than 10 µg chl/l) were observed with an intermediated stratification (between 0.2 and 0.8). With an increase of stratification the concentration of chl-a became higher, reaching a maximum of 60 µg chl-a/l with a value of dS/So of 1.55.

Looking at the distribution of the chl/a as both, a function of the salinity and of the stratification parameter (Figure 6b), it is possible to see that when high values of stratification were found in the outer regime high concentrations of chl-a were

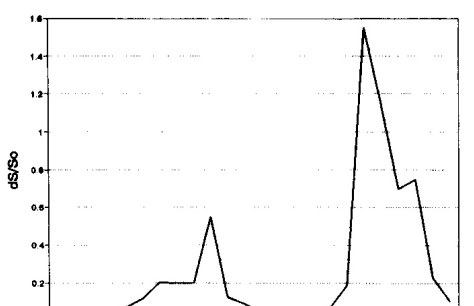

Figure 5: Variation of the stratification parameter dS/So over time during 1986-1987.

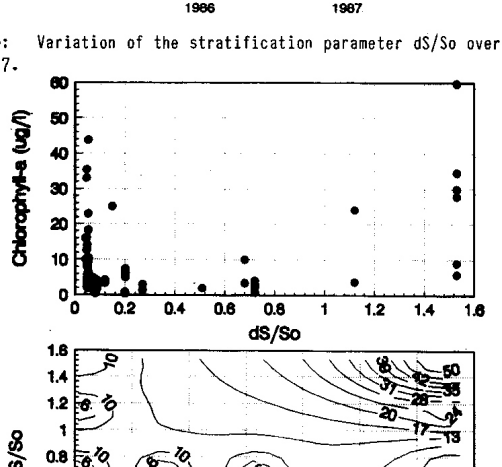

Figure 6: Chlorophyll-a (μg/l).a) Chlorophyll-a as a function of the stratification parameter dS/So. b) Chlorophyll-a distribution as a function of salinity (parts per mil) and dS/So. Notice high values of chlorophyll-a with both low salinities-low stratification and high salinities-high stratification.

present. In contrast the inner regime showed high concentration of chl-a when low values of stratification were present.

The concentration of phytoplanktonic cells (cells/ml) as a function of the stratification parameter dS/So is presented in Figure 7. From Figure 7a we can see that with low stratification the concentration of total phytoplanktonic cells were high, with values up to 19 x 10^3 cells/ml. In the cases of intermediate stratification the concentration was much lower, with values less than 5 x 10^3 cells/ml, while at high of dS/So the concentration of phytoplanKtonic cells increased up to almost 8 x 10^3 cells/ml.

In Figure 7b we can observe that with low stratification the diatom A. granulata reached a maximum concentration of 15 x 10^3 cells/ml. But, we should point out that few cells were also present in some cases with high stratification. In Figure 7c on the other hand we can see that when high stratification was present O.aurita reached maximum values of almost 6.5 x 10^3 cells/ml. But, we should take into account that it was also present in conditions of low stratification with values of almost 2.5 x 10^3 cells/ml.

The concentration of total phytoplanktonic cells, A. granulata and O. aurita, as a function of salinity and dS/So are presented in Figure 8. A. granulata was abundant with low stratification and low salinity (Figure 8b), while O. aurita was abundant with high salinities and high stratification (Figure 8c). Also, in salinities between 5 and 15 per mil, relatively high values of phytoplankton cells were found (Figure 8a and 8b).

DISCUSSION

In an estuarine system the distribution of phytoplankton is influenced by numerous physical, chemical and biological factors. However, circulation and mixing are frequently cited as responsible for the distribution of different kinds of particles (Roff et al, 1980). Also Ketchum (1954), has pointed to the mixing action as a limiting factor in the development and maintenance of estuarine phytoplanktonic populations.

To understand the complexity of physical circulation it is necessary to consider, in addition to the mixing and stratification processes, the wide range of salinities present in an estuary, (Kemp et al, 1982).

