ECOLOGICAL CONCEPTUAL MODEL FOR A SOUTHERN CHILEAN FJORD: THE AYSÉN FJORD CASE STUDY

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1 INTRODUCTION

The geographical location of each fjord conditions the ecological processes taking place in the system because the factors involved such as river discharges, including their origin and associated loads, and atmospheric conditions act locally converting them into singular study sites. In this paper we describe a conceptual and numerical ecological model for the Aysén fjord (Southern Chile), one of the study sites of the ECOMANAGE Project. The Aysén fjord is where the main human settlements of the XI Region of Chile are located and thus is a target of possible ecological perturbations including harmful algal blooms (HABs) by phytoplankton species harmful to salmon farming such as toxic dinoflagellates, which have been increasing their presence and distribution range in recent years (Muñoz et al. 1992).

2 MATERIAL AND METHODS

Most of the data used for the Aysén study area come from the different CIMAR-FIORDOS campaigns (hereafter, CIMAR). These campaigns consist of oceanographic cruises along the whole system of southern Chilean fjords funded by the Chilean Navy's Hydrographic and Oceanographic Service (SHOA, its Spanish acronym). The CIMAR campaigns are focused on different studies of the Chilean southern fjord system; the Aysén fjord was included in five different CIMAR campaigns. Most of these campaigns were divided in two cruises (E1 and E2).Table 1 summarises the period when each campaign took place and Table 2 the variables measured in each campaign. Due to the scarcity of data those data have to be grouped into spring-summer conditions and winter conditions. In addition to the CIMAR cruises, the Salmon Technological Institute (INTESAL, its Spanish acronym) which is part of the Salmon Industry Association, SalmonChile (`http://www.salmonchile.cl/`), made available temperature, salinity, density and oxygen vertical profile data collected on the 10th of February 2007 on nine stations along the Aysén Fjord ((`http://pronosticos.salmonchile.cl/`) (Figure 1).

2.1 Modelling efforts

The MOHID water modelling system Module Water Quality has been coupled to the hydrodynamical model described in the Chapter "Hydrodynamical vertical 2D model for the Aysén fjord" in order to sketch the ecological processes taking place in the Aysén fjord. The Water Quality Module is based on an eutrophication model developed by the EPA (U.S. Environmental Protection Agency) (Bowie et al. 1985). Initially, the model simulated the oxygen, nitrogen and phosphorus biogeochemical cycles, including both inorganic and organic forms, but recently the silica cycle has also been included. The concentrations of these nutrients along with other environmental factors such as light availability and temperature would determine the dynamics of the primary producers, in this case phytoplankton and diatoms, and indirectly the zooplankton dynamics as well. In order to model the ecological processes taking place in the Aysén fjord, it was to characterise the Aysén waterbody with two open boundaries corresponding to the Aysén River loads and the open entrance that connects the fjord with the Moraleda Channel in the Chilean Inland Sea. In order to force river discharges with realistic local values despite the lack of observed data, the Soil and Water Assessment Tool (SWAT) model (Arnold and Fohrer 2005) has been applied to the Aysén River catchment. As defined by their creators, the model consists of a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. An application of the SWAT model, on the Aysén catchment (Yarrow and Leitão 2007), produced the monthly nutrient values summarised in Table 3. The oxygen concentrations presented in the same table were obtained from seasonal data presented in CADE-IDEPE (2004). The river discharge has been implemented dividing its flow over the top six cells of the land boundary.

Cohesive sediment loads from the river were included on the model though observed data are absent. A constant concentration of 25 $mg\ l^{-1}$ was assumed for the river discharge. Concentrations along the fjord strongly depend on river flow, with the river plume presenting higher concentrations and extending further during winter, coinciding with high river discharges. The Aysén fjord initial conditions and for its coastal open boundary have been characterised by using vertical profiles from station 77 of the campaign CIMAR 1 (table 4). This station has been chosen because of its location near the mouth of the Aysén fjord and also because during the CIMAR 1 campaign were collected simultaneously more water properties. The boundary cells would be reading the boundary conditions from the interior, obtaining at each moment the immediate values resulting from the interaction of the initial values and the forcing.

The Mohid model atmospheric module has a global model of radiation that changes the emitting radiation from the high atmosphere that can be modulated by the local climatology. In the case of Aysén, relative humidity, air temperature and cloud cover was obtained from the Meteorological Annals of Chile for the years 1968-1969 at Puerto Aysén (Table 5) to characterise the Aysén fjord climatology. To favour the exchange of heat and gases taking place at the air-water interface also it was included winds collected during the CIMAR 7 campaign in 2002, as explained in the Hydrodynamical chapter. The model was previously run for a period of a year to adjust the initial values to the atmospheric, river and boundary forcing. The model results shown in this chapter correspond to the subsequent year of simulation.

