HYDRODYNAMICAL VERTICAL 2D MODEL FOR THE AYSÉN FJORD

F.J. CAMPUZANO, P.C. LEITÃO, M.I. GONÇALVES, V. MARÍN AND A. TIRONI

1 INTRODUCTION

As a first approach to model the hydrodynamics and ecological evolution of a fjord, a 2D vertical model was implemented to evaluate the sharp gradients that occur on fjords with a high river discharge. The Aysén Fjord located on Region XI on the Chilean Patagonia is one of the study sites of the ECOMANAGE Project, along with Bahía Blanca and Santos estuaries. The Aysén fjord is one of the natural connections between the Andean mountains and the system of islands and fjords in southern Chile, called the Chilean Inland Sea. In this fjord, several extreme events take place which make it special from an oceanographic point of view: very large river discharges fed by rain and by melt water from the Andes glaciers accompanied by low temperatures provoking a very sharp gradient in the vertical density structure of the system. This feature is very important for the functioning of the system from the hydrodynamic and the ecological point of view.

2 NUMERICAL MODEL IMPLEMENTATION

The Mohid modelling system (Leitão et al., this volume), has been employed to simulate the baroclinic hydrodynamics of the Aysén fjord. Turbulent vertical mixing has been reproduced using the embedded GOTM model (Burchard 2002) using the parameterisation proposed by Canuto et al (2001) with the exception of the minimum Turbulent Kinetic Energy (k_min) value for the Mellor-Yamada turbulence model, most satisfactory results were obtained with a value of $5x10^{-5}$.

2.1 Domain discretisation

The Aysén 2D vertical model domain was obtained from a previous 2D horizontal domain obtained through interpolation of the digitalised nautical charts from the Chilean Navy's Hydrographic and Oceanographic Service (SHOA, its Spanish acronym). A transect following the main axis of the fjord was defined and the extracted depths were converted into a regular grid that covers the major bathymetric features of the fjord seabed, i.e. sea mounts and sea terraces (Figure 1). The horizontal distance covered by the domain was divided into a regular horizontal grid with 64 cells (Figure 2). The first 47 cells correspond to smoothed bathymetric data to avoid numerical problems and the last 17 were added for numerical stability with the imposed boundary conditions. Vertically the discretisation consisted of 30 layers divided into two vertical domains: a cartesian domain consisting of 16 layers from the bottom to a depth of 32 m; above which was defined a sigma domain with 14 layers up to the free surface (Figure 2). Both domains been have defined taking into consideration the known vertical stratification and in order for the model to be able to reproduce cell heights decrease from bottom to top (Table 1).

TABLE 1: *Layer thicknesses of the two domains in the 2D vertical model in meters. Mohid layers are numbered from bottom to top.*

Layer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cart.	50	50	20	20	20	20	20	10	10	10	10	8	5	5	5	5
Sigma	5	5	3	3	2	2	2	2	2	2	1	1	1	1		

2.2 Hydrodynamical forcing

On each of the sides of the model domain a different hydrodynamical forcing was imposed: tides on the open boundary and river discharge on the inland area. On the ocean boundary were imposed the tidal components obtained from the Chacabuco Harbour tidal gauge records for the years 2003-2004. Tidal analysis performed on the water level series using the TASK-2000 Software (Tidal Analysis Software Kit 2000, POL/PSMSL) was used to obtain 63 tidal components.

The Aysén River, the largest river discharging into the fjord by volume, located at the head of the fjord is the only one considered to force the model thus the influence of the lateral freshwater inputs from other rivers are neglected in this model. In order to force river discharges with realistic flow 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. An application of the SWAT model to the Aysén catchment (Yarrow and Leitão 2007) produced the monthly flow values summarised in Table 2. The river discharge has been implemented dividing its flow over the top six cells at the land boundary. Monthly river temperatures were obtained by adjustment into a curve of the temperature data collected by CADE-IDEPE (2004) and it was also assumed that the water discharged was pure freshwater (0.01 PSU).