However, in the Chubut River Estuary, it is possible to facilitate the understanding of this complexity by considering separately the stratification conditions, in the inner, central and outer regime. Therefore, we will organize our discussion by explaining the phytoplankton distribution in these three regimes.

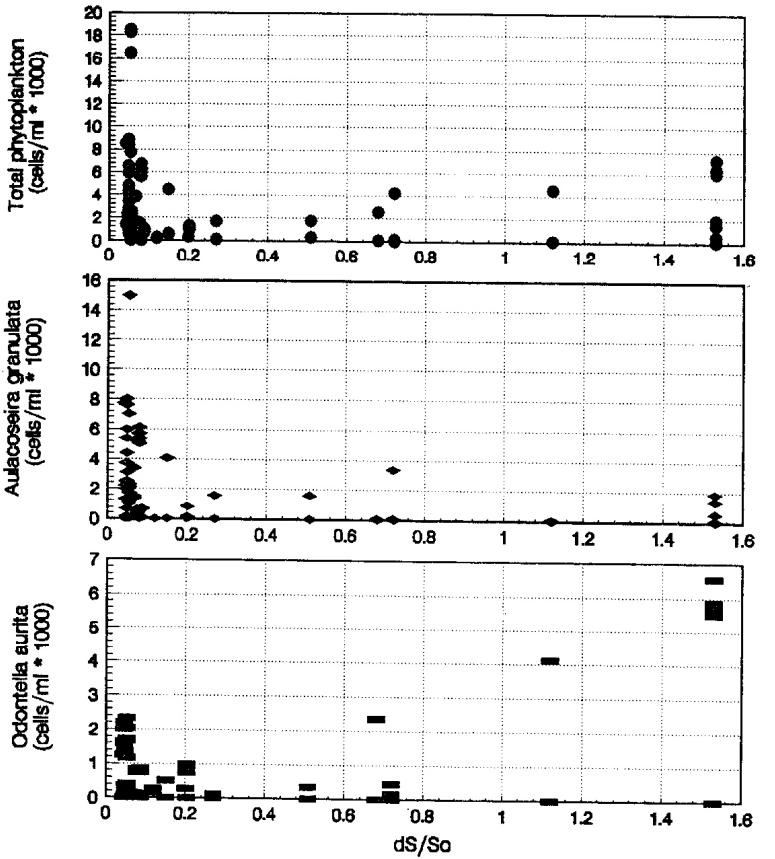

Figure 7: Phytoplankton concentration in thousands of cells per milliliter as a function of the stratification parameter dS/So. a) Total phytoplankton cells, b) Aulacoseira granulata and c) Odontella aurita.

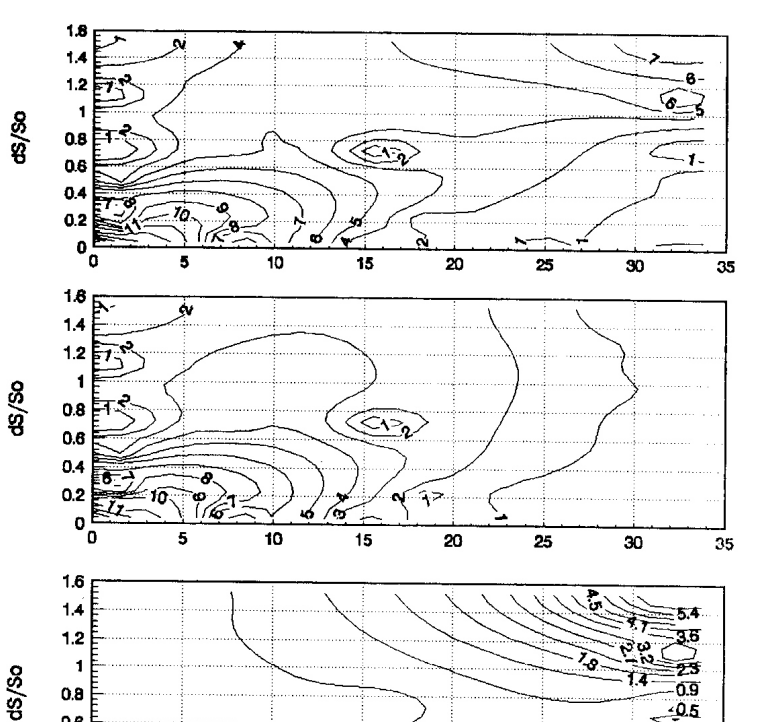

Figure 8: Phytoplankton distribution in thousands of cells per milliliter as a function of salinity (parts per mil) and the stratification parameter dS/So. a) Total phytoplankton cells, b) Aulacoseira granulata, and c) Odontella aurita.