3 DATA AND MODELLING RESULTS

3.1 Abiotic variables

Oxygen concentrations present their maximum values, close to 12 mg/l, at the surface due to exchange with the atmosphere favoured by the wind interaction and the entry of oxygenated river waters (Table 3). Though a minimum appears around 100 m, this could be explained by the deposition at the bottom near the river mouth of the organic loads at the head of the fjord where a platform stops at around 100 m. Through remineralisation processes oxygen is consumed nearly to depletion levels, under 2 mg l^{-1}. This mass of water with low oxygen levels is transported to the rest of the estuary at the same depth (Figure 2). Also is in the head of the fjord where material allochtonous coming from land is mainly deposited thus consuming oxygen near the bottom. As was observed on the residual flux velocities there are water exports from this area to the fjord waters which can be observed on Figure 2 as a plume with low oxygen concentrations. This process is permanent though during winter, levels the extension of this plume can be greater because of the increase of loads into the system, as the model results show (Figure 3).Oxygen concentrations are higher on the superficial fjords water than in the vicinity coastal waters due to the entry of more oxygenated fresh waters.

TABLE 1: *Cruises of the CIMAR program in the study area.*

Cruise	Initial Date	End Date	Season
CIMAR 1	08-10-1995	11-11-1995	Spring
CIMAR 4 E1	26-09-1998	09-10-1998	Spring
CIMAR 4 E2	25-02-1999	08-03-1999	Summer
CIMAR 7 E1	07-07-2001	21-07-2001	Winter
CIMAR 7 E2	12-11-2001	27-11-2001	Spring
CIMAR 8 E1	01-07-2002	26-07-2002	Winter
CIMAR 8 E2	15-11-2002	28-11-2002	Spring
CIMAR 9 E1	05-08-2003	25-08-2003	Winter
CIMAR 9 E2	03-11-2003	21-11-2003	Spring

TABLE 2: *Variables collected during each campaign.*

Campaign	Temp	Sal	Oxygen	Ammonia	Nitrite	Nitrate	Phosphate	Silicate	Chl *a*
CIMAR 1	X	X	X	X	X	X	X	X	X
CIMAR 4 E1	X	X	X			X	X	X	X
CIMAR 4 E2	X	X	X			X	X	X	X
CIMAR 7 E1	X	X	X	X		X	X	X	X
CIMAR 7 E2	X	X	X	X		X	X	X	X
CIMAR 8 E1	X	X	X			X	X	X	X
CIMAR 8 E2	X	X	X			X	X	X	X
CIMAR 9 E1	X	X	X			X	X	X	X
CIMAR 9 E2	X	X	X			X	X	X	X
SalmonChile	X	X	X						

TABLE 3: *Monthly values of nutrients and oxygen imposed on the Aysén River discharge.*

Month	Flow (m^3s^{-1})	Oxygen (mg l^{-1})	Nitrate (mg l^{-1})	Nitrite (mg l^{-1})	Ammonia (mg l^{-1})	Organic N (mg l^{-1})	Phosphate (mg l^{-1})	Organic P (mg l^{-1})
January	325.86	12.2	0.1262	0.0044	0.0113	0.0042	0.0076	0.0003
February	249.45	12.2	0.0808	0.0052	0.0128	0.0049	0.0080	0.0003
March	336.82	12.2	0.0885	0.0052	0.0142	0.0061	0.0073	0.0004
April	475.12	13.1	0.0856	0.0071	0.0230	0.0155	0.0096	0.0010
May	655.63	13.1	0.0916	0.0111	0.0437	0.0379	0.0152	0.0028
June	731.80	13.1	0.1089	0.0104	0.0409	0.0354	0.0150	0.0026
July	729.44	11.9	0.1385	0.0267	0.0972	0.0779	0.0347	0.0051
August	814.96	11.9	0.1136	0.0197	0.0700	0.0537	0.0268	0.0034
September	636.33	11.9	0.0877	0.0101	0.0345	0.0274	0.0144	0.0019
October	542.83	10.8	0.0752	0.0071	0.0227	0.0155	0.0104	0.0010
November	436.88	10.8	0.0623	0.0048	0.0135	0.0068	0.0075	0.0004
December	439.44	10.8	0.0578	0.0043	0.0114	0.0049	0.0066	0.0003

TABLE 4: *Vertical profiles of station 77 of CIMAR 1 used for characterising the Aysén fjord watercolumn.*