To characterise the Aysén area atmospheric conditions, monthly values for air temperature, relative humidity and cloud cover data from Meteorological Annals of Chile colleted at Puerto Aysén for the years 1968-1969 (Ministry of Defence, Table 2) were imposed in the model Atmosphere Module. Additionally, winds measured at Mitahue Island (45°24'05.94" S, 73°44'25.22" W, Figure 3), located in the Moraleda Channel near the mouth of the Aysén fjord, during the CIMAR 7 campaign in 2002 were imposed only to calculate atmosphere-sea heat exchanges due to wind. Wind forcing was not taken into consideration for hydrodynamical forcing. Though the Mitahue Island is not located in the Aysén fjord, this dataset represents wind speeds and directions registered in the vicinity of the fjord, and could be considered as a typical channel location record. Recorded data show that the wind blows predominantly from the third and fourth quadrant, from North to Southwest, and during most of the time wind speeds do not exceed 5 $m\ s^{-1}$.

TABLE 2: *Monthly averaged values for river properties (flow and temperature) and atmospheric properties (temperature, relative humidity and cloud coverage).*

Month	River Flow ($m^3 s^{-1}$)	River Temp (ºC)	Air Temp (ºC)	R Humidity (%)	Cloud Cover (%)
1	325.86	11.01	14.15	88.2	79.2
2	249.45	11.88	12.30	89.3	87.9
3	336.82	11.37	11.50	88.3	69.2
4	475.12	9.60	9.35	92.3	81.0
5	655.63	7.05	7.65	93.0	88.8
6	731.80	4.40	4.75	92.2	79.0
7	729.44	2.37	4.55	93.0	85.8
8	814.96	1.49	5.60	91.0	79.4
9	636.33	2.01	7.00	85.8	84.8
10	542.83	3.78	8.00	88.2	79.6
11	436.88	6.33	11.30	86.2	84.2
12	439.44	8.97	12.85	85.0	77.5

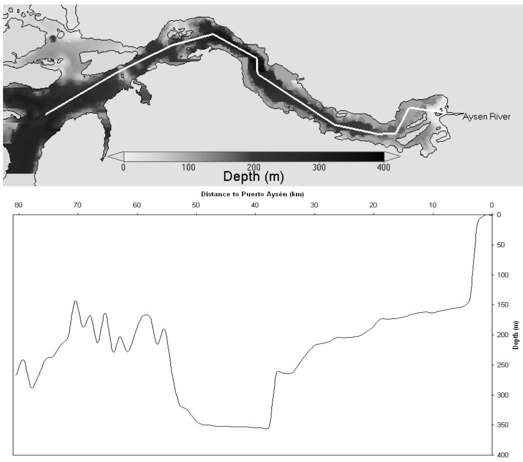

FIGURE 1: *Aysén fjord domain bathymetry with a transect along the main axis (Top) and the depth contour of this transect (Bottom).*

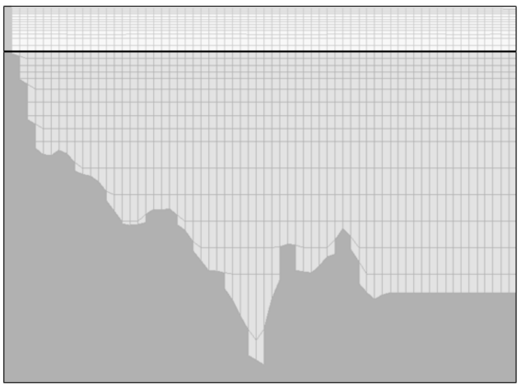

FIGURE 2: *Aysén Fjord 2D vertical model discretisation.*

FIGURE 3: *Mitahue Island geographical location (Left) and wind speeds and directions (Right).*

3 MODEL RESULTS

3.1 Hydrodynamics

The residual velocities are the net velocities obtained after averaging currents. The residual currents presented in Figure 4 were obtained from one year simulations. The residual currents present a clear three layer structure similar to the one described in the literature (Cáceres et al. 2002, Valle-Levinson et al. 2002). At the surface there is a strong seaward current immediately below there is landward. Below these two superficial layers there is a much thicker third layer where the residual current does not have a clear pattern. The two layers superficial flow is clearly induced by the density gradients caused by the input of fresh water at the head of the fjord. The fresh river water tends to lie on top of the denser sea water. This induces a seaward sea surface height gradient. This gradient generates a superficial seaward residual current, with the landward density gradient generating an undercurrent.

When the relative scale between the horizontal and vertical components of the vector is enlarged it can be seen how the interaction of the barotropic tide with the bottom topography creates internal tides. The main area of internal wave generation would be in the pinning points and the sill found at the entrance of the Aysén fjord. The irregularities on the seabed are mainly reflected in the vertical velocities as can be observed in Figure 5. This result shows that below the surface layers the model presents residual velocities with a turbulent structure highly conditioned by the internal tide. It should be kept in mind that the model was only forced with river discharge and tide. The residual current structure may be affected by other processes not considered in this implementation like wind forcing or interaction of the fjord circulation with the large scale circulation.