INNER REGIME (salinity less than 3 parts per mil):

In 1987 there was a peak in the concentration of both chl-a and total phytoplankton cells under conditions of low stratification (Figure 6 and 8). **A. granulata** was the diatom specie that accounted for more than 80 percent of the phytoplankton cells in this peak (Figure 7 and 8).

The low stratification suggests a mixing condition, in wich the normal turbidity of the river is increased due to the input of sediments and/or resuspended benthonic particles generated by turbulence, diminishing the depth of light penetration available for photosynthesis.

In the case of the Chubut River Estuary light penetration was determined with a Secchi disk, and it was around 40 centimeters in the inner regime (Livio Sala, personal communication). This low light penetration seems not to affect **A. granulata**, which can produce a large number of individuals in these conditions. This process has also been observed by several authors who have shown the capacity of **A. granulata** to adapt to low levels of light (Lund, 1954; Lund, 1955; Lund, 1971; Reynolds **et al**, 1986).

The sinking velocity of **A. granulata** is high when compared with other phytoplanktonic species (Lund, 1954; Lund, 1955; Lund, 1971; Reynolds **et al**, 1986; Davey, 1986). Probably the turbulent conditions keep cells in the water column, and reduce the loss of cells to the sediments, a situation that can occur with stable conditions of high stratification. A similar circumstance was observed by Moon & Dunstan (1990) in the James River where the sinking rate of diatoms was closely balanced by the net upward water velocity.

A. granulata can survive in sediments as resting stages, which allow it to survive in anaerobic conditions and low nutrient concentrations for long time (months). When environmental conditions are favorable to the development of **A. granulata**, or when a resuspension effect is strong enough for allowing the transport of its filaments to the water column a number of viable cells can be found (Lund, 1954; Lund, 1955; Lund, 1971; Reynolds **et al**, 1986).

However, although the low stratification conditions in 1986 were similar to that of 1987 (Figure 5), in the former year the concentration of **A. granulata** was low (Figure 4). This indicates that, although the presence of low stratification appeared to be necessary to produce high values in concentration of **A. granulata** it is not a sufficient condition, at least in this case.

During 1986 low values of dissolved inorganic nitrogen (DIN = $[NH_4]$ + $[NO_3]$ + $[NO_2]$) were observed in the inner regime. On the other hand, during 1987 DIN was present in high concentrations, primarily in the form of nitrate (Helbling, 1989). In 1986 the mean concentration of nitrate was less than 1 μM, and apparently diminished with an increase in the river discharge ($r = -0.74$, $n = 11$). In 1987 the concentration of nitrate was more than 8 μM and this nutrient was correlated positively

with the river flux (r = 0.84, n = 12) (Helbling, 1989). This suggests that during 1986 low nitrate was associated with low stratification and may have been the limiting factor in the development of phytoplankton bloom. The limiting action of nitrate in estuaries was also suggested by other authors (Head, 1970).

So, during 1986, although the mixing conditions were favorable for A. granulata, its growth was limited probably by low nitrate concentrations. During 1987 high nitrate concentrations and low stratification have apparently facilitated the development of a bloom of phytoplankton (mainly A. granulata), reaching chl-a values of 45 µg chl-a/l.

CENTRAL REGIME (salinity between 3 and 30 parts per mil)

In this range of salinities low chl-a values were observed (Figure 2), although the number of cells per milliliter was moderate in salinities between 5 and 10 per mil (Figure 3).