Depth (m)	Salinity (PSU)	Temperature (ºC)	Oxygen (mg l^{-1})	Nitrate (mg l^{-1})	Nitrite (mg l^{-1})	Ammonia (mg l^{-1})	Phosphate (mg l^{-1})	Silicate (mg l^{-1})
2	13.4558	10.8477	10.6957	0.0056	0.0018	0.0017	0.0016	2.4435
5	25.8857	10.1496	8.9678	0.1555	0.0028	0.0038	0.0375	0.5617
10	29.1555	9.5800	8.1110	0.1765	0.0045	0.0063	0.0443	0.4775
15	29.4397	9.4941	8.4395			0.0094		
20	29.5993	9.4922	8.2396			0.0074		
25	29.6338	9.5059	7.9682	0.2045	0.0014	0.0060	0.0480	0.4494
50	30.4125	9.8220	6.8544			0.0021		
75	30.7126	9.7861	7.0686	0.2395	0.0028	0.0021	0.0566	0.5536
100	30.9620	9.8179	7.5256	0.2283	0.0024	0.0021	0.0560	0.5617
150	31.0517	9.5745	7.9972	0.2255	0.0015	0.0021	0.0560	0.6741
200	31.0791	9.5326	7.6112	0.2003	0.0017	0.0021	0.0529	0.4775

On the other hand, nitrogen species on surface waters are nearly depleted for nitrate, nitrite and ammonia. In the case of nitrate, it appears to be nearly absent from the surface water of the fjord (Figure 4), mainly consumed by primary producers where light conditions favour their growth. Nitrate concentrations on the surface are higher during winter due to a higher river flow and slightly higher concentrations of this compound on river water, along with the adverse conditions for primary producers. Under the pycnocline, organic particulate matter tends to accumulate and to undergo remineralisation processes where nitrate is released and transformed into ammonia, nitrite being an intermediate in the process. The presence of nitrite indicates that transformation between nitrate and ammonia is taking place. In this sense, surface waters of the fjord present lower values of nitrate when compared with the waters of the Moraleda Channel nearby. Model results (Figure 5) reproduce the same pattern of concentrations and show that during summer the layer where nitrate concentrations are nearly depleted increases maybe due to better light conditions. Prado-Fielder (2000) considers that nitrite concentrations are, however, due to nitrification processes that would convert ammonia into nitrite.

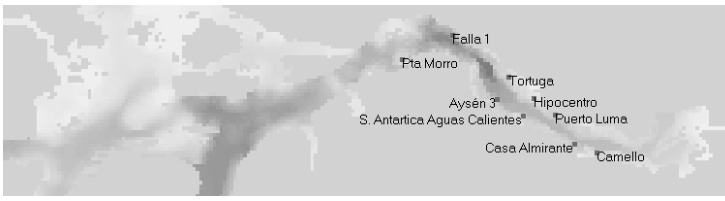

FIGURE 1: *Location of Intesal-SalmonChile vertical profiles.*

In the case of ammonia, only near the fjords head where several rivers discharge, this nutrient is present in the surface waters (Figure 6). Ammonia concentrations in the surface extend further due to higher river discharges during winter. Padro-Fielder (2000) also considered that differences in ammonia concentration between the continental fjords and the open channels correspond to a higher terrestrial input of organic nitrogen and the limited water exchange in these channels closed on one of its sides. Ammonia concentrations present a similar vertical distribution as the nitrate with subsurface maximum values due to remineralisation processes (Figure 7). However, the number of available ammonia observations is too small to reach a definitive conclusion.

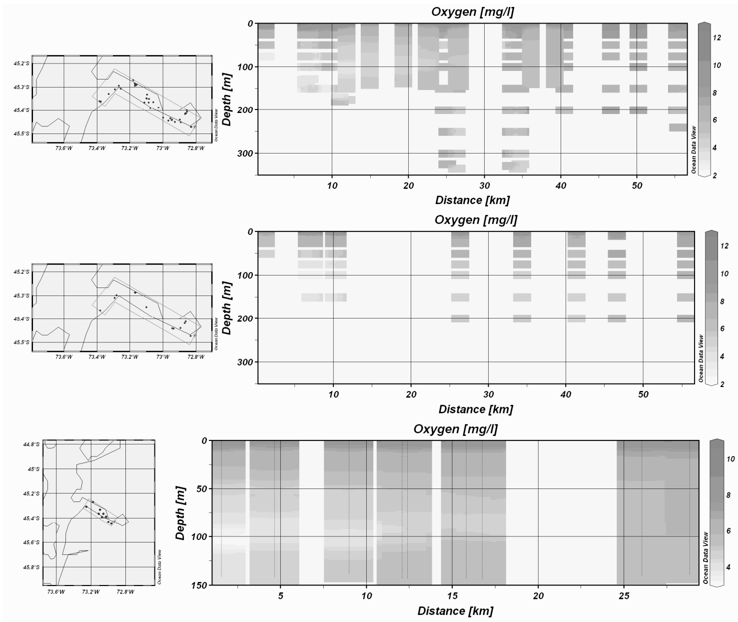

FIGURE 2: *Oxygen concentration profiles along the Aysén Fjord for the CIMAR spring-summer campaigns (Top), winter campaigns (Middle) and Intesal Campaign on February 2007 (Bottom). Distance is measured seawards from the innermost station.*