Instant maximum currents values are observed on the surface layer depending on the river discharge. In this surface layer velocities according to the model are comprised mainly between 0.1 and 0.3 m s^{-1} (Figure 6).

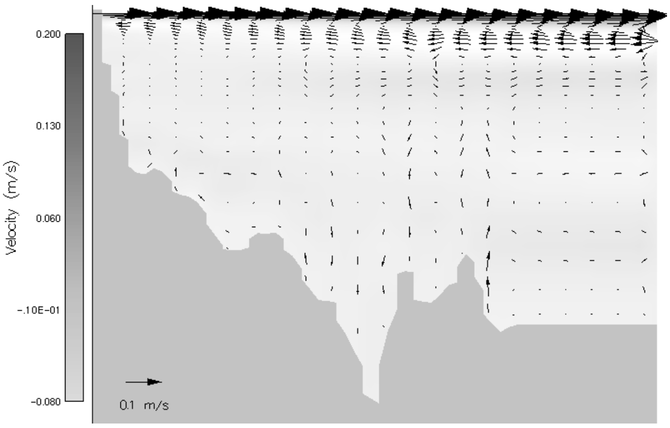

FIGURE 4: *Residual currents after one year simulation (arrows) and horizontal velocity (grey scale) showing the three layer circulation. The vertical vector component scale is 500 times the horizontal vector component.*

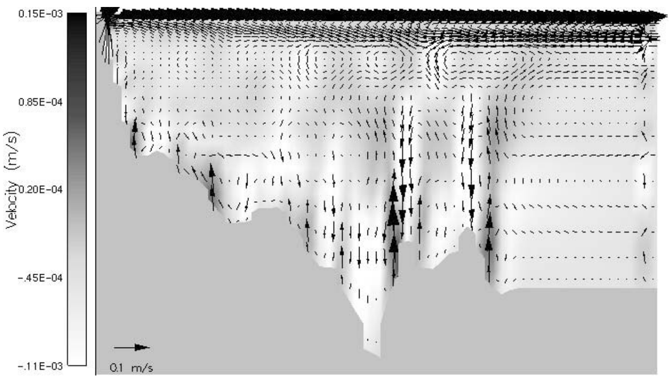

FIGURE 5: *Residual currents after one year simulation (arrows) and vertical velocity (grey scale) vertical vector component 1000 times the horizontal vector component.*

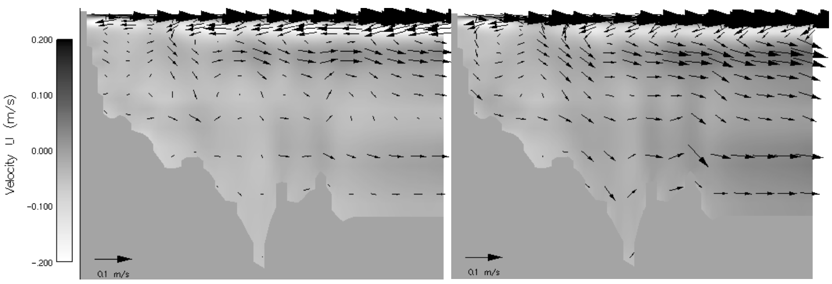

FIGURE 6: *Instantaneous currents during flood (Left) and ebb conditions (Right).*

3.2 Salinity and Temperature

Most of the data used for the Aysén study area come from the different CIMAR-FIORDOS oceanographic cruises (hereafter, CIMAR) that cover the whole system of southern Chilean fjords funded by the Chilean Navy's Hydrographic and Oceanographic Service (SHOA, its Spanish acronym). 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 profiles data collected on the 10th of February 2007 on nine stations along the Aysén Fjord. Further descriptions of these datasets can be found on the chapter "Ecological Conceptual Model for a Southern Chilean fjord: the Aysén Fjord case study".

Vertical salinity gradients in the Aysén fjord are sharp due to the high amount of water collected by the fringing watersheds that reach the surface of the waterbody by their respective watercourses. River flow characterisation is not sufficiently defined due to the lack of observations in many of the watercourses. The largest one in discharge volume is the Aysén River located at the innermost part of the fjord. The other rivers for which discharge information is available are located in the vicinity of the Aysén River.