In the central regime, A. granulata made the most significant contribution to the number of cells (Figure 3 and 4), although other species of planktonic and benthonic diatoms (Triceratium alternans, Grammatophora marina, Triceratium antediluvianum, Triceratium favus, Odontella aurita, Actinoptychus spp., Surirella spp., etc) were also present.

For explaining these moderate values of phytoplankton (cells/ml with low chl-a concentrations) it is necesary to take into account the following aspects:

a) The ability of A. granulata to form resistant stages. In this stage, the frustule remains in the sediments without any modification, but there is a contraction of chloroplasts and a reduction of protoplasm (Lund, 1954; Reynolds et al, 1986; Sicko-Goad & Stoermer, 1986). So, it is possible that cells in resting stages were not distinguished from the cells that were normally found in the plankton.

b) Distorted cells of A. granulata were also observed in an apparent stage of degradation. This cells count for the total concentration but not significantly to the chl-a. This is especially important when one takes into account the resuspension of cells caused by the turbulence effect of the shallow depth and/or the presence of wind. The wind influence in the stratification of the Chubut river estuary was pointed out by Perillo et al, 1989).

c) In the central regime the "null zone" is found, where river and sea currents converge (Roff et al, 1980; Kemp, 1982; Cloern et al, 1983; Schubel, 1986). This zone function as a particle trap in wich sediments or filaments and/or diatoms can be concentrated. So it seems that in the salinity region, between 5 and 10 per mil, the observed concentration of cells could be also explained by this particle trap mechanism.

A mechanism that selectively traps diatoms has been shown by Moon & Dunstan (1990); however in their study the location of this area was at much lower salinity. In our case, it is possible that, due to the shallow depth

of the Chubut River estuary and its botton topography, a rather big area could function as a trapping zone for phytoplankton.

OUTER REGIME (salinity higher than 30 per mil)

The peak of chl-a observed in July 1987 (Figure 2) in conditions of high stratification (Figure 6) can be attributed, mainly, to O. Aurita. As it was shown above, this diatom was present in high salinities (Figure 3) and accounts for more than 80 percent of total phytoplanktonic cells in the outer regime.

It is important to point out again that during 1986, values of stratification (dS/So) were less than 0.5, while in 1987 much higher values were found reaching a maximum of 1.55 in the month of July. In the studied area the increase in stratification is caused mainly by an increase of the river flux. This high stratification may benefit O. aurita for two reasons. First, it increases the light available for phytoplankton growth (Sharp et al, 1984). Second, a combination of high river discharge and high nitrate concentrations in river waters allowed the outer regime to receive in 1987 a nitrogen amount three times higher than in 1986 (Helbling, 1989).

The high numbers of cells of O. aurita observed during winter 1987 could be explained by taking into account: a) a high stratification due to high river fluxes, b) import of significant amount of nitrate into the outer regime and c) the fact that, low temperatures do not limit the growth of O. aurita as they do with other species. This last factor allows O. aurita to reach a high concentration without having to compete with other species (Baars, 1986).

O. aurita also presented some moderate values in low stratification (Figure 7c). We think that many of these cells could have been resuspended in this situation because they were somehow "deteriorated".

An increment in the discharge of the Chubut River caused an increase of the stratification impacting in the estuarine circulation. An increase of river discharge also set the conditions that made possible, at least in the outer regime, the development of a phytoplankton bloom. It would be interesting to know how this conditions affected other trophic levels in the area.

CONCLUSIONS

Two Phytoplankton blooms developed in the study area in 1987. Both blooms were mainly composed of a single diatom species and they occurred in different months and in different water masses. In the inner regime the bloom (up to 45 µg chl-a/l) was the diatom Aulacoseira granulata and it occurred in May 1987. It appears that the bloom could develop in conditions of low river discharge

and low stratification, situation that apparently favoured this diatom. In the outer regime the bloom (up to 60 µg chl-a/l) was of the diatom Odontella aurita and it ocurred in July 1987. This bloom was facilitated by an increase in the river discharge and an increase of the stratification of the estuary.

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