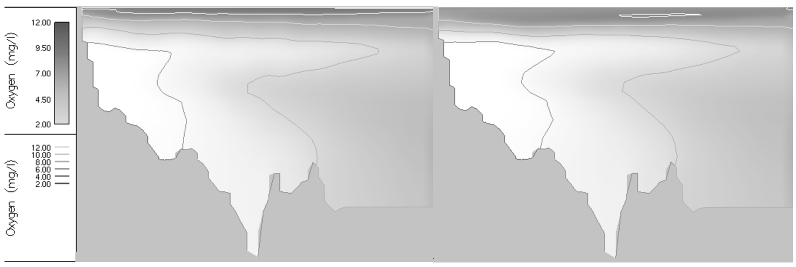

FIGURE 3: *Modelled oxygen concentrations for the months of July (Left) and January (Right).*

As in the case of nitrate, inorganic phosphorus concentrations are higher near the bottom of the fjord (Figure 8) due to remineralisation processes taking place on the sediment and to the low loads from the river. During spring/summer conditions phosphate is depleted in the fjords head, while during winter low levels are present in the top layer and concentrations are higher than in summer conditions. The fjord would act as a whole as a net exporter of phosphorus to the adjacent coastal waters. Model results (Figure 9) reproduce this same pattern of concentrations.

On the other hand, silica concentrations reach their maximum concentrations on the surface due to the river being the main source (Figure 10). Thus the maximum concentrations are found near the river mouth and decrease along the fjord and the value would be modulated by river flow. In the model a second maximum appears near the bottom due to remineralisation (Figure 11).

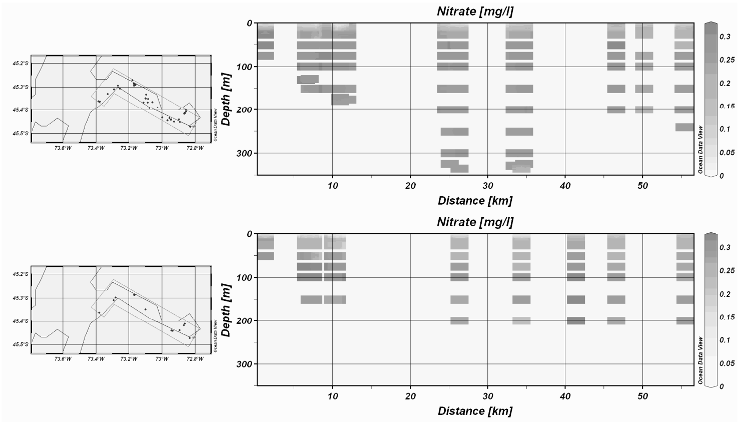

FIGURE 4: *Nitrate concentration profiles along the Aysén Fjord for the campaigns carried out during spring-summer (Top) and winter conditions (Bottom). Distance is measured seawards from the innermost station.*

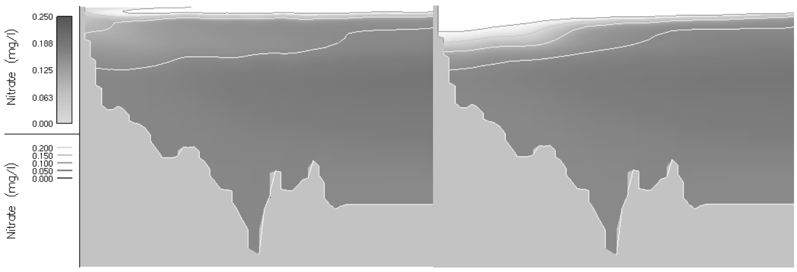

FIGURE 5: *Modelled nitrate concentrations for the months of July (Left) and January (Right).*

TABLE 5: *Monthly averaged atmospheric conditions from the Meteorological Annals of Chile (1968-1969).*

Month	Temperature (ºC)	Relative Humidity (%)	Cloud Cover (0-1)
January	14.15	88.17	0.792
February	12.30	89.33	0.879
March	11.50	88.33	0.692
April	9.35	92.33	0.810
May	7.65	93.00	0.888
June	4.75	92.17	0.790
July	4.55	93.00	0.858
August	5.60	91.00	0.794
September	7.00	85.83	0.848
October	8.00	88.17	0.796
November	11.30	86.17	0.842
December	12.85	85.00	0.775