Haline stratification occurs in the first meters where values decrease from surface values between 2.70 and 10.60 PSU (inner and outer station values) to stable deep values of around 31 PSU at 80 meters (Figure 7), though the strong halocline is in the first few meters, i.e. the inner stations go from 2.7 to 25 PSU in 3 meters. Salinity values increase steadily seawards, this stratification is also maintained by the inputs from the lateral entrance of freshwater along the whole length of the fjord, with relatively low values of salinity at the mouth of the fjord. This intense halocline extends through all the fjord from 10 to 25 m deep; however its intensity varies in time due to the variability of the river discharge and tidal variability (Guzman and Silva 2002).

The salinity on the fjord presents a nearly steady situation during the whole year due to the high river discharges. The surficial low salinities are found also in the outer reaches of the fjord because due to the strong stratification mixing with deep water is minimal (Figure 8). Deep waters permanently maintain salinity values typical of the Chilean Inland Sea of around 31 PSU. In the horizontal, the interseasonal difference would consist in the extension of the fresh water plume seawards. Model results agree with the features described for the salinity; these features are shown in Figure 9.

Temperature in the fjord also shows a steep gradient in the surface waters. Below the thermocline typical values for the fjord along the year are around 10-11 ^{o}C. On the other hand, surface waters present a seasonal range due to atmospheric heating and cooling, of 4 to 14 ^{o}C, and the rivers temperature, between 1.5 and 12 ^{o}C (Table 2). This wide range of temperatures would be important for the ecological diversity and the appearance of HABs as is described in the chapter "Ecological Conceptual Model for a Southern Chilean fjord: the Aysén Fjord". Below the thermocline near the head of the estuary at around 25 m depth a temperature inversion is present . This phenomenon is more common during spring-summer conditions though it can also be observed in winter. In the innermost stations during spring-summer conditions the typical decreasing profile is disrupted at 25 m by a mass of colder water. Also in the data collected by SalmonChile on the 10th of February of 2007, under summer conditions, when the river discharge is lower than during wintertime show this watermass with different temperature trapped in the subsurface (Figure 10). The seasonal variation in surface temperatures is larger in the fjord water than in the nearby coastal water as can be seen in Figure 11. During summer temperatures are relatively similar over the study area whereas during winter a clear gradient occurs between the fjord waters and coastal water with differences of 5 °C.

Model results are quite in agreement with the observations (Figure 12) with different temperatures and inversions also observed in the model results. During summer (Figure 12 Right) subsurface water would correspond to warmer water that enters forced by the tide underneath the surface freshwaters. During winter (Figure 12 Top), water with higher temperature than the defined range, around 0.1 °C over the surrounded water, and this water mass would be flowing seawards. The mechanism proposed for this characteristic is that during winter due to the low temperatures on the surface and of the river discharge a cold thin layer is formed that covers a warmer water that maintains the heat due to the high stratification and as was commented with regard the residual currents their exit would be through the bottom layer of circulation loosing its temperature as travels through colder waters. However, this temperature minimum seems to not influence the density profile; in fact the Aysén fjord could be regarded as a nearly uniformly stratified watermass (Figure 13). The proposed explanation for this is the contrary effect that the salinity profile has on density.

4 DISCUSSION AND CONCLUSIONS

The occurrence of harmful algal blooms (HABs) has been related to years that presented temperatures higher than the average for the Aysén fjord. Three species found in the area are related to the production of toxins: *Alexandrium catenella* (PSP- paralytic shellfish poisoning), *Dinophysis acuta* and *D. acuminata* (DSP- diarrhetic shellfish poisoning). During warm years the proportion of toxic and harmful microalgae increases in the total phytoplankton population.

Toxic dinoflagellates appeared in temperature ranges between 10.5 and 14.5 °C. (Cassis et al. 2002). For this reason, it is relevant to characterise the hydrodynamics and processes regulating temperature and salinity. Model results and analysed data suggest a three-layered circulation with a top layer dominated by river discharges that presents temperatures and salinities different from the surrounding coastal waters with the differences being more intense during winter when river flows are larger. Under this thin top layer appears an incoming current that penetrates the system mainly tidally forced, providing waters with temperatures and salinities typical for the Chilean Inland Sea. The entrance of these waters results during winter in a tongue of warmer water that is trapped between colder layers and that during summer, as the surface is heated, flows outside as part of the third layer of circulation which is mainly seawards.

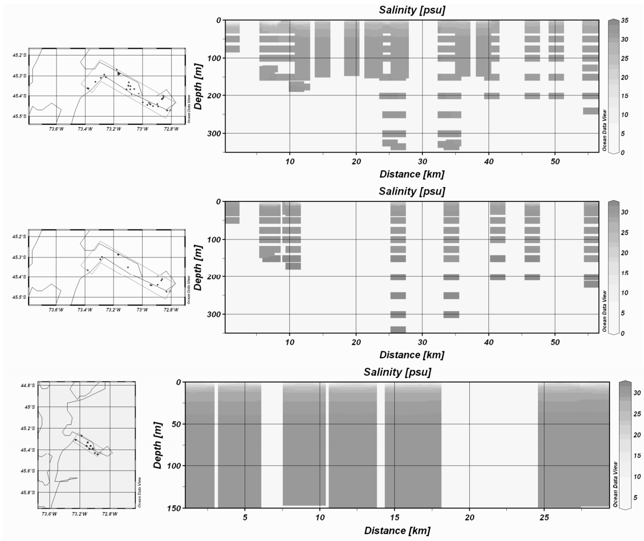

FIGURE 7: *Salinity profiles along the Aysén Fjord for the CIMAR spring-summer cruises (Top), winter cruises (Middle) and Intesal campaign in February 2007 (Bottom). Distance is measured seawards from the innermost station.*

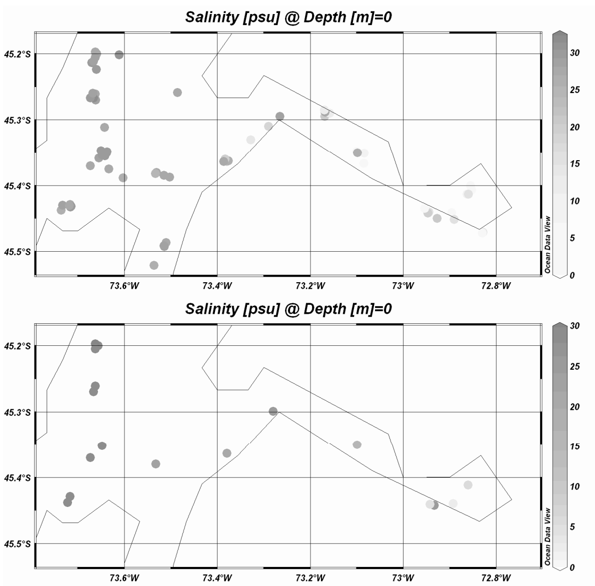

FIGURE 8: *Surface salinity in the Aysén Fjord and the adjacent part of the Moraleda Channel during the campaigns carried out in spring-summer (Top) and winter (Bottom) conditions.*

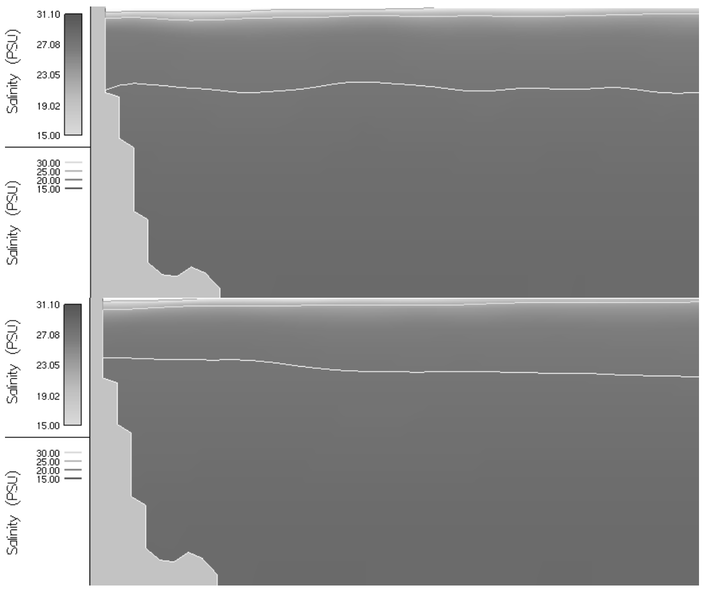

FIGURE 9: *Modelled salinities for the months of July (Top) and January (Bottom).*