3.2 Biotic variables

There is a gap in phytoplankton communities' publications in the southern Chile area (Cassis et al. 2002), with most of the studies focused on local phenomena and/or small areas. Diatoms are the dominant form of phytoplankton at the head of the Aysén fjord with 74 species out of the 106 recorded during the period 1993-1998, showing specific composition differences according to the origin of the waters (Cassis et al. 2002). Estuarine taxa stand out due to their abundance and constant presence and marine taxa because of their number of species. Estuarine species dominate the fjord with this dominance sometimes being interrupted by the entrance of continental and marine species (Cassis et al. 2002). Higher relative abundances of phytoplankton were found during summer. Biological changes in the surface layer at the head of the Aysén fjord are related to the fresh water inputs. Small *Skeletonema costatum* dominate the microphytoplankton level with very low diversity that only increases at the head of the fjord due to the presence of continental species (Avaria et al. 1997, Cassis et al. 2002).

Avaria et al (2007) during their sampling in the CIMAR 1 campaign found a good relationship between the algal biomass and the algal pigments especially in the Aysén fjord. Phytoplankton observations during that cruise in the Aysén fjord gave densities ranging between $60x10^3$ and $743x10^3$ cells l^{-1}, algal biomass concentrations between 0.1 and 0.8 mg l^{-1} and Chlorophyll a contents between $0.7x10^{-3}$ and $4x10^{-3}$ mg l^{-1} (Avaria et al. 1997). Using the maximum scales of the graphs that Avaria et al (1997) calibrated for showing the mentioned good relationship, a C:Chla factor of 225 has been obtained. Phytoplankton biomass concentrations are in agreement with the results obtained with the Mohid model water quality. They also found a negative relationship between phosphate and nitrate concentrations with the abundance of *Skelotonema costatum*. It was also observed the absence of dinoflagellates.

Euphotic depth on average was around 22 m though photosynthetically active radiation (PAR) was available down to 50 m depth. The mixing layer reaches at least 50 m depth and is larger than the euphotic area, thus, the mixing layer depth would compensate the lack of available light below 22 m (Pizarro et al 2005). The model results suggest that diatoms would bloom on the surface due to nutrients and light availability (Figure 12). The diatom blooming species would present maximum concentrations during summer enhanced by higher temperatures and existing light conditions. Below the surface a maximum of biogenic silica would appear due to diatoms respiration and death.

According to the model results, other phytoplankton groups such as flagellates, as occurs with diatoms, would bloom during summer as temperature and light conditions would enhance its growing. Maximum values for the bloom were found subsurface (Figure 13), due to the availability of nutrients and light, as they are depleted on the surface. According to the values from CIMAR campaigns (Figure 14), the phytoplankton bloom seems to occur during summer as chlorophyll a concentrations are higher than during winter conditions. This fact is more evident in the inner parts of the fjord where higher subsurface distribution variation occurs when compared with the Moraleda Channel stations.

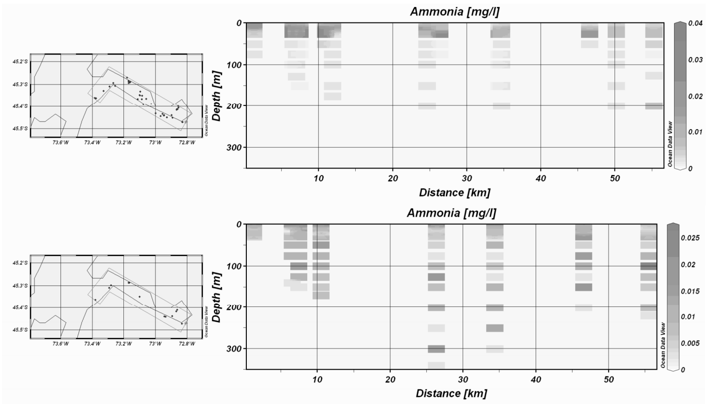

FIGURE 6: *Ammonia concentration profiles along the Aysén Fjord for the campaigns carried out during spring-summer (Top) and winter conditions (Bottom). Distance is measured seawards from the innermost station.*

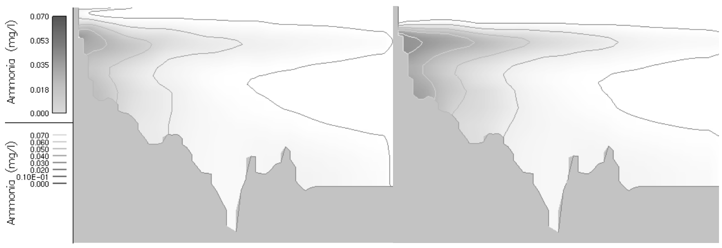

FIGURE 7: *Modelled ammonia concentrations for the months of July (Left) and January (Right).*