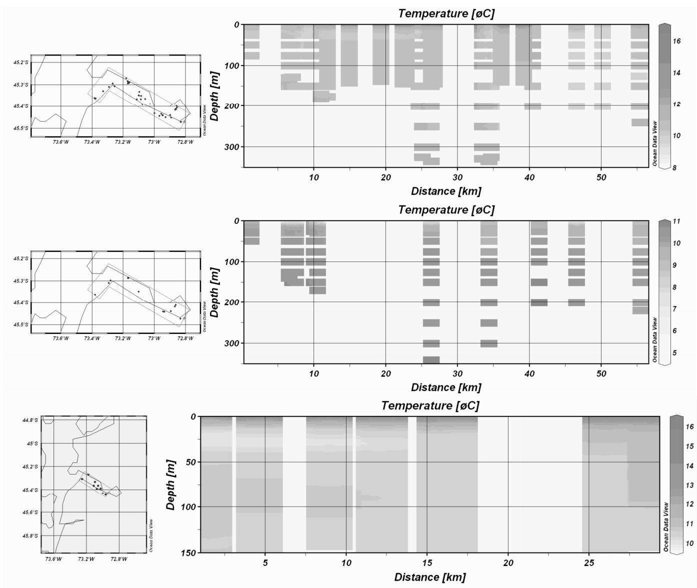

FIGURE 10: *Temperature profiles along the Aysén Fjord for the CIMAR spring-summer campaigns (Top), winter campaigns (Middle) and Intesal Campaign in February 2007 (Bottom). Distance is measured seawards from the innermost station.*

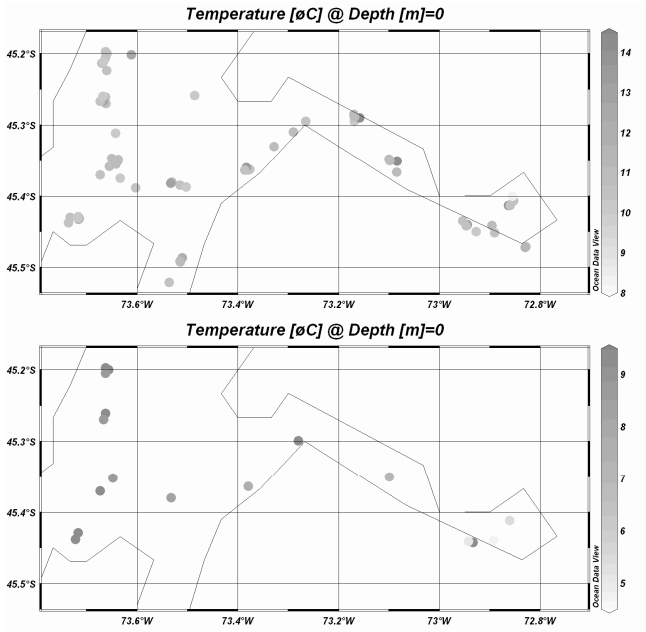

FIGURE 11: *Surface temperatures in the Aysén Fjord and the adjacent part of the Moraleda Channel for the campaigns carried out during spring-summer (Top) and winter (Bottom) conditions.*

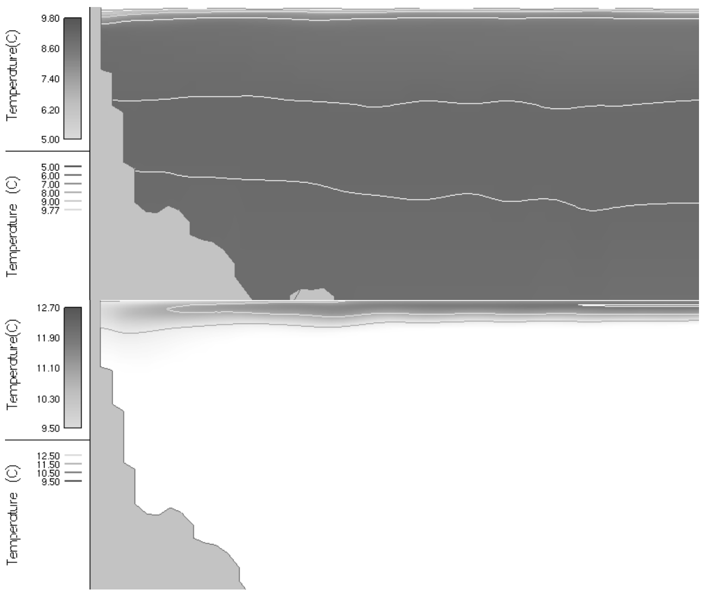

FIGURE 12: *Surface modelled temperatures for the months of July (Top) and January (Bottom).*