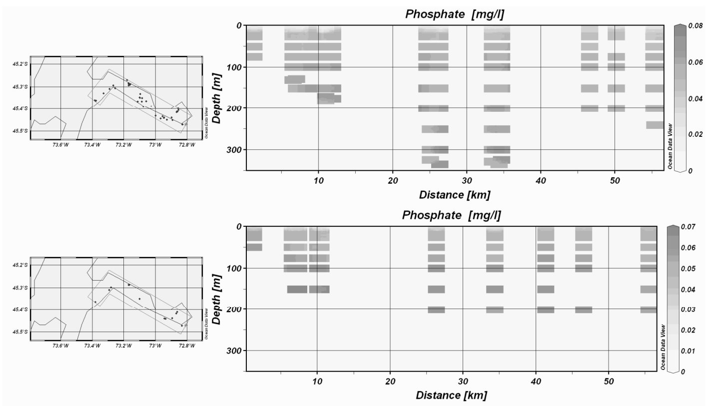

FIGURE 8: *Phosphate concentration profiles along the Aysén Fjord for the campaigns carried out during spring-summer (Top) and winter conditions (Bottom). Distance is measured seawards from the innermost station.*

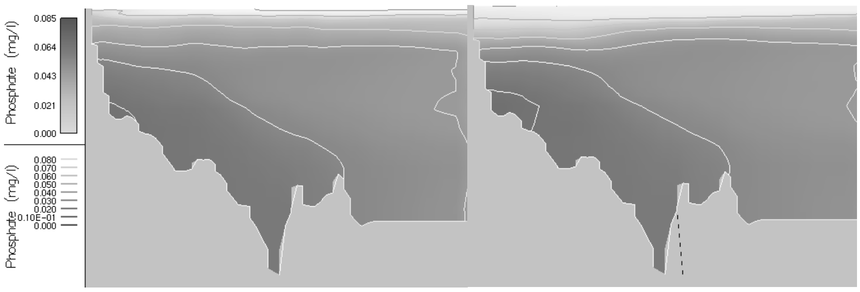

FIGURE 9: *Modelled phosphate concentrations for the months of July (Left) and January (Right).*

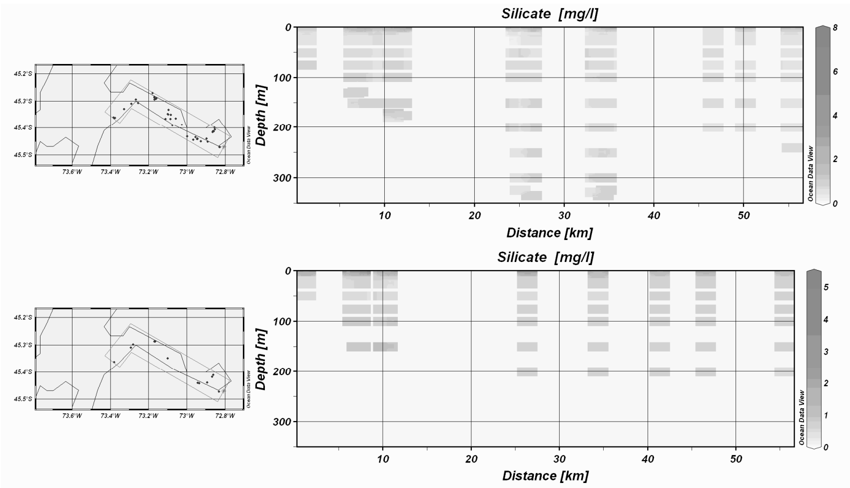

FIGURE 10: *Silicate concentration profiles along the Aysén Fjord for the campaigns carried out during spring-summer (Top) and winter conditions (Bottom). Distance is measured seawards from the innermost station.*

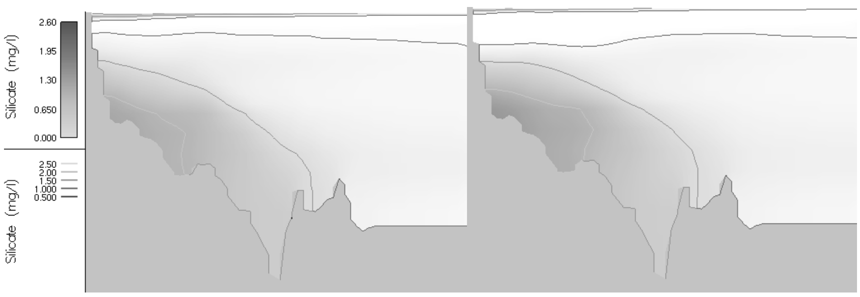

FIGURE 11: *Modelled inorganic silica concentrations for the months of July (Left) and January (Right).*