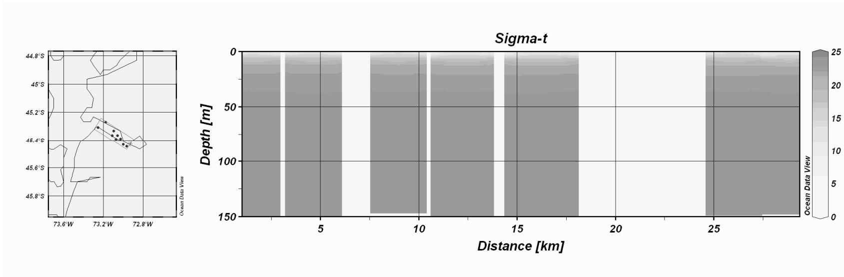

FIGURE 13: *Density profiles along the Aysén Fjord, distance is measured seawards from the first station (Source: SalmonChile).*

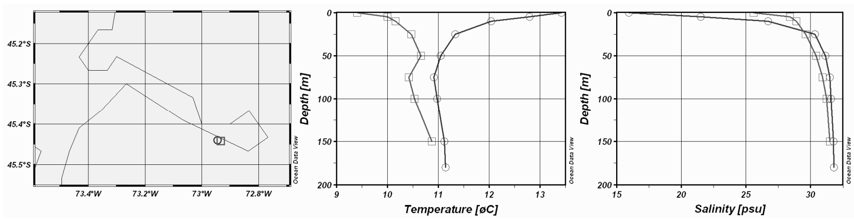

FIGURE 14: *Temperature and salinity profiles during a summer cruise (CIMAR 4, circles) and a winter cruise (CIMAR 9, squares).*

Figure 14 represents temperature and salinity profiles for two stations located at similar locations in the fjord collected during CIMAR cruises in different seasons. The differences in surface salinities and in temperature profiles can be clearly seen. Salinity values are higher during summer due to lower freshwater discharge while the vertical structure of temperature shows an intermediate water layer that breaks the typical temperature decrease.

REFERENCES

Burchard H (2002) Applied turbulence modelling in marine waters, Vol. 100 of Lecture Notes in Earth Sciences, Springer, Berlin, Heidelberg, New York, 229pp.

Cáceres M, Valle-Levinson A, Sepúlveda H H, Holderied K (2002) Transverse variability of flow and density in a Chilean fjord. Continental Shelf Research 22: 1683-1698

CADE-IDEPE Consultores en Ingeniería (2004) Diagnóstico y clasificación de los cursos y cuerpos de agua según objetivos de calidad - Cuenca del Río Aysén. CONAMA - Comisión Nacional del Medio Ambiente.

Canuto V M, Howard A, Cheng Y, Dubovikov M S (2001) Ocean Turbulence. Part I: One-Point Closure Model Momentum and Heat Vertical Diffusivities. Journal of Physical Oceanography 31: 1413-1426

Cassis D, Muñoz P, Avaria S (2002) Variación temporal del fitoplancton entre 1993 y 1998 en una estación fija del seno Aysén, Chile (45º26'S 73º00'W). Revista de Biología Marina y Oceanografía 37: 43-65

Guzmán D, Silva N (2002) Caracterización física y química y masas de agua en los canales australes de Chile entre Boca del Guafo y Golfo Elefantes (Crucero Cimar Fiordo 4). Ciencia y Tecnología del Mar 25: 45-76

Leitão P C, Mateus M, Braunschweig F, Fernandes L, Neves R (2008) Modelling coastal systems: the MOHID Water numerical lab, this volume.

Valle-Levinson A, Cáceres M, Sepúlveda H H, Holderied K (2002) Patrones de flujo en los canales asociados a la boca del Seno Aysén. Ciencia y Tecnología del Mar 25: 5-16

Yarrow M, Leitão P C (2007) Simulating Nothofagus forests in the Chilean Patagonia: a test and analysis of tree growth and nutrient cycling in SWAT- 4th International SWAT Conference July 2-6 2007