The Aysén fjord is located in one of the main areas of accumulation of zooplankton restricted to the Aysén fjord along with neighbouring Moraleda and Darwin channels (Palma and Silva 2004). However, this biomass abundance is not translated into species richness due to the spatial and temporal heterogeneity with marked gradients. Only few zooplanktonic species have been successfully adapted to the extreme oceanographic temperature, salinity and oxygen ranges (Palma and Silva 2004). During the CIMAR 8 campaign, zooplankton biomass mainly comprised copepods, chaetognaths and euphausids and highest biomass values in the system were found in the Guafo Mouth, the main connection between the Moraleda Channel and the open ocean, and the lowest values were observed in the Chile Inland Sea where the Aysén fjord is located (Palma and Apablaza 2005).

Though zooplankton is present in the model it is not controlling the phytoplankton biomass with the present parameterisation. Basically, its concentration is depending on the river discharge values that later is transported to the boundary where due to the boundary conditions they accumulate. As no data about zooplankton dynamics are available the function on regulating the primary producers' biomass is unknown.

4 DISCUSSION AND CONCLUSIONS

The model simulation reproduces the main physical-chemical features of the observed data. The sharp pycnocline acts as a barrier between the upper and bottom layers preventing mixing of water unless due to highly energetic processes. Surface waters are mainly dominated by atmospheric and river discharge processes while bottom water processes are related to sediment processes and coastal boundary processes. The main interaction between both layers consists of the particulate matter that the upper layer exports to deep waters. Surface waters are well oxygenated as the rivers discharging into the fjord present high concentrations of oxygen (Table 3). The nutrient loads from the Aysén River are of the same order of magnitude as the receiving environment, though slightly higher. In this sense, the Aysén River can be regarded as an oligotrophic river.

Perhaps, the most important effect would be the deposit of particulate matter in the adjacent fjord beds, also because the inner area would be the section of the fjord with the highest primary production. These deposits would consume oxygen through remineralisation, producing a plume of nearly anoxic waters and rich in inorganic nutrients that would extend trough the fjord transported by the deep water circulation. Oxygen is depleted near the bottom due to remineralisation of organic matter. In Figure 15 can be seen how nitrate concentrations increase landwards while oxygen concentrations decrease. Also in the inner stations can be appreciated higher concentrations of nitrite which is considered as an intermediate form of the whole process that goes from ammonia to nitrate; only the presence of nitrite concentrations indicates the active production of nitrate (Sverdrup et al. 1942).

According to the values from the CIMAR campaigns and model results the phytoplankton bloom seems to take place during summer with higher chlorophyll a concentrations than during winter, especially in the inner parts of the fjord. In this sense, also the production of the system would be conditioned by the river discharges, more due to the nutrient loads than to its flow and to light availability. Very little is known about zooplankton dynamics in the system so the control that can apply to the primary producers is practically unknown.

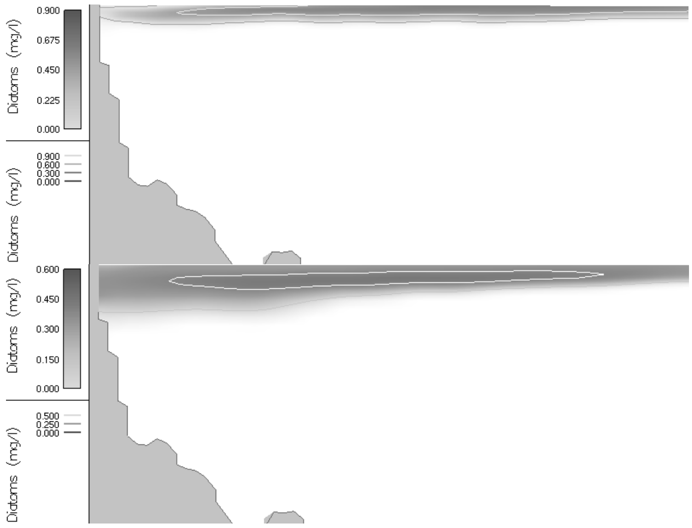

FIGURE 12: *Modelled diatoms concentrations for the months of July (Top) and January (Bottom).*

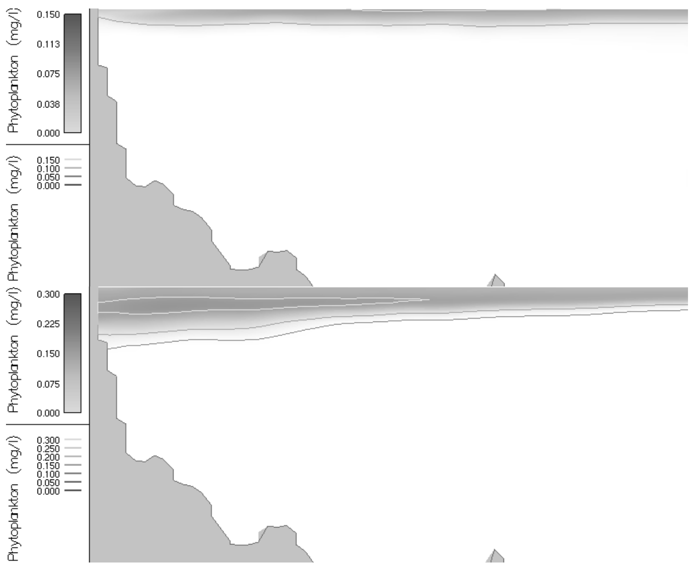

FIGURE 13: *Modelled phytoplankton concentrations for the months of July (Top) and January (Bottom).*

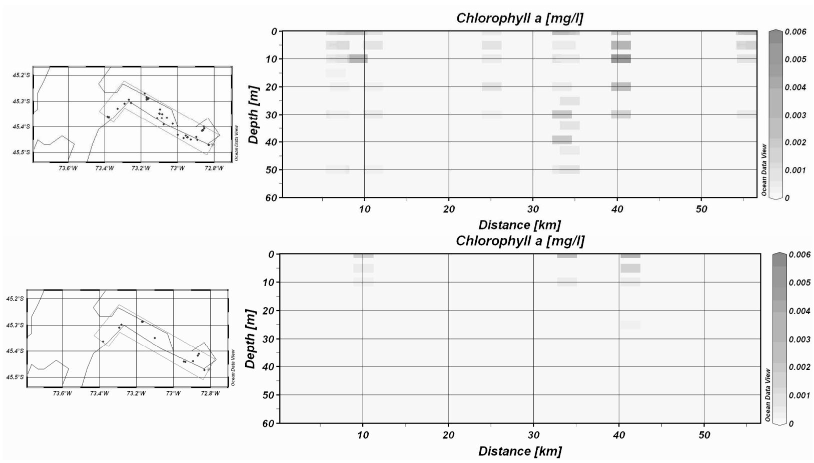

FIGURE 14: *Chlorophyll concentration profiles along the Aysén Fjord for the campaigns carried out during spring-summer (Top) and winter conditions (Bottom). Distance is measured seawards from the innermost station.*

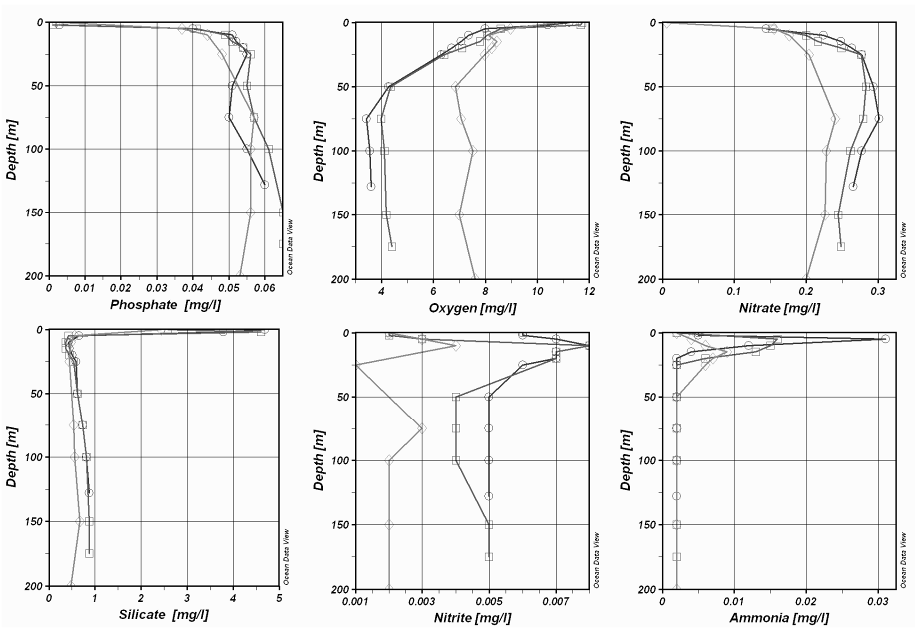

FIGURE 15: *Nutrient profiles obtained during the CIMAR1 campaign for the inner fjord (circles), middle fiord (squares) and near the Aysén fjord mouth (diamonds).*

In spite of the scarce data, knowledge of the system and model assumptions made it possible to establish a simple 2D vertical model that mainly reproduces the processes described by the bibliography and the general trends of the data. This model could serve as a first step to study the possible effects of modifying the entrance of organic matter as a product of a different management of the river catchment or other entrances of organic matter into the system.

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